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By Ji-Chao Li & Ji-Qiang Li

Hoseo University

Abstract- By investigation of movement of the Assur groups in normal connecting condition, and by inspection of the kinematic pair concept, the conclusions were found that "The freedom of Assur group is zero" in the Planar Mechanism Composition Principle conflicts with the fact that Assur group can move, and the external kinematic pairs of Assur group are inconsistent with the kinematic pair concept. Proposals were put forward then that the motion characteristics of Assur group should be studied in normal connecting conditions, Grade I Linkage Group should be introduced, and the PPP Type Linkage Group existence as an example was provided. Some new views were put forward in discussion of Planar Mechanism Composition Principle. And then an example of mechanism analysis was given to show that the correct statement of the Mechanism Composition Principle is helpful to solve mechanism analysis problems.

IMPROVEMENTONPLANARMECHANISMCOMPOSITIONPRINCIPLE

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Improvement on Planar Mechanism Composition Principle

Ji-Chao Li[α] & Ji-Qiang Li[σ]

Abstract- By investigation of movement of the Assur groups in normal connecting condition, and by inspection of the kinematic pair concept, the conclusions were found that "The freedom of Assur group is zero" in the Planar Mechanism Composition Principle conflicts with the fact that Assur group can move, and the external kinematic pairs of Assur group are inconsistent with the kinematic pair concept. Proposals were put forward then that the motion characteristics of Assur group should be studied in normal connecting conditions, Grade I Linkage Group should be introduced, and the PPP Type Linkage Group existence as an example was provided. Some new views were put forward in discussion of Planar Mechanism Composition Principle. And then an example of mechanism analysis was given to show that the correct statement of the Mechanism Composition Principle is helpful to solve mechanism analysis problems.

Keywords: planar mechanism composition principle; assur group; grade I linkage group; ppp type grade II linkage group; internal connecting pair; external connecting pair.

I. Introduction

It commonly exists such formulations in teaching materials of Mechanical Principle in universities as the member group who is the most simple, can´t be disassembled further, and whose freedom is zero, is called the basic linkage group or Assur's Group [1]. Any plane lower pair mechanism can be seen as the system made up of several basic linkage groups successively connecting to the original motive parts and the frame. This is the composing principle of planar lower pair mechanism [2].

According to the concept that freedom is the number of independent motion parameters, so the system whose freedom is zero can´t move. The freedom of the basic linkage group is zero [3]. But the basic linkage group is movable. How to correctly understand such self-contradictory statement? To find the origin of the problem, we should study those most basic element conception. The elements composed of the mechanism are simply members and kinematic pairs. So, it is necessary for us to make clear and unify those element conceptions to avoid ambiguity [4].

Here list only RRR, RRP, RPR, PRP, and RPP five kinds of basic linkage group in Mechanical Principle

Author α σ: Department of Mechanical Engineering, Graduate school, Hoseo University, Asan 31499, South Korea.
e-mails: jichao@naver.com, ljq7436@naver.com

textbooks, it denied the exist of PPP type basic linkage group. Whether the PPP type basic linkage group exist or not, we should not arbitrarily give a conclusion. We should judge it according to the definition and the practical examples of the basic linkage group. If the special mechanism using the PPP type basic linkage group can be found, and then the existing characteristics of the PPP type basic linkage group can be proved, and so the errors that exclude the PPP type basic linkage group can be corrected in the university textbooks [3,5].

II. The Statement of "the Components Group Whose Freedom is Zero"

a) The conception of "Freedom"

Before two component members (member, thereafter) compose kinematic pair, they have six relative freedoms in space. After two members compose kinematic pair, the relative movement between them will be constrained. The relationship between kinematic pair freedom (expressed as "f") and constrain number (expressed as "s") is f=6-s [6]. In planar motion, member 1 which has not formed kinematic pair with member 2, has three independent motions: moving along x axis, moving along y axis and rotating on the axis vertical to the moving plane, namely it has three freedoms. And when the two members connect with kinematic pair, the relative motions between the two members are limited. This kind of restriction is called constraint. That is the fact that kinematic pair introduces constraint and reduce the member's freedom [7].

So, the number of the independent motion parameters is the number of the freedom. If the freedom is zero, namely there is no independent motion parameter, there is no relative motions. The freedom of the basic linkage group is zero, can it move? And how to study the motion performance of the basic linkage group? As we all know that the mechanism is movable, the basic linkage group as part of it is also movable. So the difficult to judge the motion condition of zero freedom emerges.

b) The conception of "Kinematic Pair"

When members compose mechanism, various members should be connected with one another by some means, and every member should at least be connected with other one member. Obviously such connection should guarantee that there are still some

relative motions between two connected members. Such movable connection composed by two members' direct contact is called kinematic pair[1,6].

We can see that there is no kinematic pair with only one member existing, and there is also no kinematic pair when one member does not connect with other member. Separate the mechanism's frame and original motive parts connecting with the frame from follower system, and make them independent [6], this can make the kinematic pair change, for the connection has been divided, and the divided connection is not kinematic pair any more. While the basic linkage group reserves such "divided connection", I will ask if such connection is still "kinematic pair"?

c) The "Kinematic Pair" in the basic linkage group

The "kinematic pairs" in the basic linkage group have been classified. In every basic linkage group, the kinematic pairs connecting the internal members in the linkage group are called internal pairs, the kinematic pairs connecting the basic linkage group and other members are called external pairs [7], there are also conceptions as "external kinematic pairs" [9], "external connecting pairs"[10], "external end pairs" [11], "internal kinematic pairs" [6, 8], "inner pairs", "outer pairs" [12, 13].

In mechanism moving graphics, "the internal pairs" and "the external pairs" are not distinguished by different symbols. Can they be identified clearly? And can they convert into each other? As "the kinematic pairs"are movable connections composed by two members' direct contact, is there contradiction between the concepts of "external pairs" and "kinematic pairs"?

III. THE STATEMENT OF "THE COMPOSING PRINCIPLE OF PLANE MECHANISM"

a) The problem of whether the property of mechanism movement changing

Any plane lower pair mechanism can be seen as systems composed by many basic linkage groups consequently connect to original motive parts and frames [6].The connection mentioned here does not mention the uniqueness of the connecting position, if the connecting positions of frame, and those of original motive parts exchange, and thus influence the kinematic dimensions of the mechanisms, and further influence the movement property of the mechanisms.

If many basic linkage groups are arbitrarily connected to original motive parts and the frame, and then the movement dimensions can be changed, and the movement properties of the mechanisms can be changed either, can we still speak the mechanism is composed as such?

b) The Problem of Reality Reflection of Mechanism Composition

When the mechanism structure is analyzed, we commonly use the methods of low pair replacing high pair to study the composition principle of plane higher pair mechanism. So, according to the characteristics that the freedom of the basic linkage group is zero, what characteristics is the basic group with high pair existing? For example, the mechanism as figure 1(a), if we use low pair replacing high pair, we can get the mechanism as figure 1(c), and decompose as in figure 1(d). We can judge the original mechanism is Grade II mechanism. But if we do not use low pair replacing high pair, we can get figure 1(b), it is composed of one basic mechanism and one basic linkage group composed of one linkage (member 2), one high pair and one low pair. To decompose the mechanism as such, it is closer to the original mechanism reality, and it is convenient to analyze the performance.
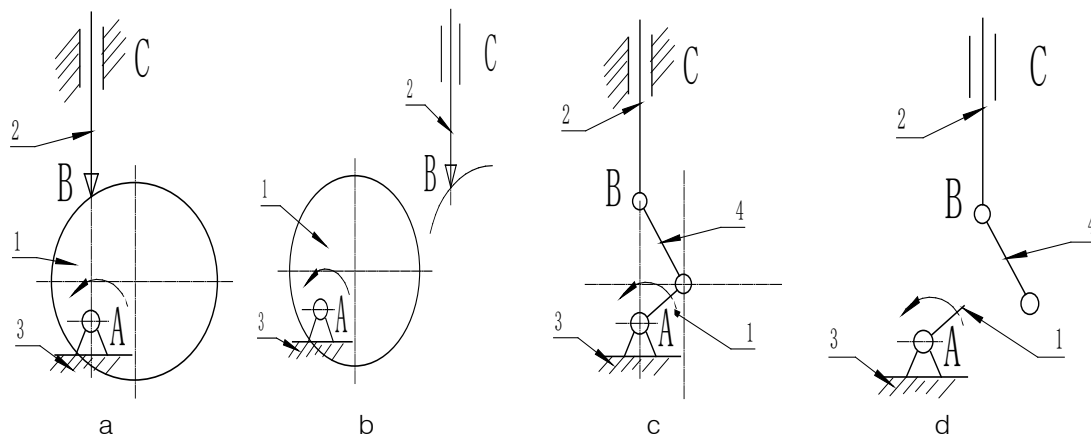
Figure 1: The mechanism structure: (a) a high pair mechanism; (b) anslyzing 1; (c) anslyzing 2; (d) anslyzing 3

IV. How to Study the Performance of "the Basic Linkage Group"

a) The premise to study the performance of basic linkage group

According to the definition of kinematic pair, strictly speaking, the external connecting pairs of the basic linkage group are only artificially assumed symbols representing kinematic pairs, which have already lost the real nature of the connection. So, to see the property of the basic linkage group, you should connect the external connecting pairs consequently to the original motive part and frame, and then those external connecting pairs have actual connecting sense, and they compose the genuine kinematic pairs.

The composing characteristics of the basic linkage group is zero freedom. It is the inevitable result people can obtain after artificially defining the basic mechanism and removing it from the whole mechanism. The basic mechanism is the members' system composed by one low pair member and the frame, and it has the same freedom as the number of the original motive parts, and it can move as well. To see whether the basic linkage group can move relatively, we should connect the external connecting pairs to the original motive part and the frame, then we can see the real properties of relative movements of the basic linkage group. Namely, we can judge the basic linkage group's relative movement properties in real connecting conditions.

b) The existence of PPP type linkage group and its proof

As a mechanism is a kinematic chain who has definitive relative movements. When any basic linkage group is connected consequently to the original mechanism and the frame, the basic linkage group should have relative motility. The basic linkage group composed of two members and three lower pairs is called grade II linkage group, and it has five types [14]. Although the freedom (F) of PPP type member group (namely the member group whose three lower pairs are all prismatic pair types, shown as figure 2) is $F = 3n - 2P_L = 3 \times 2 - 2 \times 3 = 0$, but we usually do not think it as grade II linkage group. Various teaching materials list out five types of grade II linkage group, including RRR type, RRP type, RPR type, PRP type and RPP type [6-10], it excludes PPP type linkage group. The view that PPP type linkage group is not a basic linkage group composed of two members and three lower pairs is not right.
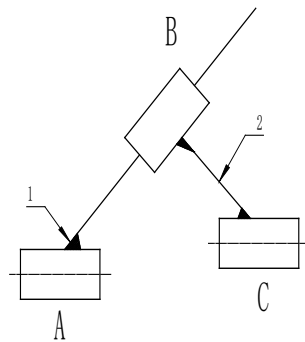
Figure 2: PPP type linkage group

To see whether the PPP type linkage group exist or not, is to see if there is such mechanism which can be composed by connecting the basic mechanism and the PPP type linkage group consequently to the original mechanism and the frame. The mechanism shown as figure 3(a) can be found, and all its kinematic pairs are movable, and it can realize determined relative motion. Its freedom $F = 3n - 2P_L - P_H = 3 \times 5 - 2 \times 7 - 0 = 1$, the number of original motive parts. So the mechanism has definitive relative movements. The mechanism can be decomposed into structural composition shown as figure 3(b). Where the PPP type linkage group is a basic linkage group composed of two members and three lower pairs. So, the PPP type linkage group is also a basic type of grade II linkage group.

a   b
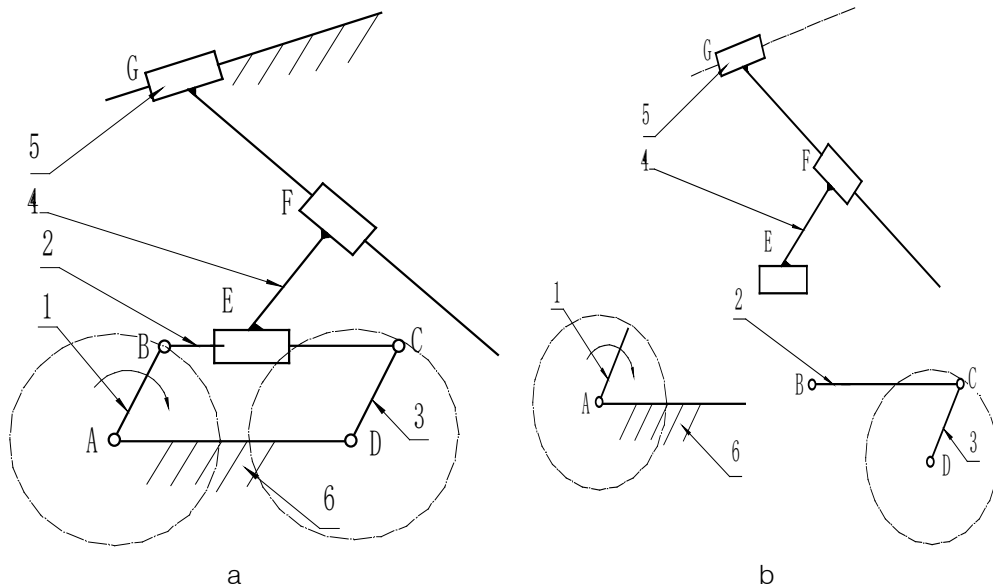
Figure 3: (a) an example using PPP type linkage group; (b) mechanism structural disassembling

The basic linkage group can move, and it illustrates that: the freedom of the basic linkage group exists. But the calculating result according to combination of members and constraints condition is zero. So, where has the freedom of the basic linkage group lost? Connect the basic linkage group only to one member, the connection will turn into a rigid body. Connect the basic linkage group to the basic mechanism, namely connect the external connecting pair consequently to the original motive part and the frame, while the original motive part moves according to independent motion law, it has freedom, And the freedom of the frame is zero. So, the motion properties of the basic linkage group actually depends on such connections, and the freedom of the basic linkage group depends on the original motive parts.

V. Correction and Improvement of the Planar Mechanism Composition Principle

In view of the above defects and deficiencies existing in the planar mechanism composition principle, correction and improvement are made on them.

a) Definition and expression of the basic linkage group

The basic linkage group is the composition of members and kinematic pairs whose freedom is zero under normal connecting conditions. The composition meets with mechanism composition formula:

$$F = 3n \times 2P_L - P_H = 0 \qquad (1)$$

Where, n is the number of movable members; PL is the number of lower pairs; PH is the number of higher pairs

The basic linkage group can separate subsequently from the frame and the original motive parts, but we should distinguish external connecting pair from internal connecting pair when the basic linkage group is drawn individually. The internal connecting pair is the actual existing connection between members among the basic linkage group, and it does not involve in the connection to the frame or the connection to the original motive parts, it only keep the connection among the basic linkage group itself. The external connecting pair maintains corresponding kinematic pair constraint properties, but it is not the actual existing connection when the basic linkage group is drawn individually. The external connecting pairs can only respectively involve in the connection to the frame or the connection to the original motive parts, and they can´t simultaneously connect to the same one member. To distinguish the external connecting pair from the internal connecting pair, suggest the former to adopt dotted line symbols to express.

b) Improvement of the planar mechanism composition principle

i. *Guarantee relative movement property unchanged*

For structural analysis of planar mechanism, the concrete relative kinematic dimensions' influence on members' relative motions should be considered, to draw dotted line symbols of corresponding kinematic pair on the separating position or to preserve the component length which is corresponding to the position of the external pair, so to accurately mark down the relative positions of the kinematic pairs.

ii. *The planar mechanism composition analysis process reciprocal to structural analysis process*

When mechanism structural analysis (group dividing) is carried out, the process should be reciprocal to mechanism composition process. Because when composing the mechanism, the external connecting pair connects with the original motive parts or the frame, so

when the mechanism is group-divided, such connection pair should not be cast away. In other words, no single-pair-member could emerge. And only the external connecting pair can connect with the frame or the original motive parts, the dividing group should not only meet with the mechanism composing equation (1), but also keep its internal or external connecting pair property. And because the basic linkage group should consequently connect to the original motive parts and the frame, so dividing the linkage group in the reciprocal process should not just separate the internal connecting pair or just separate the external connecting pair.

iii. *Grading method of the basic linkage group*

The basic linkage group's grading should according to its normal connecting condition. The higher pair element should be preserved actually within the basic linkage group, so the grade I group [15]—one member, one higher pair and one lower pair should be added. The two-linkage three-pair member group is grade II group, it has one internal connecting pair and two external connecting pairs. The four-linkage six-pair member group, which having close profile composed by three internal connecting pairs is called grade III group, which having close profile composed by four internal connecting pairs is called grade IV group [8], grade III group has a three-internal-connecting-pair three-pair linkage; grade IV group has four-internal-connecting-pair characteristics, and should be recognized in the connecting conditions to the frame and the original motive parts, such property should not be changed. For the further higher Grade linkage group, because its scare application, we do not study here.

iv. *Non-repetition Principle*

Some component-members form kinematic pairs with the same component-member, for example, many members form kinematic pairs with the frame, we should disassemble the mechanism according to every member, every kinematic pair emerges only-one- time principle, and we only mark the frame symbol in the basic mechanism, only draw the external connecting symbol in the basic linkage group.

VI. THE VALUE AND APPLICATION OF THE INNOVATION THEORY

The key of the innovation theory lies in such important studying results that the application example of PPP type grade II linkage group is found, and the existence of PPP type grade II linkage group is approved. The theory also clarify the ambiguous understanding about internal connecting pair and external connecting pair during mechanism disassembling. The theory finds an effective method to analyze the property of the basic linkage group, and find actual application basis. To use the dotted line symbol to represent the external connecting pair, and use solid line symbol to represent the internal connecting pair, it is a very simple method, and its meaning clear, and it removes communicating obstacles of ambiguous understanding and expressing problems for the development, application and improvement of the mechanism theory. So, the innovation theory has not only far-reaching theoretical significance but also important application value.
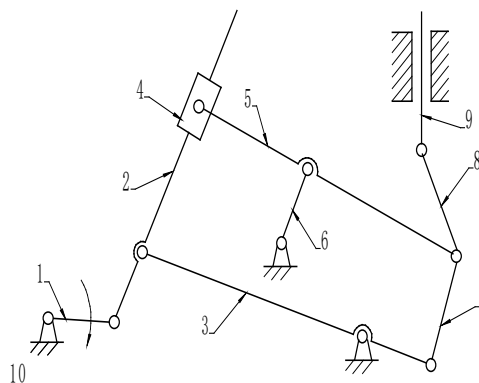
Figure 4: An example to be analyzed
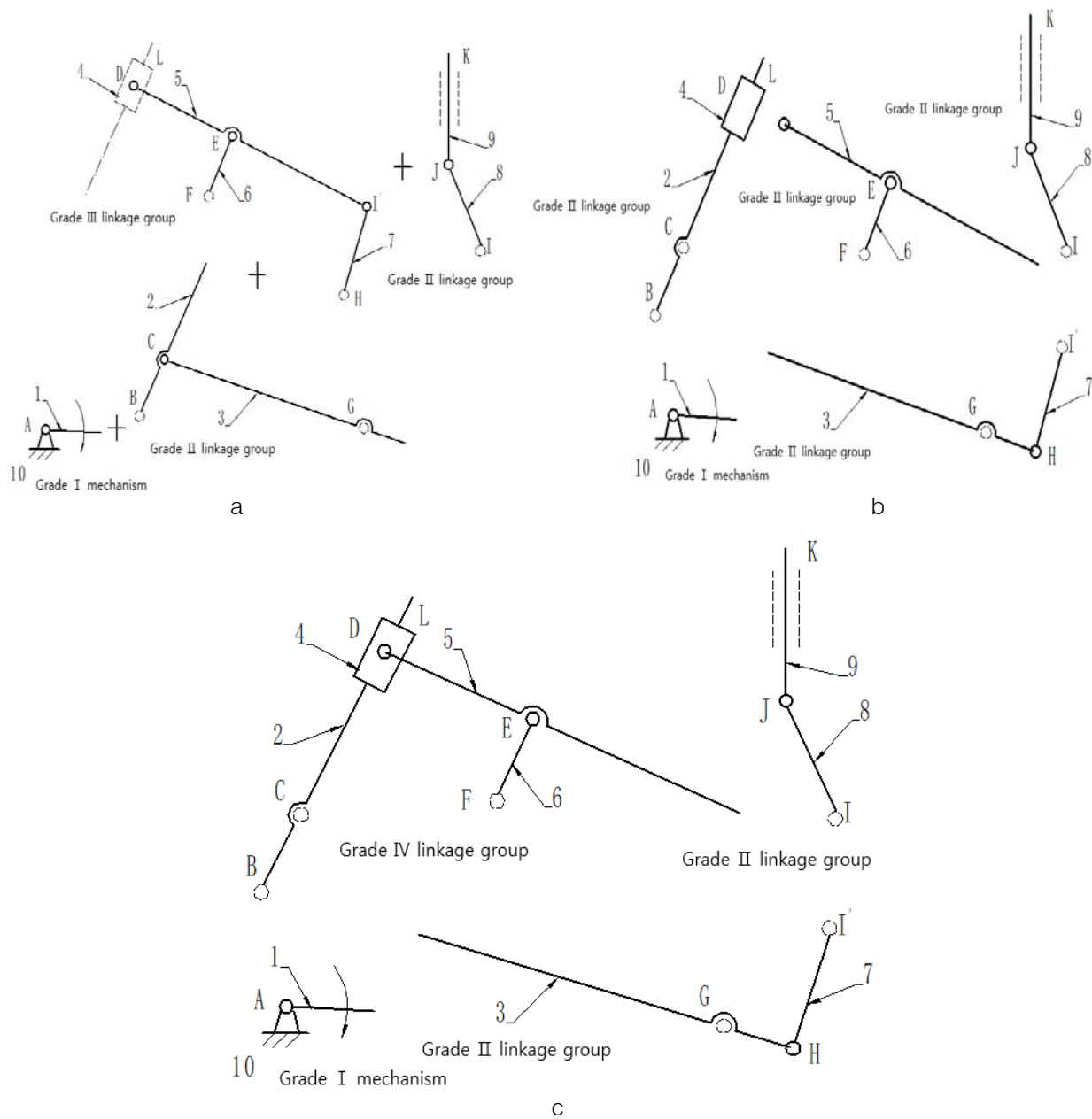
Figure 5: An example to be analyzed; (a) Result 1; (b) Results 2; (c) Results 3

Practice serves as the only standard of examining the truth. [16] For instance, we can use the above theory to analyze the structure of the mechanism shown as figure 4 [6]. We can disassemble the mechanism into the basic mechanism and many basic linkage groups as in figure 5(a). It shows that the analyzed mechanism is grade III mechanism. But if you disassemble the mechanism as figure 5(b) and figure 5(c) to analyze the structure without considering the above theory, the results are not correct. For there are no external connecting pair which connects to the frame in 2-4 basic linkage group in figure10; there are no two external-connecting-pair structural characteristics to consistent with grade IV linkage group within 2-3-4-5-6 group in figure 5(c).

ORCID iDs
Ji-QiangLi https://orcid.org/0000-0002-2129-1252

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Assessing Stability of a Pit Slope using Observed Correlation between Surficial Damage and Strain Level during a Planar Failure Monitored by Radar

By Dr. Pramod Rajmeny

Abstract- The ability to understand various field deformation indicators during a progressively failing slope and predict the probable time of failure is essential for optimizing mine production with safe working environment. Slope failure prediction methods using deformation, velocity, acceleration, strain criteria, etc., have been in practice for the last few decades. However, these require validation through field symptoms for confidence decisions, thus making the latter (field symptoms) vital for the whole failure process.

In this paper, a progressively failing slope (involving a non-day lighting plane failure mode)was investigated at an open pit mine in which growth of various surficial symptoms was measured at five locations in the field while a corresponding rise in deformation was recorded by real time monitoring by slope stability radar. The surficial damage has been characterized by field symptoms like spalling, development of face extension cracks, movement of pre-existing faults at the toe of the slope and tension cracks at the slope crest.

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I. Introduction

During the last decade, remarkable advances have been made in understanding the mechanics of slope failures, yet considerable challenges remain in characterizing and modelling the complex mechanics involved. As engineers are increasingly required to undertake landslide or slope failure hazard appraisals and risk assessments, they must address both the consequence of slope failure and the hazard or probability of failure; a critical component of both is an understanding of the underlying processes/mechanisms driving the instability so that spatial and temporal probabilities of failure can be addressed. New measurement techniques, notably borehole televiewer tools, photogrammetry, LiDAR remote sensing and real-time, high resolution In SAR monitoring, are contributing unprecedented amounts of data. Interpreting and applying this data, however, still remains largely subjective.

     The slope monitoring techniques can register and record deformation, but their outcome cannot be directly used for assessing stability. In operating mines, a Slope Stability Management Plan (SSMP) or Ground Control Management Plan (GCMP) requires evaluation of various degrees or levels of stability and incorporation of a Trigger Action Response Plan (TARP). Often total deformation and velocity-based criteria indicating various levels of triggers are set in the TARP. Many times, a progressive activity turns into regressive and accordingly, the whole TARP becomes defunct. Therefore, radar measurements must be combined with conventional monitoring techniques and validated by visual inspection of the unstable area. Relying on radar or any other monitoring dataset without a visual inspection is an unsafe practice and could result in a slope hazard being overlooked[1] (Dick et al., 2015). In this view, it is aimed to identify various symptoms of failure in the field, like spalling, extensile cracks, movement of pre-existing geological faults and tension cracks and to correlate their behaviour (i.e., degree of damage) with extensional strain. For this purpose, a non-day lighting planar failure occurred in an open pit whose identity has been purposefully not disclosed because of business interests, was chosen for detailed investigation. Based on the degree of surficial damage of the field symptoms, a broad and general stability assessment of a slope can be made from the correlation. It will help in validating radar measurement. Its back analysis particularly can be utilized for (a) delineating parameters of the TARP and (b) more vitally, for calibration of geotechnical model.

Author: Hindustan Zinc Ltd., India. e-mail: pramodrajmeny@gmail.com

II. Progressive Failure of a Mine Slope: State of the Art

The study of slope stability is an issue of great interest to mining companies across the globe. Slope instability usually involves not only significant financial implications but also serious safety concerns. Successful prediction of pit slope failures like that in Bingham Canyon highlights the importance of having a comprehensive slope monitoring system that provides an accurate prediction of the time of failure of an open pit slope. An adequate slope monitoring system allows miners to work confidently below pit walls that are deforming but are not progressing toward catastrophic failure. Confidence in the pit wall behavior allows mining to be carried out for as long as possible, resulting in optimized extraction of the mineral resources. The "monitor as you mine" approach is commonly used in mature mines where slopes are in various stages of instability and there is comprehensive experience base in the behavior of the pit walls.

Conventional methods of displacement monitoring in slopes were based on point measurement, for example, involving survey prisms. These methods indicate regressive or progressive displacement stages at discrete points and, hence, localized external or surficial damage. With the recent introduction of the latest slope monitoring techniques like photogrammetry, scanners and slope stability radar, the displacement is recorded over wide areas at pixels that can be displayed in point-cloud format. Slope radar technology not only allows improved temporal estimates of increasing/ cumulative displacements (reflecting external damage) but also the ability to spatially correlate damage/ displacements with rock mass quality variations, structures and lithology.

Proactive mines implement surface monitoring systems as the pit walls are developed instead of waiting until an instability occurs, recognizing that it is generally easier and more efficient to install surface instrumentation as the slope is mined. Surface displacement acceleration is generally the main precursor to slope failure[2] (Read and Stacy, 2009). Surface displacements are still the primary means by which mining operations evaluate the stability of a slope and are generally easier to monitor than subsurface movement.

a) Progressive failure and correlation with strain

It is to be noted that the progressive failure of slopes and factors associated with movement of slopes are extremely complex and highly nonlinear. Therefore, methods of data mining turned out to be ideal for discovering new information in the data, which are recorded periodically in continuous monitoring. Slopes seldom fail spontaneously; before the failure, instability indicators are evident in the form of measurable movement and/or the appearance of cracks. Precursors and early indicator movements can provide warning of a disaster landslide. There are different modes of deformation and failure that can happen on steep slopes. These include: (a) when a slope is excavated or exposed, there is an initial response period because of stress re-distribution[3] (Zavodni, 2001), which is common in mines with a rapid rate of excavation; and (b) in some cases, water pressure can be high initially, but as time progresses, the water pressure immediately behind the slope may dissipate, and various combinations thereof.

Stead et al.[4] (2007) describe the stages in the brittle failure of a rock slope with respect to failure processes as primary, secondary and tertiary. It is suggested that these stages also reflect similar changes in damage evident in a rock slope. Sullivan[5] (2007) recognized five stages: elastic, creep, cracking and dislocation, collapse (failure) and post failure. Progressive failure of pit slopes has been extensively investigated. A typical deformation time trend (Fig.1) has been described by[6,7,8,9,10] Dick et al. (2013), Zavodni and Broadbent (1980), Vernes (1982), Martin (1993), Mercer (2006) and others. Various stages of progressive failure, e.g., elastic, steady stage, cracking and dislocation, are described in detail.

Fig.1, modified[6] after Dick et al. (2013), shows failure divided into regressive, progressive and post-failure stages. The onset of failure occurs at the transition between regressive and progressive stages, at which time the rate of damage increases. Laboratory acoustic emission studies by Stead and Eberhardt[11] (2013) on varied rock types have shown similar stages in acoustic emission activity associated with creep mechanisms. This behavior in a low confining stress environment can be interpreted as brittle damage dominated creep mechanism, and it sometimes is adversely affected by changes in water pressure. The process of brittle failure through crack propagation in slopes is hence a fundamental damage dominated failure mechanism involving degradation of rock bridges, destruction of asperities and roughness along potential failure surfaces, and the development of through-going step path failure. Together, damage processes in rock range from the initial micro-scale (intra/inter-granular micro-cracking) through meso- and macro-scale coalescence of fractures and comminution of the rock slope mass during global slope failure.

Numerous recent studies in rock engineering have recognized the importance of crack initiation, crack damage and crack coalescence during brittle rock failure. These studies have incorporated different stress or damage thresholds to derive new failure criteria that are more applicable to brittle rock under low confinement. Recent studies demonstrated their applicability of such tri-linear or S-shaped criteria[12,13] (Diederichs, 1999; Kaiser & Kim, 2008) to large open pit slopes[14] (Eberhardt, 2008).
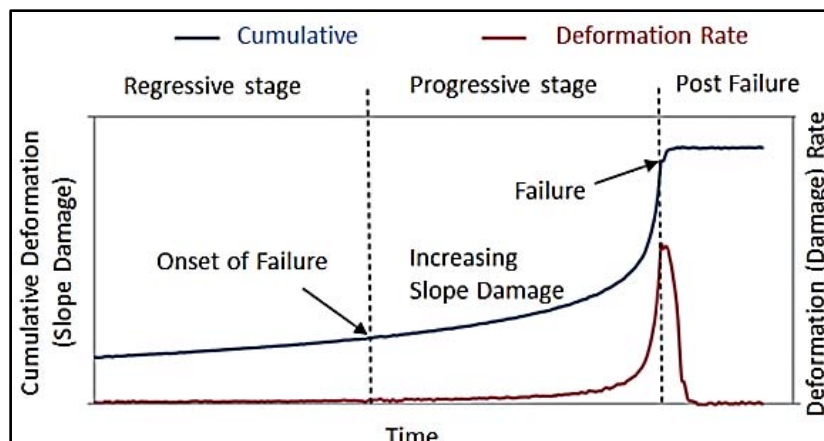
Fig. 1: Stages of slope deformation and damage in rock slopes (modified after Dick et al., 2013)

Brox & Newcomen[15] (2003) investigated a large number of slope failures correlating breaking strain with rock mass rating for various modes of failure, including plane, wedge and toppling failure (Fig.2). One of the key conclusions of the work was that the strain at failure is generally influenced by the quality of the rock and that, in general, the lower the rock quality, the higher the potential strain at failure. The results of the study suggest that the deformability of the rock mass, which can be estimated from the RMR, plays a primary role in the amount of strain a pit wall can accommodate prior to failing. However, those assessments also indicated that the failure mode must be considered when assigning the allowable strain in a pit slope. For, example, much smaller movements are more tolerable in a pit wall susceptible to planar failure than one susceptible to toppling.
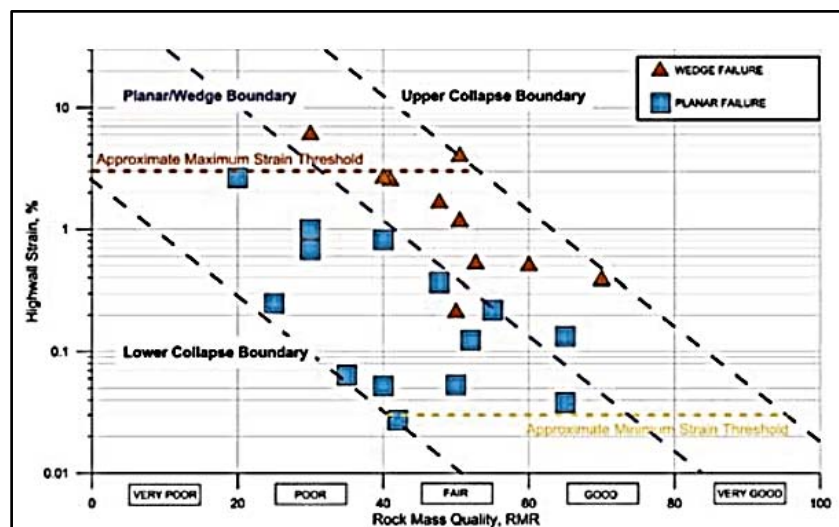
Fig. 2: Correlation between strain vs RMR for planar and wedge failures (after Brox and Newcomen, 2003)

These investigations (Fig.2)further indicate that planar failure generally occurs at the lowest strains and can occur over a relatively wide range – up to 1.5 orders of magnitude[15] (Brox and Newcomen, 2003) for a given RMR. Several slopes that experienced planar failure collapsed[15] (Brox and Newcomen, 2003) at strains between 0.03% and 0.06%.The maximum strain measured for a planar failure was about 3%. Here, the strain in the pit slope was defined as the total movement measured at the surface divided by the height of the slope below the prism.

To summarize, it must be noted that slope failure phenomena, factors associated with movement of slopes and their prediction, are extremely complex and highly nonlinear. However, slopes seldom fail spontaneously; before the failure, slope indications are delivered in the form of measurable movement and/or the appearance of stress cracks. Precursors and early indicator movements can provide warning of disaster landslide. Numerical models allow for insight into the failure mechanisms involved. Since numerical models do not pre-suppose any failure mode, they can be used to reveal the failure mode with the lowest safety margin. Thus, the technology of data mining or data mining generated by the latest measuring techniques in conjunction with numerical modeling can be used to predict movements. However, interpreting and applying these data to assess stability remains largely subjective

as geological complexity and uncertainty continue to pose major obstacles. Therefore, visual observations are very crucial for understanding the phenomena of slope failure and so is correlation with different progressive stages. Secondly, despite the evolution of the latest monitoring techniques, it is always prudent to validate both the output of the monitoring and numerical modeling with visual observations in the field.

III. THE CURRENT INVESTIGATION

Current investigations studying surficial damage and recording of corresponding deformation was carried out in an open pit mine (Fig.3) which was about 2.5km long, 1.5km wide and 420m deep. The pit was

housed in Garnet Biotite Sillmanite Gneiss (GBSG) – moderately strong rock with uniaxial compressive strength in range of 40 to 74MPa and Rock Mass Rating (RMR) 40-55. Name and location of the open-pit operation, object of the present study, are confidential (because of business interests) and therefore, cannot be disclosed as well as specific details concerning the mined ore body. The pit (which has been active for over 40 years) was worked by 10m high benches with 42° inter-ramp angle (IRA) and 35° as overall angle for the footwall and 48° as IRA and 42° as overall angle for the hanging wall. Instabilities are typically structurally controlled and relatively shallow. These include planar, wedge and topping failure mechanisms.
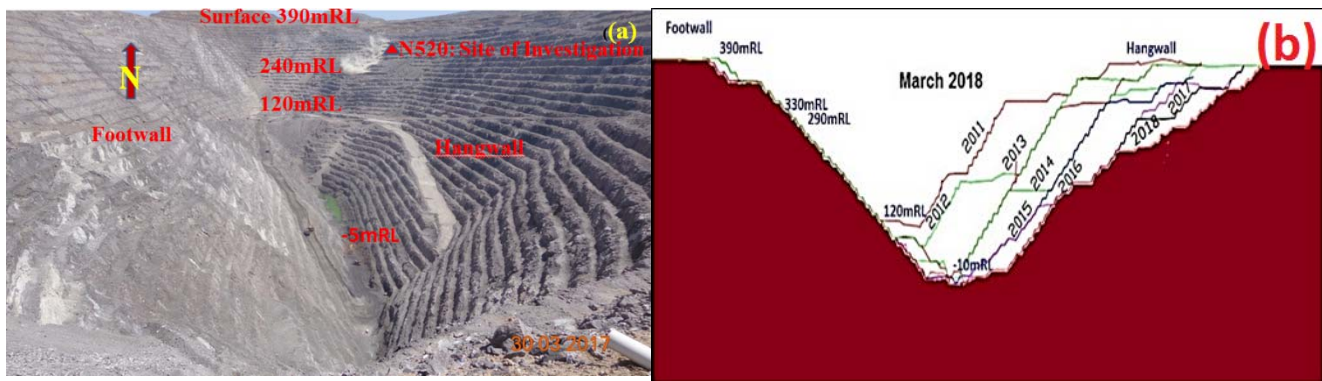
Fig. 3: Panoramic view of the open pit and a section showing progress of mine excavation

From a geological point of view, the ore body consists of an intrusion through enclosing Garnet Biotite Sillimanite Gneiss (GBSG) formation. The mine area is a stratiform, sediment-hosted deposit and occurs in Pre-Cambrian Banded Gneissic Complex. It forms a part of geological cycle of Archean age and comprising of magmatites, gneisses, graphite mica schist, pegmatite, amphibolite, etc. The rocks were subjected to poly-phase deformation and high-grade metamorphism. The deposit is a plunging isoclinal synform while the host rock occupies the core of the synform and plunges in southwestern limit at 65-70° due North East (NE). The

mineralization is hosted in Graphite Mica Sillimanite Gneiss or schist (GMS), whereas Garnet Biotite Sillemanite Gneiss and Garnet Biotite Gneiss (GBG) form the wall rocks. The wall rock, GBSG, forming about 70-80% of the matrix, is intruded with Pegmatite and Amphibolite.

The wall rock has uniaxial compressive strength (UCS) of 33-74 MPa with other average mechanical properties produced in Table 1. The rock mass of the footwall (west wall) and hanging wall (east wall) has a Rock Mass Rating (RMR) in the range of 45-55.

Table 1: Average mechanical properties of intact rocks of the mine

Rock type	Uniaxial compressive strength	Tensile strength	Young's Modulus	Poisson's ratio
	(MPa)	(MPa)	(GPa)	
GBSG	33	6.5	10.4	0.14
Amphibolite	74	14	22	0.14
Pegmatite	71	6.2	12	0.05
GMS/Ore	57	9	20	0.12
GBG	43	9	12	0.13

The footwall (Fig.4) is prominently foliated with the foliation (70°/N140°; dip/dip direction) running almost parallel to the strike direction of the pit and dips into the pit. In the northeast (NE) region of the hanging wall pit, phase-3 (Fig.4), the foliation is parallel to sub-

parallel (within ± 20°) to the strike direction of the pit profile, which makes it susceptible to instability. The situation used to get further aggravated due to the presence of geological faults, which are also sub-parallel to the pit strike in this region. The strike of the

NE pit region is along N290° (its dip direction) while the foliation having dip along with N300° and the faults with N270° (within ± 20°) respectively (Fig. 4). It is, thus, a most unfavorable combination of pit slope in the hanging wall and prone for instabilities.
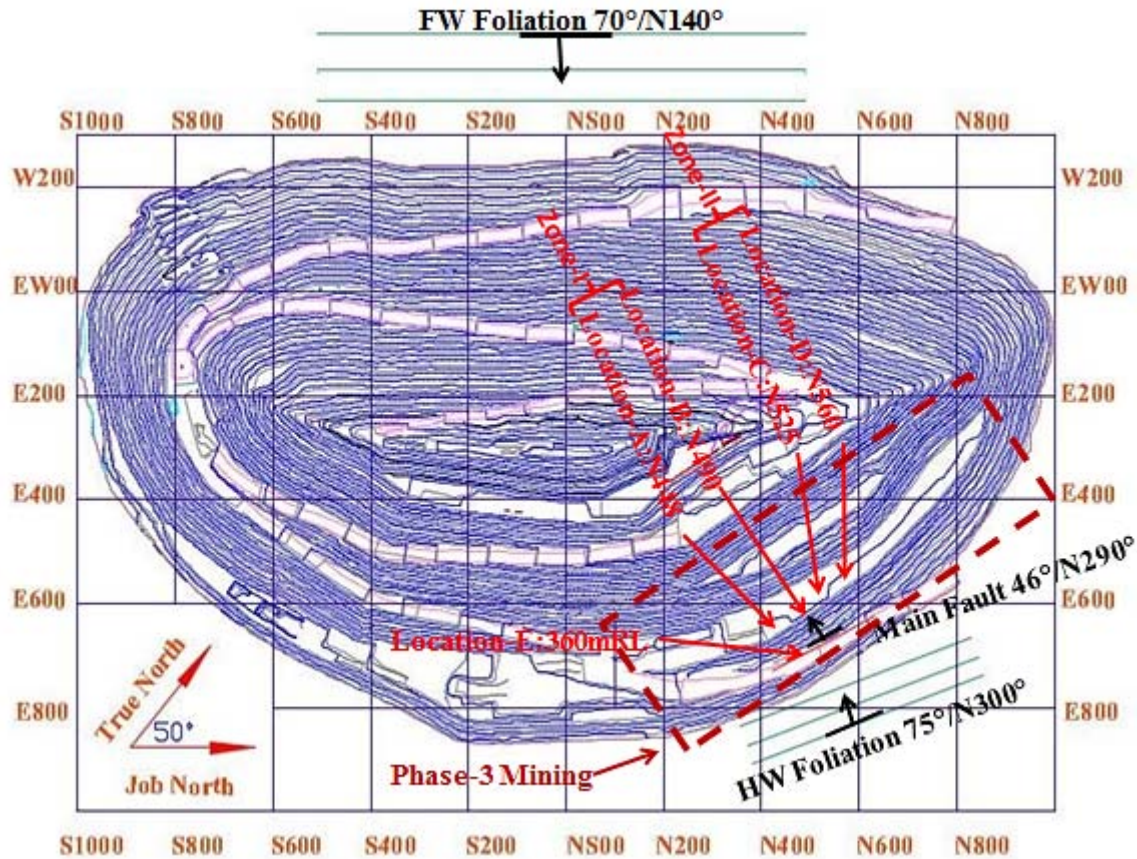
Fig. 4: Plan view showing locations of investigation & geological details

Extraction in the pit was going in the last phase of Life of Mine (known as Stage-4). The current investigation involved the northern part, situated on the east wall (i.e., hanging wall), started in April 2017 from surface 390mRL. This operation was planned to reach up to a depth of 400m (-10mRL), the ultimate depth. However, when the excavation front reached a depth of 90m from surface (at 310/300mRL, surface is 390mRL, Fig.3& Fig.4), an instability called N525 was experienced for a strike length of about 200m (between N425-N625 local pit grid). The area between 390 to 310mRL was put under critical monitoring using slope stability radar.

With gradual sliding of the slope along the failure plane (Fig. 5), the bottommost bench at 310mRL (which was accessible) experienced maximum surficial damage in form of bulging/toe crushing.

