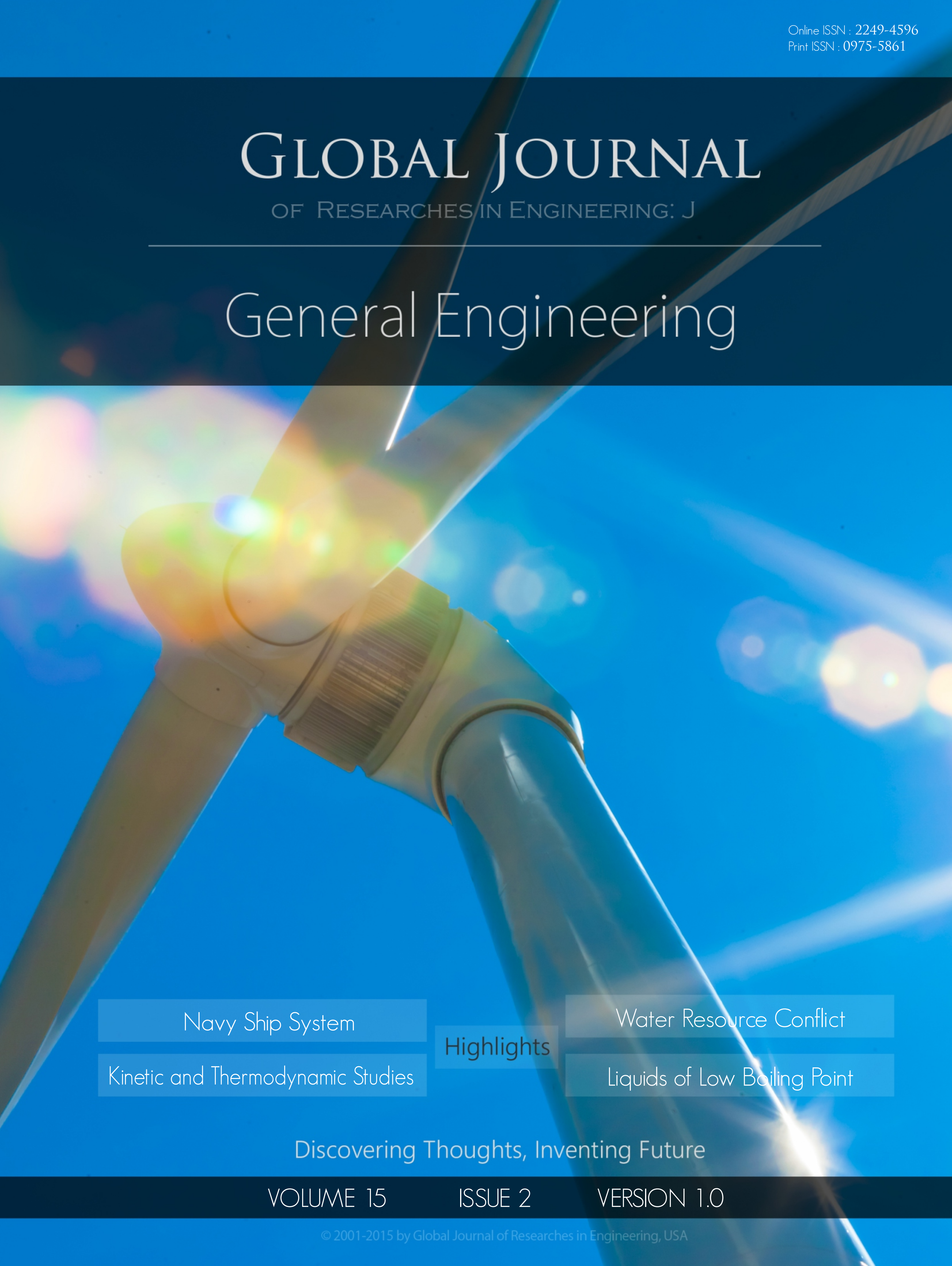

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Design and Fabrication of Vehicle with In-Wheel Motor

By Ren-Chan Lin, Shu-Wei Lin, Guo-Chen Huang & Hsin-Chen Lee

Minghsin University, China

Abstract- This dissertation is about improvement of mobility and off-road capability of state-of-art robot vehicles. The overall structure is based on tracker and wheel-type complex driving design in order to achieve the effects of ground proximity and vibration prevention during movement of robot vehicle, while the integration of tracker cantilever mechanism will enhance the off-road mobility leading to much broader range of applications in terms of task assignments. Common vehicles can only travel on common roads and slow slopes such that the scope of application has been rather limited. In this experiment we will design and develop one set of vehicle assist cantilever mechanism with high adaptability based on structural analysis with respect to the scenario of usage such that the developed vehicle can pass through rocky roads with enhanced mobility and expanded scope of investigation. Since the vehicles for military and police must not be too heavy, we select aluminum alloy as the material for such mechanism in order to achieve light weight and high mobility. This kind of tracked vehicle is bound to greatly broaden the scope of application of land-based mobile platform with market potential and mass production technology. Vehicle robot can be directly applied to various purposes such as military and national defense, handling of explosives, chemical and biological attaches, and assaults of fortified buildings. It also leads to applications in various environments of heavy mechanical and electrical industries such as high temperature, high pressure, gas leak, high radiation, and high voltage factory environments. Therefore, the purpose of this experiment is to development vehicle robots for service of mankind in response to environmental demands.

Keywords: vehicle robot, step-climbing mechanism, auxiliary cantilever, power transmission system.

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Design and Fabrication of Vehicle with In-Wheel Motor

Ren-Chan Lin [α], Shu-Wei Lin [σ], Guo-Chen Huang [ρ] & Hsin-Chen Lee [Ѡ]

Abstract- This dissertation is about improvement of mobility and off-road capability of state-of-art robot vehicles. The overall structure is based on tracker and wheel-type complex driving design in order to achieve the effects of ground proximity and vibration prevention during movement of robot vehicle, while the integration of tracker cantilever mechanism will enhance the off-road mobility leading to much broader range of applications in terms of task assignments. Common vehicles can only travel on common roads and slow slopes such that the scope of application has been rather limited. In this experiment we will design and develop one set of vehicle assist cantilever mechanism with high adaptability based on structural analysis with respect to the scenario of usage such that the developed vehicle can pass through rocky roads with enhanced mobility and expanded scope of investigation. Since the vehicles for military and police must not be too heavy, we select aluminum alloy as the material for such mechanism in order to achieve light weight and high mobility. This kind of tracked vehicle is bound to greatly broaden the scope of application of land-based mobile platform with market potential and mass production technology. Vehicle robot can be directly applied to various purposes such as military and national defense, handling of explosives, chemical and biological attaches, and assaults of fortified buildings. It also leads to applications in various environments of heavy mechanical and electrical industries such as high temperature, high pressure, gas leak, high radiation, and high voltage factory environments. Therefore, the purpose of this experiment is to development vehicle robots for service of mankind in response to environmental demands.

Keywords: vehicle robot, step-climbing mechanism, auxiliary cantilever, power transmission system.

I. INTRODUCTION

In this dissertation we will improve the mobility and off-road performance of currently developed tracked robot vehicle. The overall structure is based on tracker and wheel-type complex driving design in order to achieve the effects of ground proximity and vibration prevention during movement of robot vehicle, while the integration of tracker cantilever mechanism will enhance the off-road mobility leading to much broader range of applications in terms of task assignments. The step-climbing auxiliary mechanism will be designed to improve the off-road performance and combat effectiveness. The major R&D directions include the designs of all kinds of front wheeled claw auxiliary mechanism, step-climbing mechanism, and functional mechanism (CG adjuster). There can also be customized designs with parameters adjustment mechanism in response to environmental variations and basic environmental sensing functions in addition to stability and fast-moving features. There must be enough power for the robot vehicle to take all kinds of actions to travel through tough terrain, pile of rubble, sands and weeds. On the contrary, the in-wheel motor can enhance the flexibility of vehicle while traveling on flat ground.

The application of robot is not limited to single environmental condition such as in urban or rough terrain. It has to effectively adapt to all kinds of severe combat environments and rapidly-changing battle field conditions in order to fulfill all its functions. The auxiliary front wheeled claw will be designed for robot vehicles. The analysis and design of robustness of the entire vehicle system will be generated by data collection and structural analysis/design in order to develop highly adaptive mechanical tank tracker. This kind of tracker is bound to greatly broaden the scope of application of mechanical tank with market potential and mass production technology. Highly adaptive mechanical tank can be immediately applied to various fields such as disaster site rescue, all kinds of robots, military and national defense, handling of explosives, and assault on fortified building.

II. LITERATURE REVIEW

The first thing first for design of tracked robot is to be fully aware of the state of the art. All kinds of design approaches proposed by predecessors will be used as the reference for consideration of the most appropriate design concepts and the application improvements. Based on the collected relevant literatures, the vehicle analysis can be classified by movement method and man structure.

a) Classification by movement method

First of all, there are two types of movement methods, tracked type and wheeled type:

i. Wheeled type

The characteristics of wheel-based movement approach are fast movement speed, good mute effect,

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simple structure, fast tire replacement, low operating cost, fewer parts, and better cruise capability. However, this kind of vehicle has worse off-road performance than tracked type vehicle resulting in reduced mobility or even the loss of mobility. From the perspective of step-climbing, the consideration will be based on how to improve the mechanism design of strategic wheeled type vehicle in order to travel through the obstacles with increased degree of freedom.

ii. *Tracked type*

This tracked type vehicle can be regarded as the miniaturized version of armored tracked vehicle. Most trackers are made of metals such that the noise issue is difficult to overcome. The majority of applications of such kind of vehicle are for highly dangerous area where through wireless remote control, the use of tracker can overcome most rocky terrains while carrying different weapons or camera equipments by demands. The advantages of such kind of vehicle are the strong surveillance capability and secrecy which leads to reduced casualties. However, the disadvantages of such kind of vehicle are inability to cross the trenches, noise generation, and inability to cross the obstacles with height more than twice of the wheel diameter.

b) Classification by main structure

There are three kinds of movement methods based on this classification: main structure tracked type, main structure tracked type with front auxiliary cantilever, and main structure tracked type with both front and rear auxiliary cantilevers.

i. *Main structure tracked type*

This type of vehicle can be regarded as the miniaturized version of armored tracked vehicle mainly used for areas which are either extremely dangerous or cannot be reached by human beings. Through wireless remote control, the use of tracker can overcome most rocky terrains while carrying different weapons or camera equipments by demands. The advantages of such kind of vehicle are portability, secrecy, and high mobility. However, the disadvantages of such kind of vehicle are inability to cross the trenches, noise generation, and inability to cross the obstacles with height more than twice of the wheel diameter.

ii. *Main structure tracked type with front auxiliary cantilever*

This kind of tracked vehicle is the improved version from the main structure tracked type. The additional auxiliary cantilever will enable this tracked vehicle to overcome obstacles with heights over twice of the wheel diameters. The most unique characteristic of this kind of tracked type vehicle is its step-climbing capability. This kind of tracked type vehicle has better effectiveness of surveillance in urban battle fields and misleading the enemies, while it can be used for post-disaster rescues and operations in collapsing buildings.

iii. *Main structure tracked type with both front and rear auxiliary cantilevers*

The auxiliary cantilever mechanism of this type of tracked vehicle is located on the front and rear of the main body such that it can achieve easy step-climbing from both sides, and it can also lift the vehicle to enhance the surveillance range with raised vision. Not only the obstacles can be easily crossed, the body length has also been increased and the vehicle has been effectively extended in order to accomplish the tasks of crossing the trenches and stairs without being too much affected by terrain constraints. However, the manufacturing cost has been increased due to the additional front and rear auxiliary cantilevers, while the degree of difficulty in operation has also been increased with less control of the overall weight.

III. Research Process Flow

As for the research process flow of this dissertation, the preliminary operations include confirmation of research purposes, analysis of existing vehicle structure, determination of vehicle type, and beginning of components and parts settings. After that, the mechanism type will be further designed and planned followed by the power analysis and structural analysis. The detailed description is as shown below:

- Proper definition of research purposes: understanding of research purposes and confirmation of design objectives in order to investigate current and future market demands for vehicles.
- Confirmation of mechanism type: the targeted vehicle will be the wheeled type vehicle with additional front and rear auxiliary cantilevers, while the relevant data will be discussed in order to understand the mechanism type of wheeled vehicles.
- Selection of components and parts: components and parts such as timing belt, brushless motor, all kinds of bearings, screws, and chains will be selected based on results of previous research.
- Mechanism design: the design will be based on the required functions of the robot with confirmed limitations, while the possible issues and technology bottleneck during robot manufacturing will be analyzed. Proper materials must be adopted for the design of main body framework and connecting bars in order to achieve the economic benefits. The optimal structural design and safety coefficients can be analyzed in response to the structural strength requirements of the robot. The determination of crucial dimensions will be based on the 3D graphics constructed by CAD-assisted design and Inventor 3D graphics software before they can be compared with the experimental statistics analysis.

- Mechanism assembly and actual test: the original outsourcing case will be confirmed and the designed machine will be assembled in order to test whether or not there is interference between all modular actions. All modules will then be assembled for overall test.

IV. VEHICLE MECHANISM COMPOSITIONS

We plan to select wheeled type vehicle because of its high mobility and low noise functions in conjunction with front and rear auxiliary cantilever mechanisms such that this kind of mobile vehicle can travel in and out of designated task area without being limited by terrain variation thus leading to greatly enhanced work efficiency. The vehicle will not be limited to the height variation, where the auxiliary cantilever mechanism can be used to shift the center of gravity in order to climb over the short wall or to climb the slopes.

a) Mechanism design

Proper materials must be adopted for the design of main body framework and connecting bars in order to achieve the economic benefits. Proper materials must be adopted for the design of main body framework and connecting bars in order to achieve the economic benefits. The optimal structural design and safety coefficients can be analyzed in response to the structural strength requirements of the robot. The determination of crucial dimensions will be based on the 3D graphics constructed by CAD-assisted design and Inventor 3D graphics software before they can be compared with the experimental statistics analysis. For better efficiency, usually the manufacturing will be designed based on materials such as mid-carbon steel, aluminum alloy, carbon fiber, glass fiber, and plastics in order to complete the vehicle prototype. Due to the budget constraint and the purpose of reducing manufacturing cost, we plan to use CAD assisted design with Inventor 3D graphics software for construction 3D graphics and ANSYS software for analysis and simulation before the development of every new model in order to obtain more objective conclusion earlier and reduce the time spent on trial and error by R&D staff such that we can effectively achieve the optimal design of mechanical structure. Numerous researches in engineering industry have relied on experiences and large amount of experiments for efficiency enhancement and speedy conclusions.

The prototype of design in the place is as shown in the figure below, where tracked type auxiliary cantilever mechanisms have been installed on the front and rear of the vehicle. When this vehicle has been driven on steep slopes, roads with huge height differences, or step-climbing, its features of center of gravity shifting and auxiliary propulsion can immediately enhance the obstacle crossing capability of such robot vehicle. The active wheel of the wheeled type vehicle is located in the main body leading to high mobility and reduced body vibration during movement of robot vehicle. With the integration of suspension system, the main structural stability of the robot vehicle can be more effectively enhanced and more capable of absorbing extra vibration such that the damage to precision instruments carried by such vehicle due to vibration can be prevented as shown in Figure 4.1 and 4.2.

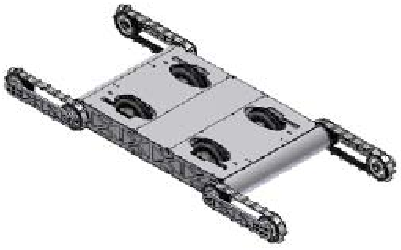

Figure 4.1 : Prototype design of vehicle with in-wheel motor

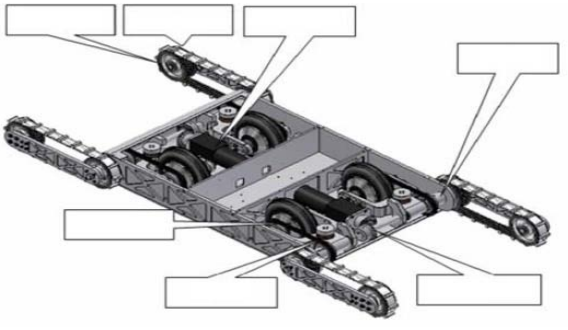

Figure 4.2 : Prototype design of vehicle with in-wheel motor (interior)

V. ANALYSIS OF DESIGN SPECIFICATIONS BASED ON SCENARIO OF USE

The vehicles with front and rear auxiliary cantilevers can do more than crossing the short walls with ease. The integration of cantilever and tracker enables this vehicle to be feasible for all kinds of road conditions (even on muddy road). It can be difficult to enhance the speed of vehicle of flat road due to the slow movement speed of tracker. In order to avoid this issue, the vehicle will be designed to have retractable cantilevers to only allow the wheel to have contact with the ground such that the speedy crossing movement can be achieved. This approach will be less affected by terrain constraints such that this kind of cantilever design is the design focus of this dissertation. In this chapter we use the graphics software “Autodesk Inventor” to simulation various scenarios in accordance with actual 3D dimensions and corresponding to different terrains and obstacles such as “passing under obstacles”, “crossing obstacles”, “crossing trenches”, and “step-climbing”. Scenarios of different terrains will be analyzed, and the breakdown of actions of vehicle with in-wheel motor passing through different environments will be graphically simulated. The default environments are filled with obstacles such as small trenches, tree trunks, and short walls.

a) Flat ground movement mode

During the movement on flat ground, both the front and rear auxiliary cantilevers will be retracted to both sides of the active tracker in order to reduce the friction caused by front and rear auxiliary cantilevers during movement and thus leading to better mobility for turning and straight movement as shown in Figure 5.1.

Figure 5.1 : Flat ground movement mode

b) Obstacle crossing mode

When the unmanned vehicle is crossing the obstacle, the front auxiliary cantilever must be in contact with the edge of obstacle in order to lift the vehicle while the tracker is activated, and the terminals of front and rear cantilevers will be the propulsion for the vehicle. In the end the cantilevers will go around the obstacle and the vehicle body will be descended in order to quickly cross the obstacle as shown in Figure 5.2.

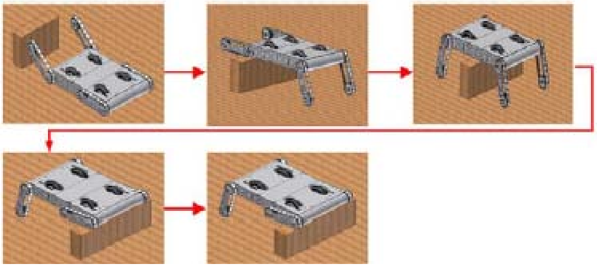

Figure 5.2 : The simulation of obstacle crossing scenario

c) Analysis and simulation of staircase obstacle

Under step-climbing mode, the front and rear auxiliary cantilevers must be kept level with the contact surface of the staircase to ensure the bulging edge of staircase is grabbed by the tracker block such that the vehicle body will not fall off due to large angle of staircase, and the step-climbing movement can be achieved as shown in Figure 5.3. The step-climbing actions of front and rear auxiliary cantilevers of the robot vehicle can be broken down into the following six steps:

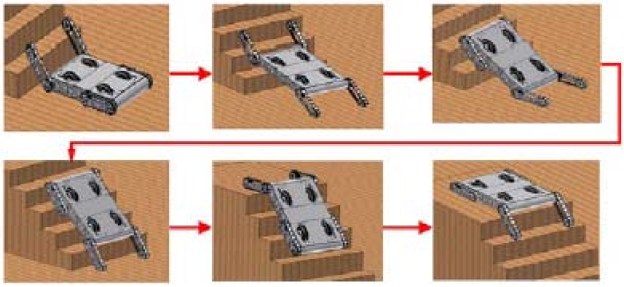

Figure 5.3 : Simulation of staircase obstacle scenario

d) Analysis and simulation of trench obstacle

The front and rear auxiliary cantilevers of the vehicle will be stretched out to be parallel to the active wheels such that the total length of the front and rear wheelbases can be as long as 1100mm. With the weight distribution ratio of the front and rear parts of the vehicle close to 50:50, this will allow the vehicle to effectively cross the trench with total length of 500mm as shown in Figure 5.4. The trench-crossing actions of front and rear auxiliary cantilevers of the robot vehicle can be broken down into the following six steps:

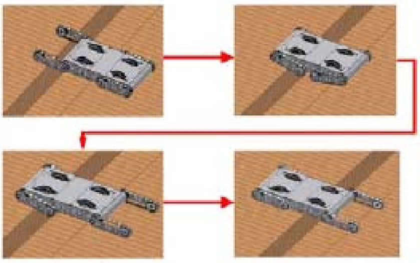

Figure 5.4 : Simulation of the trench obstacle scenario

VI. Vehicle Analysis

In this research we use ANSYS computer-aided analysis software to simulate the static analysis of main vehicle structure. The parameter settings of simplified model have been adopted for this research with the concept of simplification as described as: during the simplification process the parts can be categorized into main structural parts as the force-bearing parts and the general assembly parts (non-structural parts) as the non-force-bearing parts for the purpose of model simplification. Since this is mechanical analysis, the main structural parts will be used for structural gridding and boundary condition setting, while the stress value and displacement are observed for evaluation of material strength and structural damage.

a) Stress analysis of main framework structure

The aluminum alloy 6061-T6 is selected as the material for main framework structure with the maximum load capacity as 100Kg. The boundary conditions are: one side of main framework structure is fixed at the interior hole, while there is 100Kg evenly distributed on the surface of interior hole on the other side of main framework structure; Young's modulus of the aluminum alloy material is 70GPa, Poisson ratio is 0.3m and the density is 2700 kg/m3. Based on the analysis result, when the main framework structure is under downward force as shown in Figure 6.1, the overall deformation is 0.611 mm and the maximum displacement takes place at the edge of outer diameter. The result also indicates that the main structure has withstood 24.75MPa of stress as shown in Figure 6.2 with no structural damage. Stresses from all directions have all been within the yield strength of aluminum alloy 6061-T6 at 270MPa such that all the stresses are within the safety range.

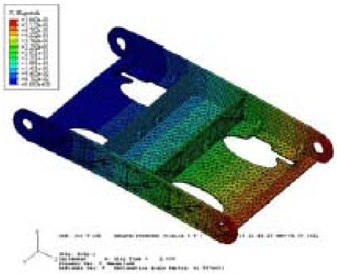

Figure 6.1 : The displacement of main structure vs. the load of 100kg

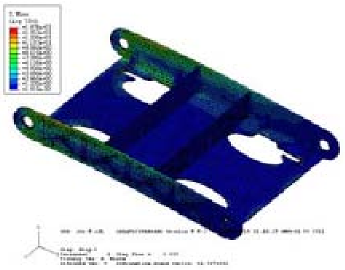

Figure 6.2 : The stress of main structure vs. the load of 100kg

b) Stress analysis of auxiliary cantilever structure

The aluminum alloy 6061-T6 is selected as the material for auxiliary cantilever structure with the maximum load capacity at the front end as 100Kg. The boundary conditions are: the large terminal of auxiliary cantilever structure is fixed at the interior hole, while there is 100Kg evenly distributed on the surface of interior hole on both sides of the front end of auxiliary cantilever; Young's modulus of the aluminum alloy material is 70GPa, Poisson ratio is 0.3m and the density is 2700 kg/m3. Based on the analysis result, when the main framework structure is under downward force as shown in Figure 6.3, the overall deformation is 0.881 mm and the maximum displacement takes place at the edges of both sides of auxiliary cantilevers. The result also indicates that the main structure has withstood 55.59 MPa of stress as shown in Figure 6.4 with no structural damage. Stresses from all directions have all been within the yield strength of aluminum alloy 6061-T6 at 270MPa such that all the stresses on auxiliary cantilever structure are within the safety range.

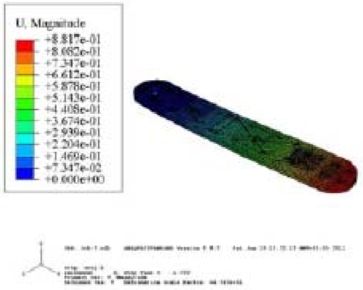

Figure 6.3 : The displacement of auxiliary cantilever structure vs. the load of 100kg

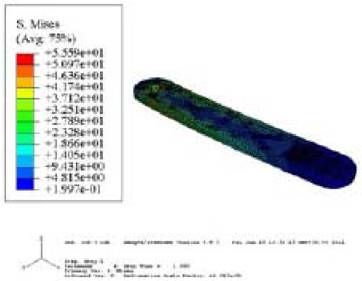

Figure 6.4 : The stress of auxiliary cantilever structure vs. the load of 100kg

c) Stress analysis of in-wheel motor cantilever structure

The aluminum alloy 6061-T6 is selected as the material for in-wheel motor cantilever structure with the maximum load capacity single-side in-wheel motor cantilever structure as 100Kg. The boundary conditions are: the in-wheel motor cantilever structure is fixed at the lower hole, while there is 100Kg evenly distributed on the surface of upper hole of in-wheel motor cantilever structure. Young's modulus of the aluminum alloy material is 70GPa, Poisson ratio is 0.3m and the density is 2700 kg/m3. Based on the analysis result, when the in-wheel motor cantilever structure is under downward force as shown in Figure 6.5, the overall deformation is 0.243 mm and the maximum displacement takes place at the edges of outer diameter. The result also indicates that the main structure has withstood 21.62 MPa of stress as shown in Figure 6.6 with no structural damage. Stresses from all directions have all been within the yield strength of aluminum alloy 6061-T6 at 270MPa such that all the stresses on active gear structure are within the safety range.