The instant investigation consisted of capturing various surficial symptoms and measuring their growth with rise in the deformation (as recorded by the slope stability radar) at five locations – four at toe of the slope (A to D) and fifth at crest of the slope (E), Fig. 4 &5. These included: (a) Spalling of bench or Toe-crushing. The intensity of spalling i.e. size and extent of spalling got progressively increased and was recorded with progress of the failure. (b) Formation of Extension cracks (which were roughly horizontal and vertical in orientation): which used to dilate progressively, and (c) Widening of existing geological faults present at the site, and (d) development of tension cracks at crest of the slope at 350-370mRL and which also widened progressively.
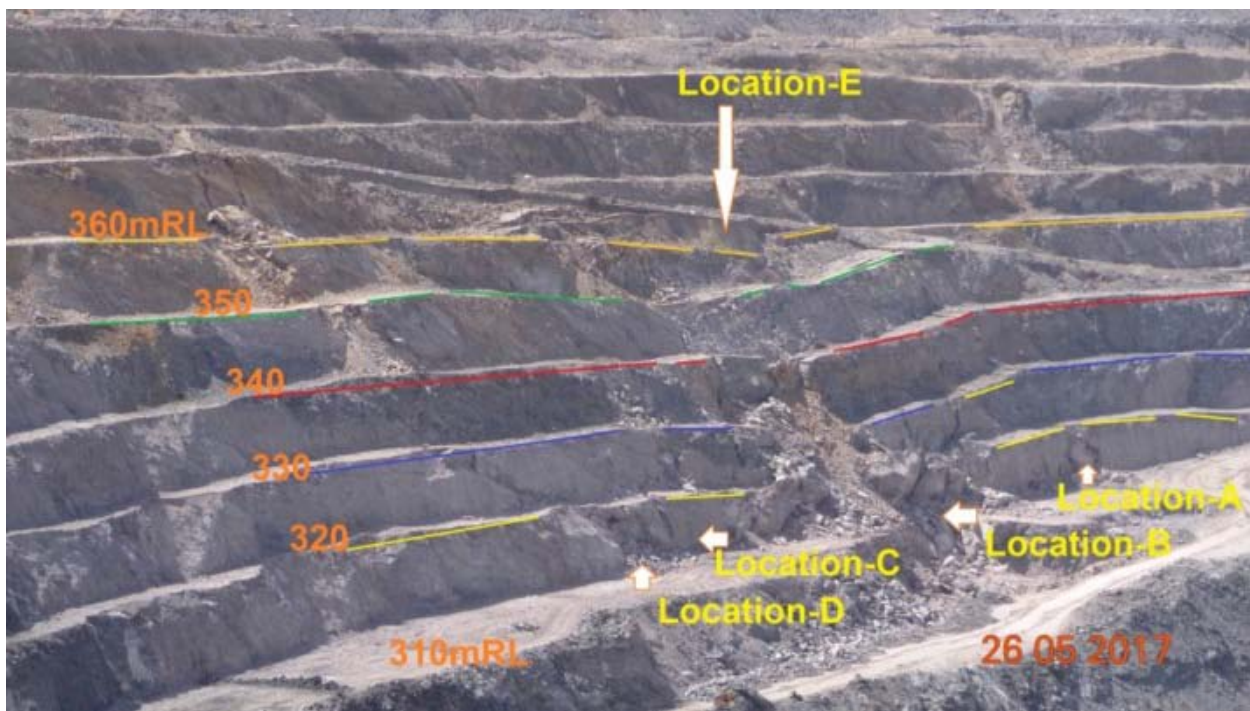
Fig. 5: Photograph showing various locations of observation

The radar recorded real time deformation (with respect to time) for zones between location A and B and location C and D separately but for the sake of simplicity and uniformity their arithmetic mean has been considered as deformation corresponding to each stage of failure in the current investigation. Similarly, same deformation quantum is used for observation point 'E' situated at the crest of the slope.
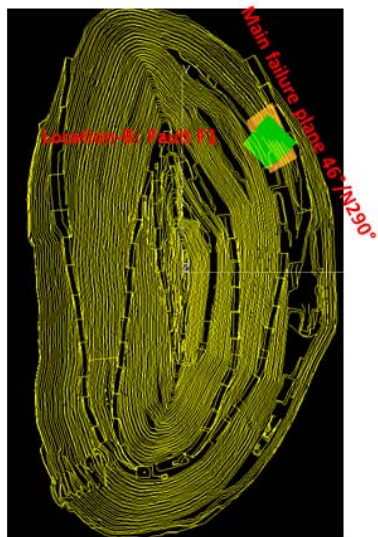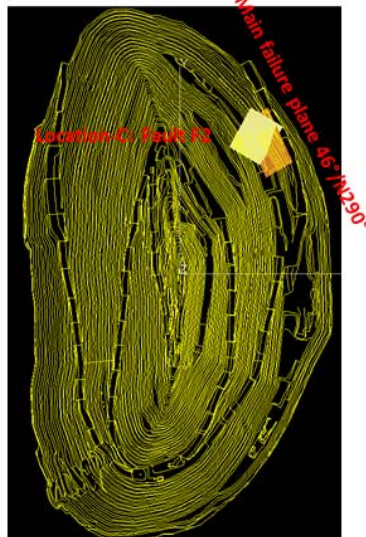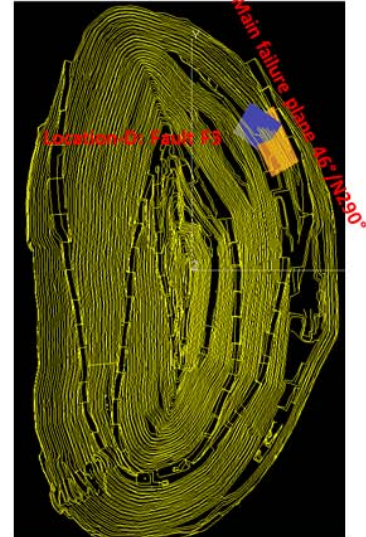
Fig. 6: Pit plan showing presence of geological fault at location B, C & D

History of growth of various field symptoms with rise in corresponding deformation and time i.e. progress of failure has been produced in Table 2 through 5.

a) Recording of surficial damage at Locations (A through D) at the toe of slope:

Location 'A' was free of any geological faults. It experienced toe-crushing or bulging with rise of deformation (or extensional strain). In due course of time, extensile cracks (which were mostly oriented nearly horizontally and vertically) were also developed, and widened. The size and extent of spalling, opening of these extensile cracks were measured (by measuring tape as given in supporting photograph in Table 2) with progress of failure. Their history of growth of various field

symptoms showing date of observation at location A, corresponding deformation recorded by the radaris produced at Table 2.

The location 'B' was traversed with a geological fault 'F1' (Fig.6). Like previous location (A), the history of

growth of various field symptoms showing date of observation, at location 'B' with corresponding average deformation recorded by the Radar are produced in Table 3.

Table 2: Showing growth of various field symptoms with date and corresponding deformation at location 'A':

Date	Deformation	Strain	Field Symptoms	
	mm	%		
10th May	104.5	0.62	Onset of toe crushing confined to lower 2-3m of bench height with size of spalled pieces upto 30-40cm	Onset of generation of horizontal and vertical extensile cracks and opened by 3-4mm
18th May	164.5	0.97	Size of the spalled pieces increased to 40cm engulfing 3-4m of bench height	
21st May	337.5	1.99	Size of the spalled pieces further increased to 90cm engulfing lower 4-5m of bench	Further widening of the extensile cracks
23rd May	426.5	2.51	Occasional acoustic sound	The horizontal cracks widened to 10-12mm
25th May	700	4.12	Size of the spalled pieces increased to 1.5m engulfing 5-7m of bench height. Continuous acoustic sound. The horizontal cracks widened to 27-30mm.	The vertical cracks widened to 35-40mm.

Table 3: Showing growth of various field symptoms with date and corresponding deformation at location 'B':

Date	Deformation	Strain	Field Symptoms	
	mm	%		
10th May	104.5	0.62	Size of spalled pieces ranged to 30- 40cm affecting lower 2-3m bench height.	Apperance of extensile cracks
18th May	164.5	0.97	Size of the spalled pieces increased up to 40cm engulfing 3-4m bench height.	Widening of vertical cracks
21st May	337.5	1.99	Size of the spalled pieces increased upto 90cm and engulfing 4-5m bench height.	Fault opened by 30-40mm
23rd May	426.5	2.51	Occasional acoustic sound.	The fault opened by 70-80mm horizontally and 35-40mm vertical movement.
25th May	700	4.12	Size of the spalled pieces further rises upto 1.5m and engulfing 7-8m of bench height. Continuous acoustic sound.	The fault opened upto 80mm.

Table 4: Showing growth of various field symptoms with date and corresponding deformation at location 'D ' and 'E':

Date	Deformation	Strain	Field symptoms at Location D	Field Symptoms at Location E	
	mm	%			
10th May	104.5	0.62	No signs of activation of the fault plane	Tension cracks opened to 30mm horizontally.	
18th May	164.5	0.97	Activation of the fault plane, development of vertical cracks and	The tension cracks opened up to 140mm horizontally	While its vertical settlement was 260mm
21st May	337.5	1.99	The fault plane came out by 30-40mm horizontally.		
23rd May	426.5	2.51		The tension cracks further opened to 240mm horizontally.	While its vertical settlement was 500mm
25th May	700	4.12	The fault plane further came out.	The tension cracks opened to 460mm horizontally.	

The location 'C' also traversed by geological fault N525 fault F2 (Fig.6) gave signs of onset of its activation when the deformation was 87mm on 10th of May 2017, as evidenced by generation of small scale spalling along its plane. The progressive increase in degree of surficial damage with respect to deformation is produced Similar is the trend for location 'D'.

b) *Recording of surficial deformation at Location 'E' situated at crest of the slope*

The behavior of tension cracks developed at location E – at 350 to 370mRL between N448 and N490 situated at the crest of the slope with rise in deformation and time i.e. progress of the failure are produced in Table 4.

IV. ANALYSIS AND DISCUSSIONS

The progressive planar failure N525 (370-310mRL) offered an excellent opportunity to measure gradual growth of surficial symptoms developed with rise in deformation (strain) on a mine scale and examine any relationship between them. These surficial symptoms included toe bulging in form of spalling, development and widening of extension cracks, movement of geological faults (situated in to e region of the failure) and development and widening of tension

cracks in crest region of the failure. The deformation was recorded real time by the radar and is produced in graphical format in Fig.7. The gradual growth of these symptoms of all five locations with corresponding deformation (and time) reported in previous section are clubbed together and produced in Table 5.
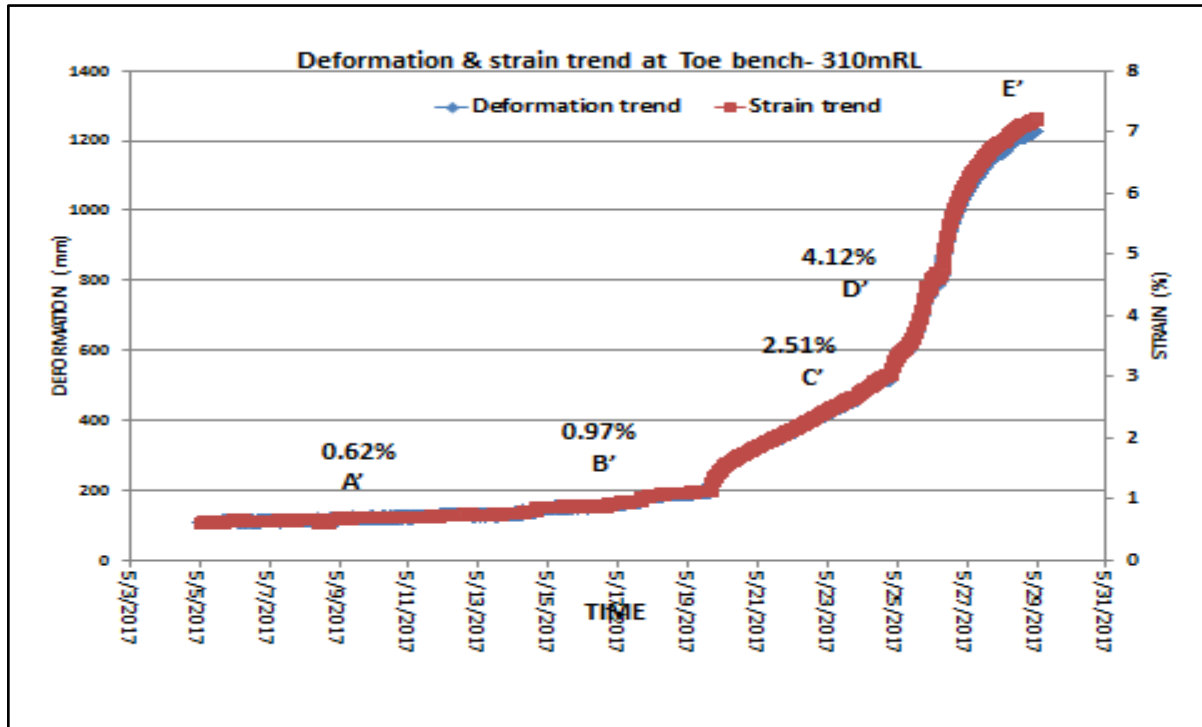
Fig. 7: Deformation & extensile strain trend of toe bench 310mRL (N490 to 525 areas, The Radar output)

For the sake of the analysis, the deformation at each stage of failure for all the locations (Table 6) has been converted to extensional strain by dividing with linear distance between the plane of the failure and the surface profile at the toe level – i.e. offset 'G' (17m at level 310RL, Fig.8). The failure plane was physically surveyed at 370mRL and was projected to 310mRL using 49°/N290° attributes. Thus,

(Extensional Strain= ((deformation recorded by Radar at location A or D)/(offset 'G' between the failure plane and slope face)*100
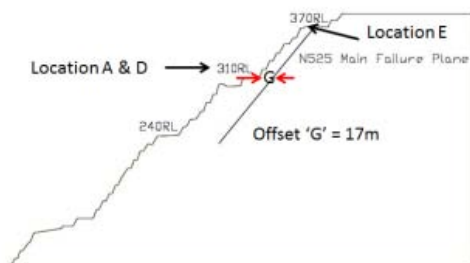
Fig. 8: Cross section through location A & D

The extensional strain for zone I (where total deformation is 0.700m and offset is 17m):

= ((0.700/17)*100)

= 4.12%

Comparison of outcome of current investigation with the studies reported elsewhere revealed that (a) the mechanism of instant rock slope sliding agrees with the observed early indicators of instability as advocated by earlier workers (Stead and Eberhardt[11], 2013), with tension cracking at the slope crest and bulging at the toe, and (b) the instability instant investigation is also progressive, with deformations taking place throughout the failure journey. It is consistent with results of a series of physical model studies stability for jointed rock slopes by Stacey[16] (2006),

a) Quantification of various stability segments

A close look at the profile of deformation (strain) verses time (Fig.7) trend recorded during the current investigation indicates that it is very much similar to the curves (Fig.9) of the classical deformation v/s time curve observed by Zavodni[3], 2001, Zavodni and Broadbent[7], 1980; Varnes[8], 1982; Sullivan[5], 2007; and Mercer[10], 2006). The very similarity between two trends permits division of the current deformation curve also into five segments on the line of generalized curve (Fig.9) and then assigning respective value of strain for each segment. These segments include -an initial elastic, steady-state segment A'B' (analogous to AB segment of Fig.9) with extension strain level upto 0.97%, cracking and dislocation segment B'C' (analogous to BC segment of Fig.9) with strain level >0.97 to 2.51%, followed by acceleration segment C'D' (analogous to

CD segment, Fig.9) and extension strain level >2.51 to 4.12% finally failure occurred at D' (analogous to point D, Fig.9) at 4.12% followed by accelerating deformation in peak segment D'E' analogous to segment DE of the classical deformation curve observed by these pioneer workers (Fig.9).

Table 5: Showing Observations of the slope damage at all the locations with date, deformation &extension strain

Date	Deformation	Strain	Location-A (N448)	Location-B (N491)	Location-D (N560 fault)	Location-E (slope crest)
May 17	mm	%	Response	Response	Response	Response
10/5	104.5	0.62	Onset of spalling engulging lower 2-3m bench height. Onset of generation of horizontal and vertical extensile cracks. These cracks opened 3-4mm & became visible to naked eyes.	Onset of bench spalling with size of spalled pieces ranged to 30- 40cm engulfing lower 2-3m of bench height. Onset of appearance of extension cracks.	There were no signs of activation of the fault in form of formation of small chips along its upper surface.	Tension crack (TC) opened horizontally by 30mm.
18/05	164.5	0.97	Size of the spalled pieces increased to 40cm. Onset of spalling along fault plane	Size of the spalled pieces was upto 40cm engulfing lower 3-4m bench height while further widening of the cracks.	Onset of vertical extension cracks formation & the fault started activated.	The TC opened to 140mm horizontally with 260mm vertical settlement.
21/05	337.5	1.99	Size of the spalled pieces further increased to 90cm engulfing lower 4-5m of bench height.	Size of spalled pieces further increased to 90cm engulfing 4-5m of bench height and the fault opened by 30-40mm horizontally.	The fault came out by 30-40mm.	
23/05	426.5	2.51	The horizontal cracks widened to 10-12mm, accompanied by occasional accoustic sounds	The fault moved to 70-80mm horizontally and 35-40mm vertically and accompanied by accoustatic sound.		The TC further opened to 240mm horizontally with 500mm vertical settlement
25/05	700	4.12	Size of the spalled pieces increased to 1.5m engulfing lower 5-7m bench height. The horizontal cracks widened to 27-30mm while the vertical cracks widened to 35 to 40mm.	Very large sized spalled pieces upto 1.5m engulfing 7-8m bench height while the fault opened by 80mm.	The fault further came out.	The TC opened to 460mm horizontally

The characteristics of the field symptoms and their degree of severity observed during each stage of stability (for all the five locations) during the instant investigation can be clubbed together, generalized and summarized as follow:
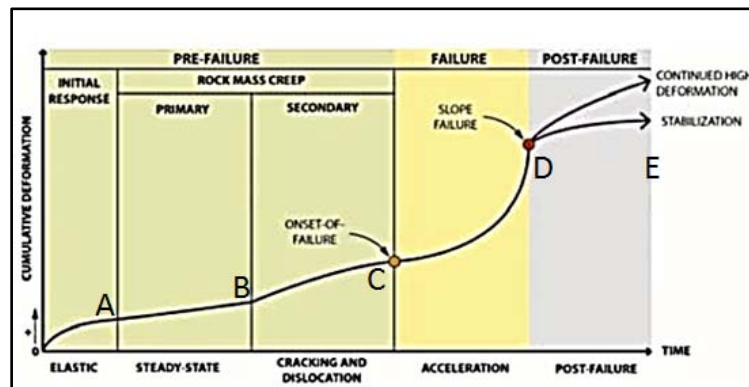
Fig. 9: Schematic deformation vs time curve leading to failure (after Zavodni and Broadbent[7], 1980; Varnes[8], 1982; Sullivan[5], 2007; and Mercer[10], 2006)

Table 6: Categorization of surficial slope damage

Strain range	Degree of damage of field symptoms	Corresponding Stability status
> 0.62 to 0.97%	Onset of spalling with size of spalled pieces upto 40cm and covering 2 to 4m bench height.	Steady state
	Onset of formation of vertical and horizontal extensile cracks having opening of about 3-4mm.	
	Gological faults getting activated exhibiting minor spalling at the fault plane.	
	Development of tension cracks. These may widen to30mm (horizontally) at 0.62% strain and further widening to 140mm at 0.97% strain. However, they may develop much before 0.62% as their initiation strain level could not be captured in the current investigation.	
≥0.97 to 2.51%	Intensity of the spalling further increases with size of the spalled pieces rising upto 90cm at 0.97% strain. It may engulf 4-5m of the bench.	Cracking & dislocation state
	The extensile cracks may open up to 10-12mm	
	The geological faults may to move to 30-40mm at 1.99% and 70-80mm at 2.51% strain.	
	The tensile cracks may (horizontally) widen to 140-240mm.	
≥2.51 to 4.12%	Intensity and volume of the spalling increase drastically. Size of the spalled pieces rises 0.9-1.5m covering half to full bench height.	Acceleration state
	The extensile cracks may widen up to 27-40mm horizontally (35-40mm vertically)	
	The geological fault may move outward 80mm and more.	
	The tensile cracks may widen horizontally to more than 240mm (with 500mm vertical settlement) at 2.51% strain to 460mm opening horizontally at 4.12% strain.	

i. Steady state segment (0.62 to 0.97% strain)
Spalling (toe bulging)

The steady state of stability can be characterized by onset of toe bulging in form of spalling in the benches situated in the toe region of the slope (like location A through D of the present case, Fig.4 and Fig.5). With rise in the extension strain, intensity of the spalling also increases. The size of spalled pieces may vary – from small chips in beginning to as large as 40cm when strain rises to 0.97% level. (Since there were no blasts taking place in the proximity of these observations sites, therefore, the observed spalling was free of any blasting damage).

Generation and opening of extension cracks

In addition to the spalling, these benches (situated in the toe region) also exhibit other symptoms like toe bulging in form of development of extensional cracks. These cracks may be oriented from horizontal to vertical. These may widen to 3-4mm at strain level of 0.62% and become visible to naked eyes. Their growth increases with rise in strain as detailed in Table 6.

Movement of Geological faults

The geological faults (like F1, F2 and F3 faults, Fig.6.) present in toe region of the slope (like locations B through D,Fig.4 and 5) experience onset of movement or activation as evidenced by generation of minor spalling along their plane in beginning when the extensional strain ranged around 0.62%.

Generation and widening of Tension cracks

With activation of the slope, the tension cracks are the first and foremost symptom to be developed in the crest region of the slope (like location E of the instant case, Fig.4 and 5). These may widen to 30mm (horizontally) when strain is 0.62%. In fact, the tension cracks developed much earlier to 0.62% of strain, but their width could not be recorded in their early stage of the instant study. With increase in strain level to 0.97%, the tension cracks opened to 140mm horizontally (with 260mm vertical settlement).

ii. Cracking and dislocation state (>0.97 to 2.51% strain)

This stability segment can be characterized by a general increase in intensity of all the surficial symptoms observed in the steady state segment. With rise in the extensional strain, the degree of toe spalling keeps on increasing to as large as 90cm with rise in strain level to 2.51% and affecting 4-5m of bench height. The horizontal extensional cracks also further widen to 10-12mm at 2.51% of strain. The geological faults move further to 30-40mm at 1.99% strain and 70-80mm at 2.51% of strain level. Likewise, the tension cracks widen (horizontally) to 140-240mm. This stage of stability accompanies with occasional acoustic sound.

iii. Accelerating stage (>2.51 to 4.12% strain)

During the Accelerating stage of stability, the severity of the surficial symptoms reach to their

respective peak. The degree of spalling at all the locations situated in the toe area of the slope get further aggravated engulfing 5-8m of bench height and the size of the spalled pieces increase to 0.9m to 1.5m at 4.12% strain. The extension cracks further widen to 27-30mm horizontally (35-40mm in vertical cracks). While the geological faults move more than 70-80mm. The tension cracks further widen to 240mm horizontally (with vertical settlement of 500mm) at 2.51% strain and opens further to 460mmhorizontally at 4.12% strain. The acoustic sound becomes regular.

b) Discussions

Slope performance is generally expressed as deformation vs time behaviour. It has found to have a classical shape of the schematic and general deformation vs time trend (Fig.9) as observed by various pioneers Zavodni[3], 2001, Zavodni and Broadbent[7], 1980; Varnes[8], 1982; Sullivan[5], 2007; and Mercer[10], 2006). However, scanty literature is available on correlation of various stability segments of the curve with strain limits and so is the case with correlation between the degree of severity of surficial damage with strain level and their progressive trend. The instant investigation is, thus, able to (a) quantify various stability segments of the schematic and general deformation vs time curve (i.e. various degrees of surficial damage level) with corresponding strain limits and (b) present detailed characteristics features of each stability segment or stage of failure along with their gradual increase in intensity or degree of severity with rise in strain or progress of failure. For example, the steady state of stability is characterized by onset of bulging of toe region in form of spalling of the bench with size of spalled pieces upto 40cm, development of extension cracks and their widening upto 3-4mm, onset of movement of pre-existing geological faults and generation of surface tension cracks with their widening upto 30-40mm. Similar is the case for other stages of the stability.

The outcome of present study i.e. correlation between degree of severity of surficial damage symptoms with strain levels (and assigning strain levels to various stability segments of the generalized deformation vs time plot,Fig.9) can be used to assess stability or performance of a slope. The assigning strain levels instead of the deformation to various stability segments has made the application of the deformation vs time curve more generalized than the site specific deformation values and without an unit (like centimeter, etc.). Moreover, the deformation value corresponding to a particular stability segment may vary mine to mine and is governed by the physic-mechanical properties of rock matrix. Therefore, to make the outcome of present study more generalized, the deformation is normalized or converted to corresponding strain. To use the outcome directly, various degree of severity of different field

symptoms need to be quantified. Say, for example, if the spalling in the toe region has size in range of 40-90cm, the extensile cracks are widened or opened to 10-12mm, the tension cracks are widened in range of 140-240mm horizontally, then the slope may in "Cracking and dislocation" stage of stability. The slope stability has worsened from "Steady state" stage and is heading towards "acceleration" stage or phase.

It is to be noted that abovementioned dimensions of spalling, widening of extensile cracks, tension cracks, etc. are general in nature. In fact, every mine needs to fine tune these dimensions for some failure cases to arrive at a definite and reliable value. Likewise, the observed correlation can be used to verify the trend captured by instruments like radar. The radar records deformation at various locations of the slope. In a open pit having detailed structural model, the deformation can be judiciously converted in to respective strain. The strains so derived on comparing with the degree of severity of surficial damage, the reliability of the measurements can be ensured. However, where it is difficult to convert the deformation to strain, the deformation and the shape of the schematic and general deformation vs time curve can also be used for assessing stability, obviously with a lesser degree of confidence.

The outcome of the present investigation estimating degree of severity from the strain level can serve as guidelines for a non-day lighting planar failure in moderately strong rocks like Garnet Biotite Sillimanite Gneiss having UCS in range of 30-70MPa, Young's Modulus of 10-20GPa and Rock Mass Rating in range of 40-55. Needless to say, the strain limits established for various stages of progressive failure- steady state, cracking and dislocations, etc. are, therefore, general in nature (not rigid) and needs to be used judiciously. More often, there may be overlap values of strain levels and degree of severity of surficial damage. As is obvious, the strain level and degree of severity of failure symptoms are governed by physico-mechanical properties, geological planes of weaknesses, depth of the slope, etc. Likewise, it is also affected by the nature of failure viz. ductile or brittle.

V. Conclusions

The instant investigation was able to capture and measure degree of severity of various surficial field symptoms with strain levels as experienced during the non-day lighting planar failure. It was progressive failure, with deformation taking place all along the failure journey which is consistent with results of a series of physical model studies stability for jointed rock slopes by Stacey[16] (2006). Major field symptoms recognized and captured during the failure process include – bulging of toe in form of spalling, development and widening of extensile cracks, movement along pre-

existing geological faults and formation of tension cracks in the crest region of the slope. These observed field symptoms are also in agreement with the observed early indicators of instability, with tension cracking at crest and bulging of toe in accordance with the concept of progressive failure advocated by earlier workers (Stead and Eberhardt[11], 2013).

The slope performance trend relating deformation with time obtained during the current investigation resembles with the classical shape of the general and schematic curve relating deformation vs time as observed by various pioneers by Zavodni[3], 2001, Zavodni and Broadbent[7], 1980; Varnes[8], 1982; Sullivan[5], 2007; and Mercer[10], 2006) and, thus, permitted its division into various stability segments viz. steady state, cracking and dislocation, acceleration segments, etc.. The present investigation has been able to (a) assign strain limits to various stability segments viz. upto 0.97% limit to steady state, >0.97 to 2.51% to cracking and dislocation, >2.51 to 4.12% to acceleration segment and failure at 4.12% of extension strain (Fig. 7 & 9), (b) provides characteristic features of each segment of stability and their increase in degree of severity with progress of failure.

The outcome of the instant investigation will be very vital for assessing stability of slopes of open pits. Knowing the degree of severity of various field symptoms like spalling, widening of extensile cracks, etc., the corresponding stability status whether steady state, cracking and dislocation, etc. can be estimated even when scanty instrument data are available. Secondly, knowing the instrumentation data – the strain vs time trend of a slope, the corresponding stability status can be estimated (using Fig.7 and Table 6). Thus, quantification of various stability stages in the schematic and general deformation vs time curve (Fig.7& 9) is a major step forward in journey of stability assessment, as often scanty data are available at the mines demarcating each stability segment and the corresponding strain limits.

Thirdly, the outcome has great potential for confirming the trends of the deformation recorded by monitoring systems like slope stability radar. For, relying on radar or any other monitoring dataset alone without a visual inspection is an unsafe practice and could result in a slope hazard being overlooked[1] (Dick et al., (2015). For example, if the radar monitoring records deformation and strain in range of >0.97 to 2.51% strain, then the slope stability would be in cracking and dislocation stage, and therefore, the slope should exhibit corresponding degree of severity of the field symptoms (i.e. severe spalling with size of spalling 40-90cm, extension cracks widening to 10-12mm, tension cracks widen to 140-240mm, etc.).Thus, the outcome is very vital because most of the time, lot of data are gathered by advanced instruments like radar, but their interpretation for assessing stability is still difficult.

Last but not the least, the results of instant investigation would be of great value in calibrating the numerical model of the slope using back-analysis, even when scanty instruments monitoring data are available. From degree of severity of surficial symptoms observed in the field, the corresponding strain level can be estimated (using Fig. 7 and Table 6) which in turn will be key element in the process of validation of the numerical modelling process of a slope.

Thus, the present investigation will be very helpful to predict the slope failure and to optimize the mine production.More number of similar experiments in different rock stuffs elsewhere will further refine the established correlation between the degree of severity of surficial symptoms and strain levels.The correlation of various stability segments i.e. degree of severity of surficial symptoms with strain levels will serve as major plank in formulating Trigger Action Response Plan (TARP) and Ground Control Management Plan(GCMP) of a mine. It would enhance confidence while taking decisions regarding mitigation and risk management.

Acknowledgement

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Using Solar Energy to Build Air Conditioning - A Case Study of Libya

By Monaem Elmnifi

Bright Star University

Abstract- The aim of this study is the evaluation of the economic and technical viability for the installation of a solar air conditioning system based on parabolic solar concentrators and adsorption technology, in an existent building. As case study was selected a bright star university located in elbrega city- Libya. Besides air conditioning, this system is also used for domestic hot water production. This solution enables the system use throughout the year in order to maximize the investment and reducing environmental pollution resulting from the use of fossil fuels in energy production. Results show that the implementation of these systems is feasible for the Libya reality and the climatic conditions enjoyed by most Libyan cities in terms of the intensity of solar radiation and most of the land is predominantly desert.

Keywords: solar energy, solar cooling, adsorption cooling, parabolic trough solar collectors.

GJRE-A Classification: FOR Code: 850599

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I. Introduction

Libya lies in the center of North Africa between latitudes 20 - 33 ° N and longitude 10 - 25 ° E. The country is located in the Sun Earth belt and about 88% of its territory is considered in the desert. According to the report of the Institute of Thermodynamics Engineering at the German Space Center in Stuttgart [1]. Which shows that direct natural solar radiation varies from 1900 kWh / m^2 / year in the far north of the country to more than 2,800 kWh / m^2 /year in parts of the south-east. Concentrated solar power plants can be considered economically valuable only for sites with direct solar radiation above 1800 kWh / m^2/ year [2]. All Libyan lands can meet this condition with higher potential than the southern parts of the country.

The sector of buildings is, on a global scale, one of the largest energy consumers (together with transport and industry sectors), becoming essential to ensure a higher energetic and environmental efficiency, thermal comfort and health conditions. Over time arose solutions to answer more directly to users comfort needs. One solution was the widespread use of air conditioning systems based on electric driven compression technology, which have improved greatly the quality of indoor environment in buildings. However, these systems improved greatly the quality of indoor environment in buildings. However, these systems immediately registered high energy consumption, heating and cooling, as well as, and nowadays represent an important share in the overall consumption of the building With comfort levels ever higher, the costs associated with air conditioning has been increasing and is expected that this growth will be even more pronounced in coming years, either due to the rising standards in comfort required by the occupants or even due to climate changes [3][4].

Nowadays in Libya, buildings account for about 60% of the electric energy consumption and about 30% of primary energy consumption [5], this makes this sector a target for intervention as regard the improvement of energy efficiency ratings. Thus, any measure to keep or improve standards in indoor comfort and at the same time allowing the reduction in the energetic bill should be aim of interest and study. With this in mind, this study proposes to analyze the use of a solar based system to obtain the required thermal energy for heating and cooling, as well as the production of Domestic Hot Water (DHW).

II. Technology

Solar cooling is a solar thermal technology that produces cold by exploiting solar energy allowing significant savings compared with traditional air conditioning plants. This is also due to the fact that the main cooling demand can be covered at the moment of maximum solar radiation. Solar energy is used to provide heat to a thermodynamic cycle that allows to produce cold water [6].

a) Parabolic Troughs

Parabolic troughs are collectors designed to reach temperatures over 100°C and up to 450°C (with a concentration ratio around 26) and still keeping high efficiency due to a large solar energy collecting area with a small absorber surface.

Author: Department of Mechanical Engineering, Bright Star University, Libya. e-mail: monm.hamad@yahoo.com

Fig. 1: Parabolic trough solar collector (PTC 1200)

Smaller parabolic troughs (Fig.1), (Poly Trough 1200) standard collector module is 1.2m wide, 24m long and 1.6m high. It consists of [7]:

- 12 composite reflector panels, each 2m long by 1.2m aperture
- 5 rigid galvanized steel mounts for ground or roof mounting with flexible spacing
- A structurally efficient galvanized torque tube
- A tubular receiver with glass envelope
- An accurate solar tracking system

b) *Adsorption chiller*

The adsorption system (Fig.2) can be compared to a conventional air conditioner or refrigerator with electric powered mechanical compressor replaced by a thermally driven adsorption compressor. The ability to be driven by heat which is used for desorption, makes adsorption cycles attractive for electrical energy savers. Also since fixed adsorbent beds are usually employed these cycles can be operational without moving parts other than magnetic valves.

This results in low vibration mechanically simple high reliability and very long life time. The uses of fixed beds also results in intermittent cycle operation, with adsorbent beds changing between adsorption and desorption stages [8][9].

Fig. 2: Adsorption chiller (SJ-10AD)

III. Methodology

To supply the energy for air conditioning and DHW was considered a system in which thermal energy is supplied through the use of Parabolic Trough solar Collectors (PTC) combined with an adsorption system (for cold production). For this, several approaches were made in what concerns the system sizing. These approaches consisted in sizing the system taking into account the energy required to meet the building energy needs, considering: monthly average area of collectors, average area of collectors in the heating period, average area of collectors in the cooling period and month in which is needed greater area of collectors. Another aspect to consider is that the installed collector power is equal to the power needed to satisfy the energy demand of the building. It is expected that total energy needs will not always be satisfied due to the fluctuation of the available solar energy along the day.

a) *Solar radiation*

In Table 1 are presented the solar radiation parameters for ELbrega city used for this study. These values were obtained from the atmospheric science data center maintained by NASA [10] and refer to the project site.

Table 1: Solar Parameters

Month	Direct Normal Radiation [kWh/m²]	Insulation [hours]
3.21	10	Jan
4.18	11	Feb
5.39	12	Mar
6.48	13	Apr
7.06	14	May
7.65	15	Jun
7.79	15	Jul
7.20	14	Aug
6.06	12	Sep
4.82	11	Oct
3.57	10	Nov
2.94	10	Dec
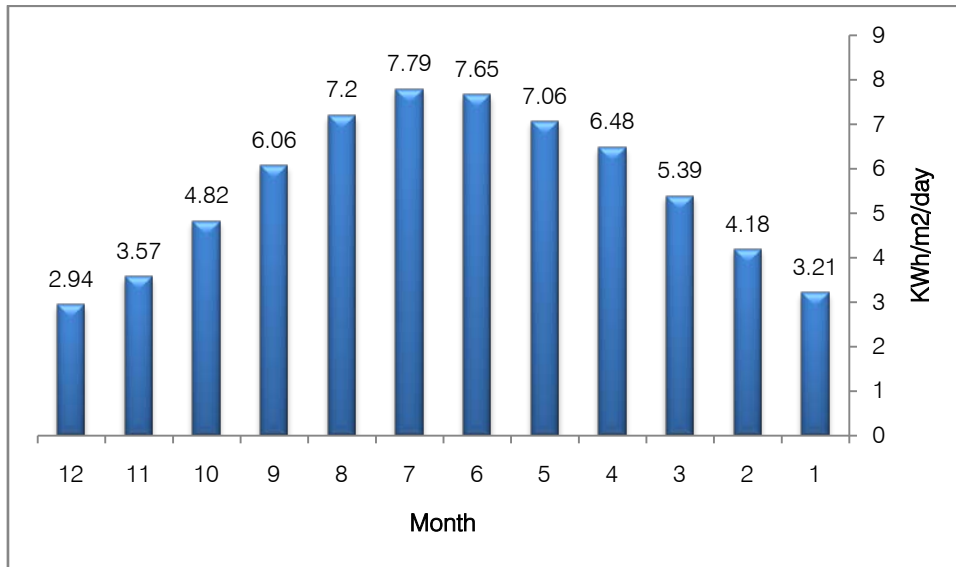
Fig. 3: The average solar radiation of ELbrega city

b) Energy costs

The considered energy costs are presented in table 2.

Table 2: Considered Prices

Electrical Energy	0.4	D/kWh

The prices presented in the Table 2 were obtained from the energy bills of the building. All prices used in this study are reported to 2010 [5].

IV. CASE STUDY

For this study was selected a administrator building of Bright Star University. The building is composed by two floors with a total surface area of 1.450 m². The building does not have any heating system.. The building is cooled using a Electrical Energy (EE). Due to the non-existence of system, it was considered that the cooling of the building is achieved by using an electrical compression chiller with a Coefficient Of Performance (COP) of 3.Table 3 lists the heating and cooling periods taken into consideration for this study.

Table 3: Heating and Cooling Periods

Heating	From November to March
Cooling	From April to October

27

جامعة النجم
الساطع
التقنية
البريقة

Bright Star University

Fig. 4: A view of building

a) System description

The thermal energy captured in the solar collectors is transferred to the internal circuit through a heat exchanger The backup will be assured by the existing hot water system (liquid/liquid). For DHW storage is used a thermal reservoir that shall come into operation when the solar collectors do not provide enough energy to satisfy the building energy demand. The system will alternate between the production of heat in the winter and cold in the summer, depending on the direction of the hot water circuit. The heating and cooling of the different indoor spaces will be done through heat exchangers (water/air) mounted in the air handling units of the building. To mitigate fluctuations in the supply of cold water, as well as to meet peak needs, the system has an inertia tank in the chilled water circuit. The operating principle diagram is presented in Fig.5.
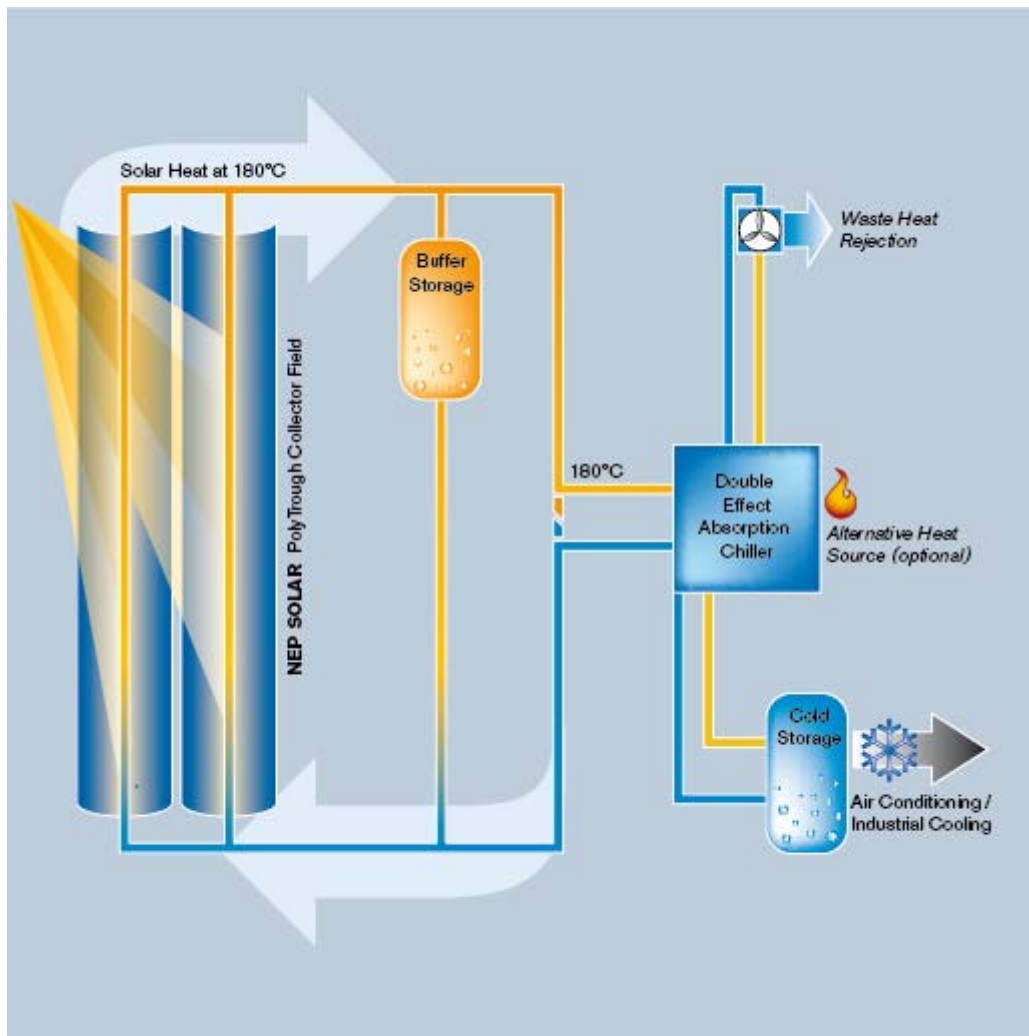
Fig. 5: Operating principle diagram

b) *Energy needs of the building*

The heating and cooling needs presented in table 4 were determined by using a Calculation equations for cooling and heating loads.

Table 4: Energy Needs

Month	Heating [kWh]	Cooling [kWh]	Total [kWh]
Jan	27.300	0	27.300
Feb	6.0001	0	6.0001
Mar	8.000	0	8.000
Apr	0	10.240	10.240
May	0	24.194	24.194
Jun	0	27.628	27.628
Jul	0	31.104	31.104
Aug	0	33.990	33.990
Sep	0	32.760	32.760
Oct	0	28.220	28.220
Nov	12.000	0	12.000
Dec	23.400	0	23.400
Total	86.700	188.136	274.836
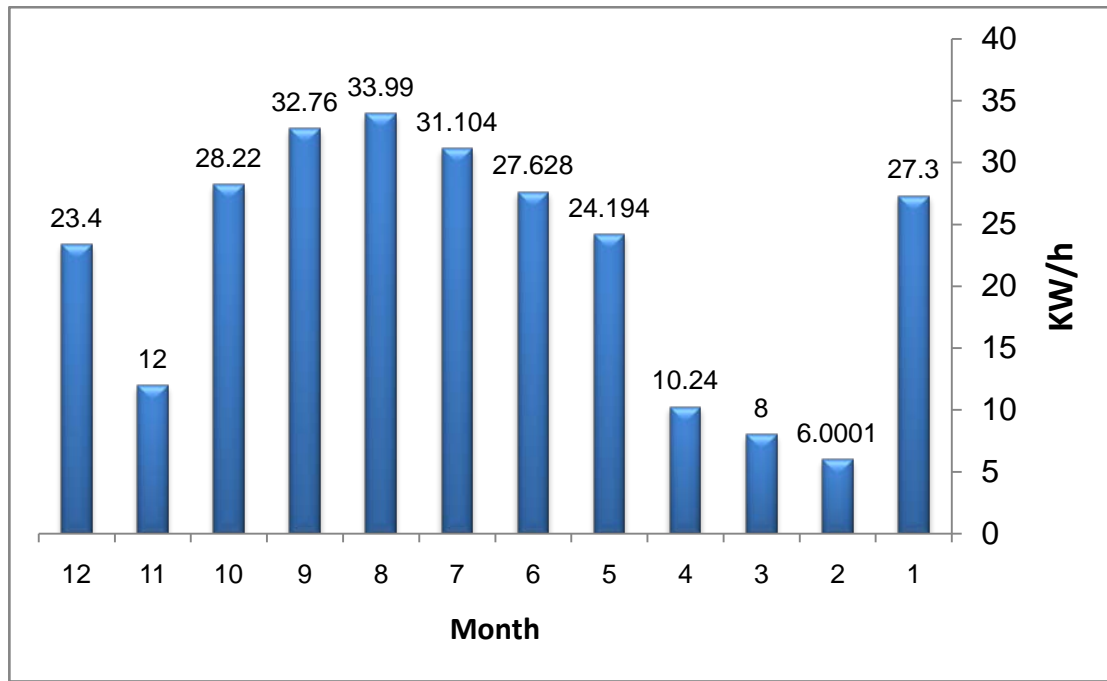
Fig. 6: Energy Needs

c) Produced Energy

Table 5 shows the monthly produced energy and the costs associated with the use of fossil fuels as backup.