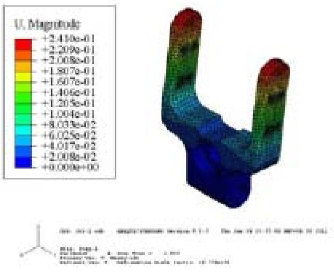

Figure 6.5 : The displacement of anti-vibration cantilever structure vs. the load of 100kg

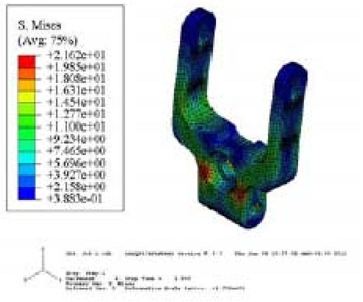

Figure 6.6 : The stress of anti-vibration cantilever structure vs. the load of 100kg

d) Vehicle model analysis

Modal analysis has been conducted with respect to main structure, auxiliary cantilever, and in-wheel motor cantilever structure in order to obtain the first ten natural frequencies and their corresponding modal shapes. The material density, Young's modulus, and Poisson's ratio will be imported first for modal analysis. In this article the boundary conditions are: the main structure is fixed at the shaft holes on both sides, the auxiliary cantilever structure is fixed at the main shaft hole, and the in-wheel motor cantilever structure is fixed at the rotary hole. Any oscillation took place among main structure, auxiliary cantilever structure and in-wheel cantilever structure during operation could lead to unexpected structural damage.

e) Results of vehicle dynamic analysis

The dynamic analysis will be set up right after the modal analysis with respect to main structure, auxiliary cantilever structure, and in-wheel motor cantilever. As for the boundary conditions, we set upward force at 490N, time of continuous load at 0.2 second, and then we observe the amplitude of variation of force application point with respect to time interval (1.5 seconds), where the analysis time for vibration attenuation process in within 1.5 seconds time frame. With the additional smooth parameter set at 0.25, the dynamic analysis can be calculated. Since there could be instant load generated when the vehicle is running on all kinds of terrains, the structural robustness of main structure, auxiliary cantilever and in-wheel motor cantilever structure can be observed by this analysis to see if the requirements of safety coefficients have been met.

From Figure 6.7 and 6.8 we find that the maximum instantaneous stress at the location of main structure element 43054 with 1.5 second interval is around 48MPa. Under this circumstance, since the yield strength of aluminum alloy material (6061-T6) is around 270MPa, the safety coefficient is set to be twice of this value such that in the 1.5 second interval the maximum stress is less than the yield strength of aluminum alloy material. Thus we conclude that the main structure should be safe. By observing Figure 6.9 and 6.10, the maximum instantaneous stress within 1.5 second interval at the location of auxiliary cantilever structure element 4965 is around 80MPa, such that the maximum stress is less than yield strength and meeting the safety coefficient. By observing Figure 6.11 and 6.12, the maximum instantaneous stress within 1.5 second interval at the location of in-wheel motor cantilever structure element 31262 is around 30MPa, such that the maximum stress is less than yield strength and meeting the safety coefficient. Therefore we conclude that there should be not safety concern for the main structure.

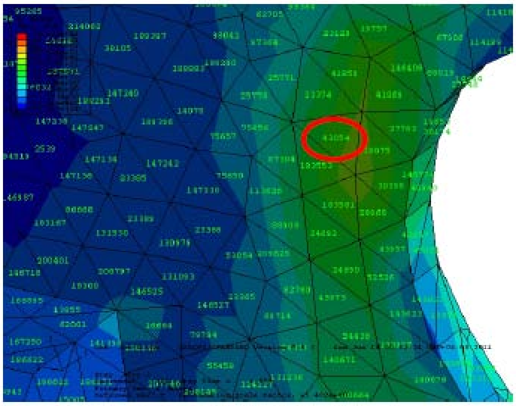

Figure 6.7 : The stress distribution at the location of main structure element 43054

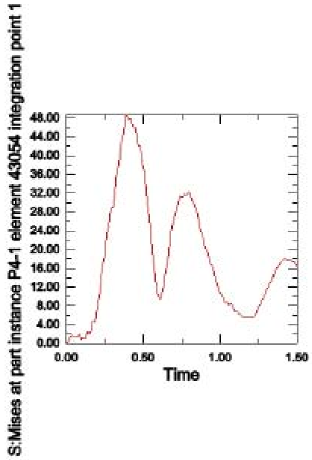

Figure 6.8 : The stress variation curve within 1.5 second interval at the location of main structure element 43054

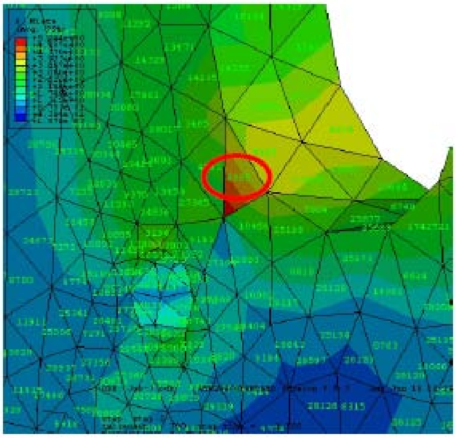

Figure 6.9 : The stress distribution at the location of auxiliary cantilever structure element 4965

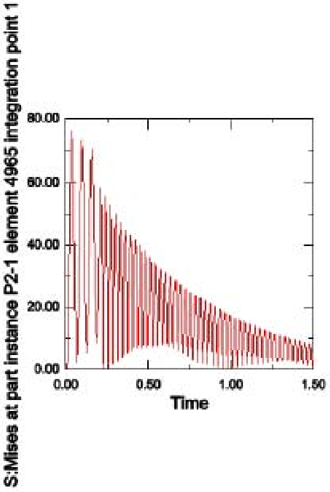

Figure 6.10 : The stress variation curve within 1.5 second interval at the location of auxiliary cantilever structure element 4965

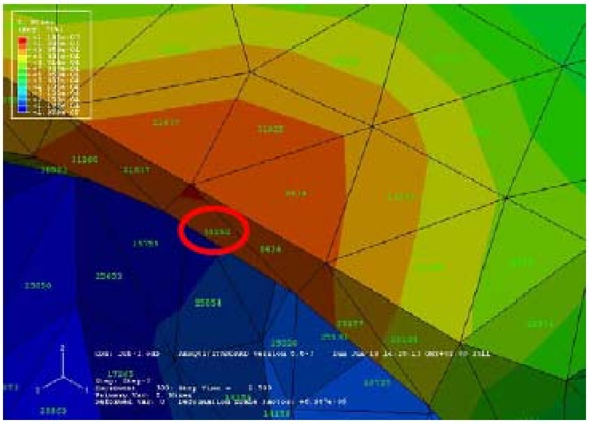

Figure 6.11 : The stress distribution at the location of in-wheel cantilever structure element 31262

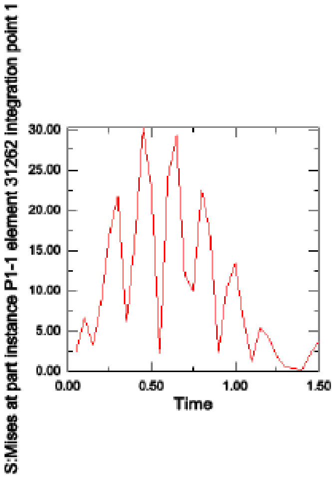

Figure 6.12 : The stress variation curve within 1.5 second interval at the location of in-wheel cantilever structure element 31262

VII. CONCLUSIONS

This research is in coordination with the technology development program of Chung-Shan Institute of Science and Technology-"Researches on design practice and power of robot vehicle". Therefore, we first conduct finite element analysis and simulation with respect to auxiliary cantilever structure, main structure, anti-vibration cantilever, transmission gear, and wheel shaft structure, and we investigate the effects of different loads on the structure. Autodesk Inventor software is used to establish the geometric model of vehicle. In the end, the stress strain statistics is calculated by finite element software simulation, and the conclusions of experimental analysis are described below:

- In this dissertation we successfully develop the vehicle with in-wheel motor which has been proven by all kinds of obstacle experiments to achieve specific targets such as moving speed at 4m/sec, climbing of 45-degree staircase, and crossing 50-cm trench. This is the evidence that our country has owned 100% of self-development R&D technology of this self-made multi-function vehicle.
- This vehicle is based on remote control such that the scope of application can be greatly enhanced to all kinds of terrains such as staircase. This vehicle has superior mobility such that it can still be driven even if it has been rolled over. It can carry various equipments such as weapon, camera, and mechanical arms with enhanced scope of application, market potentials, and mass production feasibility. The wireless vehicle can be directly applied to various purposes such as military and national defense, handling of explosives, biological and chemical attacks, assault on fortified buildings,

factories of heavy mechanical and electrical industries, and high temperature/high pressure/gas leak/high radiation/high voltage environments which are not suitable for human operation.

- The developments of robot vehicles in US, Japan, and Germany have been leading the world, but they are also more expensive. In addition to the R&D cost, the intelligent disaster handling robot developed by our country also requires high costs of talent cultivations and regular robot maintenance and services. However, the vehicle developed in this research is based on 100% customized design and 100% self-developed technology with cost of around $10000 USD. All components are products based on domestic specifications with easy access.

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Kinetic and Thermodynamic Studies of Removal of Cadmium Ion onto Synthetic Pure Zeolite from Rice Husk Ash, Thailand

By Chawikarn Santasnachok, Winarto Kurniawana & Hirofumi Hinodea

Tokyo Institute of Technology, Japan

Abstract- The rice husk ash (RHA) waste from biomass power plant in Thailand is still underutilized leaving disposal problems. Indeed, this material content high silica inside it has a possibility to become a potential zeolites precursor. In this study, small particle of RHA has been reused to prepare a Na-A and Na-X zeolites with high purity using two step method hydrothermal treatments. First, RHA was submitted to a chemical pre-treatment using NaOH powder and then adjusting the Si/Al molar ratio by adding sodium aluminate solutions, and maintaining the mixture at different temperature and heating time. Pure zeolites used to remove cadmium from aqueous solution concentration ranging from 30 to 500 mg/L and at the temperature of 20, 30 and 40oC using batch technique. The effect of time, initial concentration, pH and temperature on removal process was investigated. The results showed that kinetic data were followed more closely the pseudo-second order model than the pseudo-first order by both zeolites. The adsorption isotherms were described by Langmuir and Freundlich isotherm models, and both model fitted well with both zeolites. The thermodynamic parameters such as, Gibbs free energy changes (ΔGo), standard enthalpy change (ΔHo) and standard entropy change (ΔSo) had been determined. The results show that cadmium ion removed onto Na-A and Na-X zeolites are an endothermic and spontaneous in nature.

Keywords: cadmium; removal; synthesized zeolite; rice husk ash.

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Abstract- The rice husk ash (RHA) waste from biomass power plant in Thailand is still underutilized leaving disposal problems. Indeed, this material content high silica inside it has a possibility to become a potential zeolites precursor. In this study, small particle of RHA has been reused to prepare a Na-A and Na-X zeolites with high purity using two step method hydrothermal treatments. First, RHA was submitted to a chemical pre-treatment using NaOH powder and then adjusting the Si/Al molar ratio by adding sodium aluminate solutions, and maintaining the mixture at different temperature and heating time. Pure zeolites used to remove cadmium from aqueous solution concentration ranging from 30 to 500 mg/L and at the temperature of 20, 30 and 40oC using batch technique. The effect of time, initial concentration, pH and temperature on removal process was investigated. The results showed that kinetic data were followed more closely the pseudo-second order model than the pseudo-first order by both zeolites. The adsorption isotherms were described by Langmuir and Freundlich isotherm models, and both model fitted well with both zeolites. The thermodynamic parameters such as, Gibbs free energy changes (ΔGo), standard enthalpy change (ΔHo) and standard entropy change (ΔSo) had been determined. The results show that cadmium ion removed onto Na-A and Na-X zeolites are an endothermic and spontaneous in nature.

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I. Introduction

Rice husk is well-known as an agriculture byproduct of the rice milling industry. It is the most important agriculture residues in quantity in Thailand. The rice husk can be used as a fuel in the plant's steam boiler to generate hot steam in the power plant [1]. If the remaining ashes from burned husks are not collected and treated properly, they could become air pollutants that affect the environment due to the small particle size and light weight. The utilization of these ashes as raw materials in cement industries or insulator in steel industries has been practiced. The study of rice husk ash showed high content of silica and alumina similar to raw materials typically used in zeolite synthesis [2]. These raw materials can be coal fly ash [3, 4], oil shale ash [5], bagasse fly ash [6], or rice husk ash [7, 8, 9]. Therefore, rice husk ash is a potential raw material for zeolite synthesis. Zeolites are crystalline microporous aluminosilicates with very well-defined structures that consist of a framework formed by tetrahedra of SiO_4 and AlO_4. The isomorphous substitution of Al^{3+} for Si^{4+} in the tetrahedra results in a negative charge on the zeolite framework that can be balanced by exchangeable cations. Hence, zeolites can exchange cations but not anions. It has been demonstrated that the cationic surfactants have a great affinity to this negative charge. Zeolites have high cation exchange ability as well as molecular sieve properties. It shows special importance in water and gas purification, catalysts for hydrogenation, alkylation, isomerization and sorbents for the removal of contaminants such as heavy metals, toxic gases, dyes and organic pollutants [10]. The most common method used for zeolites synthesized were involves a hydrothermal process. There are two main methods for zeolite synthesis using solid wastes as the silica-alumina source. The methods are widely recognized as single step and two step method. The single step method aims to utilize whole part of the silica containing solid waste for zeolite production without any separation. Usually this method employs hydrothermal treatment in a single pot for all preparation sequences, i.e. dissolution of silica and alumina from the bulk solid in alkali solution and then re-crystallization of the two components into zeolites covering the un-dissolved solid. By employing this method there will be no leftover residue, however particles irregularities and crystal variety in the zeolite end products become the major drawbacks of this method. On the other hand, the two step method requires solid residue separation after most of silica and alumina content have been dissolved in the alkali solution. The residue removal increases the possibility in producing desired type of zeolite with high purity and particle regularity (shapes and sizes) but leaving a new solid waste along with very low production yield. Meanwhile, for eliminating any waste generation, a combination between the two methods has been proposed to produce high purity zeolite from the supernatant and also low grade zeolite from the mixture of the solid residue and the spent reaction time [6].

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Heavy metal in industrial wastewater represents an important source of environmental pollution [11]. Heavy metals like cadmium is an element that occurs naturally in the earth's crust and is found to be associated with zinc minerals [10, 12-14]. Mae-Sot District in Tak Province of Thailand is contaminated with high cadmium levels. O. Krissanakriangkrai, et al., 2009 have found the high concentration of cadmium in water, sediment, fish and shellfish [15]. The major sources come from industrial process which is released to the environment then become a water pollutant such as electroplating, cadmium-nickel battery, phosphate fertilizers, mining, pigments, stabilizers and alloys manufacturing [10, 16]. Cadmium is one of the most toxic metal ions as it is a non-essential and non-biodegradable metal ion. It is harmful for human and animal since it can be accumulated in the blood causing a variety of symptoms such as high blood pressure, kidney damage, and destruction of red blood cells [11]. The permissible limit for cadmium as described by the World Health Organization (WHO) is 0.01 mg/L [17]. There are varieties of water treatment for contaminated cadmium such as filtration, reverse osmosis, flocculation, activated carbon, ion-exchange, chemical precipitation or coagulation, ultrafiltration and electrochemical. However the aforementioned techniques are not economically feasible for small or medium industries and rural area or developing countries. Recently, the adsorption processes using agricultural waste products or biosorption are becoming the new alternative for waste water treatment and suitable for small or medium industries and rural area or developing countries as well. The aim of this work is to investigate the effect of reaction condition in hydrothermal treatment of supernatant (silica extraction solution) such as alkali condition for silica extraction method, treatment temperature, treatment time and amount of sodium aluminate added for zeolite preparation method. Zeolite used to study the effectiveness of cadmium ion adsorption process by determining the maximum adsorption capacity of cadmium by batch experiment. Kinetic data can be used to predict the rate at which the target contamination is removed from aqueous solutions and equilibrium adsorption isotherms are used to quantify the adsorptive capacity of a cadmium ion. Thermodynamic studies for the removal of cadmium have been undertaken to understand the process of removal in a better way.

II. EXPERIMENTAL

a) *Materials*

Rice husk ash (RHA) was corrected directly from electrostatic precipitators of Roi-Et Green power plant, Thailand after combustion at 650°C. This ash was used without any pretreatment and it properties was characterized by various techniques. Rice husk ash has content of SiO_2 above 90 wt% and other oxides below 3wt%. Quartz and cristobalite were found as the main phases. All the chemicals used in the present studies were obtained from Wako Pure Chemical Industries, Ltd., Japan.

b) *Methods*

i. *Silica extraction from rice husk ash*

Rice husk ash was sieved to remove dirt and dried in oven at 100°C overnight. The particle fraction was separated from the bulk rice husk ash by mechanical sieving using standard sieve of 25 meshes (particle size less than 0.71 mm.). The first preparation step was the extraction of silicon and aluminum content form RHA particles. 10 gram of ash was mixed with sodium hydroxide powder (Waco; 97 wt% NaOH) with different at weight ratio of RHA:NaOH (1:1) and heated temperature of 300°C for 1 h. The mixture was then cooled to room temperature. The obtained powder was mixed with deionized water with weight ratio of powder to water of 1:5 followed by aging for 2 h with agitation at room temperature. Then solid in the mixture were filtered to obtain a clear supernatant by using Whatman™ filter paper 540 hardened ashless. The concentrations of silicon, aluminum and sodium in the supernatant were measured with Inductively Couple Plasma-Atomic Emission Spectroscopy (ICP-AES) method using SPS 7800(SII).

ii. *Zeolites synthesis from rice husk ash*

Zeolites synthesis was done by hydrothermal treatment. The synthesis mixture was prepared from the high silica supernatant and sodium aluminate ($NaAlO_2$) solution from dissolution of sodium aluminate powder (Waco; 0.77M ratio of Al/NaOH) into deionized water with Si/Al molar ratio of 1.0 and 2.0 then, the mixtures were stirred for 1 hour, after that mixed thoroughly and treated at 90°C for 15 and 20 h in Teflon™ – lined stainless steel vessels of 15 mL capacity without agitation to synthesized Na-A and Na-X zeolites, respectively. The final procedures were centrifuging, washing and drying of the precipitates.

c) *Characterization of rice husk ash and synthesized zeolites*

The chemical composition of rice husk ash was analyzed by using Inductively Couple Plasma-Atomic Emission Spectroscopy (ICP-AES) method using SPS7800 (SII), N_2 adsorptions of synthesized materials were carried out using Autosorb1 (Quantachrome) and the specific surface areas were calculated using BET method. X-ray diffraction (XRD) analyses using Multiflex (Rigaku) with Cu-Kα radiation were carried out to determine the crystalline type of zeolites produced. Scanning electron microscope (SEM) using Keyence VE-8800 was conducted to observe the surface morphology and FT-IR analysis of zeolites uses performed using Perkin Elmer Spectrophotometer. The cation exchange capacity (CEC) of zeolites synthesized was measured using sodium acetate method to exchange all the cations in the material with sodium using sodium acetate and then extract all of them using ammonium acetate. The extracted sodium ions will then be analyzed using ICP-AES.

d) Preparation of synthetic waste water

Cadmium Nitrate Tetrahydrate: $Cd(NO_3)_2.4H_2O$ was used to prepare a stock solution of 1000 mg/L of Cd(II). The solution was dilute from this stock solution in the following step.

e) Cadmium removal studies

The experiments were conducted in a set of 250 mL volumetric flasks with cover cap to prevent contamination, where solutions of cadmium was carried out to 200 mL with different initial concentrations of 30 – 500 mg/L were added in these flasks. The effect of contact time at 0 – 3 h, pH at 3 – 11, zeolites dosage at 0.3 – 3.0 g/L, and temperature at 293, 303 and 313 K was investigated by placing the flask on a temperature shaker at 100 rpm. After predetermined time intervals, the zeolites were separated from solution by syringe filtration 0.22 μm. The progress of removal was assessed by determining concentration of cadmium left by ICP-AES instrument.

The percentage removal and equilibrium concentration on the removal process has been calculated for all the studied parameters using the following equation;

$$\%\ Removal = ((C_i - C_e)/C_i) \times 100\% \qquad (1)$$

$$q_e = ((C_i - C_e)V)/M \qquad (2)$$

Where C_i and C_e are the initial and equilibrium concentrations (mg/L) of cadmium ion in solution, V is the volume (L) and M is the weight (g) of the synthesized zeolites.

III. RESULTS AND DISCUSSION

a) Characterization of raw material and synthesized zeolites

The chemical composition of the rice husk ash from power plant was as follow; SiO_2 was 91.50 wt%, Al_2O_3 was 2.27 wt%, K_2O was 0.48 wt%, MgO was 1.00 wt%, Na_2O was 2.68 wt%, Fe_2O_3 was 0.10 wt% and others was 1.97 wt%. The surface area of rice husk ash was 17.13 m^2/g and the XRD pattern of rice husk ash showed in Figure 1 which confirmed the main composition of SiO_2 with crystalline type of quartz and cristobalite. The broad peak between 2θ of 21 – 32° implied the presence of an amorphous phase of carbon and silica.

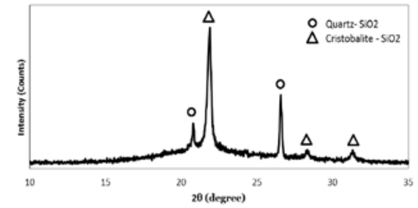


Figure 1 : XRD pattern of rice husk ash from power plant after combustion at 650°C

Fig. 2 shows the XRD patterns of synthesized zeolites to confirms that high purity of zeolite Na-A and pure zeolite Na-X prepared from the reaction mixture with proper Si/Al ratio. Numerous peaks between 2θ of 6 – 34° implied the presence of zeolite –X (PDF card No. 38-0237: $Na_2Al_2Si_{2.5}O_9.6.2H_2O$) was formed at the heating temperature of 90°C for 20 h with the SiO_2/Al_2O_3 molar ratio of 2.0. On the other hand, using lower Si/Al ratio of 1.0, zeolite Na-A (39-0222: $Na_{96}Al_{96}Si_{96}O_{384}.216H_2O$) was formed. Quartz and cristobalite disappeared completely due to the mixing step, because these compounds can easily be dissolved for zeolite formation in the later stage of hydrothermal synthesis.

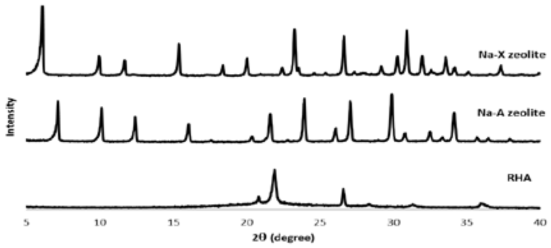
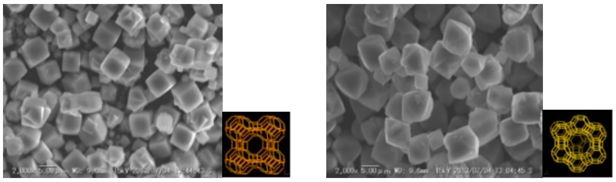


Figure 2 : XRD pattern for comparison between raw rice husk ash and zeolitic materials

The purity was also confirmed by SEM images of the two main zeolite types. It can be seen that typical octahedral particle shape of faujasitic zeolite Na-X and cubic shape of zeolite Na-A are clearly showed in Figure 3a and 3b, respectively. The surface area and CEC of the synthesis Na-A zeolite was 11 m^2/g and 958 meq/100g, respectively. The surface area and CEC of the synthesis Na-X zeolite was 1044 m^2/g and 925 meq/100g, respectively.



(a) (b)

Figure 3 : Unit cell structure and crystal morphology of (a) zeolite A and (b) zeolite X

The IR spectra of synthesized zeolites were taken in the range of 400 – 1400 cm-1 the formation of structural unit during zeolite crystallization is shown in Figure 4.

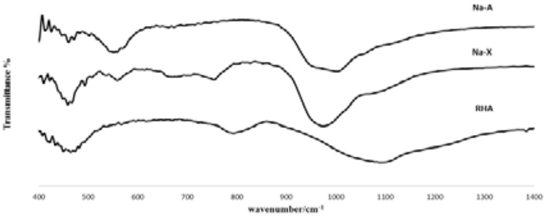


Figure 4 : FTIR spectra of rice husk ash (RHA), Na-A and Na-X zeolites

All of the band assignments of rice husk ash, zeolite A and X follow the work pioneered by Flaningen et al. [18]. The formation of rice husk ash after combustion at 650°C from biomass power plant was showing the presence of absorptions at 459, 792 and 1090 cm^{-1}. The band at 459 and 792 cm^{-1} are due to the S4R T-O-T (where T = Si or Al) symmetric stretching, while the absorption at 1090 cm^{-1} is due to siloxane bonds; Si-O-Si. The spectrum of zeolite A exhibited absorptions at 459, 554 and 1001 cm^{-1}. The 1001 cm^{-1} band was due to the Si-O-Si siloxane bond. The band at 554 cm^{-1} was attributed to the D6R T-O-T symmetric stretching. On the other hand, the spectrum of zeolite X exhibited absorptions at 456, 554, 670, 753 and 974 cm^{-1}. The 974 cm^{-1} band was due to the Si- O-Si siloxane bond. The 753 cm^{-1} band was due to the S4R T-O-T symmetric stretching while the absorption at 670 cm^{-1} was attributed to the Si-O-Al symmetric stretching. The 554 cm^{-1} and 456 cm^{-1} bands were due to the D6R T-O-T symmetric stretching and S4R T-O-T symmetric stretching, respectively.

b) *Effect of contact time and initial concentration on Cadmium removal*

Figure 5 depicts the effect of time on the removal of cadmium ion at various initial concentrations from 50 – 200 mg/L with 0.5 g/L dosage of zeolites at pH 7 solutions. The concentration of cadmium was measured at regular interval of time from 5 to 180 min. Both zeolite A and X were investigated. In the first time added zeolite onto solution, cadmium ion seems to be removed onto both zeolites above 80%. The percentage removal was decreased with increasing cadmium concentration solution. After 60 minutes cadmium ion was equilibrium by both zeolites.

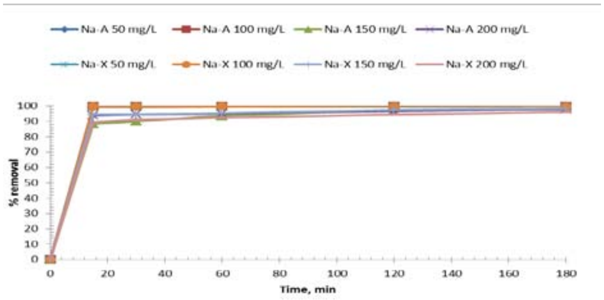


Figure 5 : Effect of time on the removal of cadmium ion solution for different initial concentrations

c) *Effect of solution pH on cadmium removal*

To study the effect of pH on cadmium removal by using both zeolite A and X, experiments were carried out at fixed zeolite concentration at 0.05 g of zeolite in 100 mL solution by maintaining 150 mg/L cadmium ion concentration using different initial solution pH values, changing from 3 - 13. Figure 6 shows that the cadmium removal was maximum when the initial pH of cadmium solution was in the range of 7 – 9 and cadmium was slightly removed at pH 3 for both zeolites.