Table 5: Produced Energy

Month	Energy Produced [kWh]	Energy Cost (0.4D\kWh) actual	Energy cost (0.068D\kWh) current	Energy cost (0.332D\kWh) Paid by the government
Jan	27.300	10.920	1856	9064
Feb	6.0001	6.400	1088	5312
Mar	8.000	3.200	544	2656
Apr	10.240	4.096	696	3400
May	24.194	9.677	1645	8032
Jun	27.628	11.051	1879	9172
Jul	31.104	12.441	2115	10326
Aug	33.990	13.596	2311	11285
Sep	32.760	13.104	2228	10876
Oct	28.220	11.288	1919	9396
Nov	12.000	4.800	816	3984
Total	23.400	100.573	17.097	*83503*

Table 5 shows the difference between the real value of subsidized cost kWh and the actual, loss and loss on the government due to the very high support rate 83,503dinars .Therefore, since the cost of the solar system to feed the building loads about 370,000 dinars, and compared to the value of the loss, the installation of the station means the possibility of restoring the value of the solar system in the first five years and then after 20 years free.

d) Design the model

Table 6 shows the design values of the solar system that we need to provide building loads

Table 6: Design Model

Technical data for the base module	
Area (m^2)	140
Width (m)	1.2
Length (m)	25
Height (m)	1.63
Focal length (m)	0.65
Rim angle	50^0
Weight (kg/m^2)	730

For this scenario is required a collecting surface area of 140 m^2 of PTCs (5 NepSolar PolyTrough 1200 solar modules) that result in 77 kW of installed power. For the cold production it was considered an adsorption system capable of delivering 48 kW of cooling power (SorTec adsorption Chillers).

e) Economic analysis

For the economical analysis, was considered a system lifetime of 25 years. The analysis was carried out at constant prices (without considering the rate of inflation) it was considered a nominal discount rate of 3 %; were not considered costs associated with the maintenance of the system and it was considered an annual cost of € 2.692 with backup energy fossil fuels . The prices mentioned in table 7 refer to PTCs and to the adsorption system; and were obtained directly from their manufacturers[11].

Table 7: Acquisition Cost

System	Acquisition cost	
PTCs	350,00	€/m^2
Adsorption cooling	1.250,00	€/Kw

V. Conclusions

Solar water heating reduces the amount of water that must be heated by conventional water-heating system used in buildings, so it can directly substitute fossil-fuel energy for renewable energy, allowing at the same time a reduction in the energy bill, with the possibility of achieving a better energy label for the building. The use of PTC when combined with adsorption technology can be used for building air conditioning, enabling the production of heat and cold besides the production of DHW, with environmental benefits. The existing technology enables the use of these systems in small size applications (less than 100 kW), once there are available in the market small PTCs that can be roof mounted, and small power adsorption systems (less than 10 kW).

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Why Conventional Engineering Laws Should Be *Abandoned*, and the New Laws That Will Replace Them

By Eugene F. Adiutori

Abstract- There are three reasons why laws such as q = hΔT and **σ** = E**ε**, and parameters such as h and E, should be *abandoned*. 1. The laws are analogs of y = (y/x)x and, if y is a nonlinear function of x, analogs of (y/x) (such as h and E) are *extraneous variables* that greatly complicate problem solutions. 2. Parameters such as h and E were created by assigning dimensions to *numbers*, in violation of the modern view that dimensions must *not* be assigned to numbers. 3. The laws purport to describe how the numerical value *and* dimension of parameters are related when, in fact, equations can rationally describe only how the *numerical values* of parameters are related.

When conventional engineering laws are abandoned, they will be replaced by new laws described by the following: 1. They are *dimensionless* because parameter symbols in equations represent *only* numerical value. 2. They are analogs of y = f{x}. 3. They contain *no* analogs of y/x, and consequently they contain *no* extraneous variables. 4. They make it possible to *abandon* analogs of y/x (such as modulus and heat transfer coefficient), greatly simplifying the solution of nonlinear problems by reducing the number of variables. 5. They have *no* parameters that were created by assigning dimensions to numbers. 6. They are *inherently* dimensionally homogeneous because parameter symbols in equations represent *only* numerical value. 7. They state that the *numerical value* of parameter y is *always* a function of the *numerical value* of parameter x, and the function may be proportional, linear, or nonlinear.

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Eugene F. Adiutori

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I. Conventional Engineering Laws—Why and When They Work Well, and Why and When They Do *Not* Work Well

Conventional engineering laws work well when applied to phenomena that exhibit *proportional* behavior because laws such as Eqs. (1) and (2) are *proportional* equations, and proportional equations accurately describe proportional behavior.

$$q = h\Delta T \qquad (1)$$

$$\sigma = E\varepsilon \qquad (2)$$

Conventional engineering laws do *not* work well when applied to phenomena that exhibit *nonlinear* behavior because laws such as Eqs. (1) and (2) are proportional equations, and proportional equations *cannot* describe nonlinear behavior. For example, if q is a nonlinear function of ΔT (as in natural convection, condensation, and boiling), Eq. (1) does *not* state that q is a nonlinear function of ΔT. It states *only* that h is a symbol for q/ΔT—ie states *only* that h and q/ΔT are *identical* and *interchangeable*.

II. Parameter Symbolism in Conventional Engineering

Since the beginning of science, scientists and engineers have agreed that parameter symbols in equations represent numerical values *and* dimensions. Therefore the meaning of equations such as Eqs. (1) and (2) should be described in the following rigorously correct manner:

The numerical value and dimension of q equal the numerical value and dimension of h times the numerical value and dimension of ΔT.

The numerical value and dimension of σ equal the numerical value and dimension of E times the numerical value of ε.

In the rest of this article, the meaning of conventional engineering equations is oftentimes described in the above rigorously correct manner in order to illustrate that Hooke and Newton were correct—dimensions *cannot* rationally be multiplied or divided.

III. The First Conventional Engineering Law

Equation (1) was the first conventional engineering law.

$$q = h\Delta T \qquad (1)$$

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Author: e-mail: efadiutori@aol.com

It was published in 1822 in Fourier's treatise *The Analytical Theory of Heat* [1a][1]. However, the meaning of Eq. (1) has changed considerably since 1822. Until sometime near the beginning of the twentieth century, Eq. (1) meant:

- It applies *only* if heat transfer is by the steady-state forced convection of ambient air flowing over a solid, warm body.
- It is *always* a proportional equation. It states that the numerical value and dimension of q are *always* proportional to the numerical value and dimension of ΔT, and the numerical value and dimension of h are *always* the proportionality *constant*.
- h is *always* a symbol for q/ΔT—ie h and q/ΔT are *always* identical and interchangeable.

Since sometime near the beginning of the twentieth century, Eq. (1) has meant:

- It applies to *all* forms of convection heat transfer.
- It states that the numerical value and dimension of q *always* equals the numerical value and dimension of h times the numerical value and dimension of ΔT.
- It may or may *not* be a proportional equation.
- The relationship between q and ΔT may be proportional, linear, or nonlinear.
- h may be a constant or a *variable* dependent on ΔT.
- If q is *not* proportional to ΔT (as in natural convection, condensation, and boiling), Eq. (1) reveals *only* that h is *always* a symbol for q/ΔT—ie reveals *only* that h and q/ΔT are *always identical* and *interchangeable*.

IV. Why Equations Could *Not* Describe How Parameters Are Related Until the Nineteenth Century

Until the nineteenth century, scientists and engineers agreed that equations *cannot* describe how parameters are related because parameter symbols in equations represent numerical value *and* dimensions, and it was globally agreed that dimensions *cannot* rationally be multiplied or divided. That is why Hooke's law is a proportion rather than an equation. It is also why Newton's second law of motion published in Newton [3] is *not* force equals mass times acceleration. It is acceleration is proportional to force.

V. How Fourier made it Possible to Create Equations that Quantitatively Describe how Parameters are Related

Early in the nineteenth century, Fourier conceived the *revolutionary* views that parameters in equations *can* be multiplied and divided, and dimensions *can* rationally be assigned to numbers. This made it possible, for the very first time, to create equations that quantitatively describe how parameters are related. Fourier's entire nearly 500 page treatise *The Analytical Theory of Heat* [1] is predicated on:

- His revolutionary view that dimensions can rationally be multiplied and divided.
- His revolutionary view that dimensions can rationally be assigned to numbers.
- The prevailing view that parameter symbols in equations represent numerical value *and* dimension.
- The prevailing view that parametric equations *must* be dimensionally homogeneous.

Fourier made no effort to prove the validity of his revolutionary views. In his entire treatise, Fourier's [1b] only defense of his revolutionary views is the following paragraph:

. . . every undetermined magnitude or constant has one dimension proper to itself, and the terms of one and the same equation could not be compared if they had not the same exponent of dimensions. . . (This view of homogeneity) is the equivalent of the fundamental lemmas (axioms) which the Greeks have left us without proof.

Fourier's treatise does *not* include the axioms the Greeks left us without proof, it does *not* specify which axioms Fourier referred to, and it does *not* cite a reference where the pertinent axioms could be found. Presumably Fourier's colleagues accepted his unproven views because, using his revolutionary views, he was able to solve heat transfer problems that had never been solved. His revolutionary and unproven views are fundamental and important views in modern engineering science.

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[1] Adiutori [2] states that Fourier made so many contributions to modern engineering science that he should be considered the father of modern engineering. For example, Fourier should be credited with the concepts of flux, heat transfer coefficient, thermal conductivity, dimensional homogeneity, the solution of boundary condition problems, the sciences of convective and conductive heat transfer, and the methodology required to create dimensionally homogeneous laws.

VI. How Fourier Created the First Conventional Engineering Law

Fourier performed experiments in convection heat transfer. His purpose was to determine a dimensionally homogeneous equation/law that describes how the numerical value and dimension of convective heat flux are related to the numerical value and dimension of the boundary layer temperature difference.

From his data, Fourier concluded that, if heat transfer is by the steady-state forced convection of ambient air flowing over a solid, warm body, the relationship between the numerical value and dimension of q and the numerical value and dimension of ΔT is *always* proportional, and is described by Eq. (3) in which c is the numerical value of the proportionality *constant*.

$$q = c\Delta T \tag{3}$$

Fourier was not satisfied with Eq. (3) because it is *not* dimensionally homogeneous. Fourier recognized that Eq. (3) could be transformed to a homogeneous equation only if it were rational to assign dimensions to numbers, and rational to multiply and divide dimensions. Consequently, Fourier conceived the revolutionary view that dimensions can rationally be assigned to numbers, and dimensions can rationally be multiplied and divided. To *number* c in Eq. (3), Fourier assigned the symbol h, the dimensions of (q/ΔT), and the name *coefficient*, resulting in Eq. (4), the dimensionally homogeneous law of forced convection heat transfer to ambient air flowing in steady-state over a solid, warm body.[2]

$$q = h\Delta T \tag{4}$$

In Fourier's view, Equation (4) states that, if heat transfer is by the steady-state forced convection of ambient air flowing over a solid, warm body, the numerical value and dimension of q are *always* proportional to the numerical value and dimension of ΔT, and the numerical value and dimension of h are *always* the *constant* of proportionality. Fourier [1c] defined h in the following:

We have taken as the measure of the external conducibility of a solid body a coefficient h, which denotes the quantity of heat which would pass, in a definite time (a minute), from the surface of this body, into atmospheric air, supposing that the surface had a definite extent (a square metre), that the constant temperature of the body was 1, and that of the air 0, and that the heated surface was exposed to a current of air of a given invariable velocity.

VII. Proof That h Is Unnecessary and Undesirable

In natural convection heat transfer, heat flux and temperature difference are often determined by *first* determining the heat transfer coefficient from a chart of Nusselt number vs Rayleigh number. If the chart is used to determine heat transfer coefficient given temperature difference, the chart can be read in a direct manner because Rayleigh number is independent of heat flux. But if the chart is used to determine heat transfer coefficient given heat flux, it *cannot* be read in a direct manner because temperature difference is implicit on both axes (since the Nusselt number hD/k (ie qD/ΔTk) is *inversely* proportional to ΔT, and the Rayleigh number is *directly* proportional to ΔT). Therefore the chart *must* be read in an *indirect* manner.

However, h can be *eliminated* from the chart by plotting the *product* of Nusselt number and Rayleigh number vs Rayleigh number. This *eliminates* h because it eliminates the ΔT in the denominator of Nusselt number, leaving qD/k in place of qD/ΔTk .

After h has been *eliminated* from the chart, the chart of Nusselt number times Rayleigh number vs Rayleigh number can be read *directly* to determine *heat flux* given temperature difference, or *temperature difference* given heat flux.

Q.E.D. h is unnecessary and undesirable.

VIII. Proof That Fluid Friction Factor f Is Unnecessary and Undesirable

In conventional engineering, if fluid flow is laminar, the relationship between fluid flow and pressure drop is described by a simple equation. But if fluid flow is *turbulent*, the relationship between flow rate and pressure drop is *nonlinear*, and flow rate or pressure drop is usually determined by *first* determining the fluid friction factor f from the Moody chart, a chart of f vs Reynolds number. If the flow rate is given and f is to be determined, the Moody chart can be read in a direct manner because the Reynolds number is independent of pressure drop. But if the pressure drop is given and f is to be determined, the Moody chart *cannot* be read in a direct manner because fluid flow rate is implicit on both axes. Therefore the chart *must* be read in an *indirect* manner.

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[2] Although Newton is generally credited with both h and Eq. (4), Adiutori [4] and Bejan [5] credit Fourier with both h and Eq. (4). Equation (4) is generally said to be "Newton's law of cooling", but Equation (4) cannot be Newton's law of cooling because cooling is transient behavior, and Eq. (4) is a steady-state equation.

However, since f is *inversely* proportional to flow rate squared, and Reynolds number is *directly* proportional to flow rate, f can be *eliminated* from the chart by plotting the *product* of f and Reynolds number squared vs Reynolds number. This *eliminates* f from the chart because it *eliminates* flow rate in the f denominator.

After f has been *eliminated* from the chart, the chart can be read *directly* to determine *flow rate* given pressure drop, or *pressure drop* given flow rate.

Q.E.D. f is unnecessary and undesirable.

IX. Proof That Hooke and Newton Were *Correct*—Dimensions *Cannot* Rationally Be Multiplied Or Divided

Multiplication is repeated addition. Six times eight means *add* eight six times. Therefore things that cannot be added cannot be multiplied.

It is generally agreed that dimensions *cannot* rationally be added. Therefore dimensions *cannot* rationally be multiplied because they *cannot* rationally be added, and multiplication is repeated addition.

Since six times eight means *add* eight six times, "kilograms times meters" *must* mean *add* meters kilograms times. Because "add meters kilograms times" has no meaning, dimensions *cannot* rationally be multiplied.

Since twelve divided by four means how many fours are in twelve, "meters divided by seconds" *must* mean how many seconds are in meters. Because "how many seconds are in meters" has no meaning, dimensions cannot rationally be divided.

Q.E.D. Dimensions cannot rationally be multiplied or divided.

X. Why Laws Such As $q = h\Delta T$ and $\sigma = E\varepsilon$ Are Anathema In Mathematics and Engineering

In conventional engineering, Eq. (5) is the law of convection heat transfer.

$$q = h\Delta T \qquad (5)$$

Rearranging Eq. (5) results in Eq. (6).

$$h = (q/\Delta T) \qquad (6)$$

Combining Eqs. (5) and (6) results in Eq. (7).

$$q = (q/\Delta T)\Delta T \qquad (7)$$

Equations (5), (6), and (7) are *identical*. All three equations are analogs of Eq. (8), and h and q/ΔT are analogs of (y/x).

$$y = (y/x)x \qquad (8)$$

Equation (8) is anathema in mathematics and engineering because, if parameter y is a nonlinear function of parameter x, parameter (y/x) is an *extraneous variable*, and it complicates problem solutions.

Consequently *all* laws that are analogs of Eq. (8), and *all* parameters that are analogs of (y/x), should be *abandoned* because, if parameter y is a nonlinear function of parameter x, parameter (y/x) is an *extraneous variable*, and it complicates problem solutions.

XI. How the Modern View of Dimensional Homogeneity Differs from Fourier's View

Fourier [1b] is generally credited with the modern view of dimensional homogeneity. However, the modern view of dimensional homogeneity differs from Fourier's view in one important way. In the modern view, it is *irrational* to assign dimensions to numbers. In 1951, Langhaar [6] stated:

Dimensions must not be assigned to numbers, for then any equation could be regarded as dimensionally homogeneous.

XII. Why Laws Such As Eqs. (9) and (10) *Violate* the Modern View of Dimensional Homogeneity, and Consequently Are *Irrational*

Laws such as Eqs. (9) and (10) are *irrational* because parameters such as h and E were created by assigning dimensions to numbers, in violation of the modern view that "Dimensions *must not* be assigned to numbers, for then any equation could be regarded as dimensionally homogeneous."

$$q = h\Delta T \tag{9}$$

$$\sigma = E\varepsilon \tag{10}$$

Consequently *all* laws that are analogs of Eq. (8), and *all* parameters that are analogs of (y/x) in Eq. (8), *should* be abandoned because they were created by assigning dimensions to numbers, in violation of the modern view that dimensions must *not* be assigned to numbers.

However, laws that are analogs of Eq. (8), and parameters that are analogs of (y/x) in Eq. (8), have *not* yet been abandoned in spite of the fact that they have, for almost a century, violated the prevailing view that dimensions must *not* be assigned to numbers.

XIII. Why Engineering Parameters *Cannot* be Proportional

It is axiomatic that pigs *cannot* be proportional to airplanes because pigs and airplanes are different things, and different things *cannot* be proportional. Therefore it is axiomatic that parameter y *cannot* be proportional to parameter x because parameter y and parameter x are different things, and different things *cannot* be proportional. However, the *numerical value* of parameter y *can* be proportional to the *numerical value* of parameter x because different *numerical values* are *not* different *things*.

XIV. Hooke's Error

In 1676, Hooke [7] concluded from his data that, in the elastic region, stress is proportional to strain. Hooke was *wrong*. Stress *cannot* be proportional to strain because stress and strain are different *things*, and different *things cannot* be proportional. Hooke should have concluded the following:

In the elastic region, the numerical value of stress is proportional to the numerical value of strain.

XV. Why Equations *Cannot* Describe How Engineering Parameters Are Related

It is axiomatic that equations *cannot* describe how pigs and airplanes are related because pigs and airplanes are different things, and different things *cannot* be related. Therefore it is axiomatic that equations *cannot* describe how parameter y is related to parameter x because parameters y and x are different *things*, and different *things* cannot be related. However, equations *can* describe how the *numerical value* of parameter y is related to the numerical value of parameter x because different *numerical values* are *not* different *things*.

XVI. Fourier's Error, and the Heat Transfer Law He Should Have Conceived

From his data, Fourier [1a] concluded that, in steady-state forced convection heat transfer from a warm, solid body to ambient air, heat flux is *always* proportional to temperature difference.

Fourier was *wrong*. Heat flux *cannot* be proportional to temperature difference because they are different things, and different things *cannot* be proportional. Fourier should have concluded that:

- The *numerical value* of heat flux is proportional to the *numerical value* of temperature difference.
- Parameter symbols in equations represent *only* numerical value. Therefore rational parametric equations are *inherently* dimensionally homogeneous because they are dimensionless.
- If an equation is quantitative, the dimension units that underlie parameter symbols *must* be specified in an accompanying nomenclature.
- Equation (11), Fourier's law of steady-state forced convection heat transfer to ambient air, is *irrational.* Equations *cannot* rationally describe how heat flux and temperature difference are related because they are different things, and different things *cannot* be related.

$$q = h\Delta T \tag{11}$$

- Equation (12) is the law Fourier should have conceived. It should have meant that the numerical value of q is *always* proportional to the numerical value of ΔT, and the numerical value of c is the constant of proportionality.

$$q = c\,\Delta T \tag{12}$$

Fourier rejected Eq. (12) because parameter symbols represented numerical value *and* dimension, and therefore Eq. (12) was *not* dimensionally homogeneous.

XVII. Ohm's Error

From his data, Ohm [8] concluded that electromotive force is proportional to electric current. He was *wrong*. Electromotive force cannot be proportional to electric current because they are different things, and different things

cannot be proportional. Ohm should have concluded that the *numerical value* of electromotive force is proportional to the *numerical value* of electric current.

In modern conventional engineering, the dimensionally homogeneous Eq. (13) is referred to as Ohm's law. It applies *only* if E is proportional to I.

$$E = IR \tag{13}$$

If E is not proportional to I, charts of Eq. (14) are often used in spite of the fact that, in modern conventional engineering, Eq. (14) is *not* dimensionally homogeneous.

$$I = f\{E\} \tag{14}$$

XVIII. The Purpose of Engineering Laws

The purpose of engineering laws is to identify the primary parameters, and to describe how the numerical values of the primary parameters are related. The relationship between the numerical values of primary parameters cannot generally be described in a specific way because most engineering phenomena exhibit more than one type of relationship.

For example, the relationship between the numerical value of convective heat flux and the numerical value of temperature difference may be proportional, linear, or nonlinear. The relationship between the numerical value of stress and the numerical value of strain may be proportional, linear, or nonlinear. The relationship between the numerical value of electromotive force and the numerical value of electric current may be proportional, linear, or nonlinear.

XIX. A Mathematical Analog of the New Laws

Assuming that symbols in equations represent numerical value but *not* dimension, Eq. (15) states that the numerical value of y is *always* a function of the numerical value of x, and the function may be proportional, linear, or nonlinear.

$$y = f\{x\} \tag{15}$$

Equation (15) is a mathematical analog of the new laws.

XX. The New Laws of Engineering

The new law of convection heat transfer is Eq. (16). Equation (16a) states that the numerical value of heat flux is *always* a function of the numerical value of temperature difference, and the function may be proportional, linear, or nonlinear. And similarly for Eq. (16b). In other words, Eq. (16) applies to *all* forms of convection heat transfer.

$$q = f\{\Delta T\} \tag{16a}$$

$$\Delta T = f\{q\} \tag{16b}$$

The new law of stress and strain is Eq. (17). Equation (17a) states that the numerical value of stress is *always* a function of the numerical value of strain, and the function may be proportional, linear, or nonlinear. And similarly for Eq. (17b). In other words, Eq. (17) applies in *both* the elastic and inelastic regions.

$$\sigma = f\{\varepsilon\} \tag{17a}$$

$$\varepsilon = f\{\sigma\} \tag{17b}$$

The new law of resistive electrical behavior is Eq. (18). Equation (18a) states that the numerical value of electromotive force is *always* a function of the numerical value of electric current, and the function may be proportional, linear, or nonlinear. And similarly for Eq. (18b). In other words, Eq. (18) applies to *all* conductors and semi-conductors.

$$E = f\{I\} \tag{18a}$$

$$I = f\{E\} \tag{18b}$$

XXI. Why the New Engineering Laws Will Replace Conventional Laws

The new engineering laws, such as Eqs. (16) to (18), will replace conventional laws because:

- Conventional laws are analogs of $y = (y/x)x$. Therefore if parameter y is a nonlinear function of parameter x, analogs of (y/x) (such as h and E) are *extraneous variables* that greatly complicate problem solutions. The new laws have *no* analogs of (y/x), and therefore they have *no* extraneous variables.

- Conventional laws and parameters such as h, E, and R were created by assigning dimensions to numbers, in violation of the modern view that dimensions *must not* be assigned to numbers. The new laws contain *no* parameters created by assigning dimensions to numbers.

- Parameters such as h, E, R, and f are *unnecessary* and *undesirable*. They are unnecessary because, as demonstrated in Sections 7 and 8, problems are readily solved without them. They are undesirable because, as demonstrated in Sections 7 and 8, when a conventional law is applied to nonlinear behavior, parameters such as h, E, R, and f are *extraneous variables* that complicate problem solutions. In the new laws, there are *no* parameters such as h, E, R, and f.

- If Eq. (19) is used to solve a problem that concerns boiling heat transfer, the solution will include the *three* thermal variables q, q/ΔT, and ΔT (q/ΔT is a variable because the relationship between q and ΔT is nonlinear). If Eq. (20) is used to solve the problem, the solution will include only the *two* thermal variables q and ΔT. (And similarly for other branches of engineering.)

$$q = h\Delta T \tag{19}$$

$$q = f\{\Delta T\} \tag{20}$$

It is axiomatic that any problem that can be solved using the *three* thermal variables (q, q/ΔT, and ΔT) can also be solved using the *two* thermal variables (q and ΔT). It is also axiomatic that it is *much* more difficult to solve problems that concern *three* variables than problems that concern *two* variables.

- Conventional engineering laws are irrational because they purport to describe how parameters are related, in spite of the fact that equations *cannot* rationally describe how parameters are related. Equations can rationally describe *only* how the *numerical values* of parameters are related. The new laws describe *only* how the numerical values of parameters are related.

- The new laws make it much easier to learn engineering science because there are fewer parameters to learn about and to think about and to apply, and because the new laws make it possible to solve nonlinear problems with the variables *separated*, the preferred methodology in mathematics.

XXII. How Texts Based On the Laws of Conventional Engineering Can Be Transformed to Texts Based On the New Laws

Texts based on conventional engineering laws can be transformed to texts based on the new laws by modifying the texts so that:

- Parameter symbols represent *only* numerical value.
- Laws are analogs of $y = f\{x\}$.
- Primary parameters are *always separated*.
- *No parameter* is created by assigning dimensions to numbers.
- *No parameter* is created by combining primary parameters.
- If an equation is quantitative, the dimension units that underlie parameter symbols are specified in the nomenclature.

XXIII. How a Heat Transfer Text Based On Conventional Laws Can Be Transformed To a Text Based On the New Laws

A heat transfer text based on conventional engineering laws can be transformed to a text based on the new laws by modifying the text in the following ways:

- Replace Eq. (21) with Eq. (22).

$$q = h\Delta T \tag{21}$$

$$q = f\{\Delta T\} \tag{22}$$

- Because the numerical value of qconduction is *generally* proportional to the numerical value of dT/dx, Eq. (23) is generally the *dimensionless* law of conduction heat transfer. If there are materials that do *not* exhibit the proportional relationship indicated by Eq. (23), Eq. (24) replaces Eq. (23).

$$\text{qconduction} = k\,(dT/dx) \tag{23}$$

$$\text{qconduction} = f\{dT/dx\} \tag{24}$$

- In the nomenclature, state that parameter symbols represent *only* numerical value. Also state that if an equation is quantitative, the dimension units that underlie parameter symbols are specified in the nomenclature.
- In *all* equations and charts in which h is explicit or implicit (as in Nusselt number), replace h by q/ΔT, then separate q and ΔT. When Eq. (22) is the law of convection heat transfer, *all* parameter groups that include h are *abandoned*.
- In *all* equations and charts in which k/t is explicit or implicit, replace k/t by q/ΔT, then separate q and ΔT.
- Separating q and ΔT in Eq. (25) results in Eq. (26). Replace Eq. (25) with Eq. (26)

$$U = 1/(1/h_1 + t/k + 1/h_2) \tag{25}$$

$$\Delta T_{total} = \Delta T_1\{q\} + \Delta T_{wall}\{q\} + \Delta T_2\{q\} \tag{26}$$

Equations (25) and (26) are *identical*. They differ only because q and ΔT are *combined* in Eq. (25), and *separated* in Eq. (26). Equation (26) states that the numerical value of ΔT_{total} equals the numerical value of ΔT_1 plus the numerical value of ΔT_{wall} plus the numerical value of ΔT_2.

All problems that can be solved using Eq. (25) *and* h can also be solved using Eq. (26) and *not* h. If q{ΔT} is a proportional equation, the solution is quite simple using either Eq. (25) *and* h or Eq. (26) and *not* h. However, if q{ΔT} is a nonlinear equation, the solution is much simpler using Eq. (26) and *not* h.

XXIV.   Conclusions

The new laws will replace conventional laws because they result in a more rational and much simpler science of engineering.

Symbols

Note: Depending on the context in which a parameter symbol is used, the symbol may represent numerical value *and* dimension, or may represent *only* numerical value.

c	pure number
E	modulus σ/ε, or electromotive force
$E_{elastic}$	elastic modulus, σ/ε in the elastic region
h	heat transfer coefficient, q/ΔT
I	electric current
q	heat flux
R	electrical resistance, E/I
T	temperature
x	unidentified parameter
y	unidentified parameter

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Modeling and Wind Flow Analysis of an Eiffel (Open) Type Sub-Sonic Wind Tunnel

By Zelieus Namirian, Shubham Mathure, Bhargavi Thorat
& Prof. Surekha Khetree

Abstract- Wind tunnel (WT) is a device that artificially produces airflow relative to a stationary body and measures aerodynamic force and pressure distribution, simulating the actual conditions with an important aspect of accurately feigning¬ the full complexity of fluid flow. The aim of the present study is to design the three dimensional geometry of a small, open-circuit (also known as Eiffel Type), and subsonic (low speed) wind tunnel (WT) capable of demonstrating or acting as a vital tool in aero-mechanics research. The project and fabrication itself, poses as an onerous task with the cynosure/central theme being the delineation/depiction of wind tunnel components such as Test Section, contraction cone, diffuser, drive system and settling chamber.

Keywords: wind tunnel, contraction cone, diffuser, open, subsonic, design, low speed, flow control, computational fluid dynamics (CFD); RANS; LES; aerodynamics; turbulence; modelling; atmospheric boundary layer; applications and importance; open circuit wind tunnel, eiffel type, gottingen wind tunnel, cryogenic wind tunnel.

GJRE-A Classification: FOR Code: 290501

MODELINGANDWINDFLOWANALYSISOFANEIFFELOPENTYPESUBSONICWINDTUNNEL

Strictly as per the compliance and regulations of:

Modeling and Wind Flow Analysis of an Eiffel (Open) Type Sub-Sonic Wind Tunnel

Zelieus Namirian[α], Shubham Mathure[σ], Bhargavi Thorat[ρ] & Prof. Surekha Khetree[ω]

Abstract- Wind tunnel (WT) is a device that artificially produces airflow relative to a stationary body and measures aerodynamic force and pressure distribution, simulating the actual conditions with an important aspect of accurately feigning¬ the full complexity of fluid flow. The aim of the present study is to design the three dimensional geometry of a small, open-circuit (also known as Eiffel Type), and subsonic (low speed) wind tunnel (WT) capable of demonstrating or acting as a vital tool in aero-mechanics research. The project and fabrication itself, poses as an onerous task with the cynosure/central theme being the delineation/depiction of wind tunnel components such as Test Section, contraction cone, diffuser, drive system and settling chamber. The paper also depicts the history, types, importance and the applications of WTs which is meant to act as an anatomization/detailed analysis. A plethora of information on CFD (Computational Fluid Dynamics), a science that studies how to predict fluid flow, heat transfer, chemical reaction and other phenomena with solving mathematical equations, is cited as well as employed with a turbulence model, to obtain the right and ideal Open WT, and verify performance of fluid flow. CFD was carried out by analysing the pattern of velocity distribution, pressure distribution and intensity of fluid turbulence in the wind tunnel. CFD allows insight into the minute flow details which otherwise are not captured using flow bench tests. The designs adopted, mathematics foreshadowing fluid flow, guidelines followed, results obtained and further scope are also discussed.

Keywords: wind tunnel, contraction cone, diffuser, open, subsonic, design, low speed, flow control, computational fluid dynamics (CFD); RANS; LES; aerodynamics; turbulence; modelling; atmospheric boundary layer; applications and importance; open circuit wind tunnel, eiffel type, gottingen wind tunnel, cryogenic wind tunnel.

I. Introduction

To gain insight for solving fluid mechanics' domain consisting of vivid aerodynamic or hydrodynamic problems, there are numerous ways, such as:

Flight Experiments, flying scale models, Rocket Sleds and Flights, Drop Tests, Water Tunnels as well as Water Tables, Whirling Arm Apparatus tests, Shock tubes, road tests, ballistic ranges and so many other techniques leading to an almost interminable list, where each test/device has its own domain of supremacy and none of them could be deemed as the "best" [45].

Amongst the above, the highly preferred device being Wind Tunnel Testing which could be subsonic, near sonic, transonic, supersonic or even hypersonic.

Wind tunnels are huge channels with airflow through them that have been used to simulate the interaction of air with an object that is flying through the air or advancing along the ground. Wind tunnels are used by researchers to gain a better understanding of how an aeroplane will fly. Wind tunnels are used by NASA to test scale models as well as replicas of vehicles and spacecraft. Some wind tunnels are large enough to fit full-size vehicles within themselves. The wind tunnel creates an illusion of flight by moving air around an object.

Large strong fans blow air through the tube most or all of the time. The object being inspected is securely retained within the tunnel, ensuring that it remains stationary and unperturbed. An aerodynamic structural member, such as a cylinder or an airfoil, an individual element, a small type of vehicle, or maybe even a full-sized waggon may be used as the object. The air moving around the fixed object simulates what would happen if the object were in motion. The motion of air can be scrutinised in a multitude of settings; for example, smoke or dye can be introduced in the air and observed as it moves around an object. To illustrate how the air moves around the object, colorful threads may also be attached to it.

The first wind tunnels were created near the end of the nineteenth century, during the early days of aeronautic research, when many people tried to build prolific bulkier, studier, and heavy-than-air flying machines. The wind tunnel was conceived as a way of reversing the normal paradigm: instead of the air remaining still while an object moves through it at high speed, the same effect could be achieved if the object remained stationary while the air moved past it at high speed. In this regard, a stationary researcher might study the flying object in flight and measure the aerodynamic forces acting on it.

The innovation of wind tunnels aligned with the development of the aircraft. During WWII, huge wind tunnels were constructed. During the Cold War, wind tunnel testing was deemed essential in the production of supersonic military aviation and ballistic missiles.

Thus, Wind tunnels are used to evaluate the subjects of aerodynamic research because they are capable of simulating actual airflow conditions through

Author α σ ρ ω: e-mails: zelieusdrez99@gmail.com, sgmathure9930@gmail.com, bhargavi.5.bt@gmail.com, surekhakothekar@gmail.com

the test section. Despite their significance, however, wind tunnels are constrained by their expense, size, and inadequate knowledge of their design. The demand for wind tunnel tests has diminished, thanks to recent advances in computational fluid dynamics (CFD) modeling on high-speed computer technology.[8] However, The requirement for wind tunnels to elucidate intricate aerodynamics snags is still needed today. [1]

II. Background

a) Different Research and Aerodynamic Study Methodologies

Theoretical/Analytical, computational, and experimental/practical approaches are all commonly used to solve aerodynamic engineering problems, each with its own set of protocols, range benefits and drawbacks. [45][46][55].

i. *Theoretical/Analytical*

They are confined to conjecture and speculation and are involved with the theory of a study or field of research.

Theoretical strategies are analytical approaches to solving fluid dynamics' governing equations. Analytical processes have the distinct advantage of producing closed form solutions. The formulae derived from an analytical approach may provide a lot of information about how the system will behave under various circumstances. Sadly, except in cases where the governing equations are linear or can be estimated as such, analytical solutions are indeed impossible to obtain or procure.

Considering only simple geometries, such as flow through an infinitely long pipe, is the only primary way to acquire linear governing equations. However, many interesting problems require complex geometries like cars or planes. Theoretical methods, but at the other hand, are essential for getting an understanding of the fundamental flow phenomena and acquiring insight for how given flow fields will interact. Theoretical methods are still significant in the confirmation of computational methodologies. Since computational solutions are approximations, evaluating the accuracy of computational algorithms on problems with analytical solutions is beneficial.

ii. *Computational (CFD-Computational Fluid Dynamics)*

The numerical approach to aeronautic design, also known as computational fluid dynamics, is the second approach. Any type of calculation that follows a well-defined model and covers both arithmetical and non-arithmetical steps is referred to as computation. It approximates the solutions to the governing equations of fluid mechanics using computational algorithms. The geometry for a given flow problem must be reproduced employing CAD. The flow domain must then be discretized into a grid/mesh, with initial and boundary

conditions determined. The solution is assumed to be constant in each cell in several methods, and the governing equations are also discretized to model how the solution changes in each cell.

The simulation should begin after an algorithm has been determined. [46] Due to the relentless advancement in computing power and memory of computers, the field of CFD has seen explosive growth in the last fifty years. Because of the rapid advancement of computers in the 1960s and 1970s, some researchers predicted that computer simulations would ultimately be able to evaluate free flight scenarios more accurately than wind tunnels, and could even replace them entirely [56].

Unlike analytical techniques, CFD only requires a few assumptions to solve a problem and can also produce time resolved flow solutions for any problem. It is possible to perform viscous simulations on a complete plane in less than a day using a personal computer, depending on the methodologies adopted [57]. Furthermore, there are issues for which obtaining experimental data and it remains difficult or impossible. Taking measurements inside a jet engine, for example, is not always feasible. As a result, CFD has become an invaluable engineering tool for cutting the levels of experimental testing required in the aerodynamic construction process.

Despite its many perks, CFD seems to have some shortcomings that prevent it from entirely replacing wind tunnel testing. Truncation errors in floating point calculations are a complication in CFD, as in any field that depends on numerical methods. Because computers can only retain a finite number of digits in arithmetic operations, round-off errors can occur in CFD. The number of grid points determines the magnitude of the error. Discretization error is also introduced through CFD. When round-off error is removed, discretization error is defined as the difference between the partial differential equation solution and the discretized approximation to the differential equation solution [55].

Furthermore, advances in computing power make a much easier remedy to increasingly complex problems. This is not always the case, though. That's because software parallelization is complicated. It's also worth noting that, while CFD can predict aerodynamic performance with increasing precision, engineers are often more obsessed with other characteristics like reliability, operability, and maintainability. CFD alone, for example, cannot predict whether an engine can revive cruise speed or how many flight hours can be attained before service is required. Turbulence modelling is another challenge associated with CFD.

Direct Numerical Simulation (DNS) simulations are one method of modelling fluid flow. This approach does not approximate the governing equations and often involves orders of magnitude more mesh points

than a computationally less expensive alternative like Reynolds- Averaged Navier-Stokes (RANS) [55] [56] [57]. RANS, on the other hand, is one of the most widely used CFD algorithms in engineering. It works by averaging the Navier-Stokes equations over time statistically. While RANS techniques can be used in cases of minor separation, they are often ineffective in cases of massive separation [57].

Large-eddy simulation (LES) is a different strategy to CFD. In the same way that RANS does, LES makes assumptions that lead to approximations of the Navier-Stokes equations. It filters the Navier-Stokes equations instead of averaging them, eliminating high wave-number components [59].

This method's computing cost and accuracy are comparable to RANS and DNS.

Despite these and other weaknesses, CFD has demonstrated to be an amazing resource in the aerodynamic design process, substantially reducing the number of design cycle iterations required.
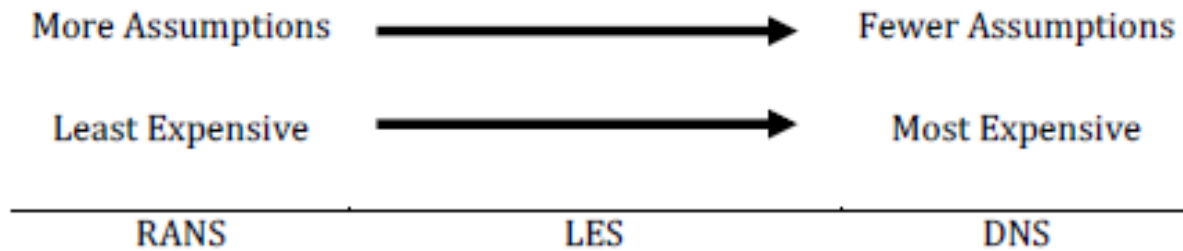
Figure 1: Turbulence Modelling, source of image: [46]

iii. *Experimental/Practical*

This third method of achieving aerodynamic probabilities is experimental and involves or employs analysis or logical reasoning; it refers to a person, concept, project, or other entity that is more concerned with or applicable to practise than hypothesis and can be done or implemented.

Since the time of the Wright brothers, wind tunnel testing has been used as the foundation for the design of all current flying crafts. Even though the number of military aircraft initiatives has been declining since the 1950s, the number of wind tunnel test hours per program has been continuously growing [8].This is due to the fact that as aeroplanes become more sophisticated, the amount of testing required to perfect a design grows. The amount of experimentally gained data for an aircraft programme has grown in recent years and will continue to do so in the future.

Wind tunnels, on the other hand, have their challenges. The cost of building and maintaining a wind tunnel, for example, varies depending on its size and characteristics, but it is seldom a low-cost undertaking. This is due to the fact that designing and building a wind tunnel will take years and numerous man-hours. Making precise models with correctly calibrated equipment is a daunting task that only adds to a wind tunnel's operating costs. The most difficult aspect of wind tunnel testing is accurately replicating flow parameters. This entails creating a model of the object of interest and replicating the desired Reynolds number at low speeds.

In addition, there are two main types of aerodynamic problems:

1. External aerodynamics, which refers to solid bodies immersed in flow, such as those found around wings or aerofoils.
2. Internal aerodynamics corresponding to flow movement inside the body, such as through ducts, turbines and piping.

b) *All about Wind Tunnels*
   i. *The Gist of Wind Tunnels*

As stated earlier, the science of aerodynamics concentrates on studying the echt (real) impact or generation of airflow of various speeds on solid objects. An inseparable tool of testing-The wind tunnel, is used in educational research, to study/simulate/analyse the effects of air moving past solid objects, under various conditions, about complete aircraft or aircraft components, the forces acting on them and their interaction/ behaviour with the air flow. Experiments are used for commercial purposes, such as studying the aerodynamics of vehicles to enhance their stability and effectiveness, and also for educational purposes, such as understanding complex fluid flows and multiple model responses to an airstream. As a result, a wind tunnel is an important tool in both fluid mechanics and experimental aerodynamics. They come in a variety of shapes and sizes, spanning from 30cm to the dimensions of a passenger aircraft. [52, 19, 26, 43, 9, 5, 49, 53, 30, 44, and 23]

A well-designed wind tunnel could supply technical information for a large number of engineering applications such as external aerodynamics (flow over automobile, terrestrial and aerial vehicles) [43], civil engineering (estimation of pollution dispersion level near

the building, investigation of wind-driven rain and building envelop, various aspects of wind loading on roofs and wind effects on towers and bridge. [52], flow over cable stayed bridges, high rise buildings, cable, electricity transmission towers etc.), sport activities (flow over cyclists, design of volley and basket balls, wind sails etc.), fundamental fluid dynamics (laminar and turbulent flow over simple and complex geometries) and an extensive frame of other options in industry and research centres at universities around the world, for a varied number of reasons such as testing of prototypes early in their design cycles, or to record a large amount of data.

It's a tube or tunnel with different cross sections in which man-made wind is blown at a controlled speed through a closed tubular passage, with the object under test mounted in the middle of the test compartment. Engineers and scientists place a model (made of steel or aluminium) of an aircraft, truck, or full-scale wind turbine in this section and investigate how air moves around it. They can get a pretty good idea of how a real-life-sized system with the same designs would respond by looking at how this smaller model interacts in the wind tunnel. [26] Aerodynamicists need to use the wind tunnel's controlled environment to measure flow conditions and forces on aircraft models as they are being developed. The ability to gather diagnostic data from models allows engineers to tweak designs for aerodynamic performance in a cost-effective and safe manner without having to construct countless fully functional prototypes.

Air is moved past the object by a strong fan system comprising of one or more fans; the fan must have straightening vanes to smooth the airflow. The test object is fitted with a delicate balance to measure the forces produced by airflow; alternatively, smoke or other substances may be injected into the airflow to make the flow lines around the object visible.[26]

The National Aeronautics and Space Administration (NASA), Boeing, Northrop Grumman, and every other company that manufactures aeroplanes and spacecraft use wind tunnels today. NASA's Ames Research Center in Moffet Field, California, has the most wind tunnels of any location on the planet, as well as the world's largest wind tunnel. [53] These facilities are costly to run, and computer modelling has taken over some of their functions. [26]

The flow visualisation provided by a wind tunnel is one of the most significant features. Sure, complex equations can be used to determine lift, drag, and efficiency. The visual aspect of a wind tunnel, as well as the controllable environment it offers, helps you to physically see what will happen in a variety of real-life scenarios. In the confines of a test lab, you can make an environment where you can see how an aircraft reacts when taking off, cruising, and landing. Then, using the same machine, you can see how air flows over a race

car's body as it speeds around a track in order to maximise productivity. The versatility and tangibility of a wind tunnel is what makes it such an important part of aerodynamic research. [19, 10, 25, 47]

As a result, wind tunnel testing of full/model-scale components is a commonly used method for guiding detailed design decisions in thermal-fluid systems and allowing basic fluid phenomena study. Many times, theoretical and/or computational methods are insufficient, either due to the problem's complexity or a lack of appropriate computational resources. [23] The majority of experimental data required in aerodynamics is produced in wind tunnels, and for these reasons, wind tunnel testing is often the most cost-effective method. [10]

ii. *Principle*

The wind tunnel was conceived as a way of reversing the normal paradigm: instead of the air remaining stationary while the vehicle or aircraft moved at high speeds through it, the same effect could be achieved if the vehicle or aircraft remained stationary while the air moved at high speeds past it. A stationary observer may study the vehicle or aircraft in action and measure the aerodynamic forces acting on the aircraft in this manner. [26, 49]

iii. *Performance*

As a result, WT is a device that can be used to explore the interaction of solid body flows in terms of [19]:

1. Physical flow phenomena such as laminar, turbulent, and separation flows, vortex, and shock waves must be monitored.
2. Obtaining aerodynamic data such as pressure, skin friction, lift, and dragas well as moments.

When compared to free flight experiments, the wind tunnel offers many advantages:

1. Specified flow conditions such as Mach number and incidence can be obtained and maintained much more easily in a wind tunnel.
2. In a wind tunnel, dangerous, uncontrollable flight conditions can be investigated safely.
3. Direct connection to ground-based facilities simplifies data acquisition and processing.