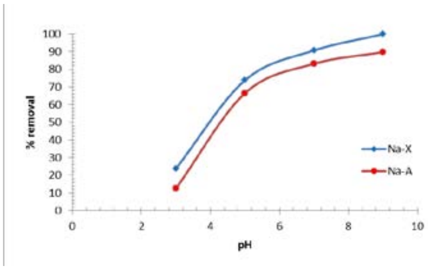


Figure 6 : Effect of solution pH on the removal of cadmium onto zeolite A and X

According to Reed and Matsumoto, 1993 [19] reported that the cadmium ion in aqueous solution can form various species or hydro complexes. The principal species of cadmium ion are formed as the following reactions;

$$Cd^{2+} + H_2O \Leftrightarrow Cd(OH)^{+} + H^{+} \qquad pK_1 = 9.0$$

$$Cd^{2+} + 2H_2O \Leftrightarrow Cd(OH)_2 + 2H^{+} \qquad pK_2 = 19.1$$

$$Cd^{2+} + 3H_2O \Leftrightarrow Cd(OH)_3^{-} + 3H^{+} \qquad pK_3 = 30.3$$

$$Cd^{2+} + 2H_2O \Leftrightarrow Cd(OH)_2(s) + 2H^{+} \qquad pK_s = 30.3$$

Figure 7 shows a speciation diagram at pH below 7, the cadmium ion predominates and at pH values just below 9, cadmium begins to precipitate out as $Cd(OH)^{-2}$. At pH 8 the species distribution is approximately 90% Cd^{2+} and 10% $Cd(OH)^{+}$. This means that the species occurring at pH values of 8 and below carry a positive charge either as Cd^{2+} or $Cd(OH)^{+}$. The point of zero charge (PZC) for the zeolite A and X used was determined at 5.5 and 5.8, respectively. This indicates that at pH lower 5.5 and 5.8, the zeolites are positively charged and the cadmium is present as Cd^{+}.

Under these conditions adsorption must be occurring not due to electrostatic attraction but to a chemical interaction with enough energy to overcome the repulsive forces between the positively charged zeolites surface and the cadmium ion, $Cd^{2+.}$ At pH greater than 5.5 and 5.8 and less than 9, the zeolite surface becomes negatively charged and the cadmium is present mainly as Cd^{2+}. In this case adsorption occurs by electrostatic attraction [20].

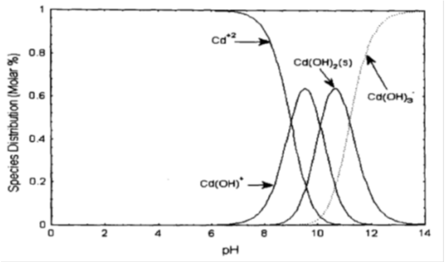
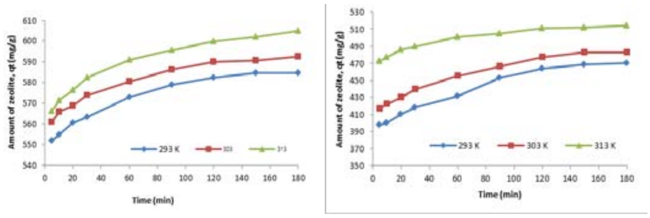


Figure 8 : Speciation diagram for cadmium complexes present in aqueous solutions

d) *Effect of temperature on reaction rate*

To study the effect of temperature on cadmium removal, temperature is an important parameter was carried out at fixed zeolite dosage at 0.03 g of zeolite 100 mL solution by using 200 mg/L cadmium concentration solution at 293K, 303K, and 313K and pH of the solution was maintained at 7. The removal process was carried out for 3 hours until equilibrium. The effect of temperature shows in Figure 8. The data showed that the amount of Cd2+ removed at equilibrium increase with increase in temperature indicating an exothermic nature of the process. Zeolite A could remove cadmium ion from aqueous solution better than zeolite X since zeolite A presented higher CEC than zeolite X due to the lower Si/Al molar ratio from 1.0 to 2.0.



(a) (b)

Figure 9 : Effect of contact time on the amount of removal of cadmium ion from aqueous solutions onto zeolite A (a) and zeolite X (b)

The rate constant of metal ion removal from the solution by zeolite A and X were determined using pseudo-first-order and pseudo-second-order rate models, respectively. The pseudo-first-order equation or Langergren's equation describes removal process in solid-liquid systems based on the removal capacity of solids [21]. It is assumed that one cadmium ion removed onto the zeolite surface:

$$B + Cd_{aq}^{2+} \xrightarrow{k_1} BCd_{solid\ \ phase} \tag{3}$$

where B represents an unoccupied sorption site on the synthesized zeolite and k1 is the pseudo first order rate constant (h-1).

The linear form of pseudo-first-order model can be expressed as:

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \tag{4}$$

where q_e and q_t (mg/g) are the removal capacities at equilibrium and at time *t* (min), respectively.

k_1 and q_e, at the temperatures evaluated experimentally, were calculated using the slope and intercept of plots of $log(q_e - q_t)$ versus *t* as shows in Figure 9 and Table 1. The results show that the experiments fit well with this model at each temperature yielded relatively high R^2 values.

The pseudo-second-order rate expression, which has been applied form analyzing chemisorption kinetics from liquid solutions [22], is linearly expressed as:

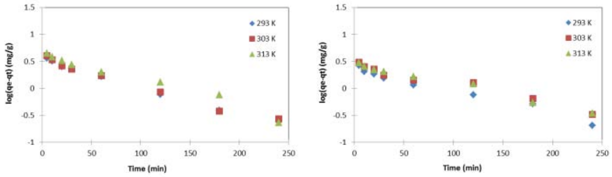
$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \tag{5}$$

where k_2 is the rate constant for pseudo second-order model, (g/mg.min) and $k_2q_e^{\ 2}$ or h (mg/g.min) is the initial adsorption rate.

This model assumes that one cadmium ion is sorbed onto two sorption sites on the zeolites surface:

$$2B + Cd_{sol}^{2+} \xrightarrow{k_2} B_2Cd_{solid\ \ phase} \tag{6}$$

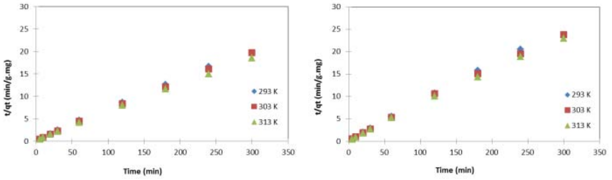
Figure 10 and Table 1 show the pseudo second-order removal parameters q_e and k_2 in Eq. (6) were determined by plotting t/q_t versus *t*. The results shown that both zeolite A and X with various temperatures are fitted with this model according to the correlation coefficients (R^2) values are 0.99 and 1.0, respectively



(a) (b)

Figure 10 : Pseudo first-order kinetic model fit for Cd^{2+} removal onto synthesized zeolite A (a) and zeolite X (b) at various temperatures

It can be observed that this model is higher than the correlation coefficients derived from pseudo first-order models fits. Given a good agreement between model fit and experimentally observed equilibrium adsorption capacity in addition to the large correlation coefficients, this suggested that cadmium ion removal were removed onto synthesized zeolite A and X surface via chemical interaction. Similar trends have been reported for the adsorption of Cd^{2+} ions aqueous solutions by other adsorbents such as orange waste, activated sludge and so on [23 – 24].



(a) (b)

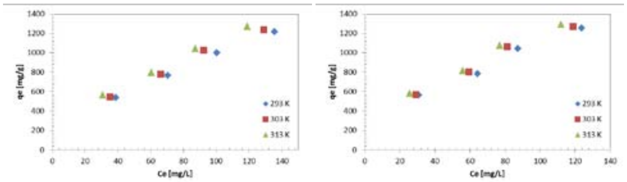
Figure 11 : Pseudo second-order kinetic model fit for Cd^{2+} removal onto synthesized zeolite A (a) and zeolite X (b) at various temperatures

Table 1 : Removal kinetic model rate constants for Cd^{2+} solution on synthesized zeolites at different temperatures

	Zeolite A					
	Pseudo first-order			Pseudo second-order		
Temp (K)	k_1 (min^{-1})	q_e ($mg \cdot g^{-1}$)	R^2	k_2 ($g \cdot mg^{-1} \cdot min^{-1}$)	q_e ($mg \cdot g^{-1}$)	R^2
293	2.178E-03	1.70	0.95	0.016	14.599	0.99
303	2.158E-03	1.73	0.94	0.013	15.314	0.99
313	2.114E-03	1.87	0.97	0.010	16.313	0.99
	Zeolite X					
	Pseudo first-order			Pseudo second-order		
Temp (K)	k_1 (min^{-1})	q_e ($mg \cdot g^{-1}$)	R^2	k_2 ($g \cdot mg^{-1} \cdot min^{-1}$)	q_e ($mg \cdot g^{-1}$)	R^2
293	1.796E-03	1.44	0.97	0.025	11.710	0.99
303	1.652E-03	1.54	0.96	0.015	12.579	0.99
313	1.571E-03	1.58	0.98	0.014	13.072	0.99

e) *Adsorption isotherms*

The maximum adsorption capacity of synthesized zeolite A and X for cadmium was investigated over a range of cadmium concentrations at three different temperatures are shown in Figure 11, the plot of the adsorption capacity, q_e (mg/g) versus the equilibrium concentration. The initial pressing sorption gives way to a slow approach to equilibrium at higher ion concentrations.



(a) (b)

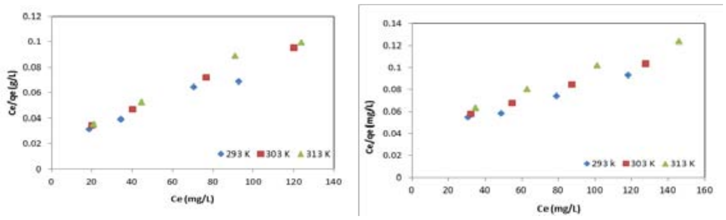
Figure 11 : Effect of temperature on the sorption isotherm of cadmium ion onto synthesized (a) zeolite Na-A and (b) zeolite Na-X

The removal of cadmium ion from aqueous solution in a wide range of concentrations was reflected the efficiency of both synthetic zeolite Na-A and Na-X. The uptake of ion increased with the increase in temperature thereby indicating the process to be exothermic.

The sorption studies were carried out at 293K, 303K and 313K to determine the sorption isotherms. The Langmuir isotherm is based on the assumption that there are uniform energies of adsorption onto the surface and no transmigration of adsorbate in the plane of the surface [25]. The linear form of Langmiur adsorption is given by;

$$\frac{C_e}{q_e} = \frac{1}{Q^o b} + \frac{1}{Q^o} C_e \qquad (7)$$

where q_e is the amount of solute sorbed per unit weight of adsorbent (mg/g), C_e is the equilibrium concentration of the cadmium in solution (mg/L), Q^o is the monolayer adsorption capacity, and b is the constant related to the free energy of adsorption. Figure 12 shows a linear relationship of C_e/q_e versus C_e using experimental data obtained. Values of Q^o and b calculated from the plot shown in Table 2. The applicability of the model suggests monolayer coverage of the adsorbate at the outer surface of the adsorbent is significant by both synthetic zeolite A and X according to the correlation coefficient (R^2).



(a) (b)

Figure 12 : Langmuir adsorption isotherm of cadmium ion onto synthetic (a) zeolite A and (b) zeolite X

Table 2 : Langmuir isotherm parameters of cadmium ion sorbed onto synthetic zeolite A and X

Temperature (K)	Q^o (mg/g)		b (L/mg)		R^2	
	Zeolite Na-A	Zeolite Na-X	Zeolite Na-A	Zeolite Na-X	Zeolite Na-A	Zeolite Na-X
293	2232.1	2525.3	0.0098	0.0066	0.92	0.96
303	2227.2	2463.1	0.0109	0.0076	0.94	0.96
313	2141.3	2331.0	0.0129	0.0095	0.93	0.95

The Freundlich isotherm is an empirical equation based on adsorption on a heterogeneous surface suggesting that binding sites are not equivalent and/or independent. The Freundlich isotherm is given as [26];

$$\ln Q_e = \ln K_f + \frac{1}{n} \ln C_e \qquad (8)$$

where Q_e is an amount adsorbed (mg/g), C_e is the equilibrium concentration of the adsorbate (mg/L), K_f (mg/g) and n are Freundlich constants related to adsorption capacity and adsorption intensity, respectively. Figure 13 shows that the sorption of cadmium ion fit with this model by both synthetic zeolite A and X. The corresponding Freundlich parameters along with correlation coefficient are given in Table 3.

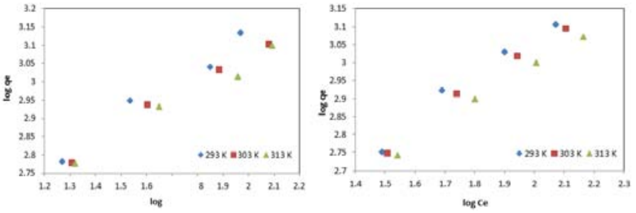


Figure 13 : Freundlich isotherm plots for the sorption of cadmium ion from aqueous solution onto synthetic (a) zeolite Na-A and (b) zeolite Na-X

Table 3 : Freundlich isotherm parameters of cadmium ion sorbed onto synthetic zeolite Na-A and Na-X

Temperature (K)	K_F (mg/g)		n		R^2	
	Zeolite Na-A	Zeolite Na-X	Zeolite Na-A	Zeolite Na-X	Zeolite Na-A	Zeolite Na-X
293	73.91	48.58	1.71	1.53	0.98	0.99
303	78.63	55.65	1.72	1.57	0.99	0.99
313	94.28	70.10	1.81	1.66	0.98	0.99

The Freundlich constant K_F is the relative sorption capacity or sorption power [27]. Value of n > 1 represents a favorable adsorption condition and results found that the adsorption of cadmium ion onto both synthetic zeolite A and X was favorable.

f) *Thermodynamic parameters of removal*

The feasibility of the adsorption process was evaluated by the thermodynamic parameters including free energy change (ΔG^o), enthalpy (ΔH^o), and entropy (ΔS^o). ΔG^o was calculated from the following equation:

$$\Delta G^o = -RT \ln K_d \qquad (9)$$

where R is the universal gas constant (8.314 Jmol-1K-1), T is the temperature (K), and Kd is the distribution coefficient. The Kd value was calculated using following equation:

$$K_d = \frac{q_e}{C_e} \qquad (10)$$

where q_e and C_e are the equilibrium concentration of cadmium ion on adsorbent (mgL^{-1}) and in the solution (mgL^{-1}), respectively. The enthalpy change (ΔH^o), and entropy change (ΔS^o) of adsorption were estimated from the following equation:

$$\Delta G^o = \Delta H^o - T\Delta S^o \qquad (11)$$

This equation can be written as:

$$\ln K_d = \frac{\Delta S^o}{R} - \frac{\Delta H^o}{RT} \qquad (12)$$

The thermodynamic parameters of ΔH° and ΔS° were obtained from the slope and intercept of the plot between ln K_d versus 1/T, respectively as shown in Figure 14. The values of ΔG°, ΔH°, andΔS° for the removal of cadmium ion onto synthetic zeolite Na-A and Na-X at different temperatures are given in Table 4.

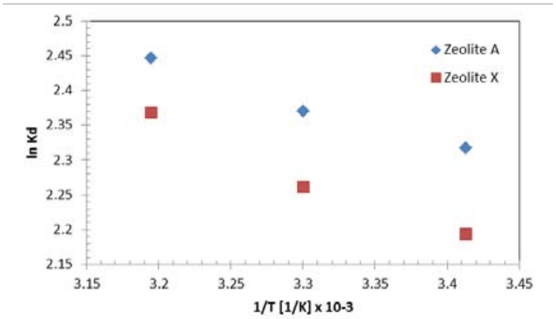


Figure 14 : The plot between In Kd versus 1/T for obtaining thermodynamic parameters by both synthetic zeolite A and X (pH: 7.0, initial cadmium conc.: 500 mgL-1, zeolite dosage: 0.3 gL-1

Both zeolites show that the standard free energy change (*ΔG°*) of the process decreases with increase in temperature, which indicates that the process is spontaneous and spontaneity increases with increase in temperature. The positive values of *ΔH°* suggest endothermic nature of adsorption and cadmium ions are adsorbed more efficiently on cork powder at higher temperatures. The positive values of standard entropy change (*ΔS°*) shows the increase in randomness at the solid/solution interface during the adsorption of cadmium ion solution.

Table 4 : Thermodynamic parameters of the cadmium ion removal onto synthetic zeolite A and X at different temperatures

Temperature (K)	ΔG° (kJ mol^{-1})		ΔS°(J mol^{-1} K^{-1})		ΔH° (J mol^{-1})	
	Zeolite Na-A	Zeolite Na-X	Zeolite Na-A	Zeolite Na-X	Zeolite Na-A	Zeolite Na-X
293	-0.153	-0.173	36.12	40.92	4.95	6.66
303	-0.158	-0.179				
313	-0.163	-0.185				

IV. CONCLUSION

Synthesis of Na-A and Na-X zeolite was achieved using rice husk ash carbonized at 650°C from power plant, rice husk ash as the silica source by employing alkali fusion and the extraction with residue removal followed by hydrothermal treatment at 90°C and Si/Al molar ratio at 1.0 after heating time 15 h and 2.0 after heating time 20 h, respectively. The pure zeolite Na-X and Na-A were presented high CEC values as 9.25 and 9.58 meq/g, respectively. The morphology of SEM image for Na-A zeolite is cubic shape. On the other hand, Na-X zeolite is octahedron shape. The result showed that Na-A zeolite was more effective in removing metal ion (Cd^{2+}) than Na-X zeolite. The cadmium removal was achieved at pH 7 – 9. The kinetic was studied the removal of cadmium ion onto both zeolites result showed that the pseudo-second order model fitted with experiment more than pseudo-first order model. The increasing of temperature, the amount of Cd^{2+} removed at equilibrium increased. The adsorption isotherms were described by Langmuir and Freundlich isotherm models, and both model fitted well with both zeolites. The experimental equilibrium data indicating that disclosing of heterogeneous and homogeneous distribution in the active sites on the surface of Na-A and Na-X zeolites. The removal capacity on cadmium ion onto Na-A and Na-X zeolites increased with increasing temperature. The negativeΔG° values indicated that the removal of cadmium ion onto both zeolites was feasible and spontaneous. The positive value ofΔH° confirmed the endothermic nature of process. The positive ΔS° suggested the increased randomness at the solid/liquid interface during the removal of cadmium ion onto zeolites. The experimental results indicated that the rice husk ash from biomass power plant can be successfully used for zeolite synthesized and removal of heavy metal such as cadmium ion from aqueous solutions.

V. ACKNOWLEDGMENT

The authors wish to gratefully acknowledge the budget and equipment supports from the Department of International Development Engineering, Tokyo Institute of Technology, Japan and the financial support from AUN/SEED-Net program. Roi-Et Green power plant, Thailand is also acknowledged for providing rice husk ash for this research.

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Profit-Function of Two Similar Warm Standby Navy Ship System Subject to Failure Due to Struck with Iceberg and Collision with Oil Tanker

By Dr. Ashok Kumar Saini
BLJS College, India

Abstract- Notable Disasters- The sinking of RMS Titanic in 1912, with 1,517 fatalities, is probably the most famous shipwreck, but not the biggest in terms of life lost. The wartime sinking of the Wilhelm Gustloff in January 1945 in World War II by a Soviet Navy submarine, with an estimated loss of about 9,400 people, remains the greatest maritime disaster ever. In peacetime, the 1987 loss of the ferry Doña Paz, with an estimated 4,386 dead, is the largest non-military loss recorded. In this paper we have taken failure due to struck with iceberg and collision with oil tanker. When the main unit fails then warm standby system becomes operative. Failure due to collision with oil tanker cannot occur simultaneously in both the units and after failure the unit undergoes Type-I or Type-II or Type-III repair facility immediately. Applying the regenerative point technique with renewal process theory the various reliability parameters MTSF, Availability, Busy period, Benefit-Function analysis have been evaluated.

Keywords: *warm standby, failure due to struck with iceberg, failure due to collision with oil tanker, first come first serve, MTSF, availability, busy period, benefit -function.*

GJRE-J Classification : *FOR Code: 291899*

Profit-Function of Two Similar Warm Standby Navy Ship System Subject to Failure Due to Struck with Iceberg and Collision with Oil Tanker

Dr. Ashok Kumar Saini

Abstract- Notable Disasters - The sinking of RMS Titanic in 1912, with 1,517 fatalities, is probably the most famous shipwreck, but not the biggest in terms of life lost. The wartime sinking of the Wilhelm Gustloff in January 1945 in World War II by a Soviet Navy submarine, with an estimated loss of about 9,400 people, remains the greatest maritime disaster ever. In peacetime, the 1987 loss of the ferry Doña Paz, with an estimated 4,386 dead, is the largest non-military loss recorded. In this paper we have taken failure due to struck with iceberg and collision with oil tanker. When the main unit fails then warm standby system becomes operative. Failure due to collision with oil tanker cannot occur simultaneously in both the units and after failure the unit undergoes Type-I or Type-II or Type-III repair facility immediately. Applying the regenerative point technique with renewal process theory the various reliability parameters MTSF, Availability, Busy period, *Benefit*-Function analysis have been evaluated.

Keywords: warm standby, failure due to struck with iceberg, failure due to collision with oil tanker, first come first serve, MTSF, availability, busy period, benefit - function.

I. Introduction

Many maritime disasters happen outside the realms of war. All ships, including those of the military, are vulnerable to problems from weather conditions, faulty design or collision with oil tanker. Some of the disasters occurred in periods of conflict, although their losses were unrelated to any military action.

Year	Country	Description	Lives lost
1912	United Kingdom	RMS *Titanic* – A passenger ocean liner and, at the time, the world's largest ship. On 14 April 1912, on her maiden voyage, she struck an iceberg, buckling part of her hull and causing her to sink in the early hours of 15 April. 706 of her 2,223 passengers and crew survived. Her loss was the catalyst for major reforms in shipping safety and is arguably the most famous maritime disaster, being the subject of countless media portrayals.'	1,517
1987	Philippines	*Doña Paz* – On 20 December 1987, the ferry bound for Manila with more than its capacity of unlisted passengers collided with the oil tanker *MT Vector* in the Tablas Strait, near Marinduque. The resulting fire and sinking left an estimated 4,386 dead which included all but 24 of *Doña Paz*'s passengers, and all but two of *Vector*'s 13-man crew.	4,386

In this paper we have taken failure due to struck with iceberg and collision with oil tanker. When the main operative unit fails then warm standby system becomes operative. Failure due to collision with oil tanker cannot occur simultaneously in both the units. After failure the unit undergoes repair facility of Type-I or Type- II by ordinary repairman and Type-III or Type IV by multispecialty repairman immediately when failure due to struck with iceberg and failure due collision with oil tanker. The repair is done on the basis of first fail first repaired.

II. Assumptions

- λ_1, λ_2 λ_3 are constant failure rates when failure due to struck with iceberg failure due to collision with oil tanker respectively. The CDF of repair time distribution of Type I, Type II and multispecialty repairmen Type-III, IV are $G_1(t)$, $G_2(t)$ and $G_3(t)$ $G_4(t)$.

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- The failure due to collision with oil tanker is non-instantaneous and it cannot come simultaneously in both the units.
- The repair starts immediately after failure due to struck with iceberg and failure due to collision with oil tanker and works on the principle of first fail first repaired basis. The repair facility does no damage to the units and after repair units are as good as new.
- The switches are perfect and instantaneous.
- All random variables are mutually independent.
- When both the units fail, we give priority to operative unit for repair.
- Repairs are perfect and failure of a unit is detected immediately and perfectly.
- The system is down when both the units are non-operative.

III. SYMBOLS FOR STATES OF THE SYSTEM

a) Superscripts O, CS, SIF, COTF,

Operative, Warm Standby, failure due to struck with iceberg failure due to collision with oil tanker respectively.

Subscripts nsif, sif, cotf, ur, wr, uR

No failure due to struck with iceberg, failure due to struck with iceberg, failure due to collision with oil tanker, under repair, waiting for repair, under repair continued from previous state respectively

Up states – 0, 1, 2, 3, 10 ; Down states – 4, 5, 6, 7,8,9,11, regeneration point – 0,1,2, 3, 8, 9,10

b) States of the System

$0(O_{nsif}, CS_{nsif})$ One unit is operative and the other unit is warm standby and there is no failure due to struck with iceberg of both the units.

$1(SIF_{sif,\ urI}, O_{nsif})$ The operating unit failure due to struck with iceberg is under repair immediately of Type- I and standby unit starts operating with no failure due to struck with iceberg

$2(COTF_{cotf,\ urII}, O_{nsif})$ The operative unit failure due to collision with oil tanker and undergoes repair of Type II and the standby unit becomes operative with no failure due to struck with iceberg

$3(COTF_{cotf,\ urIII}, O_{nsif})$ The first unit failure due to collision with oil tanker and under Type-III multispecialty repairman and the other unit is operative with no failure due to struck with iceberg

$4(SIF_{sif,uR1}, SIF_{sif,wrI})$ The unit failed due to SIF resulting from failure due to struck with iceberg under repair of Type- I continued from state 1and the other unit failed due to SIF resulting from failure due to struck with iceberg is waiting for repair of Type-I.

$5(SIF_{sif,uR1}, COTF_{cotf,\ wrII})$ The unit failed due to SIF resulting from failure due to struck with iceberg is under repair of Type- I continued from state 1and the other unit fails due to collision with oil tanker is waiting for repair of Type- II.

$6(COTF_{cotf,\ uRII}, SIF_{sif\ ,wrI})$ The operative unit failed due to collision with oil tanker is under repair continues from state 2 of Type –II and the other unit failed due to SIF resulting from failure due to struck with iceberg is waiting under repair of Type-I.

$7(COTF_{cotf\ ,uRII}, SIF_{sif,wrII})$ The one unit failed due to collision with oil tanker is continued to be under repair of Type II and the other unit failed due to SIF resulting from failure due to struck with iceberg is waiting for repair of Type-II.

$8(SIF_{sif,urIII}, COTF_{cotf,\ wrII})$ The one unit failure due to struck with iceberg is under multispecialty repair of Type-III and the other unit failed due to collision with oil tanker is waiting for repair of Type-II.

$9(SIF_{sif,urIII}, COTF_{cotf,\ wrI})$ The one unit failure due to struck with iceberg is under multispecialty repair of Type-III and the other unit failed due to collision with oil tanker is waiting for repair of Type-I

$10(O_{nsif}\ COTF_{cotf,\ urIV})$ The one unit is operative with no failure due to struck with iceberg and warm standby unit fails due to collision with oil tanker and undergoes repair of type IV.