The primary drawback of using a wind tunnel is that it is rarely possible to accurately recreate full-scale motion. This is mostly due to the use of scaled models in order to reduce tunnel costs and energy consumption.

iii. *Quick Facts*

1. World's First Wind Tunnel

Frank H. Wenham (1824-1908), a Council Member of the Aeronautical Society of Great Britain, is generally credited with designing and operating the first wind tunnel in 1871. [60].

2. World's Largest Wind Tunnel

The largest wind tunnel in the world is at NASA's Ames Research Center. This subsonic tunnel, which can test planes with wing spans of up to 100 feet, is over 1,400 feet long and 180 feet high [63].

3. Oldest Wind Tunnel

NASA Langley 30-by-60-Foot Full-Scale Wind Tunnel, NASA's oldest operating wind tunnel until its closing in October 1995 [64].

4. Fastest Wind Tunnel (Deemed)

It has been revealed that China is set to build the world's fastest hypersonic wind tunnel that will be used to aid the development of spacecraft. "The 265-meter-long tunnel can be used to test hypersonic aircraft that can travel at speeds of up to Mach 25 (30,625kph), 25 times the speed of sound," Han Guilai, a Researcher from China's State Key Laboratory of High Temperature Gas Dynamics of the Chinese Academy of Sciences. [61][62].

c)   Types of different Wind Tunnels

  i.   *High-Reynolds-Number Wind Tunnels*

It is often impractical to obtain full-scale Reynolds numbers in an experimental facility using a full-scale vehicle; however, there are ways to increase the Reynolds number using smaller tunnels and models. [45]

  a.   *Pressurized Wind Tunnels*

One of the oldest methods is to construct a pressurised tunnel. In fact, pressurised tunnels were used to conduct some of the first definitive research on Reynolds number effects. Examining the equation of state for a perfect gas and the equation for Reynolds number reveals the reason for pressurisation: increasing the pressure by a factor of 20 increases the density, and thus the Reynolds number, for a given size and speed by 20 times

Some fundamental issues concerning the construction and operation costs of pressurised tunnels must be considered. For pressurised tunnels, the cost of compressor equipment will increase, and for larger facilities, providing access to the model test area without decompressing the entire tunnel will increase construction complexity and cost. Pressurized facilities require more time to change the pressure condition and access the model, which reduces the facility's productivity and thus raises the cost to users.

  b.   *Different Working Fluid*

Changing the working fluid is a second option. The use of Freon 12 can increase the Mach number by a factor of 2.5 and the Reynolds number by a factor of 3.6 for a given power input. Many of the problems that have plagued a pressure tunnel will resurface, including initial cost, pump costs, gas costs, and a method for making the test section habitable for model, changes. The National Aeronautics and Space Administration (NASA) Langley's Transonic Dynamics Tunnel is an

example of a tunnel that began using Freon 12 as the working fluid in 1960. [45]

  c.   *Cryogenic*

The use of a cryogenic tunnel is a third option. The National Transonic Facility (NW), which NASA built at its Langley Research Center in the beginning of 1971 [36], was the first of its kind. The same concept applies to a low-speed tunnel, even though this tunnel is designed for transonic experiments. The NTF tunnel combines the ability to operate at cryogenic temperatures with the ability to change pressure up to 9 atm, making it the world's largest piece of cryogenic research equipment in operation. The working fluid is nitrogen, and the gas is cooled by injecting liquid nitrogen upstream of the fan.This technique allows any pressure tunnel to operate over a wide range of dynamic pressures and Reynolds numbers at a constant temperature up to the tunnel's stagnation pressure limit. Alternatively, the tunnel can be run at constant dynamic pressure and the Reynolds number changed by changing the temperature. The range of Reynolds and Mach numbers in units is impressive. This type of facility is both costly to build and operate, but it does demonstrate what can be accomplished in a wind tunnel. The NTF's low productivity has kept it from being useful as a development facility due to the long times it takes to cycle and stabilise the temperature.

The European Transonic Facility in Cologne, Germany, is another high-Reynolds-number tunnel based on cryogenic operation. It is a joint venture between the United Kingdom, Germany, France, and the Netherlands. KKK (Kryo-Kanai K61n): This large cryogenic wind tunnel was built at DLR Cologne as a conversion of a traditional closed-circuit fan-driven atmospheric pressure tunnel.[36]

  ii.   *Vertical Short Take-off and Landing V/STOL Wind Tunnels*

Because of the large downwash angles generated by powered lift systems in the transition flight region, these tunnels require a much larger test section for a given size model. The transition region has low flight velocities, so tunnels with large test sections used for this purpose do not require high velocities, with the maximum being in the 6&100 mph range, compared to the 200-300 mph range for a conventional low-speed wind tunnel. The installed power requirement is reduced because power varies with the cube of velocity. In both the Boeing Helicopter Co. (test-section area 400 ft2) and the NASA Langley VERTICAL SHORT TAKEOFF AND LANDING (V/STOL) tunnels, this was the solution.

  iii.   *Free-Flight Tunnels*

Many "free-flight" tunnels were constructed in the 1930s. These open-return tunnels were designed to allow dimensionally and dynamically scaled models to be flown under gravity's influence. The air stream could be tilted to match the model's glide path. In these

tunnels, the model's dynamic behaviour could be studied, and control surfaces could often be deflected by a trailing wire. Because the simulations in these tunnels are done at very low Reynolds numbers, extrapolating the results to much higher Reynolds number conditions should be done with caution.

iv. Spin Tunnels or Vertical Wind Tunnels

The tendency of some aircraft to spin after a stall, as well as the need to determine actions to recover from the spin, have long been a source of concern for aircraft designers. In a spin tunnel, the recovery from a spin is studied. In most cases, this is a vertical wind tunnel with air drawn upward by a propeller near the tunnel's top.

v. Stability Tunnels

In 1941, NASA Langley constructed a stability tunnel. There were two 6 ft. long interchangeable test sections in this tunnel. In one test segment, a series of spinning vanes formed a vortex in the airstream. The second test section was bent to mimic turning take-off. The tunnel was moved to Virginia Polytechnic Institute and State University in 1958, and it is still used as a general-purpose and special-purpose wind tunnel there today. Related findings can be achieved using oscillating model techniques or free-flight tests in traditional tunnels. [45]

vi. Propeller Tunnels

Propeller tunnels are identical to traditional tunnels, but they usually have an open test section and a round cross section. Stanford University designed one of the first propeller tunnels in 1917, with a 5.5-foot-diameter test section. In 1922, NASA Langley built a propeller tunnel with a 20-foot test area. Aside from propeller tests, this tunnel revealed the best position for engine nacelles relative to the wing and the configuration of radial engine cowls (NASA cowl) to minimise drag.

vii. Propulsion Tunnels

The simulation of both flight velocity and atmospheric pressure and temperature variations is required for experimental evaluation of aircraft engines, whether reciprocating or jet. The exhaust gases must be removed from a closed circuit tunnel or an open circuit tunnel must be used because the engine must be operated in the tunnel.

viii. Icing Tunnels

The NASA 6 X 9-ft Icing Research Tunnel, located near Cleveland, Ohio, is a low-speed closed return tunnel with a refrigeration device to lower the air temperature to -40°F and atomizers upstream of the test segment to produce water droplets that freeze. The tunnel's shell is tightly shielded, which helps to keep the tunnel cool. To keep the fan from freezing during model shifts, the facility requires that it be operated at idle rpm. Ice accumulation on aircraft is a significant safety concern for aircraft and helicopters flying at low to medium altitudes.

ix. Low-Turbulence Tunnels

In order to maximise the size of the settling chamber without raising the total circuit dimensions, these tunnels typically have a wide-angle diffuser just ahead of the settling chamber.

x. Two-Dimensional Tunnels

Airfoil portions are mainly evaluated in two-dimensional tunnels. They've been made in both open circuit and closed return configurations. Tall short test sections with height-to-width ratios of 2 or greater can be found in these tunnels.

xi. Smoke Tunnels

Smoke tunnels are mainly used to visualise flow. Since photos and video capture are the main types of data recording, these tunnels are usually non return. Smoke tunnels of two and three dimensions have been constructed. While many other products have been used as smoke sources, current usage seems to favour vaporised light oils, kerosene, or propylene glycol. To achieve smooth laminar flow, smoke tunnels used for testing rather than demonstration purposes often have very high contraction ratios (up to 24 : 1) and a large number of antiturbulence screens at the inlet. Smoke tunnels are typically slow, moving at 30-60 feet per second.

xii. Automobile Wind Tunnels

Experiments are conducted with miniature models or at full scale in larger tunnels to obtain aerodynamic parameters that influence vehicle performance, handling, engine cooling, brake cooling, and wind noise. Contrary to popular belief, building tunnels to house full-scale vehicles is both practical and general practise. Using moderate scale models, such as 0.25-0.4, and doing tests at full-scale Reynolds numbers are also beneficial.

Examples

Several car manufactures and race teams use the Lockheed low-speed wind tunnel in Marietta, Georgia, as well as the National Research Council tunnel in Ottawa, Ontario, for testing. The General Motors Research Laboratory has SCALE TUNNELS that are both model- and full-scale.

Wind tunnels are owned and used widely in the aerodynamics of vehicles by firms such as Ford of Germany, Pmsche, Opel, BMW, Volvo, Mercedes, Audi, Fiat, Pininfarina, Volkswagen, and the Motor Industry Research Association (MIRA) of Great Britain. All of Japan's major automakers, including Nissan, Honda, Mazda, and Toyota, have excellent aerodynamic testing facilities.

The tests were carried out in the Volvo Cars Aerodynamic Wind Tunnel (PVT) in Gothenburg, Sweden. It has a slotted wall test section with a cross-sectional area of 27 m2 and a slot open area ratio of

30% and is of Gottingen type. All of the experiments were conducted with a wind speed of 140 km/h and no yaw. [35]

xiii. *Climatic Wind Tunnels*

The other kind of wind tunnel is one that allows engineers to test drive units, air conditioners, door and window seals in simulated hot and cold weather conditions, as well as under arbitrary operating cycles. These facilities can heat and cool the airstream, simulate intense sun rays, simulate fog, and drive cars on dynamometers around the clock for long periods of time.

xiv. *Aeroacoustic Wind Tunnels*

Submarines, ships, and other forms of marine vessels and appendages, as well as their wake distributions, have long been a concern in the military, just as noise control for aircraft and ground vehicles has been in the civilian world.

Eg. The David Taylor Research Center planned and developed the Anechoic Flow Facility after realising the benefits of keeping the model and measuring instrumentation still and making the fluid move, as well as the tremendous expense of conducting full-scale tests and the fact that noise reduction is easier with air than with water.

With features like the use of a wide-angle diffuser to achieve a 10:1 contraction ratio without a long diffuser and high-cost return direction. Instead of the more common four 90" turns, two 100' turns and two 80° turns were used. This allowed for the fan noise suppressors to be longer, but with a shorter passage. Noise-reducing fabrics on walls, ceilings, and spinning vanes, as well as very hard concrete constructions. The transparent research section is surrounded by an anechoic chamber, which results in the lowest noise levels ever reached in a wind tunnel. Section separation, as well as the isolation of the entire tunnel from the ground by multiple feet of crushed rock, is used throughout. [10]

Another example of an anechoic or aeroacoustic tunnel is Delft University of Technology's recently refurbished vertical tunnel (V-tunnel), which has been redesigned as a state-of-the-art facility for experiments in aeroacoustics (A-tunnel), as well as fundamental studies in laminar-turbulent transformation and flow control.[14]
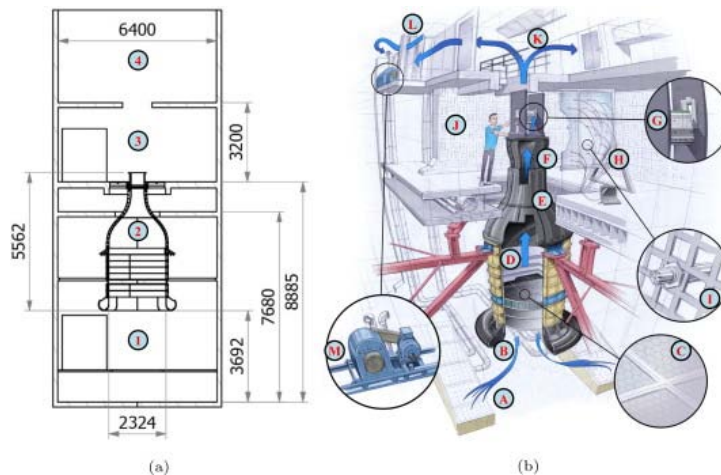
Figure 2: Aeroacoustic Tunnel, Source: [14]

xv. *Aquadynamic Flume or Water Tunnels*

Water tunnels, are not wind tunnels. However, Water tunnels, are used in precisely the same way as low-speed wind tunnels which work under the same mathematical mechanisms. Cavitation phenomena may be investigated directly in a water tube, which is not possible in a wind tunnel. For obtaining the same Reynolds numbers, water tunnels are physically smaller than wind tunnels. However, the challenge of using water instead of air as the operating fluid more than offsets this obvious advantage. The wind tunnel's aerodynamic rules apply similarly to watercraft, with the exception that water is more viscous and therefore exerts larger forces on the material being tested. For underwater aquadynamic research, a looping flume is often used. Pure wind tunnel research is only partially applicable due to the interaction between two distinct kinds of fluids. A towing tank, on the other hand, conducts related studies. [45, 86]

xvi. *General-Purpose Wind Tunnels*

Many of the wind tunnels that have since become general-purpose facilities were initially built to meet the needs of experiments on aircraft of the World War I period. The 7 X 10-ft class wind tunnel is the most general, with those estimated dimensions for their test parts. All NASA research centres dating back to the NACA era have or have one or more of the following: The US Air Force has one, the US Navy has two, five US universities have tunnels of this kind, and a variety of other governments and organisations around the world have or have had tunnels of this type.

xvii. *Computer Controlled*

The following conclusions have been reached after the construction and testing of new computer-controlled wind tunnels:

1. Several different mean wind profiles can be created by individually manipulating each fan, and symmetrical profiles and turbulences can be created both under the ceiling and on the surface.
2. Each fan may be regulated in a periodic or dynamic manner to generate high turbulence intensities and integral scales.
3. It is possible to simulate the necessary atmospheric wind characteristics by systematically manipulating several variables. [12]

d) CFD VS WT

Computational/ theoretical tests or Wind tunnel Test for a model?

In the 1970s and early 1980s, it was thought that the use of wind tunnels, especially in the subsonic regime, would rapidly decline as computational fluid dynamics (CFD) or FEA (Finite Element Analysis) software would become a more cost-effective method for obtaining data for many engineering applications. ([45] Barlow et al. 1999).

Nonetheless, computational simulations have progressed since then, but they are still far from being able to completely replace the need for experimental evidence in development projects. During this period, the computational method will certainly predict basic models such as actual flow in a wind tunnel, but it also takes a long time, making it complex and costly. Furthermore, as compared to wind tunnel results, the computational method also does not have a satisfactory measurement of drag. As a result, wind tunnel testing will continue to be the most popular method for aeronautical growth in the near future. [19, 45]

Matter of fact, the investigative approaches that led to quantitative forecasts were a mix of experiment and theory, with computational methods emerging as a new effective tool in this area. Furthermore, although the utility of CFD methods has increased over time, thousands of hours of wind tunnel testing (WTT) are still needed for the construction of an aircraft, wind turbine, vehicle, or some other design that requires complicated interactions with the flow.

Subsequently, due to the budding attention of other branches of industry and science in low speed aerodynamics, and due to the persistent incapability of achieving accurate solutions with numerical codes, even with advancements, low speed wind tunnels (LSWT) are essential and irreplaceable during research and design. [18]

Many times, when testing new designs and materials, FEA software fails to create the interactions and properties that are unknown, and wind tunnels step in to help produce accurate flow modelling results.

Because of their ability to combine various types of data, wind tunnels prove to be a critical device in the efficient and detailed design procedure of anything that involves fluids. [21]

Thus, across a wide variety of manufacturing and research applications, experimental explorations remain the mainstay for collecting evidence for designers to produce detailed performance and final decisions.

e) Importance

The Wind Tunnel is well-known for its vast potential in civil, environmental, automotive, and aeronautical applications. Everyone's key priority in today's world is to save time, content, and resources, which has forced everyone to opt for preliminary experimentation on miniature models before forming the finished product. One such platform is the Wind Tunnel, which provides us with the ideal atmosphere conditions around the model sized to the required dimensions.[52]

Wind tunnels are a vital instrument in the simple, effective, and rigorous design phase of something that requires fluid dynamics, as well as sharing concepts with peers or clients, due to their ability to merge all forms of data, i.e. quantitative data and visualisation.[47]

Prototypes may also be used for concept checking or recording vast amounts of data in wind tunnels, although the most valuable feature of wind tunnels is that they precisely simulate the maximum complexity of a fluid flow.

Aerodynamic testing has now grown into other areas such as the car industry, engineering, the atmosphere, education, and so on, making low-speed wind tunnel experiments increasingly important.[18]

f) Applications and Other Effects

Technical information for a large number of engineering applications such as external aerodynamics (flow over terrestrial and aerial vehicles), civil engineering (flow over bridges, buildings, cables, etc.), sport activities (flow over cyclists, design of volley and basket balls, wind sails etc.), fundamental fluid dynamics (laminar and turbulent flow over simple and complex geometries) could be aided with Wind Tunnels forming extensive frame of other options in industry and research centres at universities around the world. It can also be used in wind engineering to calculate the velocity around structures, as well as forces or pressures on structures, and to precisely measure the air movement of fans, turbine blades, and propellers.[52]

i. *Specific Applications*
 a. *Aerodynamic Applications*

Wind tunnels are used by scientists and engineers to investigate the pressures, forces, and air flow direction that impact an aircraft. [23, 45, 47]

b. *Calibration*

Wind Tunnels are used to calibrate instruments, too.

c. *Fluid Flow*

Fluid flow researchers have been researching fluid flows in different ways for decades, and fluid flow analysis is still a significant area of study today. Fluid flow is important in a variety of situations. Gaseous flows are observed in the construction of automobiles, aeroplanes, and spacecraft, as well as in the design of turbines and combustion engines. Liquid flow study is important for maritime applications like ship construction, as well as civil engineering ventures like harbour design and coastal defence. Fluid flow in reactor tanks is significant in chemistry, and the flow in blood vessels is studied in medicine. Numerous other examples could bementioned. In all kinds of fluid flow research, visualization is a key issue. Wind Tunnels are great instruments to visualize flow [3] [19]

ii. *Non-Aero applications*

a. *Architecture*

In architecture, due to the fact that buildings are placed on the ground and are usually of relatively low height, they are well within the atmospheric boundary layer.

The airflow around large structures, tall buildings, and Office towers with odd or complicated shapes is studied in wind tunnels (such as building with a parabolic or a hyperbolic shape). Aerodynamic assessments of any famous structure, nearly everywhere, are regularly requested by architects. Any construction part must pass an aerodynamic test before being approved for use in hurricane-prone areas like Florida. [45, 18, 19, 26, 52, 85].

EG. [31] Yoshihide Tominaga, Bert Blocken- "Wind tunnel analysis of flow and dispersion in cross-ventilated isolated buildings: Impact of opening positions"-This paper uses a Wind Tunnel to provide a systematic experimental study of cross-ventilation flow and dispersion in five generic isolated single zone buildings with various opening positions.

Aerodynamic influences are substantial in the design of large bridges. Cable suspension bridges or cable stayed bridges are analysed in specialized atmospheric boundary layer wind tunnels.

b. *Vehicles*

Airplanes

Aerodynamic considerations, with differing degrees of attention to performance, endurance, stealth, acquisition expense, operating cost, time to completion, and any other factor that a customer may need for planned missions, dictate the shapes of aeroplanes.

Another application is the combustion testing of aircraft engines, which necessitates the purchase of an expensive device to purify the air in the tunnel and ensure the same air quality. Another increasingly significant aspect of aircraft construction is their noise footprint, which is usually only tested in a wind tunnel.[18, 19]

Airport Glide Paths

EG:[38] In this paper- Wind tunnel research was performed in Tongji University's TJ-3 boundary layer wind tunnel to analyse the impact of complex terrain on the wind characteristics of the glide paths at Hong Kong International Airport's North Runway. Cobra probes were used to assess the wind speed and direction at the North Runway glide paths. The influence of terrain on wind characteristics such as turbulence strength, turbulence integral size, and mean headwind speed was investigated. The findings suggest that terrain variations have a major impact on the glide path wind characteristics. With the turbulence strength in the wind direction at the same altitude, turbulence intensities in the cross-wind and vertical directions increase; the inflow can affect aircraft landing due to the decrease in headwind speed at glide path 25RA caused by obstruction of certain terrain

The terrain model used was: Lantau Island and HKIA were included in the test simulation set, which was a circular area with a diameter of 27.2 km. The model was produced with a 1:4,000 geometric scale ratio and a diameter of 6.8 inches.

Automobiles

There are millions of cars on the road today that bear witness to the impact of exterior aerodynamics on design decisions. It goes without saying that in automotive applications, the car's aerodynamic drag is important. Despite this, owing to the current high degree of regulation of this parameter, as well as imposed speed limits, the majority of efforts are focused on reducing aerodynamic noise. The ground effect simulation is therefore very significant, which necessitates the use of very sophisticated facilities in the test section to enable testing of both the ground effect simulation and noise generation. [18]

EG. [35] The standard open road simulated configuration is contrasted to simulations in which the computational environment is a computer model of the full slotted wall wind tunnel test segment geometry in this research paper. A sedan-type car is tested in various configurations, and the simulation effects are compared to physical force and pressure measurements. When compared to uncorrected calculation evidence, the results show that simulating the car inside the wind tunnel can predict the absolute drag coefficient with high precision. Despite the high level of consensus for drag, the estimation of lift is less accurate.

F1 Cars

The rising need for fuel in cars necessitates an increase in automotive aerodynamics in order to

conserve energy more easily and efficiently. Upgrade pressure on aerodynamics has increased rapidly, especially on F1 race cars. Aerodynamic forces have the ability to drive the tyre force against the road, increasing the vehicle's momentum. A spoiler may be mounted to raise the downward impact. To perform intensive research in developing vehicle aerodynamics, F1 car designers develop their own wind tunnel. One simple way to tackle aerodynamic issues is to use a low open type wind tunnel. [1, 2]

Bikes

Experiments have shown that the amount of wheel spokes and other data affect drag. The use of wind tunnels has proved to be useful in demonstrating to bike riders how to travel with the least amount of drag. [19]

Yachts

Racing-yacht keels are the focus of extensive research in the hopes of gaining a few seconds per mile advantage.

Sails and Above-Water Parts of Ships

Over the years, the efficiency of sails has been tested in a small number of wind tunnels. Sail tests, in general, include measuring side impact, drag, yaw, and roll on a model placed on the tunnel floor in an atmospheric tunnel with a correctly simulated boundary layer.

Rails and Trains

Wind tunnels are employed for testing rail as well as public vehicles of transportation. For e.g. the non-profit Rail Tec Arsenal (RTA) testing centre used Climatic Wind Tunnel located in Arsenal, Vienna to provide climatic validation for rail and public transportation vehicles. This facility had two climatic wind tunnels that could replicate different weather conditions by adjusting temperature, air pressure, humidity, and wind speed. [88]

c. *Sports*

Wind tunnel testing of athletic goods, such as golf clubs, golf balls, Olympic bobsleds, Olympic cyclists, and race car helmets, has been commonplace over the years. In open cockpit racing cars, helmet aerodynamics is especially relevant (Indycar, Formula One). Excessive lift pressures on the driver's helmet can cause neck pain, and flow separation on the back side of the helmet can cause turbulent buffeting and hence distorted vision at high speeds. [81]

Such initiatives have resulted in significant changes in clothing. Clothing has been tested in some situations to see how it will improve drag when worn by a competitor who wants to increase load during exercise. Vertical wind tunnel training has been given to airborne soldiers so that they are comfortable with the conditions they will face while jumping from planes.

Skiing

For skiers, the "form" is placed in the tunnel and assumes a set of positions during a run at about 55 mph (which is similar to full-scale "flight") in order to learn and minimises his or her drag or perhaps the lift to-drag ratio in the case of ski jumpers.

Cycling Pelotons

EG. [34] In this research, Drag on cycling pelotons was analysed by Wind Tunnel testing of Wind Tunnel Laboratory at the University of Liege in Belgium and Wind Tunnel Laboratory at Eindhoven University of Technology in the Netherlands and CFD simulations were carried out

d. *Wind Turbine Testing*

WTs are used for testing wind turbines or windmills or for effects of wind barriers on solar collectors being simulated in a wind tunnel[45]

Examples in literature:-

1. [13]In thisdetailed experiment paper, work was carried out in an atmospheric boundary layer (ABL) wind tunnel to investigate the characteristics of the complex wind loads operating on a standard three-blade horizontal axial wind turbine model in this study. The tests were carried out in a large-scale aerodynamic/atmospheric boundary layer (AABL) wind tunnel at Iowa State University's Aerospace Engineering Department. The test model depicts a wind turbine in a wind farm with a rotor diameter of approximately 90 m and a tower height of approximately 80 m at a scale ratio of 1:350.

2. [27] In this study, the output of a newly developed cross-axis wind turbine (CAWT), which combines the advantages of horizontal and vertical axis wind turbines (HAWTs and VAWTs), was tested in a calibrated open-circuit low speed wind tunnel to match the wind field in an urban environment.

3. [20] Turbulence, one of the most prominent characteristics of urban flows, is investigated in this article, as well as its effect on the efficiency of small VAWTs (often used in urban wind installations). The aim of this experiment is to test an H-Darrieus VAWT prototype in a wind tunnel under various turbulent conditions in order to investigate the effects of turbulence strength, integral length scales, and Reynolds number. The rotor of the turbine was a two-blade H-type Darrieus turbine with two NACA0018 blades, each with a 5 cm chord (c) and two inclined struts.

e. *Fan Testing*

Wind tunnel experiments are also carried out to accurately determine the airflow of fans at a certain pressure. The standardisation of the data is maintained by assessing the ambient conditions during calculation and then revising the airtightness. [86]

f. Construction

Bridges

Natural wind effects are crucial in the proper construction of long or even intermediate bridge spans. At least one event has been recorded in which low-speed aerodynamic excitation resulted in fatigue cracking of high-aspect-ratio beams in a bridge superstructure. Thus it is important to know (1) vortex shedding, which induces minimal vertical displacement or torsional oscillations at low wind speeds, and (2) flutter instability, which may induce both vertical and torsional oscillations.

Roof

EG. [24]Jimmy Colliers' thesis shows how to prototype double curved thin shell wind tunnel structures with incorporated pressure sensors using a prototyping technique. A hyperbolic paraboloid roof structure's development mechanism is depicted. The wind load distributions obtained are compared to literature for a flat roof and canopy constructed using the same technique, as well as two hyperbolic paraboloid roofs. The results show that these thin shell wind tunnel models provide more accurate wind pressure distributions over very thin canopy systems than traditional wind tunnel models.For double curved thin shell wind tunnel models that allow simultaneous pressure measurements over both sides of a thin canopy, the presented fabrication technique for scaled wind tunnel models of glass fibre composite is convenient and precise. The technique can be readily applied to a variety of organically formed membrane or shell structures, and it allows for the use of diverse materials as long as the structure can withstand wind loads during wind tunnel testing.

Low Rise Structures

Important aspects of wind tunnel model simulation experiments of theatmospheric surface layer for the assessment of wind loads on low-rise buildings canbe carried out. [29]

iii. Other Applications

a. Multipurpose Climatic Wind Tunnel

The Doriot Climatic Chambers (DCCs) are a pair of very large, extremely advanced wind tunnels/environmental chambers at the Soldier Systems Center (SSC) of the United States Army in Natick, Massachusetts. The Chambers, which were built in 1952, are a one-of-a-kind laboratory capable of simulating a wide variety of global environmental scenarios for both, evaluating military equipment and testing of human physiology, and adaptations in different conditions [89]

b. Environmental Wind Tunnels

There are tunnels that are constructed to mimic Earth's natural boundary layer, which is normally 1000-2000 feet deep. Wind loads on roofs, air pollution dispersion patterns, soil erosion, snow drifts, movement patterns in the proximity of building complexes, and so on are all calculated using them. "Meteorological wind tunnels" is a term used to describe them. The airstream in an environmental wind tunnel is not supposed to be straight and flat, as it is in other tunnels used for vehicle construction tests. To reflect the atmospheric boundary layer, it is instead manipulated to obtain a flow distribution that is nonuniform in time and space. Since the properties of the atmospheric boundary layer vary greatly depending on terrain conditions, the tunnels must be able to adapt the flow to mimic a variety of scenarios. This is achieved by installing customizable roughness elements along the tunnel's floor for up to 10-15 test-section widths upstream of the model's location. The University of Western Ontario's Boundary Layer Wind Tunnel Facility also has an expanded water reservoir for simulating flow in the marine boundary layer. [45, 46]

EG. [15]In this research, analysis and design through experimental and numerical investigations showed that the grid acting as a passive flow control device was effective to reproduce in a short wind tunnel the main characteristics of an atmospheric boundary layer.

c. Wind Engineering

However, over the last two to three decades, the techniques have evolved into increasingly advanced and complex procedures used to cope with highly non-uniform and unsteady flows and their consequences. The computational lexicon has gained a new concept of Wind Engineering. Wind engineering incorporates meteorology, fluid dynamics, structural mechanics, and mathematical analysis to reduce wind's negative effects while maximising its positive ones. In general, four distinct fields are investigated: Wind Forces on Structures and Buildings Forces, moments, deflections, local pressures, and velocities are all involved in these problems.

Static Loads and Associated Experiments on Buildings

Wind tunnel engineers may be called on to help fix structures that have already been constructed and are experiencing problems, or to advise an architect on a new design. House swaying, losing windows or cladding, losing roofing, people being knocked down by waves, whistling sounds, smoke or other gases entering into the air system, and so on are all examples of "trouble." Since the planner is normally very defensive, these experiments are tenser than those on planned houses. It is less expensive to make modifications to proposed projects.

Wind Engineering Example of Wind tunnel-A wind tunnel with two experimental chambers was designed by Diana [82] and can be used for both aeronautical and wind engineering applications. [15]

Flow Over Hills

Example – In [39] an analysis of the precision of a wind tunnel investigation of flow over a dynamic terrain model has been conducted. The Rakaia River Gorge area of New Zealand was modelled both terraced and contoured to an undistorted geometric scale of 1: 5000. Three different surface roughness conditions were tested on the contoured model. Three teams of investigators investigated up to 27 points on either side and inside the river gorge on two spring days chosen for high adiabatic down valley wind flow. Wind speed and direction were measured from a height of 10 metres. Statistical correlation and scatter diagrams were used to equate the laboratory simulation findings to the available field data. The model and field effects were used to evaluate the utility of laboratory tests as part of a plan to establish and demonstrate reliable and cost-effective methods for locating favourable wind energy conversion sites.

Research carried out in

The Department of Mechanical Engineering, University of Canterbury,

Boundary-Layer Wind Tunnel has a test section 1.22 m X 1.22 m X 12.2 m.

Boundary-layer depth and integral scales are controlled by a combination of square rod grids, fences, and surface roughness.

Unsteady Aerodynamics in Wind Engineering

In a variety of ways, the wind may trigger structural oscillations and other phenomena. The following are few examples of common situations.

Simple Oscillations

Unless critically or over damped, all natural and man-made systems have one or more natural frequencies at which they can readily oscillate. Many things (trees, signposts, etc.) have natural frequencies that are similar enough together.

Aeolian Vibrationsor Eolian

Long, clearly supporting buildings, such as smokestacks and antennas, have a propensity to oscillate at their natural rhythm in a direction normal to a relatively smooth steady wind. The convergence of structural inclination to vibrate at a normal frequency and aerodynamic phenomena of slender bodies shedding vortex streets causes this phenomenon. One of the most discussed problems in fluid mechanics is vortex shedding from spherical tubes. There is an alternating shedding of associated unsteady side force and drag over a set of Reynolds numbers. The shedding frequency corresponds to a Strouhal number of around 0.2 under a broad variety of conditions. As can be shown, there would almost certainly be a wind speed at which the shedding frequency, and therefore the side-force frequency, equals the structure's normal frequency.

There is expected to be a noticeable pulse when such a coincidence happens. This form of oscillation is known as aeolian, though the term is often limited to structures with a high natural frequency (10-100 Hz) and small displacements. The tones in a "Aeolian Harp" created by the wind are generated by such oscillations.

Galloping

A second form of motion occurs where a body's lift curve has a negative angle, and motion through the wind generates a force in the wind's path. This is common in buff bodies whose in-wind side becomes unstilled with a minor angle of attack, allowing Bernoulli-type flow to intervene. Galloping oscillations are commonly aggressive and need design modifications to remove. Twisting stranded wires or inserting spiral wrappings, for example, has been shown to be useful in many situations.

Breathing

Large-diameter stacks and other configurations may also deform at a normal frequency, changing the flow pattern at that frequency. This is distinct from body motion that is free of distortion.

d. *Agricultural*

Windbreaks

Windbreaks may be used in conjunction with structural load reduction. A second and more critical use is to minimise winter heating loads by lowering a house's convective cooling, and a third is to boost yields from wheat varieties that don't like being blown around. [45]The drag coefficient is a significant indicator of a windbreak's wind protection effect. Although there have been numerous studies on this subject, only a few have included direct measurements, particularly those involving practical windbreaks. Wind tunnel tests were performed on artificial versions of small and practical windbreaks with various porosities. [33]

Windbreaks are used all over the world to change the surface temperature and soil quality for human and animal life as well as crop production. For environmental sustainability, large-scale agro-ecosystems with vegetative windbreaks have recently been developed (e.g. Wang and Takle, 1997a). A windbreak's main impact is its aerodynamic control on surface airflow, which causes changes in microclimate, soil climate, and crop growth. The windbreak, in theory, acts as a drag on the wind area, creating a net loss of momentum in the incompressible airflow and thus a sheltering effect (Rain and Stevenson, 1977).

As a result, several analyses of windbreak drag and drag coefficient have been conducted.

The configuration of a windbreak, which can be classified into two categories: artificial windbreaks (e.g. thin screens, fences) and vegetative windbreaks, determines the windbreak drag or drag coefficient. In aerodynamic analysis, the former is often constructed

with optical porosities and is referred to as "non-thickness." As a result, these windbreaks are often referred to as "two-dimensional windbreaks." The above, on the other hand, has breadth and internal structure.

Agricultural Agronomy

Many agricultural products are pollinated by the wind, so proper plant distribution and planting patterns are important. To boost natural winds, trees on the fields' edges will need to be removed. Some trees, on the other hand, do well without a lot of wind buffering, and these need special care. The application of wind engineering to agriculture is also in its infancy. [45]

Soil Erosion

The agronomist is interested in wind-induced soil erosion because it results in the loss of topsoil. In the other side, the road engineer wants his or her roads to remain open. Windborne particles destroy vehicle windshields and paint, which is another facet of soil erosion. When a stream of wind passes over a bed of loose debris, those higher up create more drag, eventually rolling and bumping in the direction of the wind.

The majority of the motion (and end deposits) that create snowdrifts or soil erosion is caused by this process, which is known as "saltation." The particles bump hard enough to rebound into the stream when the wind velocity reaches about five times the threshold speed, and they are then Ad to be "in suspension." In the presence of dropping debris, saltation and suspension may occur at much lower speeds.

E.g. of WTs for soil erosion

In general, two types of wind tunnels can be distinguished: stationary wind tunnels used for laboratory testing and mobile wind tunnels used for field research. The size of stationary wind tunnels is often restricted due to budgetary and/or logistical constraints, while the size of mobile wind tunnels is often limited due to budgetary and/or logistical constraints.

The challenge of studying natural surface conditions is clearly a drawback of the stationary kind.

Important erodibility characteristics such as crusting and soil composition can't be readily replicated, or can only be done with a lot of work. Mobile wind tunnels, on the other hand, can be mounted on structures in the field without destroying the natural environment, allowing researchers to observe the effects of wind erosion on unique natural surfaces. [45, 32, 33]

Mobile wind tunnels are critical instruments for examining and quantifying wind erosion processes on non-imitated natural surfaces in the field under uniform, quasi-natural wind conditions. On a transect in the Republic of Niger/West Africa, a mobile wind tunnel was built at the IBS of the University of Hohenheim to test wind erosion susceptibilities under various conditions and sediment emission on dominant surfaces created under semi-arid conditions. [32]

In a wind tunnel, the proper production of saltation and quasi-natural conditions is often influenced by a physical element known as the Froude number. For all wind tunnels used in wind erosion testing, the inability to generate large-scale eddies remains a challenge.

Snow Drifting

Drifting snow will totally shut down a facility by blocking doors and highways. Fortunately, the problem can be investigated in a tunnel with strong scale correlation. Snow patterns that take years to accumulate (in the Arctic) can be replicated in a matter of hours.Kabayashi, Strom, and others offer in-depth studies of the snow-drifting phenomenon.

Evaporation and Related Issues

The growing need to understand plant transpiration and evaporation from open bodies of water has contributed to the creation of wind tunnels in which the moisture content and temperature of the air can be regulated. Tunnels of this kind can be found in Japan, England's University of Nottingham, the United States' Colorado State University, and elsewhere. Both of them are low-speed tunnels with balanced air exchange.

Pollution Dispersion

For all of the different kinds of contaminants released into the air, it's important to understand not just where they'll go, but just how far they'll have to go before absorption decreases their concentration enough to make them harmless. The sheer number and variety of contamination issues is mind-boggling. Industrial smoke, waste gases from chemical processes, efflux from nuclear power plant holding tanks, using wind to carry silver iodide aloft to increase the likelihood of rain, the necessary distance from a liquefied petroleum gas (LPG) spill to obtain a non-combustible mixture, getting rid of hydrogen sulphide smell from a geothermal power plant, and pesticide dispersal through the atmosphere are only a few examples. Furthermore, a full variety of 'weather scenarios must be considered, as well as the worst-case scenario that is "likely" to occur. Skinner and Ludwip made significant contributions to wind tunnel dispersion experiments.

Eg[37]Wind Tunnel and Numerical Simulation of Pollution Dispersion: A Hybrid Approach by R. N. Meroney.

III. Classification

Wind Tunnels can be classified on a variety of basis [5, 8, 9, 14, 19, 23, 44, 45, and 52], such as

Based on Design/ Tunnel Geometry: They can be-Closed/ Gottingen Type or Closed circuit (CCWT) (Return loop of air fed back, closed and re-circulates the air through the test section) and Open/Eiffel or Open Circuit (OCWT) (No return loop, open on both ends and draws air from the atmosphere into the test section)[8, 14, 44,19, 52]
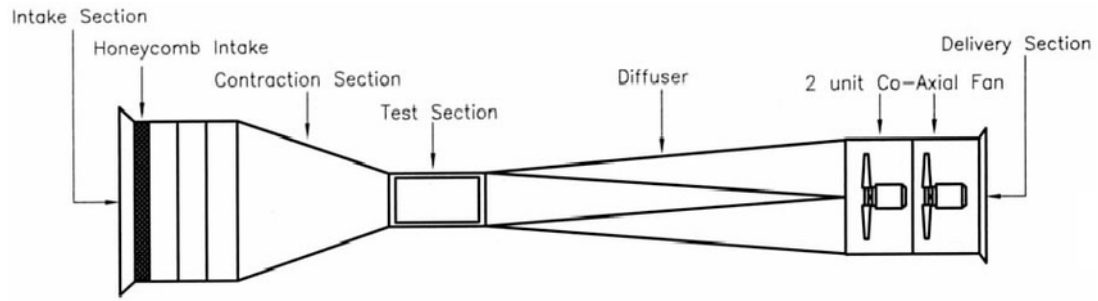
Figure 5: Open Circuit Wind Tunnel, Image source: https://www.researchgate.net/figure/School-of-Mechanical-Engineering-USM-open-circuit-wind-tunnel_fig2_233706255
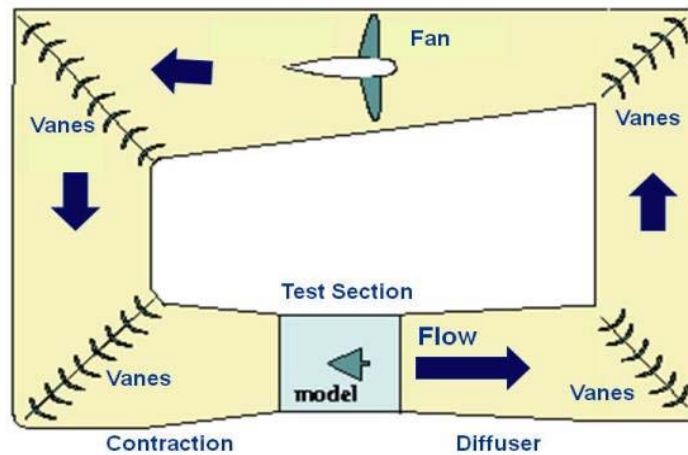
Figure 6: Closed Circuit Wind Tunnel, Source of image: https://www.grc.nasa.gov/www/k-12/airplane/tuncret.html

Based on Velocity/Speed configurations or Mach number: They can be subsonic/ low speed/ small (M < 0.8), transonic (0.8 < M < 1.2), supersonic (1.2 < M < 5.0), or hypersonic (M > 5.0). [23, 45, 19, 52].

Based on the test section of the wind tunnel itself: can be either enclosed by physical boundaries (Walls) called closed-jet or open (so called "open-jet" wind tunnels) or Semi-closed.

Figure 7: Open Test Section Wind Tunnel, Source: [21]

Figure 8: Close Test Section Wind Tunnel, source: [53]

Based on position of fan housing and diffuser: when it is placed at the end, it is called "Suck Down" whereas if it at the start, it is called "Blower" configuration

Figure 9: Blower WT, Image source: https://www.aerolab.com/products/blow-down-wind-tunnels/
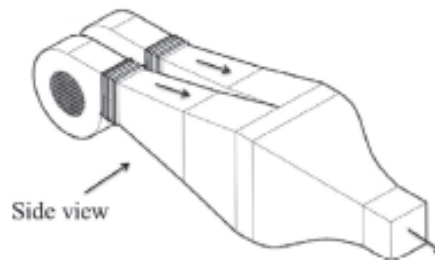
Figure 10: Blower Wind Tunnel, Source: [6]
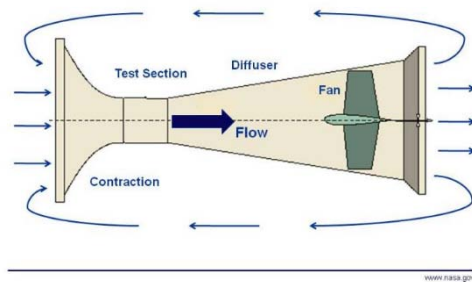
Figure 11: Suction WT, Image source- https://www.grc.nasa.gov/www/k-12/airplane/tunoret.html

Apart from this basic classification, wind tunnels can be classified as, [26]

1. Based on structure- funnel shaped or normal type, horizontal or vertical axis wind tunnel, long, short ormedium length wind tunnel
2. Based on structure material - Metallic structure or concrete type or composite structure wind tunnel
3. Based on shape of inlet section - Semi-circular, circular, square, semi- elliptical or other cross sections of various shapes
4. Based on location- outdoor location or indoor location wind tunnel

5. Based on anemometer placement - push in type, windows for anemometer, anemometer frame type.
6. Based on mode of operation - Pressure storage, in-draft or Pressure vacuum type. [23]
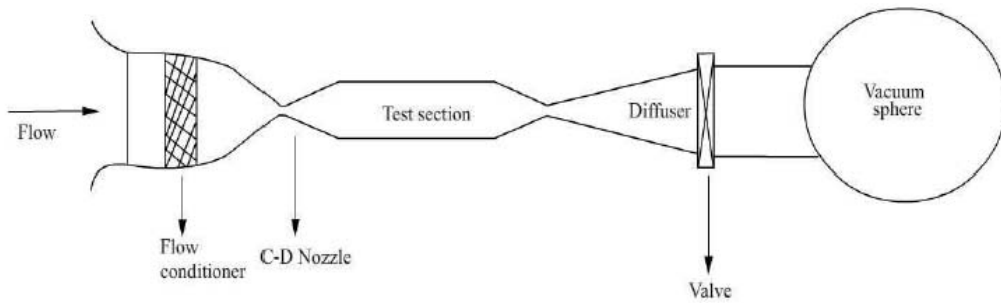
Figure 12: Indraft Wind Tunnel, Source: [23]
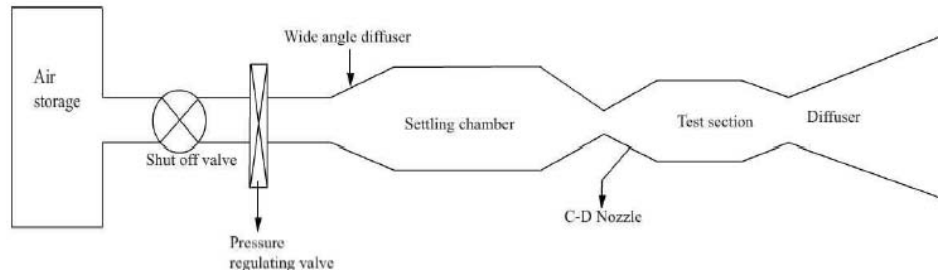
Figure 13: Pressure driven Wind Tunnel, source: [23]

7. Based on Operation - Continuous (for all speed ranges) or Intermittent; With increasing Mach number the tendency to intermittent operating wind tunnels linked with an appropriate energy storage arrangement, becomes more and more compelling. However, for measurement of low subsonic flow, the continuously operating wind tunnel is more preferred. [9]
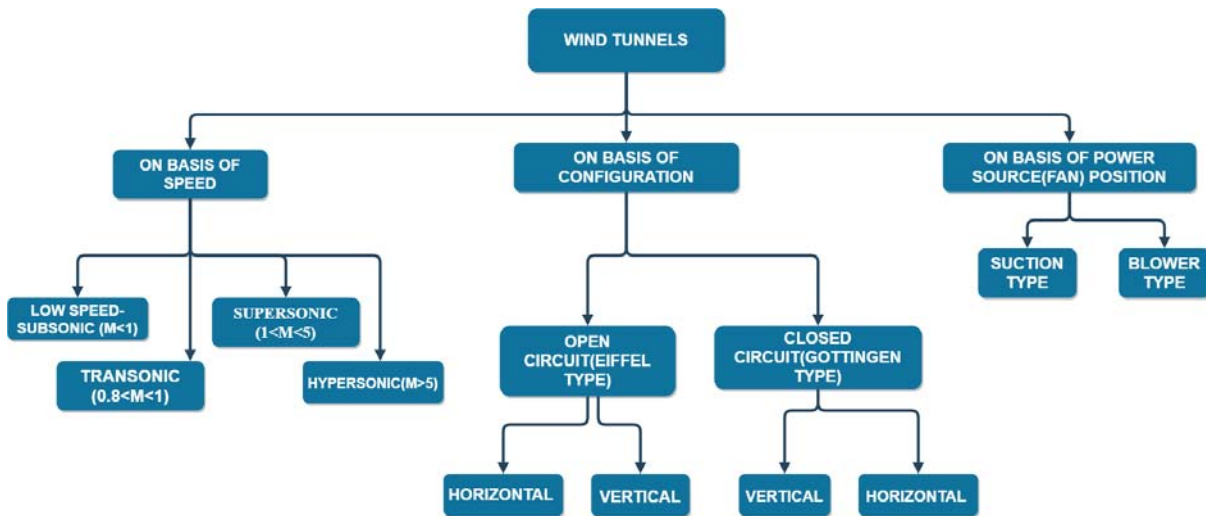
Figure 14: Basic Classification of Wind tunnels

Elaboration-

a) On the basis Design/ Wind Tunnel Geometry

In particular, the type of tunnel preferred is determined by the amount of resources invested and the intention of the project.