$11(O_{nsif}\ COTF_{cotf,\ uRIV})$ The one unit is operative with no failure due to struck with iceberg and warm standby unit fails due to collision with oil tanker and repair of type IV continues from state 10.

IV. TRANSITION PROBABILITIES

Simple probabilistic considerations yield the following expressions:

$$p_{01} = \lambda_1 / \lambda_1 + \lambda_2 + \lambda_3, \quad p_{02} = \lambda_2 / \lambda_1 + \lambda_2 + \lambda_3, \; p_{0,10} = \lambda_3 / \lambda_1 + \lambda_2 + \lambda_3$$

$$p_{10} = pG_1^*(\lambda_1) + q\,G_2^*(\lambda_2), \; p_{14} = p - pG_1^*(\lambda_1) = p_{11}^{(4)},$$

$$p_{15} = q - q\,G_1^*(\lambda_2) = p_{12}^{(5)}, \; p_{23} = pG_2^*(\lambda_1) + q\,G_2^*(\lambda_2),$$

$$p_{26} = p - pG_2^*(\lambda_1) = p_{29}^{(6)}, \; p_{27} = q - qG_2^*(\lambda_2) = p_{28}^{(7)},$$

$$p_{30} = p_{82} = p_{91} = 1, \; p_{0,10} = pG_4^*(\lambda_1) + q\,G_4^*(\lambda_2),$$

$$p_{10,1} = p - pG_4^*(\lambda_1) = p_{10,1}^{(11)}, p_{10,2} = q - q\,G_4^*(\lambda_2) = p_{10,2}^{(11)} \quad (1)$$

We can easily verify that

$$p_{01} + p_{02} + p_{03} = 1,\ p_{10} + p_{14}\,(=p_{11}^{(4)}) + p_{15}\,(=p_{12}^{(5)}) = 1,$$

$$p_{23} + p_{26}\,(=p_{29}^{(6)}) + p_{27}\,(=p_{28}^{(7)}) = 1\ p_{30} = p_{82} = p_{91} = 1$$

$$p_{10,0} + p_{10,1}^{(11)}\,(=p_{10,1}) + p_{10,2}^{(12)}\,(=p_{10,2}) = 1 \quad (2)$$

And mean sojourn time is $\mu_0 = E(T) = \int_0^\infty P[T > t]dt$

V. MEAN TIME TO SYSTEM FAILURE

$$Ø_0(t) = Q_{01}(t)[s]\,Ø_1(t) + Q_{02}(t)[s]\,Ø_2(t) + Q_{0,10}(t)[s]\,Ø_{10}(t)$$

$$Ø_1(t) = Q_{10}(t)[s]\,Ø_0(t) + Q_{14}(t) + Q_{15}(t)$$

$$Ø_2(t) = Q_{23}(t)[s]\,Ø_3(t) + Q_{26}(t) + Q_{27}(t),\ Ø_3(t) = Q_{30}(t)[s]\,Ø_0(t),$$

$$Ø_{10}(t) = Q_{10,0}(t)[s]\,Ø_{10}(t) + Q_{10,1}(t)[s]Ø_1(t) + Q_{10,2}(t)[s]\,Ø_2(t) \quad (3\text{-}6)$$

We can regard the failed state as absorbing
Taking Laplace-Stiljes transiform of eq. (3-6) and solving for

$$ø_0^*(s) = N_1(s) / D_1(s) \quad (7)$$

where

$$N_1(s) = \{Q_{01}^* + Q_{0,10}^*\,Q_{10,1}^*\}\,[Q_{14}^*(s) + Q_{15}^*(s)] + \{Q_{02}^* + Q_{0,10}^*\,Q_{10,2}^*\}\,[Q_{26}^*(s) + Q_{27}^*(s)]$$

$$D_1(s) = 1 - \{Q_{01}^* + Q_{0,10}^*\,Q_{10,1}^*\}\,Q_{10}^* - \{Q_{02}^* + Q_{0,10}^*\,Q_{10,2}^*\}\,Q_{23}^*\,Q_{30}^* - Q_{0,10}^*\,Q_{10,0}^*$$

Making use of relations (1) & (2) it can be shown that $ø_0^*(0) = 1$, which implies that $ø_0(t)$ is a proper distribution.

$$\text{MTSF} = E[T] = \frac{d}{ds}\,ø_0^*(s)\ \Big|_{s=0}$$

$$= (D_1'(0) - N_1'(0)) / D_1(0)$$

$$= (\mu_0 + \mu_1\,(p_{01} + p_{0,10}\,p_{10,1}) + (p_{02} + p_{0,10}\,p_{10,2})(\mu_2 + \mu_3) + \mu_{10}\,p_{0,10} / (1 - (p_{01} + p_{0,10}\,p_{10,1})\,p_{10} - (p_{02} + p_{0,10}\,p_{10,2})\,p_{23}) - p_{0,10}\,p_{10,0}$$

where

$$\mu_0 = \mu_{01} + \mu_{02} + \mu_{0,10},\ \mu_1 = \mu_{10} + \mu_{11}^{(4)} + \mu_{12}^{(5)},$$

$$\mu_2 = \mu_{23} + \mu_{28}^{(7)} + \mu_{29}^{(6)},\ \mu_{10} = \mu_{10,0} + \mu_{10,1} + \mu_{10,2}$$

VI. AVAILABILITY ANALYSIS

Let $M_i(t)$ be the probability of the system having started from state i is up at time t without making any other regenerative state. By probabilistic arguments, we have

$$M_0(t) = e^{-\lambda_1 t}\,e^{-\lambda_2 t}\,e^{-\lambda_3 t},\ ,\ M_1\overline{(t)} = p\,G_1(t)\ e^{-\lambda_1 t}$$

$$M_2(t) = q\,\overline{G}_2(t)\,e^{-\lambda_2 t},\quad M_3(t) = \overline{G}_3(t),\ M_{10}(t) = \overline{G}_4(t)\,e^{-\lambda_3 t}$$

The point wise availability $A_i(t)$ have the following recursive relations

$$A_0(t) = M_0(t) + q_{01}(t)[c]A_1(t) + q_{02}(t)[c]A_2(t) + q_{0,10}(t)[c]A_{10}(t)$$

$$A_1(t) = M_1(t) + q_{10}(t)[c]A_0(t) + q_{12}^{(5)}(t)[c]A_2(t) + q_{11}^{(4)}(t)[c]A_1(t)\ ,$$

$$A_2(t) = M_2(t) + q_{23}(t)[c]A_3(t) + q_{28}^{(7)}(t)[c]\ A_8(t) + q_{29}^{(6)}(t)]\ [c]A_9(t)$$

$$A_3(t) = M_3(t) + q_{30}(t)[c]A_0(t)\ ,A_8(t) = q_{82}(t)[c]A_2(t)$$

$$A_9(t) = q_{91}(t)[c]A_1(t),$$

$$A_{10}(t) = M_{10}(t) + q_{10,0}(t)[c]A_0(t) + q_{10,1}^{(11)}(t)[c]A_1(t)+q_{10,2}^{(11)}(t)[c]A_2(t) \tag{8-15}$$

Taking Laplace Transiform of eq. (8-15) and solving for $\hat{A}_0(s)$

$$\hat{A}_0(s) = N_2(s) / D_2(s) \tag{16}$$

where

$$N_2(s) =\{ \hat{q}_{0,10} \tilde{M}_{10}+ \tilde{M}_0 \} [\{1 - \hat{q}_{11}^{(4)}\}\{1- \hat{q}_{28}^{(7} \hat{q}_{82} \}- \hat{q}_{12}^{(5)} \hat{q}_{29}^{(6)} \hat{q}_{91}] + \{ \hat{q}_{01}+ \hat{q}_{0,10} \hat{q}_{10,1}^{(11)}\}[\tilde{M}_1\{1 - \hat{q}_{28}^{(7)} \hat{q}_{82}\} +\hat{q}_{12}^{(5)} \hat{q}_{23} \tilde{M}_3+\tilde{M}_2]+\{ \hat{q}_{02} +\hat{q}_{0,10} \hat{q}_{10,2}^{(11)}\} [\{\hat{q}_{23} \tilde{M}_3\}\{1 - \hat{q}_{11}^{(4)}\}+ \hat{q}_{29}^{(6)} \hat{q}_{91} \tilde{M}_1]$$

$$D_2(s) = \{1 - \hat{q}_{11}^{(4)}\}\{1- \hat{q}_{28}^{(7} \hat{q}_{82} \}- \hat{q}_{12}^{(5)} \hat{q}_{29}^{(6)} \hat{q}_{91} -\{ \hat{q}_{01}+ \hat{q}_{0,10} \hat{q}_{10,1}^{(11)} \}[\hat{q}_{10} \{1 - \hat{q}_{28}^{(7)} \hat{q}_{82}\} +\hat{q}_{12}^{(5)} \hat{q}_{23} \hat{q}_{30}] - \{ \hat{q}_{02} +\hat{q}_{0,10} \hat{q}_{10,2}^{(11)}\}\{[\hat{q}_{23} \hat{q}_{30} \{1 - \hat{q}_{11}^{(4)}\}+ \hat{q}_{29}^{(6)} \hat{q}_{91} \hat{q}_{10}]$$

(Omitting the arguments s for brevity)
The steady state availability

$$A_0 = \lim_{t \to \infty}[A_0(t)] = \lim_{s \to 0}[s\,\hat{A}_0(s)] = \lim_{s \to 0} \frac{s\,N_2(s)}{D_2(s)}$$

Using L' Hospitals rule, we get

$$A_0 = \lim_{s \to 0} \frac{N_2(s)+s\ N_2'(s)}{D_2'(s)} = \frac{N_2(0)}{D_2'(0)} \tag{17}$$

The expected up time of the system in (0,t] is

$$\lambda_u(t) = \int_0^\infty A_0(z)dz \qquad \text{So that } \bar{\lambda}_u(s) = \frac{\hat{A}_0(s)}{s} = \frac{N_2(S)}{SD_2(S)} \tag{18}$$

The expected down time of the system in (0,t] is

$$\lambda_d(t) = t- \lambda_u(t) \qquad \text{So that } \bar{\lambda}_d(s) = \frac{1}{s^2} - \bar{\lambda}_u(s) \tag{19}$$

Similarly, we can find out

- The expected busy period of the server when there is failure due to struck with iceberg and collision with oil tanker in (0,t]-R_0.
- The expected number of visits by the repairman Type-I or Type-II for repairing the identical units in (0,t]-H_0.
- The expected number of visits by the multispecialty repairman Type-III or Type-IV for repairing the identical units in (0,t]-W_0, Y_0.

VII. Benefit-Function

The Benefit-Function analysis of the system considering mean up-time, expected busy period of the system under failure due to struck with iceberg and collision with oil tanker, expected number of visits by the repairman for unit failure. The expected total Benefit-Function incurred in (0,t] is

$$C = \lim_{t \to \infty}(C(t)/t) = \lim_{s \to 0}(s^2 C(s)) = K_1A_0 - K_2R_0 - K_3H_0 - K_4W_0$$

where

K_1- revenue per unit up-time, K_2 - cost per unit time for which the system is busy under repairing,
K_3 - cost per visit by the repairman type- I or type- II for units repair,
K_4 - cost per visit by the multispecialty repairman Type- III for units repair

VIII. CONCLUSION

After studying the system, we have analyzed graphically that when the failure rate due to struck with iceberg and due to collision with oil tanker increases, the MTSF, steady state availability decreases and the Profit-function decreased as the failure increases.