Closed Circuit Wind Tunnel (CCWT) or Closed Return Wind tunnel or Gottingen/Prandtl type:

Closed circuit wind tunnels provide a closed loop (feedback) of the airstream in which exhaust flow is directly returned to the tunnel inlet, avoiding unnecessary power losses and increasing total performance of the system [47]. Closed circuit tunnels produce a steady air mass and do not account for leakage. To achieve a regulated return flow, the most high-performance wind tunnels were configured as closed-circuit types.

To cut down on the amount of energy used, a closed circuit tunnel has been established. Prandtl pioneered this category of wind tunnels in Göttingen, Germany, and thereby the name [50]. This tunnel's main function is to circulate used airflow from the diffuser to the settling chamber through the connecting channel and corner vanes. In an enclosed loop, air is recirculated. They take up so much room and are more

difficult to build and manufacture. (43, 45) It's also possible to use a cooling system. [10]

There are two kinds of closed circuit tunnels: single, and double return. Only the first of these is currently widely accepted. The air that scrapes along the walls of the return passages forms wakes in the centre of the jet and hence flies directly over the model in the double return arrangement. Unless the contraction ratio is high, the air is highly turbulent, making it impossible to interpret the test results. The fans are preferred to be connected to the connecting channel because it defends against model loss and increases fan performance. [7, 9, 14, 19, 47]
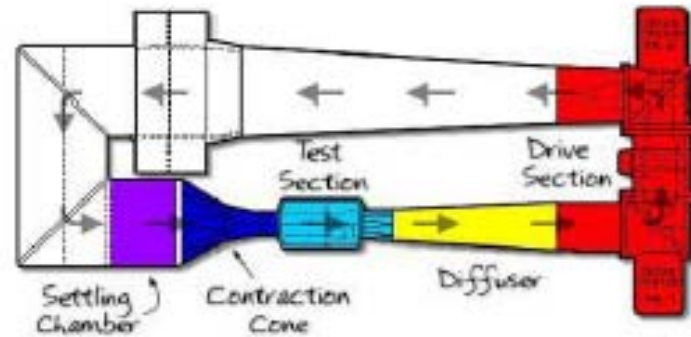
Figure 15: Closed circuit Wind Tunnel, Source: [19]

As stated above test section could be:

Open Test Section: Air is blown from the contraction cone to an open space between the contraction field and the diffuser in this location. Here is where the test method is typically mounted. This form of test section results in a significant amount of pressure loss. The creation of a jet-shear layer from the nozzle's exit characterises a wind tunnel with an open jet. As compared to their closed-section counterparts, the jet exits in a comparatively wider domain, which reduces the aforementioned wall effects and decreases background noise levels. Measurement instrumentation is also less invasive, owing to the open jet's flow and optical accessibility, which enables instrumentation, such as microphone arrays, to be positioned outside of the flow. However, because of the jet spreading and model circulation, flow consistency and synchronisation are more difficult to monitor, necessitating extensive corrections to achieve the effective angle of attack and effective aerodynamic coefficients. [14]

Closed Test Section: The contraction cone has air blown into a closed wall test segment here. This section, closed by walls is normally where the test model is kept. Wall friction is caused by the test section's walls. [44 and 50] A wind tunnel with a restricted testing region allows for a faster reconfiguration of the freestream flow, resulting in lower model blockage and airflow corrections and more closely regulated aerodynamic properties [14]. Erroneous readings of the sound frequencies produced by the model can be induced by high background noise levels [16] and reflections from the solid surfaces of the test segment.

To optimise uniformity in the return flow, CCWTs must be strategically crafted. Axial fan(s) are used to operate these tunnels upstream of the test section, and multistage compressors are often used to produce trans-sonic and supersonic air speeds. [47]

Plus points
1. Quality of flow can be well controlled by suing corner-turn vanes
2. Quality of flow is also independent of weather/outdoor conditions as well as of other activities in building
3. There is lesser noise during operation
4. For a given test section size alongside velocity, lesser energy is required, since there is decrease in the pressure and power losses. This is really helpful for a tunnel used for development experimentation with a very high usage rate (2, 3 times for 5, 6 days/week). [21, 45, 9, 47, 7]

Drawbacks
1. A huge amount of initial investment (due to return ducts and corner turning vanes)
2. There exists a necessity to purge the tunnel, if smoke or other flow indicators are used, as there could be entrapment of the same.
3. A technique of cooling would be mandatory for high utilization of the tunnel. [21, 45, 9, 47,7]

Open Circuit Wind Tunnel (OCWT)/ Eiffel Type

With an Open circuit wind tunnel, it is possible to achieve high performance, and even save space and construction cost. In essence, an open circuit wind tunnel is actually a closed circuit wind tunnel with a shabbily designed return leg/lag. OCWTs keep replenishing or keep cycling fresh fluid/air. It requires a pre requisite amount of free room around for no effect on quality of return flow. Its specific design was pioneered by French engineer Gustave Eiffel in 1909,

hence the name, "Eiffel Wind Tunnel". This classification consists of an Intake, a nozzle/contraction, test section, diffuser and a driving unit/ exhaust with no corners nor long diffusers [9, 45, and 50]. It lacks any loop feedback. This category of wind tunnels is generally used in spacious, closed rooms in order to reap the benefits of natural feedback air [7, 10, and 43]

Principle working of OCWT, is the direct sucking of external atmospheric air brought into the settling chamber with an end to the air's journey by a driving unit or exhaust lying on extremity, and then thrown away to the atmosphere.

58
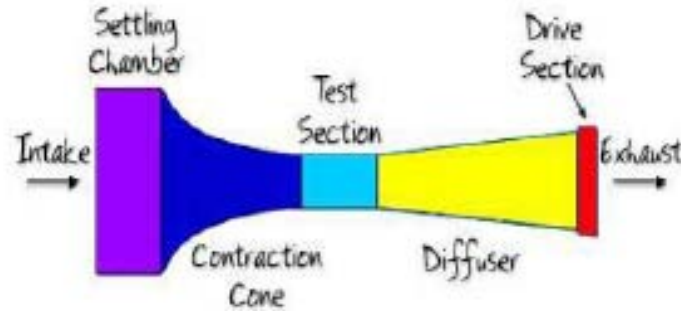
Figure 16: Open Circuit Wind Tunnel, Source: [19]

The drive units may be placed at the tunnel's downstream end, where it is run as a suction tube, or at the tunnel's upstream end, where it is operated as a blow down tunnel. Because of the consistency of the airflow, the suction tunnel is favoured in a configuration. [9, 19, 50, 10, 7]

That is, the Open circuit wind tunnels are further classified as:

i. *Blow down configuration or Blower configuration*

The blower creates a high pressure at the inlet, allowing for significant shifts in operating section configurations. Since the fan is at the inlet, the exit diffusers may be skipped (at the expense of power loss) to allow entry to the test section without upsetting the flow. Blow down tunnels are also termed versatile as test models may also be changed to match the scale of the test object. They are referred to as "free-jet facilities." [45] Some Blower configuration employ diffusers at the start of wind tunnel which could be one or even two in number

ii. *Suck down configuration*

Suck down wind tunnel creates a pressure drop at the tunnel's exit, allowing airflow to flow through it. The diffuser and fan housing is usually at the end of the Wind tunnel. The return flow of suck down tunnels is vulnerable to unpredictability. However, since the air does not flow through the blower until hitting the test, the blowing impact, and swirling effect of the air is minimised. The only benefit of a suction tunnel with a centrifugal or axial fan at the exit is the questionable claim that air from the tunnel room may be less disturbed than air from a fan. [9, 47]

Plus points

1. The main advantage of open-circuit tunnels is in the saving of space and cost.

2. They also suffer less from temperature changes (mainly because room volume > tunnel volume) and the performance of a fan fitted at the upstream end is not affected by disturbed flow from the working section.

3. They can be used to run internal combustion engines and extensively use smoke for flow visualization without the need to purge. [21, 45, 9, 47, 7, and 52]

4. Its Set-Up and Maintenance Cost, which is very small as compared to CCWT.

5. The leading manufacturer of automobiles utilize the OCWTs for the Drag and performance estimation of the vehicles since, with current tech & blueprint designs, these tunnels give results quite close to practical values under proper calibrations.

Drawbacks

1. Since, they are open to atmosphere, the pressure (mostly static pressure) is usually greater than atmospheric pressure in regions of high air speed. This implies when an OCWT with an exit diffuser is used, it gives rise to spurious jets issue from holes remaining unpatched, that is, leakage is unavoidable due to holes often drilled for mounting probes and models in test section [19, 46]. This is often minimized by impeding the outlet or by creation of an overpressure in the working sections.

2. OCWTs can be noisy if tunnels have larger test sections like 70 sqft or more. The noise causes environmental issues, it limits the hours of operations and mandates the use of sound proofing equipment or noise treatment of tunneland surrounding room.

3. In order to achieve extreme high quality flows, extensive screening at the inlet might be required, especially if the tunnel is within a room depending

on size of tunnel to room. An alternative to controlling the flow conditions (temperature and relative humidity) is housing the wind tunnel in a large closed room with an HVAC system that has a larger capacity than the load imposed by the wind tunnel.

4. OCWTs would need higher energy to run, which is a contributing factor to the high utilization rate in developmental experiments [21, 45, 9, 7, 47, 10]

5. They are generally placed in large rooms, as are sensitive to impediments in room, like furniture or walls which give rise to adverse effects in flow.

b) *On the basis of Velocity/Speed configuration or Mach number*

Small WTs/ low speed WTs/ sub-sonic WTs

They are the most common type with the flow velocity Mach number range of zero to 0.4. In them, viscous and inertial forces are dominant while compressibility effects are negligible. [19] They possess maximum speed capability up to about 300 mph (440 ft. /sec, Mach = 0.4, 134 m/s, 261 knots). [45]

High Speed WTs
The designation high speed usually includes:
1. High subsonic
2. Transonic
3. Low supersonic regimes

The range of the flow velocity for high speed wind tunnel is of Mach number between 0.4 and 1.4. Here, in principle, compressibility effects dominant [19, 23]. Also, the viscous effects come to light particularly when shock boundary layer intersection leads to flow separation.

Transonic

Occurs for Mach number nearly equal to one, wherein the speed of air approaches the speed of sound; M=1. [9] Transonic wind-tunnels are common in the aircraft industry since most commercial aircraft operate in this regime.

Supersonic wind tunnel

The flow velocity in supersonic wind tunnel is the range of Mach number between1.4 and 5.0. Compressibility effects are primarily dominant. The pressure disturbance surges in the flow field propagating downstream. Supersonic wind-tunnels are effectively used to investigate the behaviour of jet engines and military aircraft.

Hypersonic wind tunnel

The flow velocity in hypersonic wind tunnel is of Mach number above 5.0. Real gas effects are desired which require high Mach number in test section along with total temperatures. The high temperatures, linked with high pressures, give rise to vibration of the gas molecules, possibly causing dissociation and ionization. Thus, these are prevailing characteristics of hypersonic flows where the gas can no longer be treated as an ideal gas. [9] Hypersonic wind-tunnels find their applications in rockets and space vehicles.

c) *Reasons for Selection/ Design Considerations*

An important consideration to take into account is whether the wind tunnel should be closed circuit (return) type or Open circuit (non-return) type. Most of the research facilities which are small-scale and bound by financial considerations implement the open type wind tunnel. Moreover, schools and universities prefer an Open circuit Wind tunnel to assign their course work peculiarly for subjects like fluid mechanics or aerodynamics. Science fair participants who build their own wind tunnels, implement the open design, due to low utilization rates. Thus, the low initial cost, lesser maintenance drove the choice towards an open circuit tunnel.

Moving on, closed test sections are better for measurement and Suction OCWT introduce less swirl. For most of the tests, subsonic, low speeds are enough with axial fans.

Thus, we have chosen a subsonic/low speed OCWT (Eiffel Type) as prime design.

IV. Prime Design

a) *Difficulties in Design*

Since the 1930s, when the powerful influence of free-stream turbulence on shear layer behaviour became evident, focus has been placed on wind tunnels with good flow uniformity and low levels of turbulence and unsteadiness. However, due to a lack of understanding of flow through the different tunnel components, it has been difficult to formulate firm rules for wind tunnel construction. Bradshaw and Pankhurst (1964) [45] made the first attempt at presenting some instructions for the complete design of low-speed wind tunnels, and later theoretical tests of flow through individual components of a wind tunnel by Mehta, 1977, 1978 and Mehta and Bradshaw, 1979. [7, 14]

For the most part, this has culminated in a deeper perception and design theory. Over the years, the topic has gotten a lot of coverage, with around 50 articles citing specifically the design of various forms of Wind Tunnels. Rae & Pope (1984), a detailed study on the German-Dutch Wind-tunnel written and curated by Seidel, are two books and articles on the subject (1982).

However, wind-tunnel architecture is a complicated field covering multiple areas of fluid dynamics and engineering, and it is difficult to address all of them in a single article. [47]

It is a herculean task to devise prescriptive guidelines for wind tunnel design a priori (Latin for previous/scientifically) due to the vast range of tunnel designs and a lack of knowledge of flow through wind tunnel constituents such as the wide angle diffuser, mesh panels, and the blower/diffuser itself. [8][44]

Manufacturing costs and vibration in each portion due to high wind velocity are just a couple of the drawbacks. An axial fan induces a swirl. When this wind whirl goes into the wind tunnel, it has a different effect on the airfoil. In terms of wind speed, choosing the form and scale of a wind tunnel is a task in terms of engineering and fabrication. [30][7]

Based on data from successful prototypes and some initial studies, we have attempted to present our design specifications for the key components of a wind tunnel—the power source, contraction chamber, settling chamber, and exit diffuser.

b) Guidelines for Design
Crucial Parameters and Main Specifications

The flow quality within the test chamber, as well as the overall performance, are important characteristics of wind tunnels. The flow quality (described by turbulence and flow uniformity) must be specified according to utilization of wind tunnel. Flow quality is a result of design, and can be verified only during calibration tests. [45, 18] It is crucial to avoid flow separation close to the walls of the contraction zone.

Thus, theoretical maximum speed, flow uniformity, and turbulence rates are the three major parameters that are widely used to typify them [18]. The main specifications would be the dimensions of test section, along with required maximum operational speed. It has been found that lesser the turbulence, better it is to simulate flight conditions. [47]

Other Factors

When the parameters are finalized, it is important to find a balance between overall dimensions of wind tunnel, their compatibility with available room with the overall cost. This cost is dependent primarily on external shape of wind tunnel, and power plant (Fan) requirements. Other parameters to confirm with are, manufacturing process, future possible improvements, and operational/maintenance expenditure for the equipment [10, 17, 18, 21]. Energy ratio is the ratio of power (in test section) to flow losses (around the circuit) and is a measure of energy efficiency of wind tunnel. It is nearly always greater than unity for closed as well as open circuit wind tunnels except for free-jet facilities.

Design Aim

The design aim of a wind tunnel's configuration is to achieve a regulated flow in the test chamber whilst preserving flow performance and quality parameters.

Overall Aerodynamic Objective/ Project Scope

The below are the key goals that we want to accomplish with this working model:

1. Build a small scale wind tunnel using different criteria for educational and scientific purposes.
2. To simulate the velocity profile or fluid flow around a scaled model or test piece.

3. Determine the lift and drag coefficients for various test sections' particle velocities.

As a result, most wind tunnels' ultimate aerodynamic aim is to create a flow in the test section that is as similar as possible to a constant steady flow with consistent speed in the test section. Since perfection is difficult to achieve, any design is constrained by factors such as maximum cost, limited space, available time, and available information. For the available funds, it is almost always preferred to achieve the largest test portion and the fastest speed possible. Of course, high speed and huge scale are opposing demands. The cost of the tunnel shell and the power it requires tends to rise with respect to square of the test section width. [45]

Note:

In order to achieve a uniform flow in the test segment, there should be a seamless transition from the contraction section to the test section. At the end of the contraction section and the beginning of the test section, there should be a zero slope to achieve this. The velocity that the architect expects to be obtained in the test parts must first be determined, and then the continuity equation will be used to determine velocity at any cross-section of the wind tunnel. [8]

This paper focuses on the project of suction-type, Open (Eiffel Type), subsonic Wind tunnel but most of the information could be pertinent to wind tunnels in broad-spectrum. This selection pertains to optimal flow quality, while keeping the overall tunnel size limited to any allocated laboratory space.

Components

The main segments/portions/sections of an Open/Eiffel Wind tunnel are

1. Entry Section or Settling Chamber Consisting of
   a. Honeycomb Meshes
   b. Screens
2. Contraction section, also addressed as Effuser or Contraction Nozzle, some authors also use, Nozzle
3. Test Section
4. Diffuser
5. Driving System (Power Drives, e.g. Fans)

The Entry Section or Settling chamber helps make the air flow laminar as well as subdues the transverse velocity component. It achieves this via a Honeycomb Mesh (eliminates uneven flow due to fan) and a series of screens (Provides uniform steady flow).What follows next is the Contraction cone/section (Effuser/Nozzle) whose main objective is to propagate the flow to required velocity for the test section without generating turbulence, but with gradual reduction in area. The test section is that portion, where the aerodynamic model to be experimented/tested is placed, along with instruments for measurement and sensors for analysis. The next section is the diffuser, it helps to regulate, steady and make the flow consistent

by maintaining constant air speed in test section. The final section of the wind tunnel is the fan and it's housing, also called, power drive or drive system which is the primary source of wind, drawing air into the wind tunnel, by expelling air out, thus, reducing turbulence and providing greater control of air velocity through the tunnel. [9, 18, 30, 43, 47, 52]

In wind tunnels, the chief drive systems found could be: Compressor driven or Fan. Compressor (generally from storage tanks) through a meticulously monitored valve/ regulator supplies pressurized air to the tunnel, in the former, whereas for the latter, Fans/Blowers are employed, which are either shaft or belt driven (depending on cost and sought after performance characteristics). [10]

Compressor-driven facilities could deliver large pressure ratios for relatively little cost but are time and again preferred for high-speed facilities that require high stagnation pressures. Fans tend to work best with low-speed facilities.

Hence, Fan Drive System is chosen as the prime source of power.

Settling chamber

It is region designed to deliver controlled quality flow to contraction cone by diminishing the various flow constituents accountable for turbulence. It makes the flow straight, parallel, uniform and subsides transverse velocity component of incoming air. Itencases, houses/utilizes Honeycombs, Screens to achieve that. Individually used, these sub-sections produce pressure loss, and hence, to obtain better flow characteristics, combination of both are used. The configuration which is found optimal is honeycomb located upstream with one or two screens, following them. [5, 9, 10, 18]

The irregularities of flow found in Wind Tunnels are:
1. Spatial non uniformity- When mean velocity is not uniform over cross section. This could be avoided by transfer of excess total head from high velocity regions to low velocity ones,
2. Swirl- When Flow rotates about an axis causing variation in direction of flow. Flow straighteners like honeycombs help reduce swirl. [10]
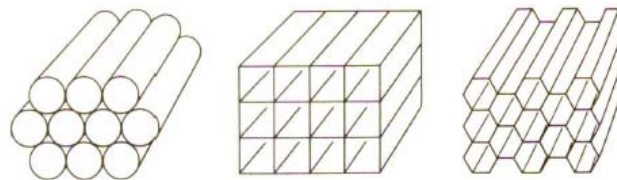
3. Low frequency pulsation-There are rapid increments of mean velocity. When occurred, time taken for balanced flow to happen becomes large. The source of such pulsations are challenging to locate. [23]
4. Turbulence- Generates small eddies of different sizes and intensity and causes time variations of velocity. When asymmetrical fluxes are superimposed on mean flow it is defined as turbulence

To reduce these flow irregularities, the settling chambers implement flow straighteners called:
i. *Honeycomb*

They aid to diminish tangential velocity of the airflow caused by the axial fan by rendering air filaments parallel and levelling the flow. It reduces the radial component of large scale turbulence, that is, vorticity as well as swirl of the incoming airflow [10, 14, 23 and 45]. Hence, their function is to align/even the flow with respect to the axis of wind tunnel and eliminate large-scale flow unsteadiness [9, 10]. Flow uniformity as well as turbulence intensity in test section is pioneered by honeycomb mesh. This section must possess sufficient structural rigidity, without any deformations, to withstand force during operation. This is because if Mach number of flow incoming is large, it may lead to choking the flow. [10]

Mehta and Bradshaw [4, 7] cite the use of 150 cells in mesh per chamber (settling chamber) hydraulic diameter Dh. (around 25000 in total, are adequate, as the cell size is generally smaller than the minutest lateral wavelength of velocity variation)[44, 47]

The authors also profess/insist that to avoid stalling of honeycomb cells, which reduce their efficiency as well increase pressure loss, the yaw angle of incoming air, must be lesser than 10 degree. [5, 7, 10]

The various cross-sections of honeycomb cells could be circular, triangular, square (fabricated due to ease of construction [7]) and hexagonal. The hexagonal shape of honeycomb cell is optimum, as it has the least pressure drop coefficient.[10, 45]

Figure 17: Mesh shape, source: [23]

Design parameters for honeycombs are ratio of stream-wise length to single cell hydraulic diameter, and the porosity/solidity.[45]The length of the honeycomb section should be smaller than the smallest lateral wavelength of velocity variation is recommended by [4, 6, and 10]. Optimum performance exists when the

length to diameter ratio is between 6 and 10. Also, from studies [4] [5] [6] [7], it has been found that cell of honeycomb of length (thickness) 5-10 times the diameter (cell width or diameter) terminates the lateral turbulence[5, 23, 44, 47]. Porosity is generally in the

range around 0.8 leading to honeycomb loss coefficients to low value of 0.5. [45]

Honeycombs are effective flow straighteners, but not that effective as screens to even non-uniformities in flow speed. [18] They are not proficient at minimizing lateral turbulence, moreover, induce axial turbulence of size equal to its diameter, which limits/confines the thickness attainable for honeycomb.

ii. *Screens*

Screens help increase uniformity of the airflow, as faster flows have higher pressure drops than slower flows. The purpose of the screen is to subdue the turbulence levels of incoming flow, and destroy large number of turbulent eddies into smaller ones which eventually decay [9, 10]. The scale of eddy decay depends on the Reynolds number of flow which in turn is influenced by the wire diameter used for screen constructions. Screens impose a static pressure drop proportional to the square of speed, increasing the ability of the reducing boundary layer thickness to endure the pressure gradient [2, 5, 7, and 18]. Just a single screen reduces pressure grad by 0.5% which is reasonable for some aeronautical purposes. Screens are sometimes, even tensioned before flow start. When RE< 40, eddies are practically absent. [23]

These screens are square/rectangular generally constructed interweaving metal wires, nylon or even polyester threads. The gauze action of screen as well reduction in turbulence is effected by:

1. Pressure drop coefficient K= f_1 (β, R_E,θ) {Function of open-area ratio (β, $\beta = \left(1 - \frac{d}{l}\right)^2$ [23]), Reynold's number (R_E), and θ which is flow incidence angle measured normal to the screen) K also depends on density, kinematic viscosity and mean velocity of fluid. Non-uniformities in the flow (caused by generation of tiny vortices and random coalescence of small jets emitted by the screen) occur for the screens with low open-area ratios. That is why, at least one screen (generally last) possess open area ratio of β<0.57

2. Deflection coefficient α= f_2 (β, K, θ)

The basic parameters to typify screens are "Porosity" (B), "Wire Reynold's number" (R) and the "Mesh factor" (K). Mesh factor differentiates smooth and rough wire (screen material could be different), they were given by Idel'chik as 1.0 for new metal wires, 1.3 for circular average metal wire (smaller meshes are mostly preferred) and 2.1 for silk threads [45]. Porosity is a function dependent on wire diameter, weave density, and geometric factors. It is the given by the expression

$$B = 1 - d_w \rho,$$

Where, B is porosity,

d_w is wire diameter, $\rho = \frac{1}{w_n}$ is the mesh density, w_n is width of one square mesh

The complement of screen porosity, known as screen solidity is also cited by many authors which is given by: 1-B (1-porosity). Porosity is 0 for packed weaves and 1 for vanishing screen.

Frontal area of the screen should not exceed 40% of cross-sectional area of settling chamber to ensure flow stability. For turbulence reduction, screen used should have porosity greater than 0.57, and it should be noted that screens with smaller porosity suffer from flow instability that acts in the test section, later. [45].

To achieve lowest turbulence in the test section, multiple screens of different porosities could be positioned, with the coarsest screen closer to the incoming flow and the finest screen nearer to test section, along with some free section to decay the variabilities/fluxes created by screens, themselves [7, 9, and 10] (Watmuff, 1998). The turbulence reduction factors are a product of the individual screens, while the pressure drop is sum of the pressure drops of individual screens, when multiple screens are implemented.

The only issue with screens is their capability to gather dust/dirt, and dust always possesses a non-uniform distribution. This changes the screen porosity, the pressure drop, influencing the velocity and angularity distribution in test section, in an erratic manner with time. This problem intensifies when flow-visualization techniques of china clay, oil (vaporized), and smoke are used. Therefore, screens must be mounted in a manner that they can be later cleaned, and quality of flow in test section must be monitored for the same.

The screens do not considerably impact the lateral turbulence and rather are pretty efficient at reducing longitudinal turbulence. [18] This gives rise to lateral turbulence being less attenuated in contraction chamber. A single screen reduces the longitudinal turbulence level radically, however implementing series of 2, 3 screens attenuates turbulence level in two directions up to 0.15%. Spacing flanked by the screens (between them) should be adequate so that flow pressure has fully recovered from the disturbance (i.e. dp/dy = 0) when the flow passes through them, moreover, they generally should lie in the order of the length scale of large energy containing eddies [10]. An ideal spacing of 0.2 times settling chamber diameters (or $0.2D_H$) was suggested [4, 5, 7, and 47]. Additionally, the spacing between the last screen and the contraction entry should sldo be 0.2 cross-section diameters ($0.2D_H$). [18, 4, 5, 7, 14]

If the Reynolds's number is based on screen wire diameter, it should, preferably, be lesser than 60% to prevent additional turbulence due to vortex shedding,

as suggested by Schubauer, Spangenberg and Klebanoff (1950).

Contraction Cone/Nozzle/Chamber (Effuser or Node)

A vital component of all wind tunnels, and the most significant single parameter in design having the highest influence on flow quality of air-flow in the test section, is the contraction nozzle/cone/chamber (also called Effuser or node by certain authors [5]). In spite of the usage of the term "nozzle", contraction cone is never conical in shape. They are primarily attached upstream in the wind tunnel [2, 4, 8, 18, 6, and 45]

With shrinkage of flow area along the length, the contraction component proliferates/escalates the airflow speed prior to test section entrance [5, 10, and 51]. (It abates/curtails both mean and fluctuating velocity variations to minor ratios of the average velocity while increasing the corresponding mean velocity) [7]. It serves a few purposes:

1. It facilitates low velocity at a location where, screens are placed. This low entrance velocity is preferable as it reduces pressure loss in wind tunnel.
2. Mean and fluctuating velocity variations are diminished to smaller fractions of average velocity as stated above.
3. Tones down the spatial variations of velocity in Wind tunnel cross section [23]
4. Subdues flow turbulence and non-uniformities, according to Derbunivich *et al.* (1987), as well as accelerates, and aligns the flow into the test section [10, 21]

The key parameters of influence are: Contraction Ratio (C.R., ratio of inlet and outlet areas), Shape of Wall/Degree of curve of Wall, Contraction Length and shape of Contraction. For designing subsonic/supersonic wind tunnels, it is paramount that the contraction portion shouldn't possess adverse pressure gradient in stream, and effect of the same at exit of contraction section should be insignificant. [6]

Tennekes and Lumley (1972) stated via their research that, vortex filaments are overextended in contraction section, which consequently, reduces axial fluctuations, however, the lateral turbulent fluctuations are strengthened. Contractions are less proficient in subduing longitudinal turbulence than mean velocity variation for axisymmetric contraction, was derived in rapid distortion theory by Batchelor (1953). [7, 9, 10 and 21]

Contraction Ratio (C.R.)

The Non-uniformity reduction, as well as flow acceleration are governed by ratio of cross-sectional area of Inlet to outlet, designated as "Contraction Ratio". (Deemed as "N" or "C.R", even "q" is found in research literature)

In theory, value of N should be large enough to destroy axial fluctuations in the flow, increase efficiency and foster the air in the test section to propagate slower relative to air in the test section [46], but practically, N possesses an upper limit, since, it intensely effects the Wind Tunnel's overall dimension, driving the cost upwards [18]. Thus, a compromise for this parameter is vital, conditional to anticipated applications.

Typical C.R.s found optimal are between 6 and 9. [2, 7, 8, 9, 14, 46 and 47]. For civil/industrial applications, contraction ratios between 4.0 and 6.0 are sufficient to reduce flow turbulence and levels of non-uniformities to order of 2%, which is also adequate of other applications

Cross Section Shape

Another stricture/constraint to be chosen a priori is Shape of cross section of contraction. The optimum cross sectional shape speculated is circular, the reason being, the low velocities encountered in the regions where surface streamlines intersect and separation of corner flow occurring for non-axisymmetric nozzles. Additionally, crossflows and secondary flows arising in corners of polygonal cross sections. [7, 45] Hence, many of the early designs implemented, were circular or octagonal cross sections (Octagonal ones, are achieved using a 45 degree fillet at nozzle start and carrying that throughout the test section and diffuser [45]).

However, later, began a compromise between rectangular, square and circular due to insights provided by Mehta Et.al., 1978, [7, 14], who showed that even for square or rectangular cross-section, corner flow traits remain confined, and these do not drift to affect test section wall flow. Thus, the cross-sectional shape that may be employed could be chosen to match tunnel components, especially the test section [7], which is usually square or rectangular [5, 9, and 51].

Contraction Chamber Curvature-Degree of Curve (Shape of Wall)

Various authors enunciate/articulate different degree of polynomials for the longitudinal-section silhouette/boundary.

Bradshaw et.al. [45], recommend contraction curve to reach 1st or 2nd derivatives at inlet and outlet by implementing two segments of 3rd degree polynomial curves of contraction wall. [16-20, 49]

Most of other authors [4, 7, 14, 18, and 43] suggest a 5th or 6th order polynomial as it satisfies most of the requirements discussed above. Moreover, because these curves give reasonable Reynolds number, flow uniformity and are free of separation (On centreline as well as in corners), they are better than first variation stated above at operational conditions such as 15 m/s velocity. Bell and Mehta also, devised their Bell-Mehta fifth order polynomials for the curvature [51].

Hence, a 5th order degree of curve wall shape is optimum for walls of contraction cone. A research for design and optimization of contraction with the help of conic section theorems [5], suggests even a sixth order polynomial with seven parameters. [83, 84]
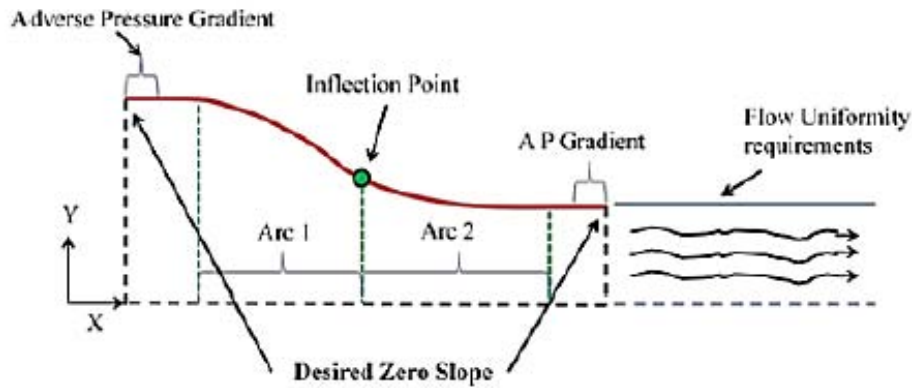
Figure 18: Contraction curve, source: [9]

Contraction Semi Angles and radius of curvature

For tunnels with low speed or laminar flow, escalated rate of growth of boundary layer thickness is observed causing centrifugal instability, leading to slow acceleration too, when the radius of curvature is huge, at the upstream end. Thus, the nozzle is fabricated either by method of "Design by Eye" or by alterations of fairly accurate methods, which insists that the radius of curvature should be lesser at the exit rather than the entrance. [6, 45].

The contraction semi-angles: *α*/2 and *β*/2 are suggested to be in the range of 12°, this allows the contraction cone to retain a judicious length and a decent fluid dynamic behaviour. [5, 18]

Parameterization of contraction profile/curve

If a coordinate system is defined at the origin of the wind tunnel's centre line of contraction inlet plane where the x coordinate increases downstream and y coordinate carves the contraction profile then the contraction itself could be split into two arc sections. The point of where it splits is termed as "inflection point" [5], first part having concave shaped walls, and other part having convex shaped walls. Concave part should be elongated as much as possible to evade wall-boundary layer separation. In this section there exists is a positive pressure gradient, however, streamline curvature could effect this gradient and stimulate the risk of separation. It is important to note that, flow separation could occur in the vicinity of test section due to positive pressure gradient of the convex wall as well.

Length of Contraction cone

To ward off hefty adverse pressure gradients along the wall, originating from streamline curvature, (leading to flow separation at the inlet, rise in cost and exit boundary thickness), and to decrease boundary layer growth, the length of contraction should be adequately small. Also, if a contraction is too lengthy, boundary layer thickens and is not reduced that much, making it vulnerable to separation near the exit. Thus, the length must be optimized between too long, and too short [6]. A study by Bell and Mehta, suggests a ratio of

the total length of contraction and double semi side length of inlet cross section to be around 1 (i.e. $L/2y_0 \cong$ 1). If the ratio is lesser than 0.667 then it leads to air flow detachment before outlet of contraction, while if it is greater than 1.79, it gives rise to surges in boundary layer thickness [51]. After running various computations, on numerous designs, minimum acceptable L/H_i was around 0.89 or 0.9, which may be a good trade-off. [7, 10, and 51]

Thus, the contraction designed using guidelines from papers, allows no separation of boundary layer, as well as keeps boundary layer thickness in check, and provides favourable flow to test section.

Test Chamber Design

The most tantalising, chief component of wind tunnel, also termed as "Heart of the Wind tunnel", is the test section. It is a region of controlled flow for experimental study, measurement, observations, on which the scaled model or test part, along with sensors are mounted. [18, 43]

The first step in design of Wind tunnel is determining the size and shape of test section, as expressed by Barlow et.al. (1999) [21, 51]. The size is driven by: Wind tunnel specifications-Operating speed, and desired flow quality. This in turn is used to estimate maximum proportion of models and maximum achievable Reynold's number [18, 49]. Choice of the section depends on intended usage of the facility, which is inherently concomitant to financial resources obtainable to construct the apparatus, whereas the power required and size of facility, is directly determined by the cross-sectional area (influenced by hydraulic diameter of Test section [51]) and the length of test section. That is, Power/Cost of tunnel vary with square of test section hydraulic diameter while power consumption varies with the cube of test section airspeed.[45, 46]

Many of the test sections employ scaled down models, aerofoils, as well as component testing for analysis with respect to velocity, force or pressure to know the fuel efficiency, performance, and control of the

model (a sphere, building scaled down, automobile, submarine, racing yacht, wind turbine and possibly others as well.) [45]

The test section could be an open test section meaning no walls surrounding the model, closed test section (with walls surrounding the flow), partially open or convertible [Chapter 3, [45]] [5, 8]. Test section with closed test section in preferred here, for open circuit wind tunnels.

Cross section

The test section should have a constant cross-section area, according to the configuration[9]. Round, elliptical, circular, rectangular, hexagonal, octagonal, rectangular with filleted corners, flat roof, and floor with half round ends have all been implemented as test parts over the years. Because of the cross-sectional shape, the disparity in losses throughout the test segment is small. As a result, the test section's shape should be determined by the functionality, operation, and aerodynamic requirements of the models to be studied [8]. Its cross-section is traditionally square in shape, and its area can be determined according to the scale model that will be evaluated. [5, 9, 45, 51]

Blockage ratio, Frontal Area, dimension

Test specimens under study are generally bluff bodies, in order to evade the need of creating non-linear blockage corrections, the equivalent frontal area of the model should not exceed 10% of test chamber cross sectional area [10, 18]. A good practice is that model/probe could consume 80% width of test section [46]. The correct techniques about blockage corrections are existent in Maskell (1963).

In accordance with Mehta and Bradshaw (1979), test section rectangular dimension sizing is around 1.4:1 by a common rule of thumb. [7, 9, 10, 21, 46]. For 3-D testing, typical width to height ratio professed is 4:3, meanwhile for 2-D testing it is 2:5, these advised ratios ensure lesser boundary layer thickness in the test section than the model span [9, 18].

Construction

The Test Section Assembly comprises of the Test Section (Plexiglas) and the Test Section Base to minimize pressure loss (wooden stand and sensor mounts). The test section should be constructed in such a way that the user can quickly navigate it and install or mount the test models in it.[10, 14-19, 45]

Scaling factors

The scale factor that can be employed varies from 1:10 to 1:20. [21]

Length

In tunnels constructed for aeronautical work as the primary objective, the length of the test section ranges from one to two times the section's main dimension. Length to hydraulic diameter fraction is 2 or more for test section [45]. With respect to other authors, they state the test chamber length to be 0.5 to 3 times of hydraulic diameter [Barlow, [45] and [51]]. Base value of 0.5 for uniform flow and 3 as to limit growth of boundary layer thickness.

Diffuser

The diffuser plays a pivotal role for the control of flow quality (by avoiding detachment of flow) inside test chamber and its good performance is paramount to success of the tunnel. It generally should possess a gentle flaring shape (that is the area increases gradually along the axis of wind tunnel), to inhibit the separation of flow, this in turn makes the flow consistent and keeps the air speed persistent in test section, which is a requirement of diffuser. [10, 47]

Diffusers could be fitted in the start (upstream) as in blower or blow-down wind tunnels or at the end (downstream), as suction or suck-down wind tunnels. They could be start or exit diffusers.

Power losses in the tunnel generally vary as the cube of speed, making the chief objectives of a well-designed efficient diffuser:

1. To decelerate the high speed flow from test chamber, while expending least amount of energy to ensure maximum static pressure recovery, and reduction of load on drive system.
2. To recover/retrieve the kinetic energy of flow in test section as pressure energy.[5, 21]
3. To complete and close the circuit. [18]

Minimum energy loss is often relative to maximum pressure recovery. Moreover, the decline of velocity in the least distance possible (without sustaining flow separation) is looked forward to, because it retains good efficiency as well reduces construction costs (by limiting the overall size of the tunnel shell). Thus, the vital parameters of design of diffuser are Area ratio, and equivalent expansion angle [21, 45]. The pressure gradients/recovery, and risk of separation depend on these parameters, wall contours and cross section of the diffusers. [7]

Semi Opening Angle

For conical diffusers to avert flow detachment and boundary layer separation, the general practice sets forth the equivalent semi-opening angle or the divergence half of the diffuser (Walls) to be smaller than 3.5 degree [7, 9, 10, 14, 18, 21, 45, and 48]. The minimalistic value of pressure loss is in fact, obtained at 3 degrees [11], but causes the construction to have large lengths [9]. That is the reason for some authors to cite angle between 7.5 to 8 degrees as well. In [22], cone angle is held between 0.5~1 degrees for sharp corner possessing diffusers. Smaller angles are desirable [45]. Mehta (1977), professes that the diffuser-included angle for a conical diffuser must lie within ranges of 5 degree (for best flow steadiness) and 10 degree (for best pressure recovery). [5, 7, 10, 47, 51]

Apart from this, the allowable diffuser angle suitable to evade flow detachment is 20 degree [4], some authors implement 30, 50, even 100 as diffuser angles for flow steadiness. [5, 8, 9, 21, 45] In these cases, diffusers implemented possess aggressive expansion and are termed as "Wide angle diffusers" (WADs, [8]). They employ 22.5 degree equivalent conical angles and are used to propagate air flow quality. These so called "wide angle" diffusers require use of screens as they introduce additional losses and separation of flow [46]. They are not used in present design, and for more additional information on them, reader is advised to go through Mehta Notes [7, 14, and 25]

Area Ratio (A.R.)

Area ratio is the ratio of the outlet (the end section), and the inlet (the test chamber), and should lie between 2 and 5. [2, 5, 7, 9, 21, 45]. Again, here as well, smaller values are desirable

Length of Diffuser

The diffuser length, is dependent on this area ratio as well as on the diameter or cross sectional area of the diffuser section. It is at least 3 to 4 times the length of test-section. Even though, longer diffusers influence pressure recovery, there is a limit due to costs associated.

Some authors suggest the use of Kline's flat diffuser curves (Runstadler et.al. 1975) for design of diffuser (Non CFD based) [10]. It is plot between the Area ratio (Entry/Exit) and the diffuser length to entrance height ratio.

Diffusers are prone to design errors triggering a steady separation or even at times, intermittent separation, that make it difficult to localize them, moreover they lay groundwork for vibrations, oscillating fan loading, surging (variation in test section velocities) and increased losses in tunnel.

Fan Housing and Fan or Power Plant or Drive System

The final part of Wind Tunnel, is the fan and its housing, also called the power plant or the drive system of Wind tunnel. The sought after flow rate, as well as pressure drop necessities, must be delivered by the drive system, while preserving reasonable energy efficiency and flow uniformity. [5, 10, 18].

The prime source of wind drive could be a fan, a blower or sometimes, even a compressed gas that is regulated using valves. In case of Blower type open wind tunnels, centrifugal blowers, also called squirrel cage blowers are used, which can utilized for closed circuit tunnels too, if mounted in a corner. However, the device which is spotted regularly for driving the air-flow, especially in subsonic wind tunnels is the axial flow fan (or propellers). This component is notorious for generating swirl in the induced flow, unless a mish-mash of pre-rotation and straightening vanes are present. [47]

The engineer responsible for the fabrication must calculate the fan power desired as well as consider the background noise generated by the drive system.

The power of fan is calculated via the product of VFR (Volume Flow rate) required or wanted. However, the selection of the fan, is rather complicated, as the resistance offered by the system is unknown [5, 7]. The vanes itself absorb some of the energy, while the fan acts as a power source.

The area occupied the fan divided by the area of test section, is deemed as area ratio (Housing unit), and is usually between 2:1 or 3:1 (i.e. 2 to 3) [7, 51]. When this ratio is large, risk of meagre velocity profile before the fan exists with an increase in cost because of the size. Meanwhile, if the ratio is small, incoming velocity is bigger in value due to high fan rpm, retaining optimal blade angles [51]. The fan-nacelle (Housing/ Enclosure) diameter is usually 30-50% of the fan section diameter.[45]

If the test cross-sectional area S_{TC} is known, desired operating speed V is fixed via fan, and if total pressure loss coefficient ζ is calculated then [18]:

$$Pressure\ increment, \Delta p = \frac{1}{2}\ \rho \cdot V^2 \cdot \zeta$$

$$Volumetric\ Flow\ Q = V \cdot S_{TC}$$

$$Power\ P = \ \Delta p \cdot \frac{Q}{\eta}$$

$Where,$
$\rho\ is\ operating\ air\ density$
$\eta\ is\ fan\ efficiency\ (aerodynamic\ and\ electric)$

Another equation for design of Drive/Power, is that of estimation of Tunnel power factor, [5]

$$\lambda = \frac{H}{0.5\rho_t U_t^3 A_t}$$

Where, H is input shaft power, subscript t refers to test section.
This equation helps in selection of correct power plant rating.

If instead of single fan, multiple fan arrays are utilized then, an equation for estimating number of fans required is given by [26]:

$$n = \frac{Area\ of\ Wind\ tunnel\ through\ which\ air\ passes\ (Sq.m) \times Velocity\ required(\frac{m}{s})}{Air\ Delivery(\frac{m^3}{s})}$$

Installation and additional guide

Paper Honeycombs that are impregnated are implemented for small tunnels which pose to be adequate. For high performance or bigger wind tunnel dimensions, aluminium honeycombs are used (they are also prevalent in aircraft sandwich constructions). These have precise dimensions than paper counterparts. [7]

Plastic Screens display an 'overshoot' in the velocity profile at the edge, owing to the screen deflection angle, (which is greatest at the wall) as well as produce a more uniform flow beyond the boundary layer edge, owing to the weaving properties. This overshoot may be advantageous in terms of overcoming a given pressure gradient or preventing separation. [7]

Normally, screens are nailed to wooden frames, whereas, the honeycomb is literally pushed onto its own frame. On wide working parts, it's also a good idea to install removable side panels on pinned hinges, which makes 'single-handed' removal easier, faster and safer.

Also, during construction, Barlow [45] mentions that the components should be designed to with stand the high stagnation pressure with safety factor around 4. [46]

Wind Tunnels are created with variety of materials like wood, plywood, thin/heavy metal, concrete or even plastic. Plywood is the go to choice for small scale wind tunnels as it allows holes, chips easily to be patched or even allow entire components to be replaced. Moreover, plywood possess the ability to be bolted together as well as have wood or steel supports. [46]

A vital issue with regards to design aspect of wind tunnel is the unique wavy shape, commonly a cubic, or 5th degree polynomial or combination of radiuses. It is even discussed on NASA's website: "Wandering Wind Tunnel."

If one is really constrained on the budget, an unconventional way to construct a honeycomb mesh is to use straws. This idea seems far-fetched but is rather not as the Myth Busters themselves used it in their wind tunnel constructed, it was also used in an experimental wind tunnel at MIT (Maniet1) [46]

To avoid pressure drop, a taper angle of 1° could be provided.

Test section material used is typically Plexiglas or any clear material for viewing the model/probe. Instead of all 4 sides made of Plexiglas, one could utilize 2 or 3 sides made out of it, to curtail the cost.

There exists a ton of trade-offs and so many design options, with different parameters in mind such as: Cost, performance, and ease of construction.

V. Measurement Techniques

For the purpose of measurement of different values, there exists a variety of methods, some based on the size of wind tunnel as well. These are:

a) *Pressure Measurement Flow instrumentation*
Carried out using-
1. *Manometers*

The manometer is one tool for determining pressure. It is one of the simplest and oldest instruments for calculating differential pressure, or the difference in pressure between two points [46]. The pressure ranges around the test model traditionally are also, calculated by drilling a series of small holes along the airflow path and measuring the pressure at each hole using multi-tube manometers. [86, 90]
2. *Pitot tubes*

Pitot tubes are used to measure pressure variations along with help from a manometer, too. In contemporary experimentation, a tool that incorporates a pitot tube with a static pressure measurement device is commonly used to calculate both static and stagnation pressure (total pressure) at the same time [47].Termed as wake survey, uses a single pitot tube is used to collect multiple readings downstream of the test model, or a multiple-tube manometer is installed downstream and all of its readings are collected. This wake survey is used to assess pressure distributions on a test model [40]. Pitot-static tubes may have either a rounded or square tip. Although square-tipped tubes are more effective at higher angles relative to the incoming flow, hemispherical tips provide fewer flow field disruptions near the second set of holes. If the second set of holes is located more than 5 or 6 tube diameters downstream from the base, tip-effect errors become insignificant. [46, 91]
3. *Pressure Transducers*

A pressure transducer is another way to calculate pressure. Devices that provide an electric potential or current in response to a pressure or change in pressure are referred to as pressure transducers [46]. They are further sub-divided as:
Diaphragm type and Piezoelectric type
4. *Condenser Microphone*
5. *Pressure Sensitive Paint, also called PSP*

In aerodynamic conditions, pressure-sensitive paint (PSP) is a tool for calculating air pressure or local oxygen concentration. PSP is a paint-like coating that fluoresces at different intensities depending on the

external air pressure added locally to its surface under a certain illumination wavelength.

To aid the PSP, model is photographed when the wind is on, by cameras typically mounted at strategic viewing points across the walls, roof, and floor of the wind tunnel. The photographic effects can be digitised to create a complete distribution of external pressures operating on the model, which can then be projected onto a computational geometric mesh for direct comparison with CFD results. [86, 87]

Note:

PSP measurements may be useful for capturing pressure fluctuations through a sample, but they often involve additional pressure taps on the model's surface to validate the absolute magnitude of the pressure coefficients. Since the temperature inside the wind tunnel will change significantly after continuous working, one valuable property of well-behaved PSP paints is that they should be temperature insensitive. The failure to reliably calculate the leading and trailing edge impact in areas of high curvature due to weaknesses in the camera's ability to achieve an advantageous viewing angle is a typical issue when using PSP. Furthermore, PSP on the leading edge is often discouraged because it adds a finite thickness that can allow early flow divergence, causing results to be compromised. This is one of the major issues, along with the adherence of the paint for longer periods and frequency issues (requiring time to stabilize before achieving the proper results). [87]

6. Pressure Belts

Pressure distributions can also be easily measured with pressure-sensitive pressure belts, a modern invention that integrates several ultra-miniaturized pressure sensor modules into a flexible strip. The strip is taped to the aerodynamic surface and sends signals that depict the pressure distribution over the surface. [87]

7. Cone probes

Cone probes help in determination of pressure

b) Temperature Measurement

They are implemented for compressible flow, due to variety of changes, and temperatures could be measured using-
1. Thermocouple
2. Resistance Thermometer
3. Glass Thermometer

c) Aerodynamic Forces

Measurement of these are of paramount importance, as test models usually employed in Wind Tunnels are aerodynamically analysed, using:

1. Aerofoils
2. Vanes
3. Potentiometers
4. Angular protractors for Lift angles

5. Beam Balances

Aerodynamic forces on the test model are usually measured with beam balances, connected to the test model with beams, strings, or cables. [87]

d) Velocity

Another parameter of importance to measure is velocity. One could use the Bernoulli's principle, other ways of measurement are carried out implementing:

Anemometers

Anemometer is used to measure speed of air. Anemometer can be of following types [26, 86]:

Cup type of anemometers –

Cup anemometers, also known as rotational anemometers, are the most basic types of anemometers which have been used for a long time. These indicators are made up of a vertical central pole and four horizontal arms at the top, each of which has a cup attached to it. The wind speed can be measured for these instruments by multiplying the number of revolutions the cups make in a minute by the circumference the cups establish. This approach would give you a general idea of how fast the wind is blowing. These devices have the downside of being susceptible to friction.

Propeller type of anemometers –

The wind velocity is measured by these anemometers, much like the cup anemometers. They can also see which way the wind is blowing and they have a propeller on the front of the unit and a tail section behind it that is on the same axis as the propeller on a central pole. The propeller turns while the wind pushes toward it, and the faster the propeller spins, the faster the windmill anemometer's velocity. The windmill anemometer gets its name from the shape of a windmill. In order to operate correctly and have correct readings, the windmill anemometer must be parallel to the direction of the wind.

Ultrasonic anemometer –

Ultrasonic wind measurement uses acoustic waves to determine the velocity of the wind. The gadget sends sonic pulses along a path to sensors along the way that can detect the incoming pulses. Since wind has the potential to interrupt sonic pulses, the disturbance is used to calculate the wind's direction. These anemometers can provide extremely precise wind data measurements.

Thermal anemometers-

Hot-wire anemometers, also called Constant Temperature Anemometer (CTA), are highly preferred and are used for wind tunnels for many research papers [7, 10, 46and 50]. Since the wind flow rate varies, the operational concept of a Constant Temperature Anemometer (CTA) is based on the mechanism of variable heat transfer in the probe with the convective heat transfer coefficient h. It takes advantage of this

thermal property of thin wire/film in the sense that, faster the transfer of thermal energy, faster is the air moving past this wire/film [10, 31, 40, 46, 50, 51, and 52]. A Pitot Tube Anemometer (PTA), on the other hand, works by converting the kinetic energy of the flow into pressure energy.

Laser velocimeters or LDV
Used for velocity measurements [10].
1. Forward Scatter
2. Backward Scatter

Particle Image Velocimeters
PIV is an approach in which a laser sheet is expelled through a slice in the tunnel's wall, allowing an imaging instrument to detect the local velocity orientation of particles in the laser sheet's plane. Seeding the airflow with visible content is often used in this practice. The velocity and direction of flow through the areas caught in the laser's plane can be measured quantitatively using this procedure. Upstream of the test model, smoke or liquid bubbles could also be introduced into the airflow, and their path around the model can be photographed. [10, 21, 46, 51, 86, 87]

For e.g. to calculate the acceleration of a flow field, Liu and Katz used a four-exposure PIV method. They were able to measure the pressure distribution of the test segment using this information.

Note:
Both commercial and open-source versions of PIV applications are available. OpenPIV is an open-source option that comes in Matlab, Python, and C++ versions.

Pitot Tubes
These devices used for pressure measurement are also famous for velocity measurements via semi-empirical formulae. Pitot static tubes are instruments that measure the difference between a flowing fluid's overall and static pressures. The equation of state, based on a measured temperature and static pressure, can be used to quantify the density of the fluid. This allows for the calculation of velocity. Bernoulli's equation, which is a statement of energy conservation, is the basis for a pitot-static tube.

e) *Boundary Layer and Surface shear stresses*
Devices used are:

1. Boundary Layer Mouse
For boundary layer determination
2. Preston Tube
Wall coefficient of skin friction could be experimentally measured using this device. It estimates the total pressure measured by Pitot tube that touches the surface.
3. Liquid Crystals
These are employed for shear measurement. These coatings obtain indications of transition locations and has been utilized for decades.

f) *Flow Field Visualization*
The most important aspect of wind tunnel is the determination of flow around the model. These flow fields could be generated using:

Qualitative Methods
1. Tuft Wands and Tuft grids
Tufts of yarn attached to the aerodynamic surfaces may be used to calculate the direction of airflow around a model. Threads in the airflow ahead of and aft of the test model may be used to imagine the path of airflow entering a surface. Mini-tufts, or flow cones, can be added to a model and stay intact attached to wind tunnels during testing. They're useful for determining air flow trends and flow segregation. To aid visualisation, tufts are often made of fluorescent material and lit under black light. [40, 87]
2. Smoke
Generated via incense sticks or machine, they clearly depict the streamlines of flow. Also called "Smoke Rake" [21, 47]
3. Carbon Dioxide Injection
4. Helium filled soap bubbles
5. Dry Ice [47]
6. Evaporating suspensions
Evaporating suspensions are essentially a mixture with a low latent heat of evaporation combined with fine powder, talc, or clay. When the wind blows, the liquid rapidly evaporates, leaving the clay behind in a pattern like the air flow. [87]
7. Oil
As oil is added to the model surface, the transition from laminar to turbulent flow, as well as flow separation, can be seen clearly.
8. Tempera Paint
Tempera paint can be added to the surface of the model in the same manner as oil paint is applied: in spaced out dots. The flow path and separation can be determined after the wind tunnel has been powered. Another technique for using tempera paint is to use black lights to produce a luminous flow pattern for the paint. [86, 87]
9. Fog
An ultrasonic piezoelectric nebulizer creates fog (usually from water particles). Inside the wind tunnel, the fog is carried (preferably of the closed circuit and closed test section type). Before the test portion, an electrically heated grid is added, which evaporates the water particles in its proximity, creating fog sheets. When lit by a light sheet, the fog sheets serve as streamlines over the test model. [86]
10. Flow sublimation
If a sublimatable material is spread and coated on the model, when the wind tunnel is powered, regions where airflow is laminar contains the material attached to the model, while for turbulent areas of the model, the material evaporates off it. This approach is specifically

used to ensure that trip dots positioned at the leading edge to force a transition are actually producing the desired result. [87]

11. Cameras and image techniques

High-speed turbulence and vortices can be impossible to view with the human eye, but strobe lights, video cameras, or high-speed optical cameras can help catch phenomena that might otherwise be lost to the naked eye. When the test subject is travelling at a high rate, such as an aviation propeller, high-speed cameras are often needed. Stop-motion images of how the blade slices through the particulate streams and how vortices form around the trailing edges of the moving blade can be captured with the camera.

Quantitative Methods

These include methods discussed above such as Pressure Sensitive Paint (PSP), Particle Image velocimetry (PIV) and a method called Model Deformation Measurement (MDM). MDM operates by putting markers on the wind tunnel model at established geometric positions and photographing the shift in marker position as the wind in the tunnel is incorporated. The translational difference in place of the marker can be determined by observing the change in marker locations from various camera viewing angles. The degree to which the model is flexibly yielding due to the air load can be determined by obtaining data from a few markers.

g) Instrumentation for Advanced sub-sonic Open circuit Wind tunnels

The Instrumentation implements all of measurement techniques described above along with additional components such as: Data Acquisition Systems (DAQs) for proper functioning, Pressure and Flow measuring abilities, Motion control, Flow Visualization and Image Acquisitions. [52]

The method of sampling signals that quantify real-world physical conditions and translation the samples into digital numeric values that can be manipulated by a computer is known as data acquisition. For interpretation, data acquisition systems transform analog waveforms to digital values. Components of DAQs are:

1. Sensors (that equate physical parameters to electrical signals),
2. Signal conditioning circuitry (which converts sensor signals into a shape that can be processed to digital values), and
3. Analog-to-Digital converters (convert conditioned sensor signals to digital values)

Flow Visualization with Image Acquisition, Multipoint Differential Pressure Scanning, Hot Wire Anemometry, Force and Moment estimation using internal balances, Roll, Pitch, and Yaw angle measurements, as well as Noise and Temperature measurements can all be incorporated into the framework.[46, 52] In regards to Pressure and flow measurement, and automation of measurement instrumentation, the devices could be coupled with Data acquisition systems like LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) software from National Instruments (NI), and scanners/ sensors. A great example would be a wind tunnel used in [28]. As the measurement and control aspects are challenging as well as time consuming, instrumentation system is automated using LabVIEW which is analysed for performance using MATLAB and implemented by a simple instrumentation architecture, enhancing productivity and curtailing cost. The automation is carried out in terms of speed control of wind, balance of the model and auto-switching of the wind tunnel at critical temperature. On the similar lines of force or moment instrumentation: Six -component Strain Gauge Balances could be implemented (However, most of them employ only 3 components). Light sheets with Argon-ion lasers, CCD (Charged coupled devices) cameras, and monitoring devices can be used to film and study the precise direction of flow particles, with IMAQ Vision for LabVIEW being incorporated occasionally (hardware and software).

A wind tunnel can be used for full-model experiments with sting support mechanism, half-model testing with external balance, two-dimensional model testing, ground effect simulation with moving belt, gust and cross wind simulation, and aero-acoustic testing, among other items, with the right configuration and instrumentation. The instrumentation needed for a Wind Tunnel with M<0.3 is not overly difficult, but it does require care in order to achieve reliable and precise data. [45, 86, 92, 93].
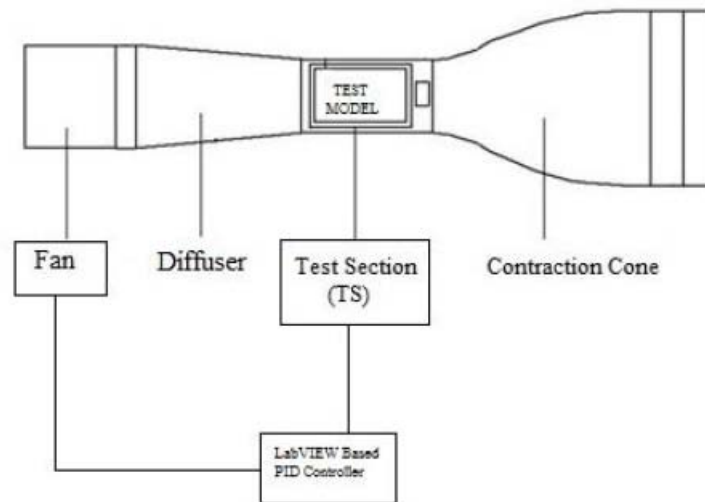
Figure 19: Instrumentation of Wind Tunnel, source: [28]

VI. IMPORTANT DEFINITIONS AND MATH INVOLVED

a) Fluid Mechanics Terminology

Fluid Mechanics

Having wide range of applications such as Mechanical, civil, chemical, biomedical, geophysics and astrophysics, Fluid Mechanics is a branch of physics pertaining to fluids-Liquids, Gases and Plasmas. It could be further subdivided as Fluid Statics (Study of fluid at rest) or Fluid dynamics (Study of forces and its effects on motion of fluid) [97]. It a subset of continuum mechanics, a study concerning macroscopic viewpoint of matter. Fluid Mechanics, is notorious in terms of active research.

Fluid Statics

Study of fluids (compressible as well as incompressible) or pressure in/exerted by fluid on immersed bodies, at rest in stable (Hydrostatic) equilibrium is termed as Fluid Statics or Hydrostatics. It gives a plausible reasons for phenomena like change in atmospheric pressure with altitude, water floating in oil and retainment of shape of water in the container. It is the root and lays foundation for Hydraulics. Plate tectonics (Meteorology), Blood pressure (Medicine) and so many other fields are applications for the same [98, 99]. Terms such as Buoyancy, hydrostatic pressure are part of this study.

b) Fluid Dynamics

Another sub-discipline of fluid mechanics pertaining to fluid flow (science of liquids or gases in motion) is called Fluid Dynamics [100]. It follows a systematic approach of utilizing empirical and semi-empirical laws derived from measurement of flow to solve practical issues. These solutions involve calculations of properties such as velocity, pressure, density, and temperature of fluid as functions of Space and time. It lays the foundation for: Aerodynamics-Study of air/gases in motion [100-104] and Hydrodynamics (Study of liquids in motion) [105-106] Calculation of forces and movements on aircraft, estimation of mass flow rate, prediction of weather patterns as well as modelling of explosions could be achieved by Fluid Dynamics.

Flow Types

Laminar Flow

Laminar flow is the passage of fluid in thin parallel layers that roll over one another like paper sheets. Each layer is subjected to heavy viscous forces from neighbouring layers, which dampen flow disturbances, allowing flow downstream of an obstacle to easily return to its original state.

Turbulent Flow

Turbulent flow is a particularly random and turbulent flow characterised by the forming of eddies and vortices of various sizes. It occurs at high Reynolds numbers and is characterised by the formation of eddies and vortices of various sizes. Unlike laminar flow, where viscous forces are the primary determinant of fluid behaviour, turbulent flow is governed by inertial forces. Fluid behaviour in turbulent flow is notoriously difficult to quantify. [47]

Compressible Flow

Fluids and fluid flow that undergo change in density due to change in pressure or temperature are compressible fluids/flows

Incompressible Flow

Fluids and fluid flow, for which changes in density are insignificant when pressure and temperature change are incompressible fluids/flows. In most cases, modelled flow is incompressible. Mathematically when expressed, density not changing as it moves in flow field is represented as:

$$\frac{D\rho}{Dt} = 0$$

Where, $\frac{D}{Dt}$ *is material derivative (sum of local and convective derivatives)*

Steady Flow

A flow which isn't a function of time and whose properties do not alter over time are deemed as steady flows

Transient or Unsteady Flow

Flow dependent on time is called unsteady or transient Flow. Choice of frame of reference depicts whether flow is steady or unsteady.

Newtonian and Non-Newtonian fluids

In a variety of fluids like water or air, where, stresses due to viscous forces are directly proportional (related linearly) to strain rates are called Newtonian Fluids (Shown by Isaac Newton). This coefficient of proportionality is termed as Viscosity of fluid (property independent of strain rate)

On the other hand, Non-Newtonian fluids, are much more complex involving non-linear stress-strain behaviour, and include fluids such as blood, polymers, honey and lubricants.

Drag

A constituent of force projected along the direction of motion is called as Drag. Shear forces as well as pressure induce drag for body in motion. Skin friction drag, also known as parasitic or profile drag, is a portion of overall drag encountered by a body in a fluid flow as a result of frictional forces between the fluid and the body's surface. It is more substantial in streamlined entities. Skin friction is the only source of traction where there is no boundary layer separation [47]. Pressure drag on the other hand is noteworthy in case of blunt objects. [19, 14]

The drag force is generally non-dimensionalized as a function of Reynolds, which referred as drag coefficient [19].

$$C_D = \frac{F_D}{0.5\rho V^2 A}$$

The pressure coefficient could be obtained on the same terms, by normalizing dynamic free stream pressure and then rewritten as reduced pressure coefficient. [19]

$$C_P = \frac{\Delta p}{0.5\rho V^2}$$

$$c_P = \frac{q}{q_\infty}$$

Boundary Layer

Boundary layers are regions of fluid immediately adjacent to an immersed object or wall, under which flow velocities are controlled by viscous forces. They possess a pivotal role in experiments. The fluid in this area is responsible for the bulk of the drag forces and heat exchange endured by the object. Boundary layers usually start out as a thin laminar flow area that thickens with rising Reynolds numbers and then transforms to a turbulent layer flowing over a viscous sub-layer. Outside of the boundary layer, the flow is unaffected by Reynolds number criteria. Two dimensional boundary layers are suggested to reduce the disparity between theory and tests. [19, 21, 50, 94]
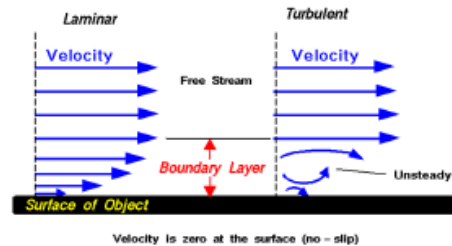
Figure 20: Boundary layer, source: [19]

c) Fundamental Equations

The equations of paramount importance derived for modelling Wind tunnels especially low speed ones, are three in number [45, 46]. They are also, the fundamental principles/axioms governing fluid mechanics, (all are based on classical mechanics, modified in quantum mechanics and general relativity wherever, needed). They are expressed via Reynolds Transport theorem generally. The principles are:-

1. Conservation of Mass or Mass Continuity theorem.
2. Conservation of Momentum or Newton's Second Law linking force and motion
3. Conservation of Energy or First Law of Thermodynamics governing energy exchanges

The Conservation laws could possess an integral or a differential form and are applied to regions called as control volumes, which are discrete volumes in space where fluid is estimated to flow. For description of changes in mass or energy within control volumes, integral formulations are implemented, meanwhile, differential formulations apply Stokes Theorem to yield expressions which could be referred as integral forms applied to infinitesimally small volume (at points) within flow.

In addition to these, we utilize definitions of fluid properties, their variations with pressure and temperature (e.g. Gas Law PV=nRT) for added accuracy. Also, fluids are assumed to obey the continuum assumption that they are not discrete, rather continuous, and properties such as velocity, density etc. are well defined at infinitesimally small points varying

continuously at different points. Only a brief gist is presented here. To delve into the topic further, readers are suggested to refer to Anderson [95], and Currie [96].

Mass Continuity (Conservation of Mass)

Mass is neither created nor destroyed in a control volume, hence, rate of change of fluid inside control volume is equal to net rate of flow in the volume, itself [107]. It is also referred to as equation of continuity [46, 50]. A differential form of continuity equation, by the help of divergence theorem could be stated as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot u) = 0$$

Where, **ρ** is the fluid density, u is the flow velocity vector, and t is time.

For quasi 1-D incompressible (density of fluid constant) flows, it simplifies [47] down to $A_1V_1 = A_2V_2$

Conservation of momentum

Newton's second law of motion applied to a control volume (element of fluid) gives the statement: Changes in momentum of fluid within control volume are caused by net flow of momentum into the volume as well as by the external forces acting on it. This momentum balance is valid for stationery as well as moving control volumes. [46, 107]

When volume is curtailed to infinitesimally small point, the differential form is obtained:

$$\frac{Du}{Dt} = F - \frac{\nabla p}{\rho}$$

ρ is Fluid density

F is Force and consists of both, surface forces (viscous/shear forces) and body forces. It can also be expanded for frictional, electromagnetic or gravitational forces acting at point in flow. [46]

Navier Stokes Equation

In aerodynamics, air is believed to be a Newtonian fluid, which implies that the shear stress (due to internal friction forces) and the rate of strain of the fluid are linearly related. The equation above is a three-dimensional vector equation that can also be expressed as three scalar equations in three coordinate directions. The Navier–Stokes equations are the conservation of momentum equations for compressible, viscous flow cases [107] such as, fluids that do not possess ionized species, are sufficiently dense to be in continuum, and retain that velocities to be minor in comparison to speed of light.

Navier Stokes equations (after, Claude-Louis Navier and George Gabriel Stokes) are a non-linear set of differential equations describing flow of a fluid whose value of stress depends pressure and on the flow velocity gradients linearly. They relate pressure, density, temperature, velocity of fluid through use of stress and strain rate tensors and depict the force balance at a given point in fluid [47]. When a body travels through a fluid, forces produced by the fluid's viscosity, inertia, elasticity, and gravity, are explicitly described by the different terms in these equations [Chapter 2, [45]]. For an incompressible fluid with u as the velocity vector, the Navier Stokes equations are: [109-112]

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\frac{1}{\rho}\nabla P + \nu\nabla^2 u$$

Additionally, at times gravitational or Lorentz forces are added. Which result in set of five coupled differential equations and additional state for solution.

These differential equations are analogous to Newton's equation of motion for particles for deformable materials. Here, momentum (force) change is depicted in contrast to pressure P and Viscosity is parameterized by kinematic viscosity ν

The solutions to these equations for any physical problem is usually sought after using calculus, however practically, only simple cases could be solved using them (involving non-turbulent, steady flow, whose Reynolds number is small). For complex cases (ones with turbulence involved [47]), such as aerodynamics, hydrodynamics, global weather systems etc., the solutions could only be found via computers and their aid, as these unsimplified equations do not possess general closed form solutions. This aid, for partly or wholly unsolved practical problems addressed by numerical methods/approximations gave rise to the branch of "Computational Fluid dynamics (CFD)" [47, 113-117]

Note:

Newton's 2nd law helps describing dynamics of fluid particles, however, an accelerating parcel of fluid experiences inertial forces. Reynold's number discussed ahead, a dimensionless quantity charecterises flow.

When R_E is low and <<1, viscous forces are predominant rather than inertial forces, and if inertial forces are neglected, the flow is called "Stokes or creeping Flow".

When R_E is high and >>1, inertial forces are predominant and the viscous forces are neglected, thus the flow modelled is called "Inviscid flow"

If the viscosity effects are eliminated from Navier-Stokes Equations, it simplifies to "Euler Equations"

When the Reynolds number is high, this strategy can be very effective. However, certain issues, such as those concerning solid boundaries, can necessitate the inclusion of the viscosity. Since the no-slip state creates a thin area of high strain rate. The boundary layer, in which viscosity effects prevail, produce vorticity, viscosity cannot be ignored along solid boundaries. As a result, viscous flow equations must be used to quantify net forces on bodies (such as wings) and the inviscid flow theory struggles to simulate

drag forces, a drawback known as the d'Alembert paradox.

A widely used model in computational fluid dynamics is infact the use of 2 flow models: the Euler equations away from the body, and boundary layer equations in a region close to the body. The two solutions could be then compared with each other, using the method of matched asymptotic expansions.

Conservation of energy

The total energy will always remain constant, even though it could convert from one form to other. The expression could be given as:

$$\rho \cdot \frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla \cdot (k \cdot \nabla T) + \emptyset$$

Here, the left side expression is a material derivative where, h is the specific enthalpy, k is thermal conductivity of fluid, T is temperature and phi is the viscous dissipation function governing the rate of conversion of mechanical energy to heat. It is generally positive, that is viscosity cannot create energy within control volume. [108]

Another way of stating this law would be: Change in total energy comprising of internal and kinetic energy is nothing but the sum of total work done on system and energy transferred by thermal conduction [46].

Bernoulli's Principle

A huge pivotal principle is fluid dynamics is the Bernoulli principle, stating that "Increase in speed of fluid occurs simultaneously with decrease in static pressure or decrease of fluid's potential energy" (named after Daniel Bernoulli, publishing it in his book "Hydrodynamica" in 1738). Euler also, put forward paramount Bernoulli equation confirming deductions of pressure decrement when flow speed is increased.

It is applicable for isentropic flows (enthalpy constant) where irreversibility, and non-adiabatic processes are neglected. This principle has many forms as it could be applied to various flows resulting in different form. The basic form (stated here below) is the Bernoulli principle for incompressible flow. Higher advanced forms applicable to compressible, unsteady flows are not presented in this study.

Bernoulli's principle could be derived from either Principle of Conservation of energy or from Newton's second law of motion. (Both stated above). In terms of conservation of energy it states "For steady flow, sum of all forms of energy in a fluid along a streamline is at all points along that streamline", whereas, in terms of the 2nd law of Newton (conservation of momentum), "There is more pressure behind rather than in front when a small volume of fluid flows horizontally from region of high pressure to low pressure, giving rise to net force on volume, which accelerates it along the streamline".

It represents a relation between velocity, density and pressure [50]. The equations assumes *incompressible (constant density), steady and inviscid (viscosity negligible) flow) flow*and could be given by:

$$\frac{1}{2}\rho u^2 + \rho g Z + P = constant \ (c)$$

Where, g is acceleration due to gravity, Z is elevation of fluid from arbitrary datum, P is Pressure (static pressure), ρ is fluid density, and u is velocity. [18, 45, 46]

The term $\frac{1}{2}\rho u^2$ is referred to as dynamic pressure (also called velocity pressure by authors), and expresses fluid's kinetic energy per unit volume

The term $\rho g Z$ is the gravitational potential energy of the fluid

The end term P is the static pressure, or a measure of internal energy of the system

Sometimes a term $h = Z + \frac{P}{\rho g}$ is also used, which stands for Hydraulic Head or Piezometric head.

For many practical applications like flight of aircrafts and wind tunnels, the gravitational potential energy term is minor as compared to the other two, as change in height is minimal, and if neglected, gives the equation for Stagnation pressure:

$$P_o = \frac{1}{2}\rho u^2 + P$$

$Total\ pressure = Static\ pressure + dynamic\ pressure$

Note: The stagnation pressure of a system is constant under the same set of assumptions, however, in practice, for non-ideal systems like wind tunnel, viscous forces are not negligible throughout. Hence, inefficiencies in the Wind tunnel can be expressed as drops in stagnation pressure. This could aid the fundamental design process.
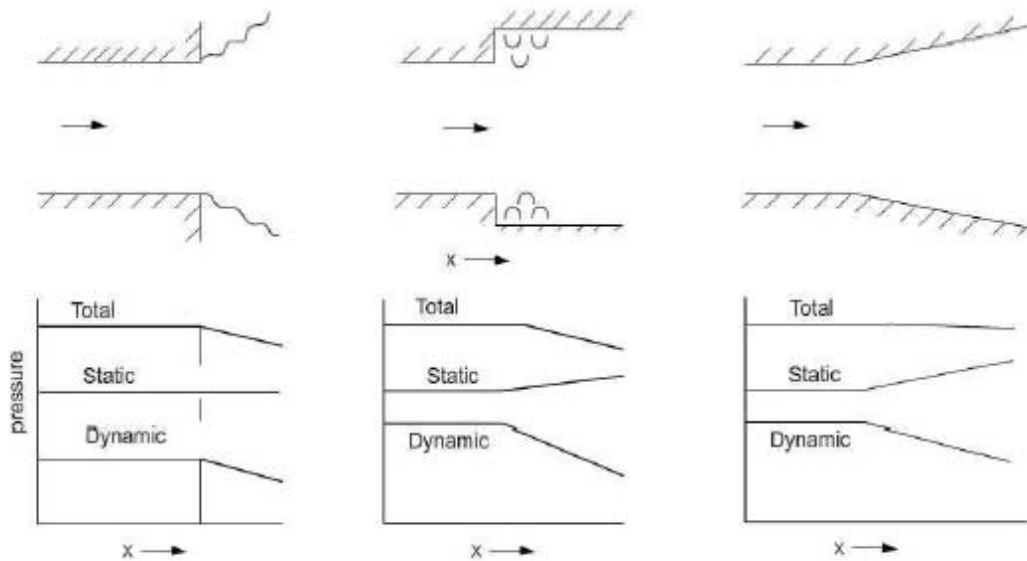
Figure 21: Pressure changes in Wind Tunnel, source: [23]

d) Important Testing Parameters and Scaling of Models in Wind tunnel

The test models or probes need to be scaled down to fit the dimensions of the wind tunnel's testing section. When scaled down, apart from just geometrical similarity, there are certain parameters that must retain themselves which are pivotal for aerodynamic calculations of the model and important for obtaining the same wind flows around the model at its actual true full scale. These parameters are Reynold's Number (For low speed Wind Tunnels), Mach number (For Medium Speed Wind Tunnels), and Froude Number (For High Speed Wind Tunnels) formed by relating various forces to inertia force (some are excerpts from non-dimensional Navier stokes equations as well.)

Reynolds Number

It is a chief parameter used by engineers to estimate the flow whether it is laminar (smooth flow free from eddies) or turbulent (consisting eddies and randomness). Implementing the dimensionless forms of Navier Stokes equations, Reynold's number is determined as the ratio of inertial forces to the viscous forces (with no dimensions). [10, 47]

Using the mean velocity (u), Characteristic diameter/length (L_{char}), density(μ) and viscosity, valid for any fluid, Reynold's number could be calculated as:

$$R_E = \frac{Inertia\ Forces}{Viscous\ Forces} = \frac{\rho \cdot u^2}{\frac{\mu \cdot u}{I}} = \frac{\rho \cdot u \cdot L_{char}}{\mu}$$

It is dependent on geometry of section, roughness of the walls. [19]

Osbourne Reynolds had identified this parameter in 1883. A common distinction found is: If $R_E < 2100$, flow is laminar, $R_E > 4000$, flow is turbulent, and otherwise it is in transit. [19, 47]

Reynolds number is a vital and primary similarity parameter for low-speed wind tunnels with M < 0.3 [Chapter one, [45]] [10]

Mach number

It is of paramount importance for flows occurring at high velocities which cause variation of density and temperature of fluid. Speed of an object traversing through air or any other fluid divided by the speed of sound gives, "Mach number", a dimensionless quantity. [47, 50, 52]

$$M = \frac{Speed\ of\ object}{Speed\ of\ Sound} = \frac{u}{V_s}$$

It is generally used for representing speeds of object close or above speed of sound. It is affected by the composition of medium surrounding it, and also, by the local conditions such as temperature and pressure. Mach number is used to detect whether flow is Incompressible or not. Incompressibility is a good assumption for certain liquids, but in case of acoustic studies, soundwaves is considered compressible.

Froude Number

This number plays an effective role when gravity forces are involved, reason why, they are used for model drop tests. It helps simulate supersonic waves as well [19].

It is defined as:

$$F = \frac{V}{\sqrt{gI}}$$

Froude Number is good for flows which have free surfaces and it is an important similarity parameter only if there exists unsteady boundary conditions, or for dynamic systems such as towed bodies. [Chapter one, [45]] Froude number is absent when fluid body forces

are ignored, which is a common assumption for most of the fluid flows.

Note: Prandtl number- Not in consideration in this study, as it appears only in cases of heat conduction. It is ratio of viscous diffusion rate to thermal diffusion rate.

Scaling Principles

The requirements for big models to be scaled down to be placed inside wind tunnels are:

Geometric Similarity

The geometric similarity between the model and the prototype is one of the most significant considerations for models. By geometric similarity, we say that the model and prototype should have the same ratios of corresponding dimensions (scalability). [23]

Dynamic Similarity

The dynamic similarity theorem states that a scale model with the same similarity parameters such as Reynolds number and Mach number would have forces and moments that can be directly scaled. The full-scale body and the model would have identical flow patterns [19, 23]

In reality, matching both Reynolds number and Mach number to full scale in a model experiment is rare. In truth, there are times when neither the Reynolds number nor the Mach number can be balanced. After that, decisions must be taken based on the parameter is considered to be the most relevant for the type of flow situation in question. Mach number matching is normally only applied to flight vehicles in the high-speed flight area, where Mach number effects predominate and Reynolds number effects are less significant. In low-speed flight, Reynolds number effects predominate, and Mach number matching is less important. However, every experiment should provide a thorough examination of the impact of Reynolds and Mach numbers to ensure that the effects can be generalised to the full-scale problem. [45]

This principle is used in other engineering fields as well, giving numbers such as: Stanton Number (St, ratio of heat transferred into fluid to thermal capacity), Strouhal number for experiments with oscillating flow, Knudsen number (K_n) for low density flows, Euler number, Eckert number etc. [49, 23]

Note: If scaling is successful, the non dimensional functions for fluid velocity components, pressure coefficient, density, viscosity, and temperature would be the same. As a result, the force and moment coefficients for the model and full-scale flows would also be similar. Chapter 2 of [45] states

"Under these conditions, the forces developed by the model can be directly related to the forces on the full-scale article by multiplying the force coefficients obtained in the experiment using the model by the factor $\frac{1}{2}pv^2L^2$ with the values of parameters in the factor

corresponding to full scale." And "the moments developed by the model can be directly related to the moments on the full-scale article by multiplying the moment coefficients obtained in the experiment using the model by the factor $\frac{1}{2}pv^2L^3$ with the values in the factor corresponding to full scale."

E.g. To improve design of golf ball- If a golf ball has a diameter of 0.04 metres and travels at 25 metres per second in air at sea level, it has a Reynolds number of 68,200 and a Mach number of 0.06. As long as the Reynolds number is the same, you can make a big model, say 0.2 in diameter, and test it in your wind tunnel. Since there is no noticeable compressibility effect, the Mach number may be overlooked. To meet Reynolds number, you'd have to use a wind tunnel with a free stream velocity of 5m/s. The golf ball's boundary layer and the wake behind it will be perfectly scaled under these conditions. If the golf ball in flight has a 0.001 metre thick boundary layer at one point, the model's equivalent point would have a 0.005 metre thick boundary layer.

VII. CFD Involved and Turbulence Models

CFD standing for Computational Fluid Dynamics, tries to solve differential equations governing fluid flow using approximation of numerical means. It had been use first with respect to performance enhancements for wind turbines with 2D aerofoil properties, but now is employed at all scales: Airfoil to atmospheric boundary layers. CFD has been termed as "Multiscale virtual wind tunnel" due to its vivid applications and as it provides deeper insights [2]. It helps in exploration of shape, and character of fluid flow. It simulates closer to real conditions flows, as well as curtails the errors via tolerances. Variety of parameters such as velocity, turbulence intensity, distribution of fluid flow, pressure distribution could be obtained via CFD [3].

Despite numerous advantages, there are limitations imposed by CFD in terms development and application of a mathematical model to simulate the results of turbulence known as turbulence modelling (eg. Real life scenarios, including the flow of blood through the cardiovascular system, the airflow over an aircraft wing, the re-entry of space vehicles etc.). As mentioned above, exact solutions of turbulent flows is extremely difficult and complex, especially for high Reynolds number. Modelling turbulent flows is an impediment for fluid mechanics [45]. Regardless of decades of study, there is no analytical hypothesis that can determine how these chaotic flows will evolve. CFD simulations use turbulent models to simulate the evolution of turbulence in most real-world turbulent flows. This turbulence models are simplistic constitutive equations that forecast turbulent flow statistical

evolution. Treatment of transition to turbulence and roughness implications are critical topics that the scientific community are currently addressing.

a) The Closure issue

The Navier Stokes equation described above, governs velocity and pressure of fluid flow, which could be split into a mean and fluctuating components for a turbulent flow giving rise to "Reynolds-averaged Navier Stokes (RANS) equations". Due to non-linearity of Navier stokes equations, the velocity fluctuations still appear in RANS equations in the non-linear form $-\rho\,\overline{u_i'u_j'}$ from convective accelerations, which is termed as Reynolds Stress R_{ij}. It effects the mean flow in the same way as stresses like pressure or viscosity. By removing reference to fluctuating parts of velocity, closure of RANS equations by modelling of R_{ij} as function of mean flow, is needed to obtain equations containing only mean velocity and pressure, which is the "Closure problem".

b) Eddy Viscosity Models

The first to delve into closure issue was "Joseph Boussinesq" who introduced the "Eddy Viscosity" concept, relating stresses of turbulence to mean flow in order to close the system of equations. The models are coined as "Eddy viscosity models" (EVMs) [121].

This Boussinesq hypothesis brought about a variety of turbulence models offering lost computation costs which help replicate right flow conditions, such as the "Spalart-Allmaras" (S-A), "k-ε" (K-epsilon), and "k-ω" (k-omega). S-A utilizes only one additional equation to model the turbulence viscosity transport while, the other two use two additional equations. A brief overview of these models:

Spalart-Allmaras (S-A)

A one equation model solving the modelled transport equation for kinematic eddy turbulent viscosity, employed for applications of aerospace (wall-bounded flows) is the S-A turbulent model [122]. It provides nice results for boundary layers subjected to adverse pressure gradients and is popular amongst, turbomachinery applications.

k-ε (K-epsilon)

One of the most common CFD turbulent model, used to simulate mean flow characteristics for turbulent flows and possessing 2 equations to provide general description of turbulence by means of transport equations (PDEs)[123]. First thought for K-epsilon was for improving mixing length models and finding an alternative to algebraic of turbulent length scale in moderate or complex flows. It is proposed and is robust enough to predict airflow away from wall/surface and calculates factor turbulence kinetic energy 'k' (energy transport) and dissipation energy (rate) 'ε' using Boussinesq hypothesis. [2, 3]

k-ω (K-omega)

Another common two-equation turbulence model used to solve closure issue. It tries to predict turbulence using 2 partial differentials for 2 variables: k (turbulence kinetic energy) and ω (specific rate of dissipation of k into internal thermal energy and ω≈ε/k) [3, 124]. It possess the ability for predicting airflow nearer to wall or surface, and calculating freestream value, moreover, offers accuracy in predicting free shear flows. [3]

SST (Shear Stress transport)

Menter's Shear stress turbulence model is commonly employed robust 2 equation model used in CFD. It combines both k-ε and k-ω models in such an efficient way that the k-omega implemented in the inner region of boundary layer switches to k-epsilon in free shear flow. [125]

Large Eddy Viscosity Model

It is analogous to DNS (Direct numerical solutions) with high R_E (Reynold's number). It uses a filter that passes through a small turbulence energy to the average and model a flow, a method known as "subgrid scale modelling". The hurdles in applying LES (Large eddy viscosity) to wall-bounded flows, mainly caused by impractical grid requirements in the near-wall region. [2, 3]

c) Reynolds Stress equation model (RSM)

Referred to as 2nd moment closure model, RSM model is one of the most complete classical turbulence model approach. While the above 4 utilize eddy viscosity equations, RSM implements Reynolds Stress transport equation. The drawbacks of k-epsilon and k-omega such as flows with anisotropy, streamline curvatures, flow separations, and recirculating flow zones influenced by rotational effects are overcome by RSM models offering much better accuracy. [3, 126-128]. Also, in regions where turbulent flow behave like elastic mediums predominant in eddy viscosity closure's rapid distortion limit, RSM is much more helpful [129, 130]. The basic concept is similar to other models mentioned above but RSM could help calculate pressure strains of each unit in all directions (by partially resolving it) which is generally reasonable for asymmetric turbulence phenomena. [3]

d) Measurement using CFD

Turbulence Kinetic Energy, as well as Flow velocity are most common strictures to estimate performance of the Wind tunnels. [49]These parameters could be found from both CFD (Computational fluid dynamics) as well as experimental results.

In some papers like [8], a CFD code is applied for calculations of 3 dimensional RANS as well as continuity equations, which utilizes control volume method alongside Semi-implicit Method for Pressure-Linked Equations (SIMPLEC) velocity pressure coupling

algorithms with 2nd order upwind discretisation. Performed on basis of standard k-epsilon model. Another one [3], uses commercial ANSYS FLUENT release 15, and the same SIMPLEC algorithms.

VIII. Our Design and Analysis

a) *Procedure or Plan of action implemented*
1. Research and delving into the topic
2. Literature review and accumulation of design data about a variety of Wind tunnels
3. Arranging of data
4. Shortlisting of design according to guidelines, strictures and constraints
5. Design modelling in Autodesk Fusion 360.
6. Choosing a single design as basic design
7. Creation of assembly of the same design in Autodesk Inventor
8. Import of model in Autodesk CFD
9. Study A:- Keeping basic set of assumptions and constant boundary conditions, different turbulent models are deployed, (k-ε, k-ω, SST k-ω and LES) on:
   a. Plywood as material of components, while test section as glass
   b. Plywood as material of components, while test section as acrylic
   c. Aluminium as material of components, while test section as glass
   d. Aluminium as material of components, while test section as acrylic
10. On basis of conclusions obtained, choosing the material and right turbulent model to be constant for next set of testing.
11. Study B:-With fixed material and turbulent model, and again, keeping the basic set of assumptions and boundary conditions fixed, this time different geometries are used-
    a. Circular diffuser
    b. Octagonal contraction cone
    c. Contraction Cone with different polynomial of wall curve
12. Study C:-With the previous optimized model, different scenarios are used.
    d. Increased length of settling chamber
    e. Thickness is varied
    f. Test section length reduced.
13. Comparisons are made with our basic square cross section contraction and diffusers and inferences are made
14. Final Design is created in Autodesk Fusion 360

b) *Preliminary data collection*
First a number of Wind Tunnels were analysed and their data were arranged in various tables using MS Excel. The variety of tunnels were of different types, dimensions and speeds.

From Literature review and analysis of all wind tunnel data, we get the below "Table of Design".

PAPER OF RESEARCH	OPEN OR CLOSED	TOTAL LENGTH	VELOCITY (in m/s)	CONTRACTION RATIO (USUALLY 15 TO 1)	CONTRAC- TION LENGTH	CONTRACTION ANGLE/ SEMI OR FULL IN DEGREE	TEST SECTION (L,B,H)	SHAPE OF TEST SECTION	DIFFUSER	DIFFUSER LENGTH	DIFFUSER ANGLES	ADDITIONAL COMMENTS	ANY FACILITY	TEST MATERIAL HC AND SCREENS	DETAILS OF	FAN SPECS

Figure 23: Table of Design Data

c) Data segregation

The Wind tunnels which matched the description of tunnels we wanted, mentioned above: "Open Circuit (Eiffel) Type Wind Tunnel with closed test sections and with a suck-down apparatus diffuser and fan" were shortlisted. The list was very short, with only a handful of them. They laid the foundation for design in software such as the Autodesk Fusion 360. (Chosen for collaboration, and ease of handling, constructing and modelling data)

Thus, the table of shortlisted designs is given below

SHORTLISTED DESIGNS

SR no	PAPER	OPEN OR CLOSED	TOTAL LENGTH	VELOCITY (in m/s)	CONTRACTION RATIO (USUALLY IS TO 1)	CONTRACTION LENGTH	CONTRACTION ANGLES SEMI OR FULL IN DEGREE	TEST SECTION (L,B,H)	SHAPE OF TEST SECTION	DIFFUSER	DIFFUSER LENGTH	DIFFUSER ANGLES	ADDITIONAL COMMENTS	ANY FACILITY	TEST MATERIAL	DETAILS OF HC AND SCREENS	FAN SPECS
10	Design of an open circuit subsonic wind tunnel for educational purpose	OPEN	4.5m	20-25 m/s	6.25	1m		(0.7*0.4*0.4)m	square	2.405	1.0m	6 TO 7	FULL SPECS GIVEN				
13	Design and fabrication of low speed wind tunnel and flow analysis	OPEN		36 m/s and uniform pressure 36bar	4	1.18m	24	(0.7*0.5*0.5)m	sqaure	Outer 0.7m, Inner 0.5m	1.8m	7	settling chamber- (0.3*1*1)m		The test section was made with the help of plywood and fiber glass. The manufacturing of test section top and bottom surface of the test section was fabricated of plywood and side surface was fabricated with the fiber glass.		Component Specification Motor power 7.5 HP Maximum Speed of motor 1440 rpm Types of motor 3 phase induction motor Types of fan Axial fan Fan diameter 1000
	WEBSITE	OPEN	8FT			7	2 ft	1*1*2 (w*h*L)	Square		4ft				Plywood and Plexiglass		Notice that the fan is circular, but the end is a square, and that the corners of the board are actually walls that will disturb the airflow. This can cause turbulence in the Diffuser and affect the airflow in the rest of the wind tunnel. However, your fan will negate almost all of this turbulence by drawing the corner air to the circle and blowing it out.

From Research papers in literature review and references

Figure 24: Table of Shortlisted designs

d) Design Modelling
The 3 designs plotted in Autodesk Fusion 360
1. Design 1
Model drawn with foundations used from [5].
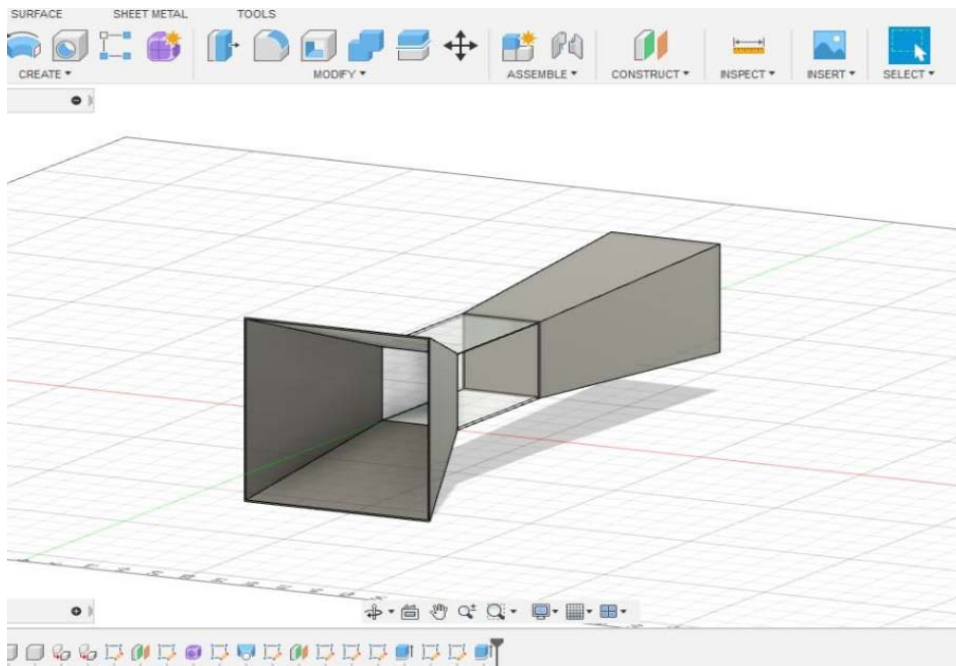
Figure 25

2. Design 2
Model drawn using principles of [21]
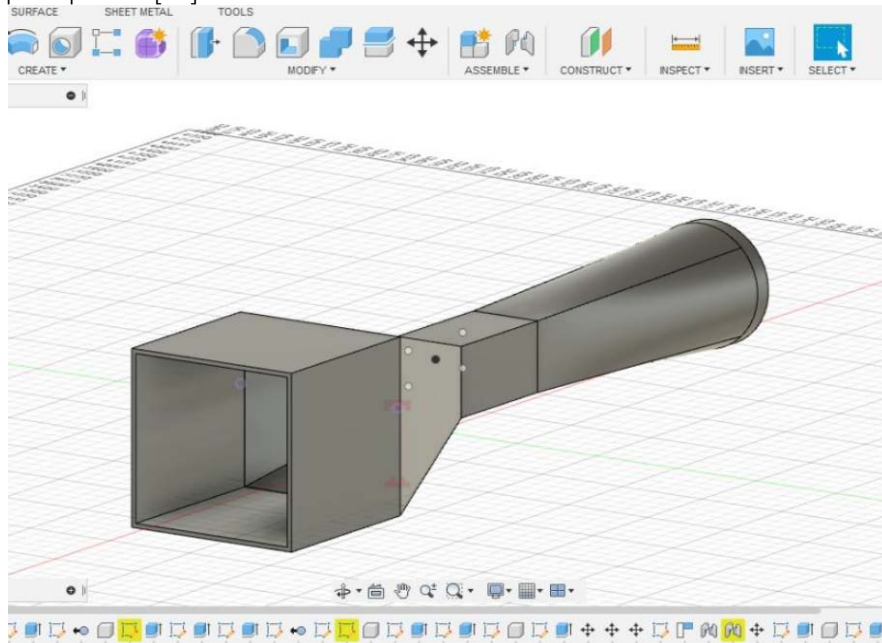
Figure 26

3. Design 3
A little tweaking and using the basic principles from [131].
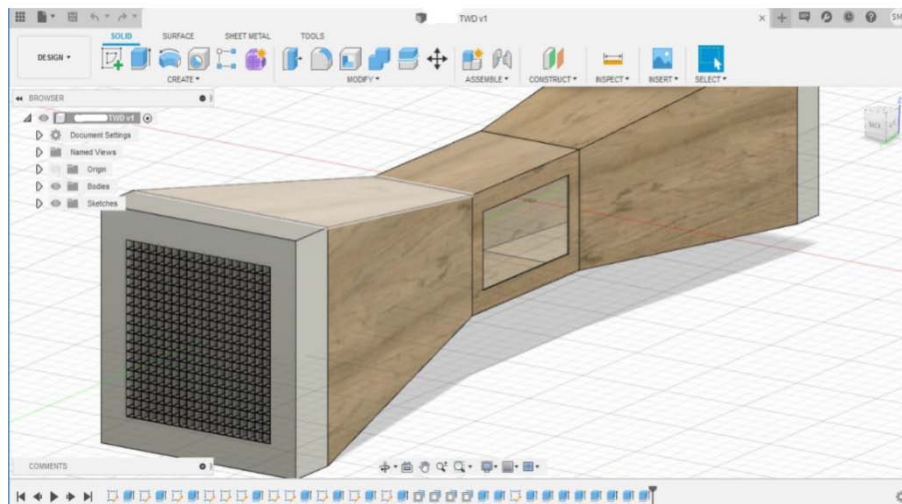
Figure 27

e)   Choosing a Base Foundation

The Wind tunnel mentioned in [131], that is after little modifications the design 3 mentioned above, surpassed our expectations and was chosen as a base design. It matched most of the guidelines of design principles mentioned above.

f)   Creation of assembly or Model Preparation

This Open circuit wind tunnel was then built in Autodesk Inventor (Implemented for modelling and assembling which is then used as basis for Autodesk CFD analysis later). Separate parts of wind tunnel such as settling chamber, contraction, test section and diffuser were constructed with a thickness of 0.25 inch and proper scale was employed. The mating with constraints was carried out and the assembly was thus, generated.

Note

In this tunnel, the Settling chamber (consisting of Honeycomb Mesh and Screens) was neglected. This neglecting step was implemented only after failure/error occurring during design study analysis in Autodesk CFD with the screen not responding and the CPU requiring a lot time and processing resources to produce any suitable result for use.

Components
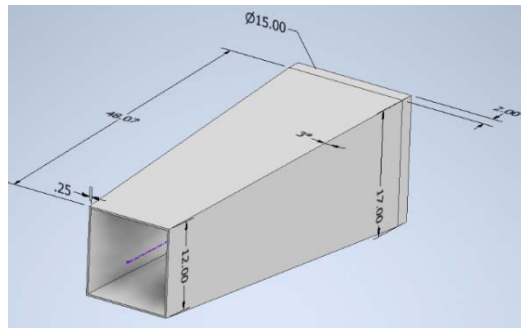
Figure 28: Diffuser
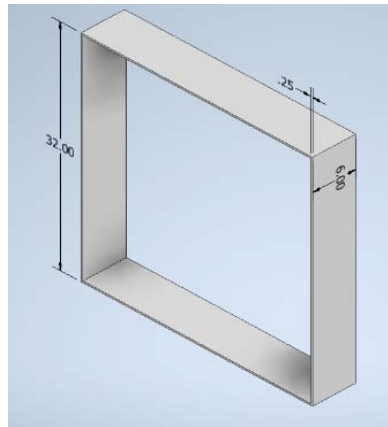
Figure 29: Settling chamber
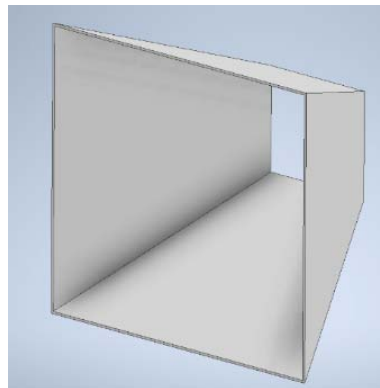
Figure 30: Square contraction cone
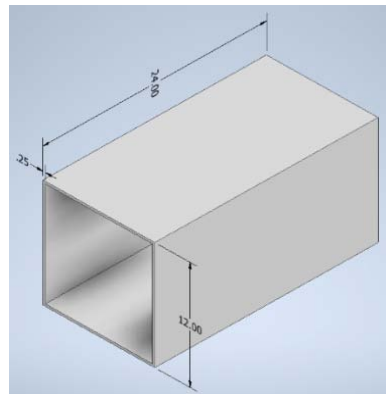
Figure 31: Test section

Model in Inventor after assembly:
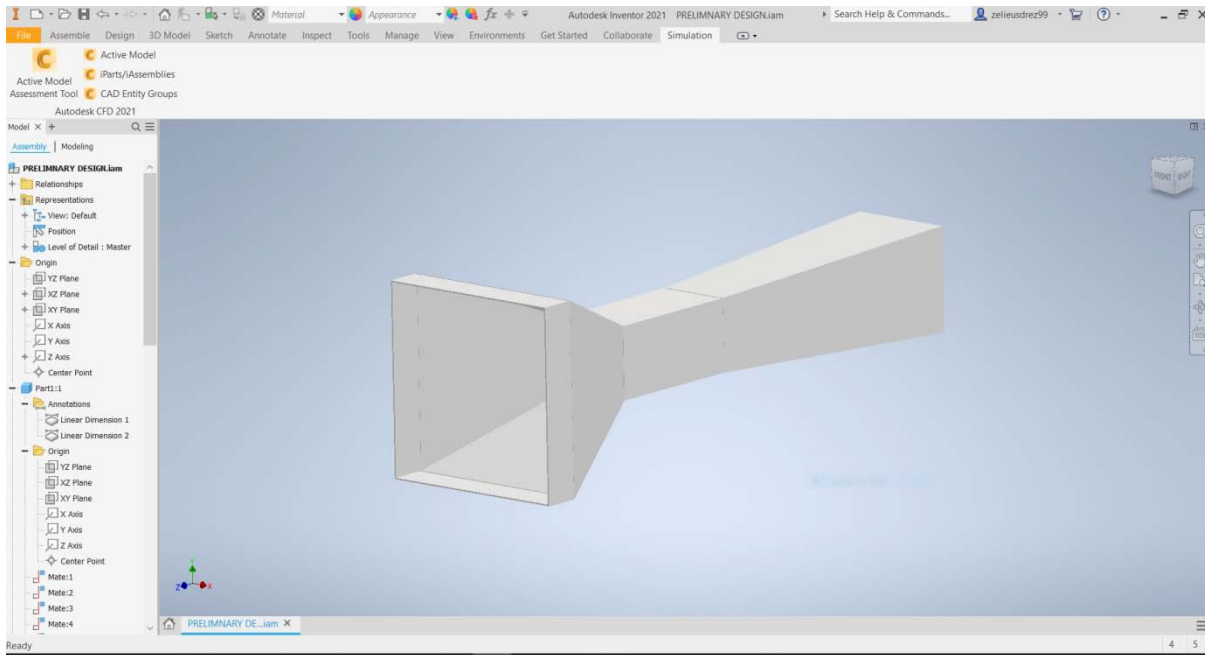
Figure 32

g) Import of Model

Thus, in the following step, this assembly from Inventor is imported to Autodesk CFD for analysis. This software allowed the materials to be set, the control volumes and surfaces to be generated, boundary conditions to be implemented, Meshing to decide, generation of results after solving and reports.

Example of a model in Autodesk CFD-
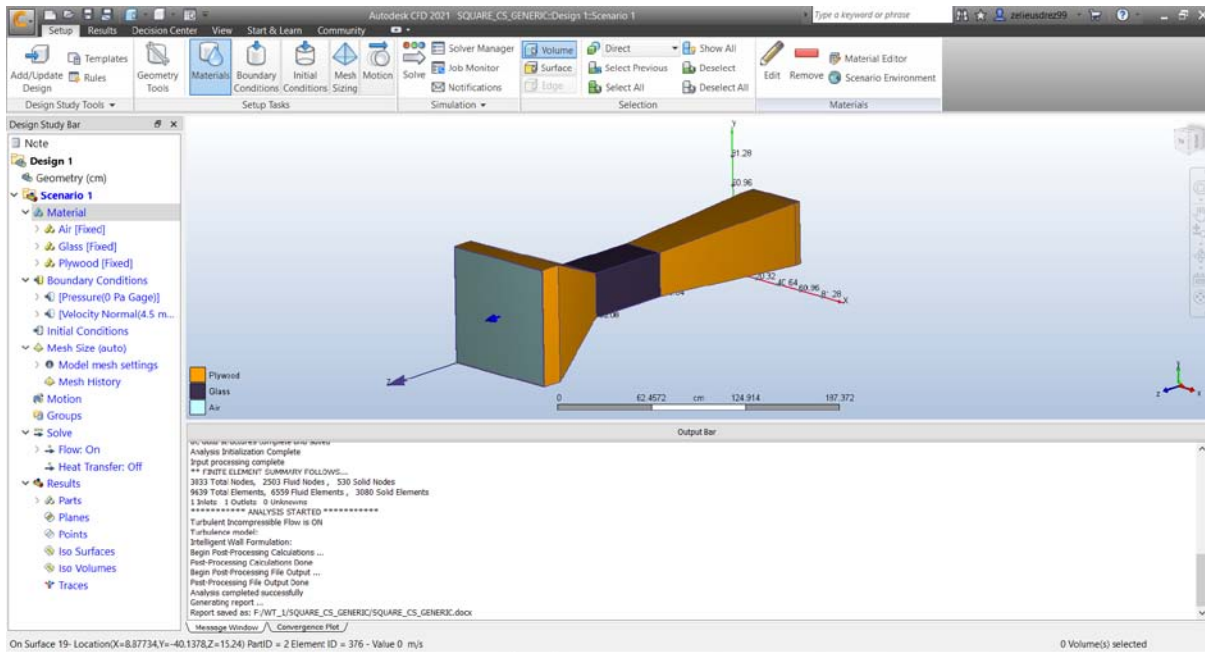
Figure 33: Plywood components and Glass test section
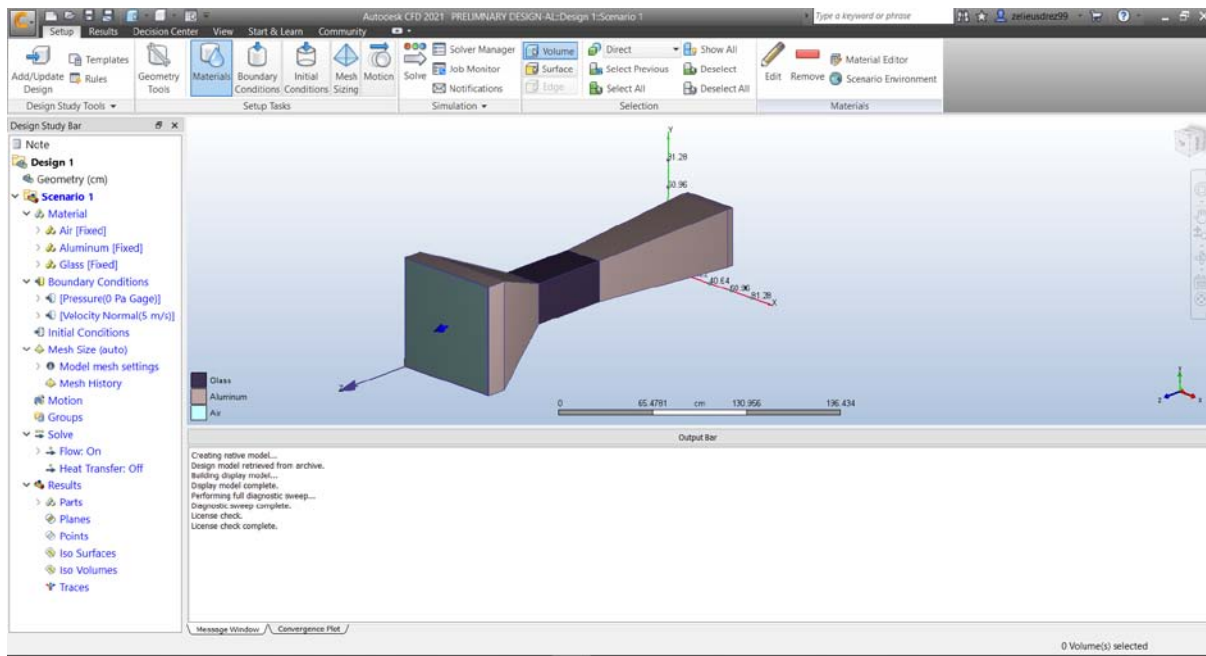
Figure 34: Aluminium components and glass test section

h) Boundary conditions and assumptions

For every model, a few conditions always remained the same:

1. Wind blowing in the Z-direction, since the tunnel runs in X-Y plane
2. Velocity to be normal and of the magnitude 4.5 m/s at the inlet of the cross section or control volume. This value of velocityis used in particular, because, after application of Bernoulli's equations we get decentfan speed capped at 14 or 15 m/s (most fans have speed in these ranges or CFMs of magnitude 7000+)
3. Pressure for the outlet being 0 (static pressure zero, as outlet is open to atmosphere). [1, 21]
4. Control Volume or fluid used is air at standard conditions. (78% Nitrogen, 21% Oxygen, traces of H_2O, CO_2), below is table for air at STP in imperial and metric units.

Air at "Standard" Condition

Temperature, T	$59°F = 518.67°R = 15°C = 288.16°K$	
Density, ρ	0.002378 slug/ft^3	1.225 kg/m^3
Pressure, p	2116 lb/ft^2	$101,325$ Pa (N/m^2)
Viscosity, μ	3.74×10^{-7} lb-sec/ft^2	1.791×10^{-6} kg/m-s
Kinematic viscosity, ν	1.55×10^{-4} ft^2/sec	1.44×10^{-5} m^2/s
Reciprocal of ν	6452 sec/ft^2	$69,440$ s/m^2
Gas constant, R	1714.9 ft-lb/slug-°R	287 N-m/kg-°K
	Imperial	Metric

Figure 35: Air at STP

5. Meshing used is automatic. To keep the study simple and to not change the meshing dimensions each time after importing model, we choose Automatic Meshing. This generates mesh of a particular size, automatically with adequate grid refinement. Moreover, there exists a minimal amount of symmetry within the tunnel. For more processing power, and accurate results one could use unstructured meshing [3].
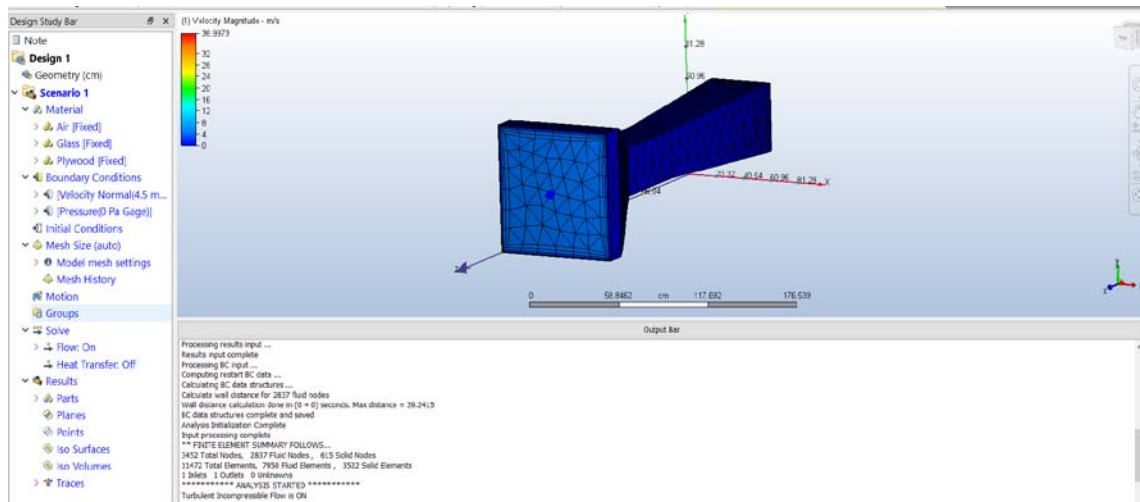
Figure 36

6. Steady Flow is assumed rather than transient as the time conditions are difficult to execute.
7. Also, the flow is assumed to Incompressible and turbulent, hence, turbulence models are employed.

i) Study A-Turbulence models and Material

Keeping the basis assumption in mind, the first study had the same model imported in Autodesk CFD,

but each time the turbulence specification used differed and the material used for components of Wind tunnel, differed too. The studies carried out for our analysis comprise of 4 turbulent models- K-epsilon, K-Omega, SST k-omega and LES Model on the preliminary base inspired design. The comparisons are then laid out with some proper inferences and conclusions.

Example of Result Valuation:
Velocity Plane:

Figure 37

Traces or Flow Visualization:

Figure 38

With less coarse/seed of Trace:

Figure 39

Tabular data with different turbulent models employed and material:
1. Plywood Contraction, diffuser and settling chamber with different test sections and Turbulence Models

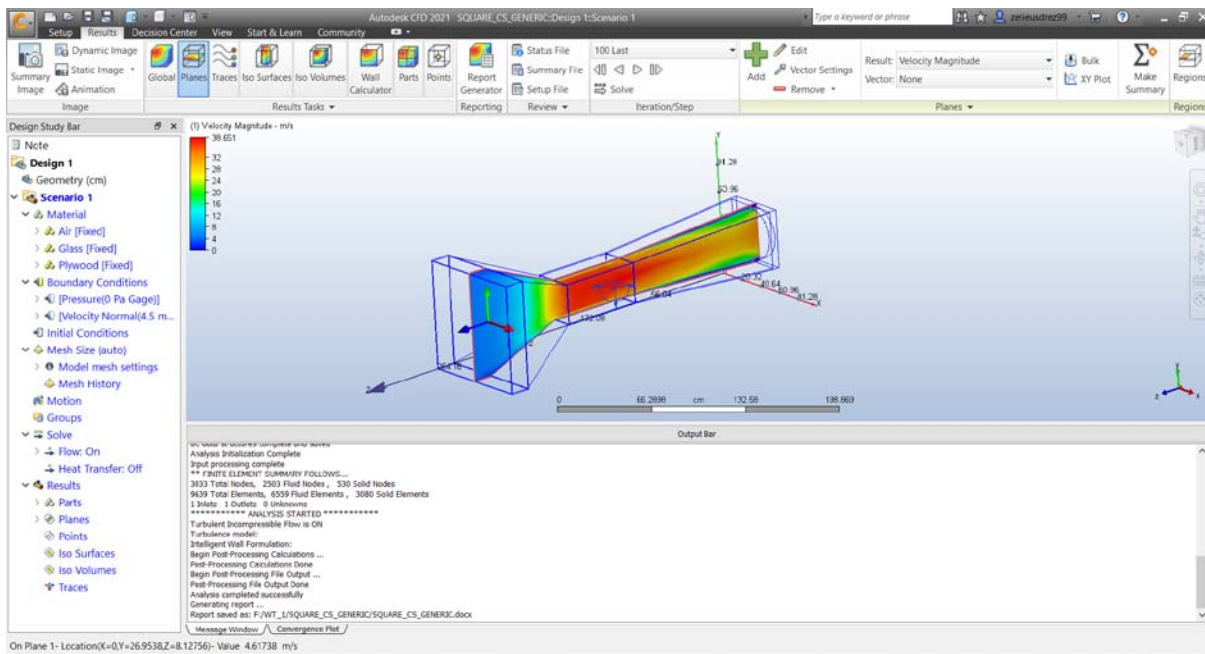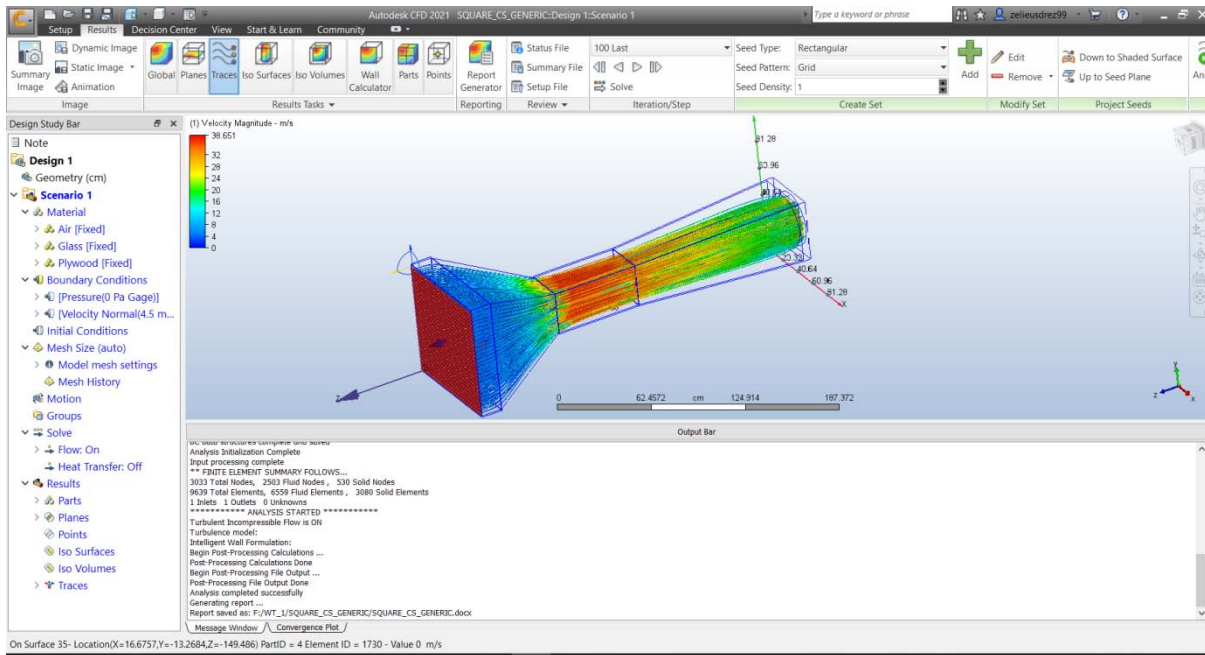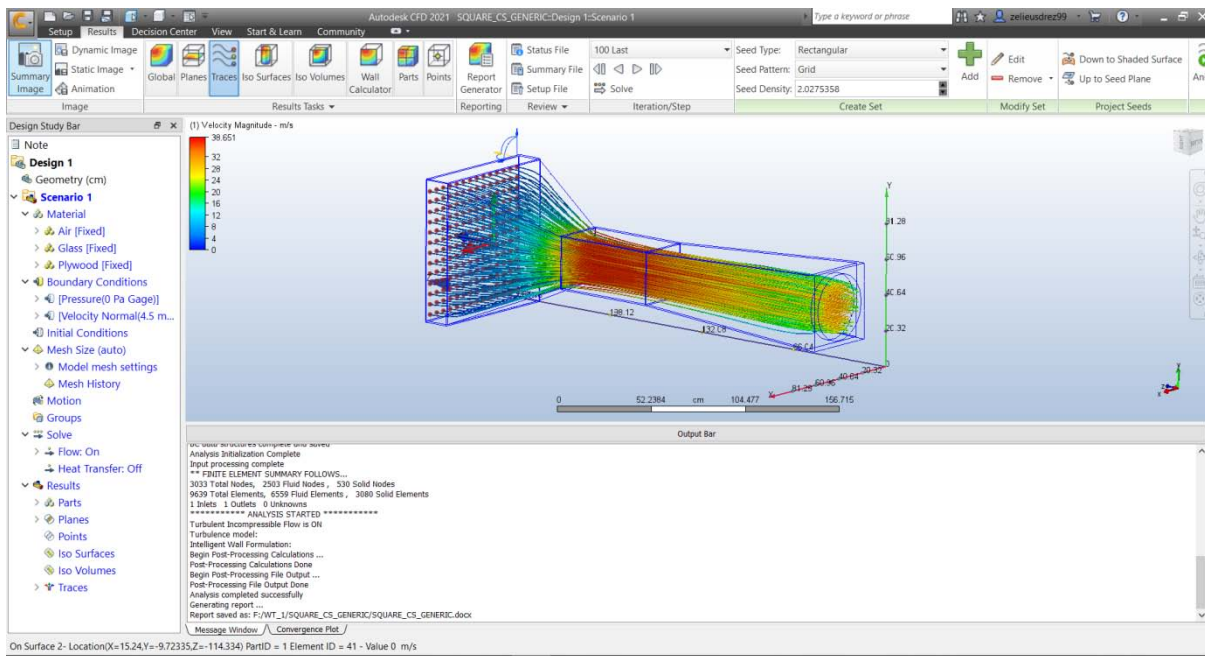| MATERIAL USED		TURBULENCE MODELS -->					
OTHER	TEST SECTION	PARAMETERS		K-EPSILON	SST K-OMEGA	LES	LAMINAR
PLYWOOD	GLASS	VELOCITY	X	754.536 cm/s	756.567 cm/s	750.624 cm/s	879.154 cm/s
			Y	753.112 cm/s	758.37 cm/s	746.656 cm/s	874.972 cm/s
			Z	620.577 cm/s	703.199 cm/s	818.29 cm/s	1948.63 cm/s
		T-D	MAX	150448000.0 cm^2/s^3	905059.0 cm^2/s^3	27.3952 cm^2/s^3	0
			MIN	27.3952 cm^2/s^3	1.52879 cm^2/s^3	1.0 cm^2/s^3	
		T-K	MAX	330843.0 cm^2/s^2	653430.0 cm^2/s^2	253.125 cm^2/s^2	
			MIN	1.817e-07 cm^2/s^2	0.0 cm^2/s^2	0.0001 cm^2/s^2	
		PRESSURE	pressx	2644.3 dynes	16203.0 dynes	14472.0 dynes	-23984.0 dynes
			pressy	27319.0 dynes	15160.0 dynes	13243.0 dynes	-45657.0 dynes
			pressz	-40947000.0 dynes	-42514000.0 dynes	-44433000.0 dynes	-33559000.0 dynes
		SHEAR	shearx	88.773 dynes	-152.34 dynes	-3.9577 dynes	0.8264 dynes
			sheary	-7.0527 dynes	-26.774 dynes	-3.0545 dynes	-25.309 dynes
			shearz	-301670.0 dynes	-624360.0 dynes	-6706.1 dynes	-9575.5 dynes
	ACRYLIC	VELOCITY	X	754.626 cm/s	756.573 cm/s	750.622 cm/s	Laminar Flow is not considered as by reynolds's number, flow is turbulent, above shown laminar is only for comparison and should not be considered
			Y	753.236 cm/s	758.363 cm/s	746.655 cm/s	
			Z	620.856 cm/s	703.228 cm/s	818.142 cm/s	
		T-D	MAX	150454000.0 cm^2/s^3	905059.0 cm^2/s^3	27.3952 cm^2/s^3	
			MIN	27.3952 cm^2/s^3	0.326481 cm^2/s^3	1.0 cm^2/s^3	
		T-K	MAX	330784.0 cm^2/s^2	653437.0 cm^2/s^2	253.125 cm^2/s^2	
			MIN	1.817e-07 cm^2/s^2	0.0 cm^2/s^2	0.0001 cm^2/s^2	
		PRESSURE	pressx	4290.0 dynes	16159.0 dynes	14473.0 dynes	
			pressy	26706.0 dynes	15189.0 dynes	13251.0 dynes	
			pressz	-40942000.0 dynes	-42514000.0 dynes	-44433000.0 dynes	
		SHEAR	shearx	90.554 dynes	-100.75 dynes	-3.9561 dynes	
			sheary	-0.25071 dynes	-32.444 dynes	-3.0665 dynes	
			shearz	-301610.0 dynes	-624300.0 dynes	-6706.1 dynes	

Figure 40: Plywood Table with different turbulence models

2. Aluminium Contraction, diffuser and settling chamber with different test sections and Turbulence Models

MATERIAL USED		TURBULENCE MODELS -->					
OTHER	TEST SECTION	PARAMETERS		K-EPSILON	SST K-OMEGA	LES	LAMINAR
ALUMINIUM	GLASS	VELOCITY	X	754.226 cm/s	756.628 cm/s	750.626 cm/s	879.158 cm/s
			Y	752.796 cm/s	758.425 cm/s	746.658 cm/s	874.982 cm/s
			Z	621.58 cm/s	703.216 cm/s	818.28 cm/s	1948.66 cm/s
		T-D	MAX	150461000.0 cm^2/s^3	905059.0 cm^2/s^3	27.3952 cm^2/s^3	0
			MIN	27.3952 cm^2/s^3	1.52902 cm^2/s^3	1.0 cm^2/s^3	
		T-K	MAX	330903.0 cm^2/s^2	653417.0 cm^2/s^2	253.125 cm^2/s^2	
			MIN	1.817e-07 cm^2/s^2	0.0 cm^2/s^2	0.0001 cm^2/s^2	
		PRESSURE	pressx	5067.5 dynes	16193.0 dynes	14474.0 dynes	-23985.0 dynes
			pressy	26823.0 dynes	15208.0 dynes	13247.0 dynes	-45654.0 dynes
			pressz	-40931000.0 dynes	-42514000.0 dynes	-44433000.0 dynes	-33559000.0 dynes
		SHEAR	shearx	88.634 dynes	-139.04 dynes	-3.9577 dynes	0.82472 dynes
			sheary	-0.0089166 dynes	-16.825 dynes	-3.0609 dynes	-25.285 dynes
			shearz	-301560.0 dynes	-624360.0 dynes	-6706.0 dynes	-9575.1 dynes
	ACRYLIC	VELOCITY	X	754.564 cm/s	756.563 cm/s	750.623 cm/s	Laminar Flow is not considered as by reynolds's number, flow is turbulent, above shown laminar is only for comparison and should not be considered
			Y	753.167 cm/s	758.376 cm/s	746.656 cm/s	
			Z	622.894 cm/s	703.196 cm/s	818.253 cm/s	
		T-D	MAX	150465000.0 cm^2/s^3	905059.0 cm^2/s^3	27.3952 cm^2/s^3	
			MIN	27.3952 cm^2/s^3	1.48268 cm^2/s^3	1.0 cm^2/s^3	
		T-K	MAX	330789.0 cm^2/s^2	653436.0 cm^2/s^2	253.125 cm^2/s^2	
			MIN	1.817e-07 cm^2/s^2	0.0 cm^2/s^2	0.0001 cm^2/s^2	
		PRESSURE	pressx	4883.5 dynes	16219.0 dynes	14475.0 dynes	
			pressy	26235.0 dynes	15240.0 dynes	13250.0 dynes	
			pressz	-40943000.0 dynes	-42514000.0 dynes	-44433000.0 dynes	
		SHEAR	shearx	88.823 dynes	-118.73 dynes	-3.9588 dynes	
			sheary	-0.048968 dynes	-22.677 dynes	-3.0655 dynes	
			shearz	-301600.0 dynes	-624270.0 dynes	-6706.0 dynes	

Figure 41: Aluminium Table with different turbulence models

3. Legend or Index for Navigation

LEGEND		
Acronym	**Full Text**	**Depiction**
K-E	K-Epsilon Model	TURBULENCE MODELS
SST K OMEGA	Shear Stress Transport K-turbulence model	
LES	Large Eddy Simulation or Eddy Viscosity Model	
LAMINAR	Laminar Flow	NON TURBULENT
T-D	Turbulence Density	RESULT PARAMETER
T-K	Turbulence Kinetic Energy	

Figure 42: Legend for data

INFERENCE TABLE:

INFERENCES FROM MATERIAL	
1. Although laminar is seen in the above table, flow is turbulent and should be ignored.	VELOCITY
2. Velocity in X direction does not vary by a vast amount when test material is switched from glas to acrylic, and by a negligible amount when switch from	
3. Velocity in Y direction gives the same results	
4. Velocity in Z direction is same for most of the models and materials, but is the highest for LES Model	
5. Turbulence Density (T-d) is same for all materials, highest turbulence is found in K-Epsilon Model while LES gives the least turbulence, which makes LES a	T-D
6. Turbukence Kinetic Energy (T-k) gives similar results to T-d, thus the scale again, tips towards LES	T-K
7. For all turbulence models, Pressure in X direction increases when acrylic is used except for Aluminium	PRESSURE
8. Presure in Y direction also increases when acrylic is used except for K-E Model	
9. Pressure in Z is almost equal regardless of model and material, but negative	
10. Shear in X direction is negative for SST K Omega and LES	SHEAR
11. Shear in Y and Z direcion is negative for all turbulence models	
12. Shear in X and Y direction reduces when Aluminium is used	
13. Shear in Z direction remains same for material	

Figure 43: Table of Inferences for Study A

Conclusions of Study-A

1. Velocities, T-D and T-K are almost similar for most of the models used.
2. LES (Large Eddy Simulation or Viscosity) is the model with least turbulence and will be selected as primary basis for comparison in geometry part of the study.
3. Although the pressure/Shear reduces by a very small amount, glass or acrylic both give same result.
4. Aluminium does give a very slight increase in velocity, but trading for cost value, given that for same cross section, Plywood is Rs. 950 while Aluminium is Rs.1650, plywood is favoured and recommended as it provides equivalent results.

Contraction Cone with 3rd degree polynomial
As component

LES Models are sufficient with lesser turbulence and plywood is an affordable, effective material for wind tunnel along with Glass as the test section. LES model is thus, the preferred choice of computing flow and Plywood with glass test-section, the go-to materials.

j) Study B-Geometry

Using the same materials, as stated above, plywood contraction, diffuser and settling chamber but with glass test section, as well as the same set of basic assumptions and constant boundary conditions, we carry out studies implementing different scenarios. The scenarios are Geometry change-Circular diffuser, Octagonal Contraction, Contraction with different wall shape-polynomial.

Figure 44

Assembly with Square diffuser
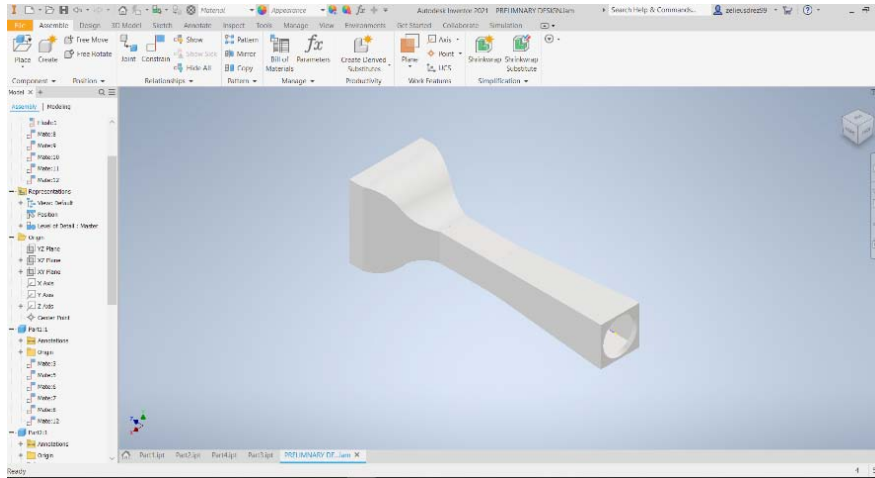
Figure 45: Rear view
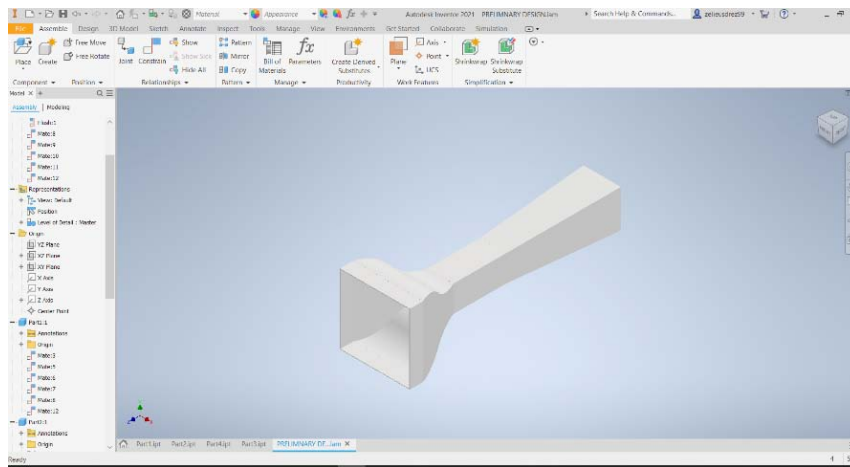
Figure 46: Front view

Model with material in Autodesk CFD
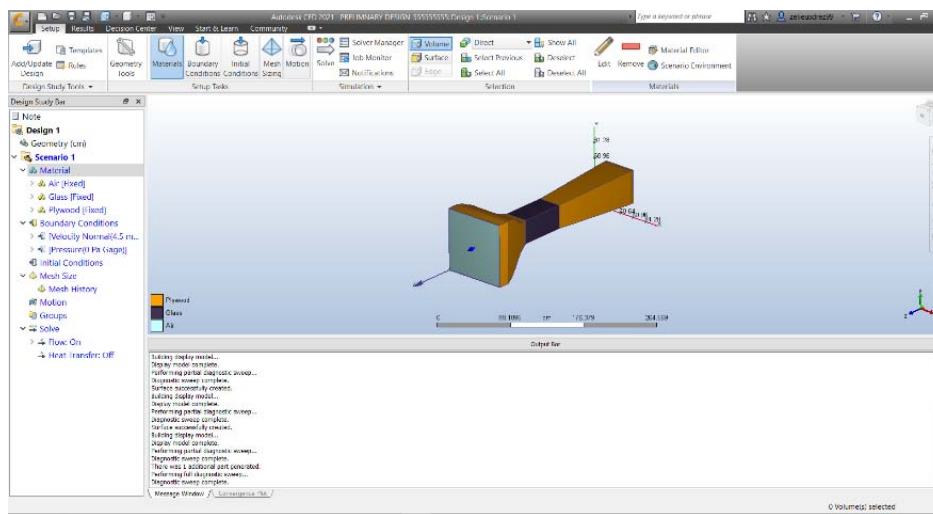
Figure 47

Velocity profile and Flow field around model
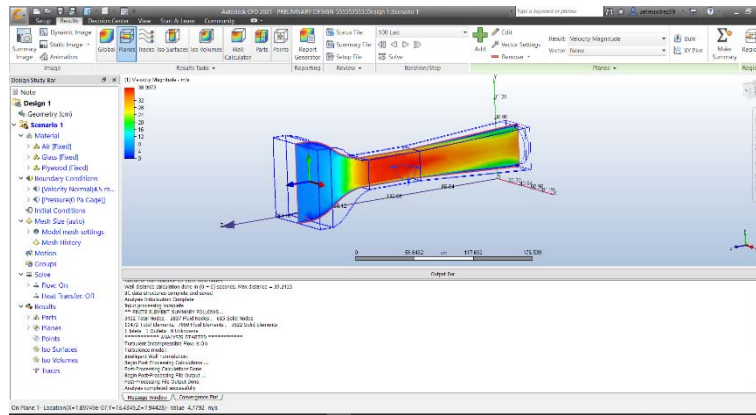
Figure 48
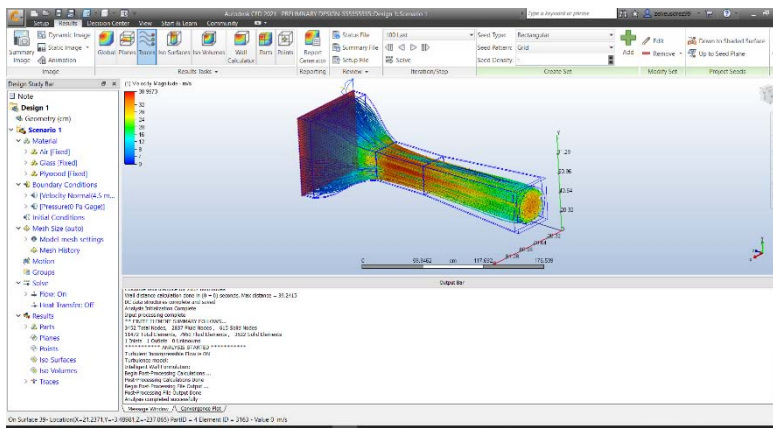
Figure 49

Contraction curve with 5th degree of curve of wall
Similar to 3rd degree contraction curve results and analysis are developed for 5th degree curve.
As component
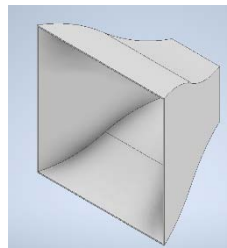
Figure 50

As assembly with material, and square diffuser
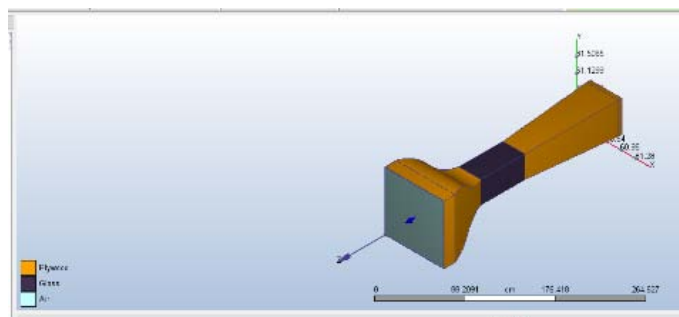
Figure 51

Octagonal Contraction cone with square diffusers and test section
Assembly with material
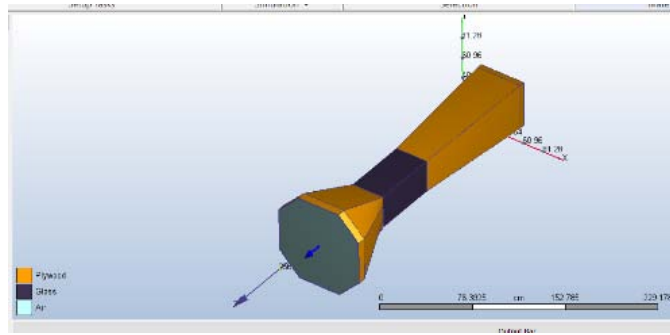
Figure 52

Velocity Profile
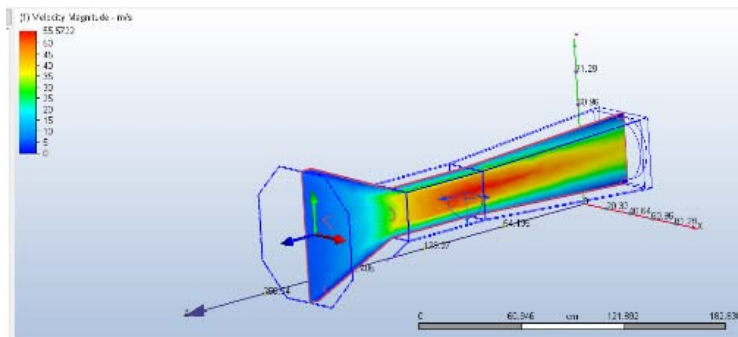
Figure 53

Circular diffusers with
a. Square Cross section Contraction chamber
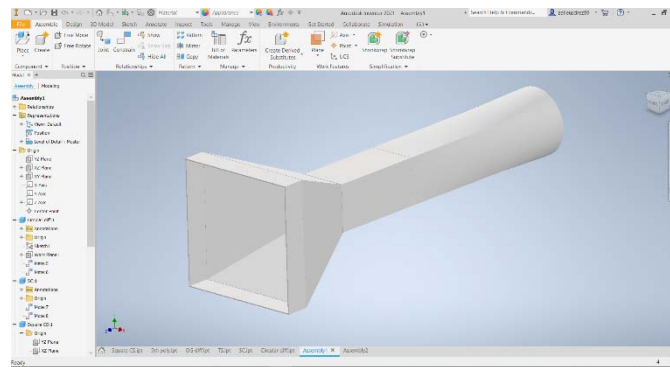
Figure 54

b. Square cross section with 3rd degree and 5th degree wall curves

Figure 55
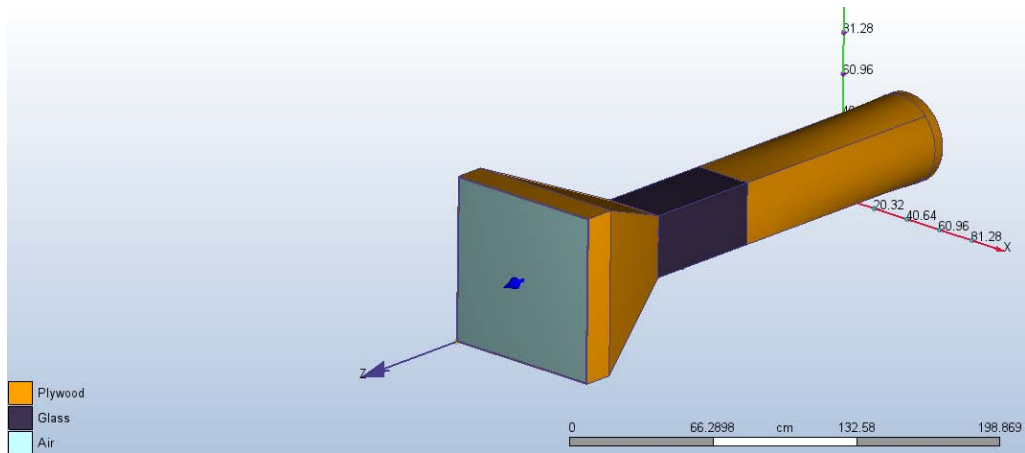
Figure 56
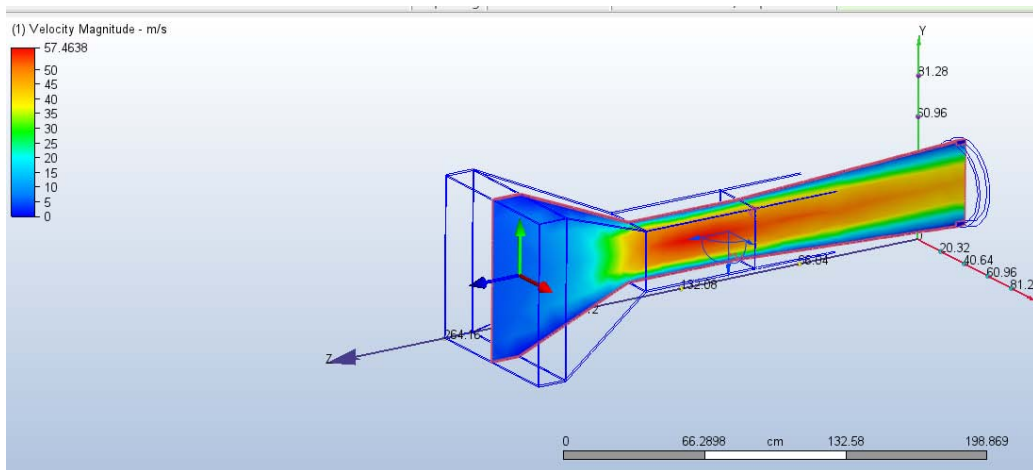
Figure 57
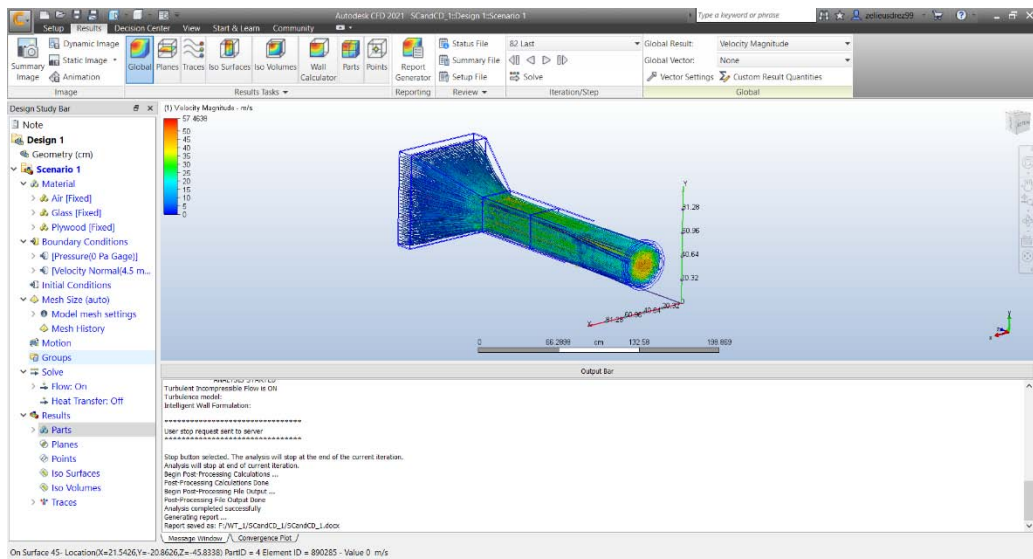
Figure 58

Important Note

One must avoid leakage errors as shown below in the figure. The CFD would never process under such conditions
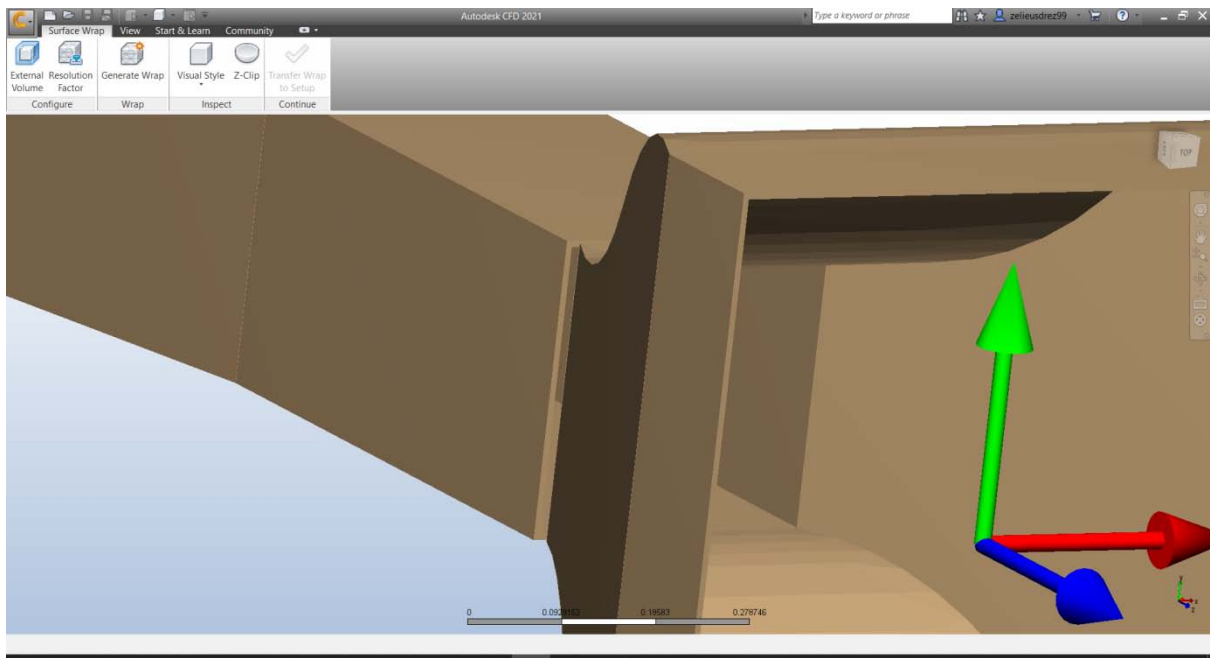
Figure 59

The 5th and 3rd Degree polynomial curves are different in a very small aspect:- The steepness of curve, figure below shows the plot of the same. Blue is the cubic polynomial.
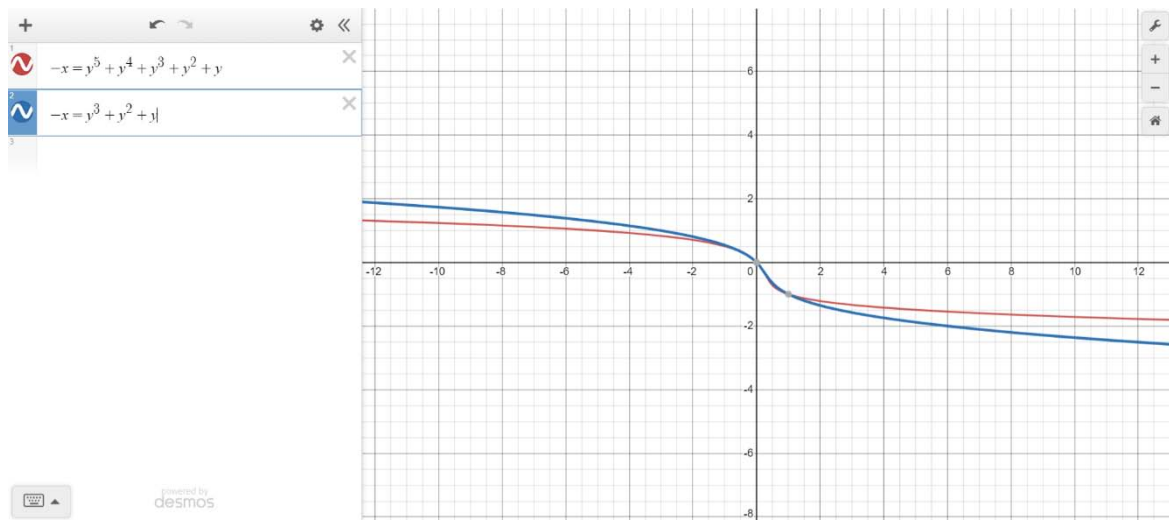
Figure 60: Curves

Tabular Data of collected conditions of geometry

GEOMETRY - STUDY B														
GEOMETRY	PARAMETERS -->	VELOCITY			T-D		T-K		PRESSURE			SHEAR		
	CONDITIONS	X	Y	Z	MAX	MIN	MAX	MIN	pressx	pressy	pressz	shearx	sheary	shearz
CONTRACTION CHAMBER														
Square contraction chamber	Square test section, settling chamber, and generic diffuser.	750.625 cm/s	746.648 cm/s	818.217 cm/s	27.3942 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	14421.0 dynes	13212.0 dynes	-44433000.0 dynes	-3.8814 dynes	-3.0763 dynes	-6706.1 dynes
Square Contraction with 3rd degree wall curve polynomial		930.12 cm/s	784.446 cm/s	823.952 cm/s	27.4036 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	1279.2 dynes	18962.0 dynes	-46825000.0 dynes	-5.4671 dynes	-21.526 dynes	-6617.1 dynes
Square Contraction with 5th degree wall curve polynomial		920.204 cm/s	692.823 cm/s	847.677 cm/s	27.3956 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	10055.0 dynes	9323.0 dynes	-44021000.0 dynes	-6.6323 dynes	-5.9466 dynes	-6584.8 dynes
Octagonal Contraction chamber, thickness of octagonal start is 3 inch.	Square Test section and generic diffuser, but no settling chamber	734.611 cm/s	782.598 cm/s	823.574 cm/s	9.44916 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	667.36 dynes	15876.0 dynes	-63782000.0 dynes	21.73 dynes	-43.307 dynes	-82265.0 dynes
DIFFUSER														
Generic Diffuser, Square cross section	Square test section, settling chamber, and Straight Square contraction Cone	750.625 cm/s	746.648 cm/s	818.217 cm/s	27.3942 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	14421.0 dynes	13212.0 dynes	-44433000.0 dynes	-3.8814 dynes	-3.0763 dynes	-6706.1 dynes
Circular diffuser	Square test section, settling chamber, and 3rd degree polynomial curve of walls of Square contraction Cone	675.358 cm/s	677.719 cm/s	863.25 cm/s	32.5923 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	16204.0 dynes	6728.4 dynes	-103220000.0 dynes	51.077 dynes	68.879 dynes	-177060.0 dynes
	Square test section, settling chamber, and 5th degree polynomial curve of walls of Square contraction Cone	743.177 cm/s	681.398 cm/s	872.69 cm/s	32.5923 cm^2/s^4	1.0 cm^2/s^4	253.125 cm^2/s^3	0.0001 cm^2/s^3	-39929.0 dynes	3790.1 dynes	-105820000.0 dynes	115.51 dynes	-205.29 dynes	-184590.0 dynes
NOTE:														
Assumed thickness=0.25inch, Incompressible flow, LES Turbulence Model, Automatic Mesh, Plywood Other components, and glass test section. Test Section is same throughout all models.														

Figure 61: Tabular data of Study B

Conclusions and Inferences
1. When the contraction degree of wall curve is increase the cross flow due to velocity in X direction does increase by a small amount.
2. The turbulence energy dissipation and Kinetic energy of turbulence remains same.
3. Pressure along Y direction decreases as the wall curve degree increases.
4. Shear is in negative and is neglected.
5. The octagonal contraction chamber surges the velocity in Z direction with a focused flow by curtailing velocity in X and Y directions.
6. The pressure on the wall (Y-direction) escalates by a small amount when Octagonal test section is used rather than square peculiarly the one with 5th degree curve.
7. In case of diffusers, velocity fluctuations are reduced when circular cross section ones are implemented rather than the square ones .
8. Moreover, when circular cross sections are used, velocity in Z-direction also soars, with better velocity profiles.
9. Pressure reduces on the walls (Y direction) when square cross section with 5th degree curves are utilized with circular diffusers but on the cost of shear.
10. Thus, a good tip in the balance would be towards a square contraction cone with 5th degree curve and a circular cross-section.

k) Study C- Other Scenarios
Include, increasing length of settling chamber, changing thickness of plywood and reducing length of test section.

Tabular data of variations

SCENARIOS	PARAMETERS -->	VELOCITY			T-D		T-K		PRESSURE			SHEAR		
		X	Y	Z	MAX	MIN	MAX	MIN	pressx	pressy	pressz	shearx	sheary	shearz
SCENARIO-STUDY C														
DIFFERENT THICKNESS OF PLYWOODS (IN INCHES)														
Varying Thickness of Plywood	0.25	750.625 cm/s	746.648 cm/s	818.217 cm/s	27.3942 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	14421.0 dynes	13212.0 dynes	-44433000.0 dynes	-3.8814 dynes	-3.0763 dynes	-6706.1 dynes
	0.5	744.415 cm/s	748.805 cm/s	814.825 cm/s	28.0373 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	-29619.0 dynes	4595.3 dynes	-45150000.0 dynes	4.8144 dynes	-5.9991 dynes	-6474.7 dynes
	0.75	802.979 cm/s	805.256 cm/s	720.951 cm/s	28.0373 cm^2/s^4	1.0 cm^2/s^4	253.125 cm^2/s^2	0.0001 cm^2/s^2	-39130.0 dynes	13238.0 dynes	-46563000.0 dynes	13.287 dynes	-8.3238 dynes	-6054.8 dynes
TEST SECTION LENGTH VARIED (in Feet)														
REDUCED TEST SECTION LENGTH	2FT	750.625 cm/s	746.648 cm/s	818.217 cm/s	27.3942 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	14421.0 dynes	13212.0 dynes	-44433000.0 dynes	-3.8814 dynes	-3.0763 dynes	-6706.1 dynes
	1FT	741.449 cm/s	731.889 cm/s	839.382 cm/s	27.3906 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	18672.0 dynes	15429.0 dynes	-43079000.0 dynes	-5.6367 dynes	-5.4169 dynes	-5423.0 dynes
LENGTH OF SETTLING CHAMBER VARIED (IN INCHES)														
INCREASED LENGTH OF SETTLING CHAMBER	6IN	750.625 cm/s	746.648 cm/s	818.217 cm/s	27.3942 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	14421.0 dynes	13212.0 dynes	-44433000.0 dynes	-3.8814 dynes	-3.0763 dynes	-6706.1 dynes
	12IN	737.505 cm/s	748.881 cm/s	900.96 cm/s	27.4057 cm^2/s^3	1.0 cm^2/s^3	253.125 cm^2/s^2	0.0001 cm^2/s^2	2124.7 dynes	-11972.0 dynes	-44876000.0 dynes	0.24949 dynes	1.2893 dynes	-6914.9 dynes
NOTE:														
Assumed Incompressible flow, LES Turbulence Model, Automatic Mesh, Plywood for other components, and glass test section. Square contraction chamber, settling chamber, test section and diffusers used.														

Figure 62: Tabular data of Study C

Conclusions and Inferences
1. Using lesser thickness of Plywood increases velocity in test section as seen from V_Z.
2. In other words, the larger thicknesses of plywood, increase the resistance to flow of Wind.
3. The distribution towards X, Y directions of velocity increases as thickness of plywood increases.
4. The value of T-K and T-E remain more or less the same, irrespective of thickness.
5. The reduction of test section, increases velocity by a slight amount but on the expense of higher pressure and reduced test section area to place model.
6. The increase in the length of settling chamber does help reduce pressures inside tunnel, with higher uniformity, but the shear forces rise. The velocity achieved in the test-section, too, increases.
7. Thus, the optimal thickness would be that of 0.25 inch of plywood, proper length of test section would be 2ft, meanwhile a compromise for settling chamber would be 7 inches.

IX. FINAL DESIGN AND SPECIFICATIONS

As mentioned, material chosen was glass for the test section, plywood for the components of wind tunnel. The contraction cone is square but with a 5th degree polynomial curve for the walls. The test section is square. The diffuser is circular. Settling chamber is employed at the start with Honeycomb mesh and screen to reduce the turbulence. Thus, these components are shown below and modelled in Inventor.
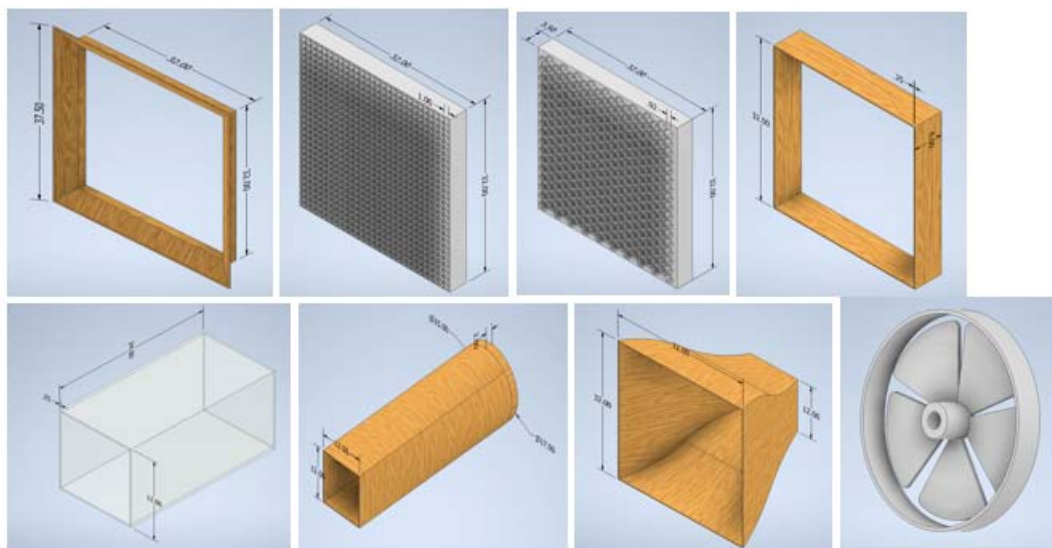
a) Components

Figure 63: Components

b) *Exploded view*
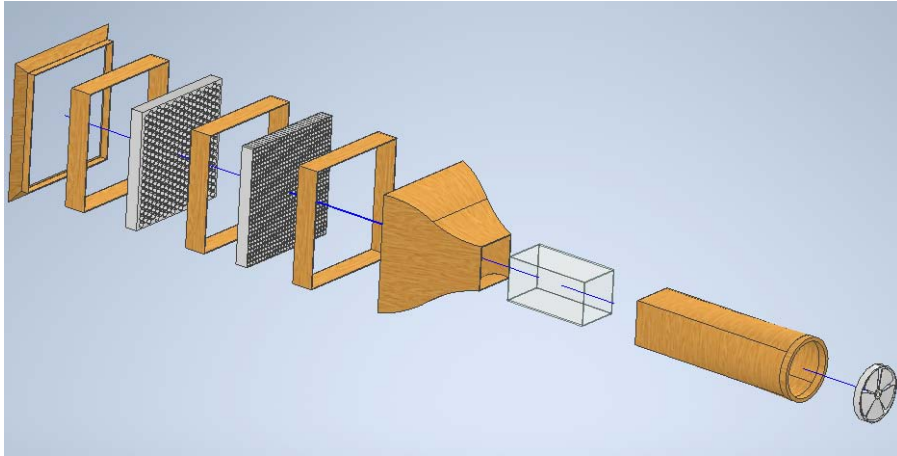
Figure 64

c) *Overview*
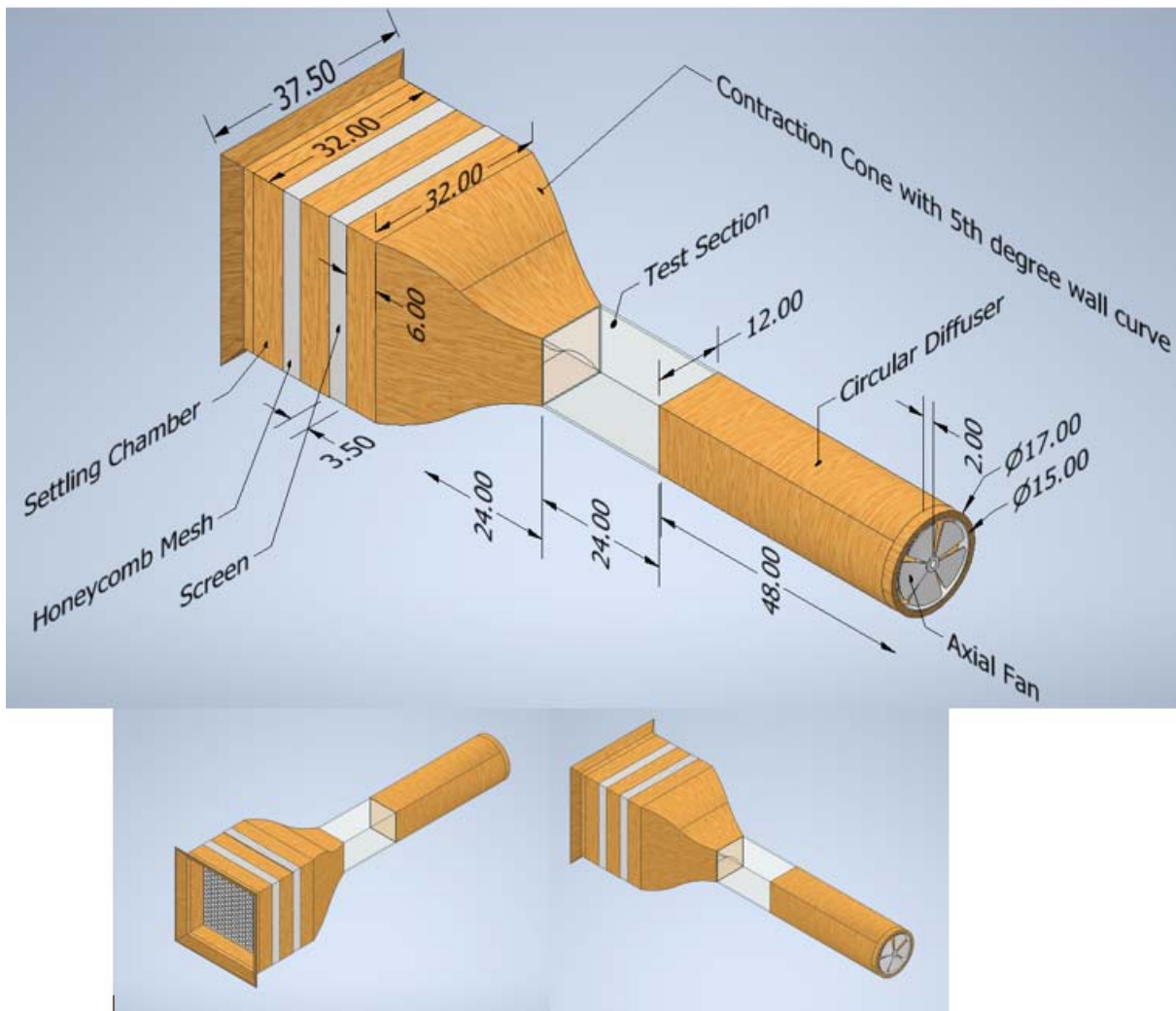
Figure 65: Overview with 2 Oblique views

X. The Next Steps

The consequent step after the design would be the manufacturing of the tunnel for college and research purposes.

A structure can be adopted to keep the wind tunnel mounted. Aluminium pipes could be adopted for honeycomb mesh due to its low weight, and considerable strength. Nails and bonds with adhesive glue seems considerable enough as well. For the plywood constructed diffusers, along with holding structures, dampers could be used to absorb the vibrations. It is important to check for leakages of air as well. [9, 10]

Piano hinges could be used open and close test section windows made from plexi glass. Digital scales over mechanical being superior could be employed if the budget is suitable

There is a formidable amount of effort required for the selection of fan, especially the variable frequency part, seems a little onerous, but provides very good ranges and test velocities. The motor could be mounted in special hub casing with blades from aluminium if needed, to reduce the weight of tunnel. Controllers are implemented to operate the fan properly. Entire structures and wind tunnel mountings could be even placed on tables for feasibility if need be.

Based on "Memento des pertes de charge: Coefficients de pertes de charge singulièreset de pertes de charge par frottement", by I.E. Idel'cik [Eyrolles, 1986], authors of [18] have presented an aided spreadsheet as well, for helping with the design of closed wind tunnels. Dimensioning schemes are present on excel spreadsheet on "http://www.aero.upm.es/LSLCWT"

Thus with these beneficial and profound aspects, the designed model could lead to the effective learning and practical applications of the concepts mentioned.

One can additionally, investigate pressure distribution for drag reduction or enhancement of life. There is also, mention for self-correcting wind tunnels in transonic zone, where the blockage could be alleviated by ventilating wind tunnel walls [25, 18, 8].

Some papers like [46] mentioned studying ice accumulation on airplane wings, which could be studied for e.g. NASA Glenn Wind tunnel. Possibly an area of future research could be "Plasma actuation", a technique of actively controlling airflow. [48]

Figure 66: Example of Wind tunnel to manufacture,
source: https://www.tecquipment.com/subsonic-wind-tunnel-600mm

XI. Conclusions

Although a condition such as the end of diffuser being square but with circular fan poses a disturbance of airflow, this effect is negated with axial fan.

Thus, this paper tries to provide the right guidelines one could utilize for design of an Open circuit Wind tunnel. The right material and geometry with discussions using Autodesk Inventor and Autodesk CFD have been presented.

The Study A using different turbulent models helps give a picture about pattern of fluif flow distribution in test chamber with superiority of each model complementing each other.

Moreover, the confabulated Wind tunnel foreshadows so many research principles and R.D Mehta notes, hence, this design would suffice as a research tool in field of fluid mechanics and is not limited to just that.

Acknowledgment

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| Career | Credibility | Reputation |

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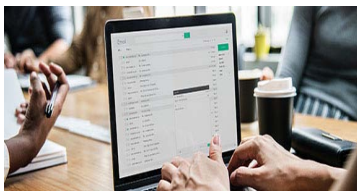
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Associate	Fellow	Research Group	Basic
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Gradation of Research	**Gradation** of Research	**Gradation** of Research	
10 research contacts/day	**Unlimited** research contacts/day	**Unlimited** research contacts/day	
1 GB Cloud Storage	**5 GB** Cloud Storage	**Unlimited** Cloud Storage	
GJ Community Access	**Online Presense** Assistance	**Online Presense** Assistance	
	GJ Community Access	GJ Community Access	

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Acknowledgments

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The following is the official style and template developed for publication of a research paper. Authors are not required to follow this style during the submission of the paper. It is just for reference purposes.

Manuscript Style Instruction (Optional)

- Microsoft Word Document Setting Instructions.
- Font type of all text should be Swis721 Lt BT.
- Page size: 8.27" x 11'", left margin: 0.65, right margin: 0.65, bottom margin: 0.75.
- Paper title should be in one column of font size 24.
- Author name in font size of 11 in one column.
- Abstract: font size 9 with the word "Abstract" in bold italics.
- Main text: font size 10 with two justified columns.
- Two columns with equal column width of 3.38 and spacing of 0.2.
- First character must be three lines drop-capped.
- The paragraph before spacing of 1 pt and after of 0 pt.
- Line spacing of 1 pt.
- Large images must be in one column.
- The names of first main headings (Heading 1) must be in Roman font, capital letters, and font size of 10.
- The names of second main headings (Heading 2) must not include numbers and must be in italics with a font size of 10.

Structure and Format of Manuscript

The recommended size of an original research paper is under 15,000 words and review papers under 7,000 words. Research articles should be less than 10,000 words. Research papers are usually longer than review papers. Review papers are reports of significant research (typically less than 7,000 words, including tables, figures, and references)

A research paper must include:

a) A title which should be relevant to the theme of the paper.
b) A summary, known as an abstract (less than 150 words), containing the major results and conclusions.
c) Up to 10 keywords that precisely identify the paper's subject, purpose, and focus.
d) An introduction, giving fundamental background objectives.
e) Resources and techniques with sufficient complete experimental details (wherever possible by reference) to permit repetition, sources of information must be given, and numerical methods must be specified by reference.
f) Results which should be presented concisely by well-designed tables and figures.
g) Suitable statistical data should also be given.
h) All data must have been gathered with attention to numerical detail in the planning stage.

Design has been recognized to be essential to experiments for a considerable time, and the editor has decided that any paper that appears not to have adequate numerical treatments of the data will be returned unrefereed.

i) Discussion should cover implications and consequences and not just recapitulate the results; conclusions should also be summarized.
j) There should be brief acknowledgments.
k) There ought to be references in the conventional format. Global Journals recommends APA format.

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It is necessary that authors take care in submitting a manuscript that is written in simple language and adheres to published guidelines.

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The title page must carry an informative title that reflects the content, a running title (less than 45 characters together with spaces), names of the authors and co-authors, and the place(s) where the work was carried out.

Author details

The full postal address of any related author(s) must be specified.

Abstract

The abstract is the foundation of the research paper. It should be clear and concise and must contain the objective of the paper and inferences drawn. It is advised to not include big mathematical equations or complicated jargon.

Many researchers searching for information online will use search engines such as Google, Yahoo or others. By optimizing your paper for search engines, you will amplify the chance of someone finding it. In turn, this will make it more likely to be viewed and cited in further works. Global Journals has compiled these guidelines to facilitate you to maximize the web-friendliness of the most public part of your paper.

Keywords

A major lynchpin of research work for the writing of research papers is the keyword search, which one will employ to find both library and internet resources. Up to eleven keywords or very brief phrases have to be given to help data retrieval, mining, and indexing.

One must be persistent and creative in using keywords. An effective keyword search requires a strategy: planning of a list of possible keywords and phrases to try.

Choice of the main keywords is the first tool of writing a research paper. Research paper writing is an art. Keyword search should be as strategic as possible.

One should start brainstorming lists of potential keywords before even beginning searching. Think about the most important concepts related to research work. Ask, "What words would a source have to include to be truly valuable in a research paper?" Then consider synonyms for the important words.

It may take the discovery of only one important paper to steer in the right keyword direction because, in most databases, the keywords under which a research paper is abstracted are listed with the paper.

Numerical Methods

Numerical methods used should be transparent and, where appropriate, supported by references.

Abbreviations

Authors must list all the abbreviations used in the paper at the end of the paper or in a separate table before using them.

Formulas and equations

Authors are advised to submit any mathematical equation using either MathJax, KaTeX, or LaTeX, or in a very high-quality image.

Tables, Figures, and Figure Legends

Tables: Tables should be cautiously designed, uncrowned, and include only essential data. Each must have an Arabic number, e.g., Table 4, a self-explanatory caption, and be on a separate sheet. Authors must submit tables in an editable format and not as images. References to these tables (if any) must be mentioned accurately.

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Figures are supposed to be submitted as separate files. Always include a citation in the text for each figure using Arabic numbers, e.g., Fig. 4. Artwork must be submitted online in vector electronic form or by emailing it.

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Although low-quality images are sufficient for review purposes, print publication requires high-quality images to prevent the final product being blurred or fuzzy. Submit (possibly by e-mail) EPS (line art) or TIFF (halftone/ photographs) files only. MS PowerPoint and Word Graphics are unsuitable for printed pictures. Avoid using pixel-oriented software. Scans (TIFF only) should have a resolution of at least 350 dpi (halftone) or 700 to 1100 dpi (line drawings). Please give the data for figures in black and white or submit a Color Work Agreement form. EPS files must be saved with fonts embedded (and with a TIFF preview, if possible).

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TIPS FOR WRITING A GOOD QUALITY ENGINEERING RESEARCH PAPER

Techniques for writing a good quality engineering research paper:

1. Choosing the topic: In most cases, the topic is selected by the interests of the author, but it can also be suggested by the guides. You can have several topics, and then judge which you are most comfortable with. This may be done by asking several questions of yourself, like "Will I be able to carry out a search in this area? Will I find all necessary resources to accomplish the search? Will I be able to find all information in this field area?" If the answer to this type of question is "yes," then you ought to choose that topic. In most cases, you may have to conduct surveys and visit several places. Also, you might have to do a lot of work to find all the rises and falls of the various data on that subject. Sometimes, detailed information plays a vital role, instead of short information. Evaluators are human: The first thing to remember is that evaluators are also human beings. They are not only meant for rejecting a paper. They are here to evaluate your paper. So present your best aspect.

2. Think like evaluators: If you are in confusion or getting demotivated because your paper may not be accepted by the evaluators, then think, and try to evaluate your paper like an evaluator. Try to understand what an evaluator wants in your research paper, and you will automatically have your answer. Make blueprints of paper: The outline is the plan or framework that will help you to arrange your thoughts. It will make your paper logical. But remember that all points of your outline must be related to the topic you have chosen.

3. Ask your guides: If you are having any difficulty with your research, then do not hesitate to share your difficulty with your guide (if you have one). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work, then ask your supervisor to help you with an alternative. He or she might also provide you with a list of essential readings.

4. Use of computer is recommended: As you are doing research in the field of research engineering then this point is quite obvious. Use right software: Always use good quality software packages. If you are not capable of judging good software, then you can lose the quality of your paper unknowingly. There are various programs available to help you which you can get through the internet.

5. Use the internet for help: An excellent start for your paper is using Google. It is a wondrous search engine, where you can have your doubts resolved. You may also read some answers for the frequent question of how to write your research paper or find a model research paper. You can download books from the internet. If you have all the required books, place importance on reading, selecting, and analyzing the specified information. Then sketch out your research paper. Use big pictures: You may use encyclopedias like Wikipedia to get pictures with the best resolution. At Global Journals, you should strictly follow here.

6. Bookmarks are useful: When you read any book or magazine, you generally use bookmarks, right? It is a good habit which helps to not lose your continuity. You should always use bookmarks while searching on the internet also, which will make your search easier.

7. Revise what you wrote: When you write anything, always read it, summarize it, and then finalize it.

8. Make every effort: Make every effort to mention what you are going to write in your paper. That means always have a good start. Try to mention everything in the introduction—what is the need for a particular research paper. Polish your work with good writing skills and always give an evaluator what he wants. Make backups: When you are going to do any important thing like making a research paper, you should always have backup copies of it either on your computer or on paper. This protects you from losing any portion of your important data.

9. Produce good diagrams of your own: Always try to include good charts or diagrams in your paper to improve quality. Using several unnecessary diagrams will degrade the quality of your paper by creating a hodgepodge. So always try to include diagrams which were made by you to improve the readability of your paper. Use of direct quotes: When you do research relevant to literature, history, or current affairs, then use of quotes becomes essential, but if the study is relevant to science, use of quotes is not preferable.

10. Use proper verb tense: Use proper verb tenses in your paper. Use past tense to present those events that have happened. Use present tense to indicate events that are going on. Use future tense to indicate events that will happen in the future. Use of wrong tenses will confuse the evaluator. Avoid sentences that are incomplete.

11. Pick a good study spot: Always try to pick a spot for your research which is quiet. Not every spot is good for studying.

12. Know what you know: Always try to know what you know by making objectives, otherwise you will be confused and unable to achieve your target.

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Verbs have to be in agreement with their subjects. In a research paper, do not start sentences with conjunctions or finish them with prepositions. When writing formally, it is advisable to never split an infinitive because someone will (wrongly) complain. Avoid clichés like a disease. Always shun irritating alliteration. Use language which is simple and straightforward. Put together a neat summary.

14. Arrangement of information: Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. Never start at the last minute: Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. Multitasking in research is not good: Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.

22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.

23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

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Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

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- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

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Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- Single section and succinct.
- An outline of the job done is always written in past tense.
- Concentrate on shortening results—limit background information to a verdict or two.
- Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- Explain the value (significance) of the study.
- Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

o   Report the method and not the particulars of each process that engaged the same methodology.
o   Describe the method entirely.
o   To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
o   Simplify—detail how procedures were completed, not how they were performed on a particular day.
o   If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

o   Resources and methods are not a set of information.
o   Skip all descriptive information and surroundings—save it for the argument.
o   Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

o   Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
o   In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
o   Present a background, such as by describing the question that was addressed by creation of an exacting study.
o   Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
o   Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

o   Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
o   Do not include raw data or intermediate calculations in a research manuscript.
o   Do not present similar data more than once.
o   A manuscript should complement any figures or tables, not duplicate information.
o   Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

o   You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
o   Give details of all of your remarks as much as possible, focusing on mechanisms.
o   Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
o   One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
o   Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

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Topics	Grades		
	A-B	**C-D**	**E-F**
Abstract	Clear and concise with appropriate content, Correct format. 200 words or below	Unclear summary and no specific data, Incorrect form\n\nAbove 200 words	No specific data with ambiguous information\n\nAbove 250 words
Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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