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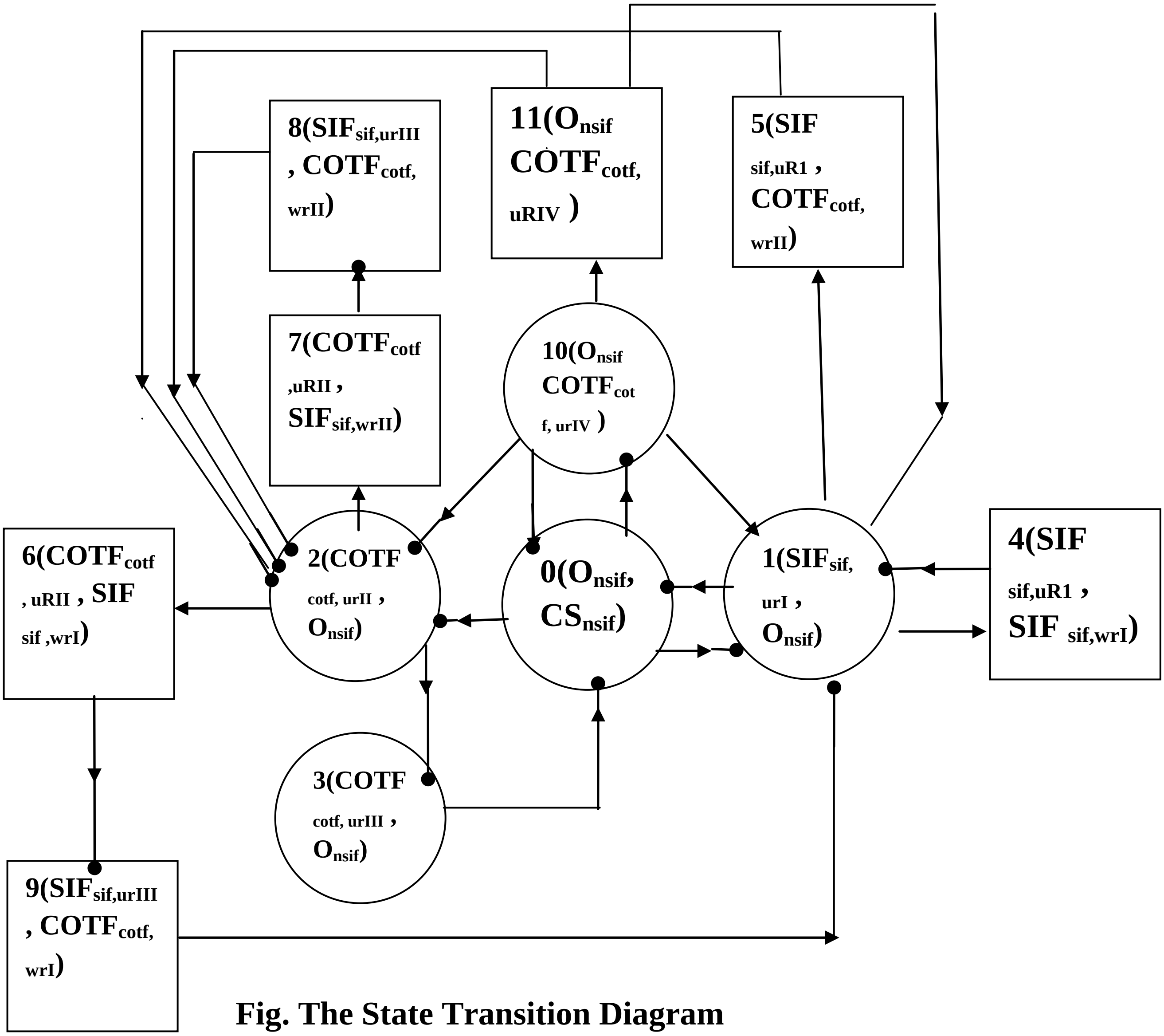

Fig. The State Transition Diagram

Up-State ○ **Down-State** □

● **regeneration point**

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Study of Two-Metal (Cu-Ag) Micro Heat Pipe of Convergent-Divergent Circular Cross Section using different Working Liquids of Low Boiling Point

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Abstract- With the modernization of electronic machines, the size or weight to efficiency ratio is getting small enough to leave the equipment highly thermally stressed. To manage this stress, an experiment on thermal effects of a two-metal (Cu-Ag) micro heat pipe (TMMHP) of convergent-divergent cross section, which provides variable conductivity and pressure gradient, at steady state are investigated to compare with a single metal micro heat pipe (SMMHP). Internal fluid flow is considered as one dimensional which is axially flowing. It is a 150 mm long convergent-divergent hollow circular tube having a hydraulic diameter of 3.74 mm and thickness of 0.3 mm. The evaporator and condenser sections are made of pure copper and silver respectively while the adiabatic section is made of both copper and silver. Water and three low boiling point liquids — ethanol, methanol and iso-propanol — are used as working fluids. In view of the real situation of machines usage, tests are conducted by placing the heat pipe at three different inclinations of 0o, 45o and 90o. To provide heat flux, an electric heater-coil has been wrapped around the evaporator simulating the heat-generation within an actual device, and simultaneously the condenser section is directly cooled by ambient water in an annular space. Ten calibrated K-type thermocouples are installed at different locations — five of them are to measure the temperatures of internal fluid and five are used to measure the surface temperatures of the tube. Temperatures are monitored by digital electronic thermometers. Unlike in the SMMHP, it is found that the super heater effect in the evaporator of TMMHP simplifies the initially developed complex two-phase flow into a single-phase of super heated vapor. Thus, it increases TMMHP's heat transfer capability several times higher than that of a SMMHP.

Keywords: *micro heat pipe, two-metal micro heat pipe, TMMHP, convergent-divergent, hydraulic diameter, steady state, one dimensional flow, different inclination.*

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I. INTRODUCTION

Micro heat pipe (MHP) is a heat transferring device based on the phase change phenomenon of fluid contained in it. Before filling with the fluid, the container must be vacuumed to below the atmospheric pressure. MHP is generally of small diameter, usually not over 3.0 mm. The micro heat pipe receives heat at one end to vaporize the fluid which is evaporator, and then travels through the next section losing no heat called adiabatic section, and terminates at the condenser part from where the carried heat dissipates to the atmosphere. Usually, micro heat pipe is made with good heat conducting metal, i.e. copper, stainless steel, nickel etc. Depending on the operating temperature range, selected working fluids may be water or hydrocarbon compounds or it can be cesium, bismuth, sodium, lithium etc. Fluids of low boiling point (LBP) indicate here the fluids that have boiling points below the water at atmospheric pressure. A wick is inserted within the heat pipe spanning end to end to let the condensate crawl back to the evaporator by capillary action. The wick can be made of stainless steel mesh, sintered metal powder, fiber, wire braid etc. In a micro heat pipe, the presence of sharp or non circular edges, and in other cases, radially etched micro grooved inner walls are also replacing wicks to provide the capillary service. Comparing with solid metal, heat transport ability of a heat pipe of the same geometry is found to be many times higher with the same small temperature difference. MHP's applications are widely endorsed in cooling microelectronics and nuclear reactors such as in space satellites. Globally many researchers have been engaged in improving the MHP concepts for the last several decades. A few of their works are cited.

Study on heat pipe has been in practice since 1942 when R. S. Gaugler of General Motors, USA proposed it [1]. However, heat pipes did not receive a target oriented attention until 1963 when Grover et al. [2] directed the heat pipe's condensate-returning mechanism from its confined gravitation-fed state to the simple capillary-force action of wick structure inserted in it. By the U.S. government funding, between 1964 and 1966, RCA was the first corporation to undertake research and development of heat pipes for commercial applications [3]. Starting in the 1980s Sony began incorporating heat pipes into the cooling schemes for some of its commercial electronics products instead of the more traditional finned heat sink with and without forced convection. But, it was twenty years later in 1984 when T. P. Cotter first introduced the idea of "micro" heat pipes [1]. Sreenivasa et al. [4] determined the

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optimum fill ratio in a miniature heat pipe that indicates the same performance as the evaporator section was half filled rather than filling in full. Akhanda et al. [5] tested an air cooled condenser to investigate the thermal performance of MHPs charged with different fluids and oriented a different inclinations. Sakib [6] at Islamic University of Technology (IUT), Organisation of Islamic Cooperation (OIC) has performed tests on different cross sections of MHP of the same hydraulic diameter charged with water at different inclinations. It was found that the best heat transfer coefficient at the circular cross section was at an angle of 90° vertical. Further observation was made as the thermal resistance of micro heat pipe increases with increasing of flatness ratio and its heat transfer coefficient decreases also with increasing of flatness ratio. Finally, Sakib developed an empirical equation from the experimental data and correlated all his findings which showed ± 7% nearness with the developed equation. Moon [9] used a miniature heat pipe which was squeezed in the Notebook PC to cool elements that may be heated up to 100° C. The output of the experiment using miniature heat pipe with woven wire wicks found it to be a quite viable candidate for a stable cooling unit of Notebook. Babin et al. [10] developed the model that analyzes the heat transport behavior of micro-heat pipe, and presented the model of micro-heat pipe based on the analysis by Chi [11] in a steady-state operation. Longtin et al. [12] presented the improved prediction results, considering partially the shear stress in liquid-vapor interface of groove in a micro heat pipe. Swanson and Peterson [13] analyzed thermo-dynamically the heat transport phenomena in the liquid-vapor interface of heat pipe, and Wu and Peterson [14] studied the thermal performance of micro-heat pipe in an unsteady state. Le Berre et al. [15] studied experimentally the performance of a micro heat pipe array for various filling charges under various experimental conditions. The results showed that the performance of the micro heat pipe array is favored by decreasing the input heat flux or increasing the coolant temperature. Kole and Dey [16] investigated thermal performance using Cu-distilled water nano-fluid, which enhanced thermal conductivity by 15% at 30° C. Chiang et al. [17] developed a magnetic-nanofluid (MNF) heat pipe (MNFHP) with magnetically enhanced thermal properties. The results showed that an optimal thermal conductivity exists in the applied field of 200 Oe.

Throughout this survey, it has been found that only a single metal or bimetal alloy has been used to manufacture heat pipes including varieties of isometric geometry. In these cases, heat transfer occurs only at constant heat conductivity at both ends of MHP for a single metal or an alloy. No individual or company has attempted doing as investigation on a variable heat conductivity micro heat pipe. Thus, a two-metal micro heat pipe (TMMHP) made with two different metals (i.e. Cu and Ag) of close heat conductivity (i.e. 398 W/m-K for copper and 429 W/m-K for silver) for generating *variable heat conductivity* has been selected by the author Iqbal [8] in his doctoral thesis. Moreover, because of its geometry (convergent-divergent), the pressure gradient of the working fluid will also be variable in the respected TMMHP sub-sections. A series of heat inputs ranging from 2W to 16 W have been supplied to the evaporator keeping the MHP at 0° to study the heat transfer behavior of pure water along with ethanol, methanol and iso-propanol. Then it was reexamined at 45° and 90° positions (evaporator uphill) while the condenser was being cooled by ambient water at a constant flow-rate of 400 ml/min. At the end, the fluid temperatures within the TMMHP as well as the surface temperature at designated locations at steady state have been recorded to compare with other researchers' experimental data. To confirm the reproducibility of the data, the experiments were repeated and found to be the same.

II. EXPERIMENTAL SETUP

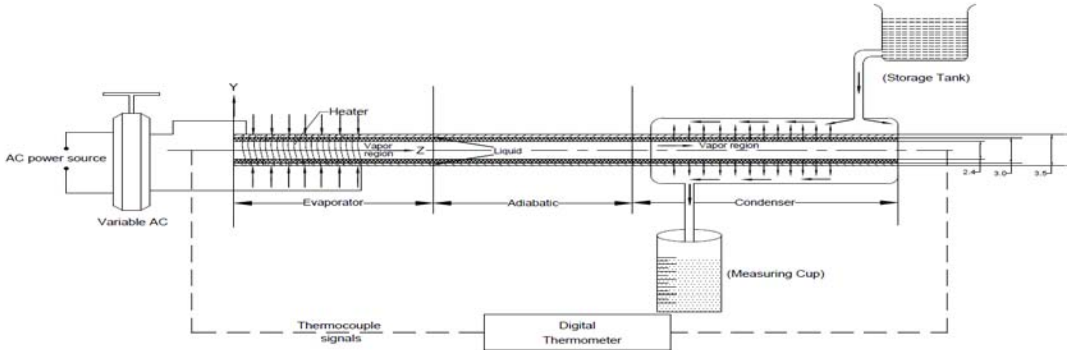


Figure 1 : Schematic diagram of the experimental setup at 0° inclination

The experimental set up is essentially consisting of a TMMHP, a storage tank, a measuring cup, a power source and a digital thermometer. The schematic diagram of the experimental set up is shown in Figure 1. Table 1 provides the physical dimensions of the TMMHP. The TMMHP used in this experiment is a 150 mm long with a convergent-divergent cross section of 4.5 mm diameter on divergent side and 3.0 mm on convergent made with 0.3 mm thick metal tube which is made half with pure copper and the other half with pure silver. The copper-end is the evaporator section while the silver-end is the condenser. The lengths of the evaporator and adiabatic sections are of equal length of 45 mm each and the rest 60 mm is the condenser section. Thus, the evaporator and condenser are fully covered with copper and silver respectively while the adiabatic section is with both metals. The evaporator side is then welded to seal. For wick, a steel mesh of 0.3 mm thickness with the equal length of TMMHP has been wrapped around a mandrel and inserted into the tube so that the wick radially press fit the inner wall of the tube. Five 1.1 mm holes are drilled according to the Figure 2. Five copper constantan (K-type) thermocouples have been inserted to reach the vapor core and brazed with silver to know the internal working fluid's state. Then another five thermocouples have been attached right beside the holes by quick fixing adhesive to measure the surface temperatures at those locations.

Table 1 : Physical Dimensions of TMMHP (Convergent-Divergent)

Specifications	Dimensions	Materials
Heat pipe total length	150 mm	Copper & Silver
Evaporator section length	45 mm	Copper
Adiabatic section length	45 mm	Copper & Silver
Condenser section length	60 mm	Silver
Divergent side diameter	4.5 mm	
Convergent side diameter	3.0 mm	
Heat pipe profile height	3.8 mm	
Heat pipe wall thickness	0.3mm	
Mesh number of wick	7 holes per cm	
Wick thickness	0.3 mm	
Working liquids	Ethanol, Methanol, Iso-propanol and Water	
No. of surrounding heater in the evaporator section	1 [SGW36]	
Insulating material	(45 + 45) mm	Asbestos rope

The condenser-end of the heat pipe is then plugged into one end of a capillary tube while the other end is attached with a vacuum pump. When pressure within the heat pipe goes well below the atmospheric pressure, then is locked for a couple of minutes to reconfirm its air freeness. Then a pinch-clip is used to choke the capillary tube near the junction, and a slim syringe (Dispovan, 1 ml) filled with 0.60 ml of distilled water, which is 85% (Fill Ratio) of the empty space of the evaporator, is injected into the capillary tube. Actually, the water is sucked into the capillary tube spontaneously because of having lower than atmospheric pressure within the tube. After filling, the condenser-end of the TMMHP is now pinched and sealed by brazing.

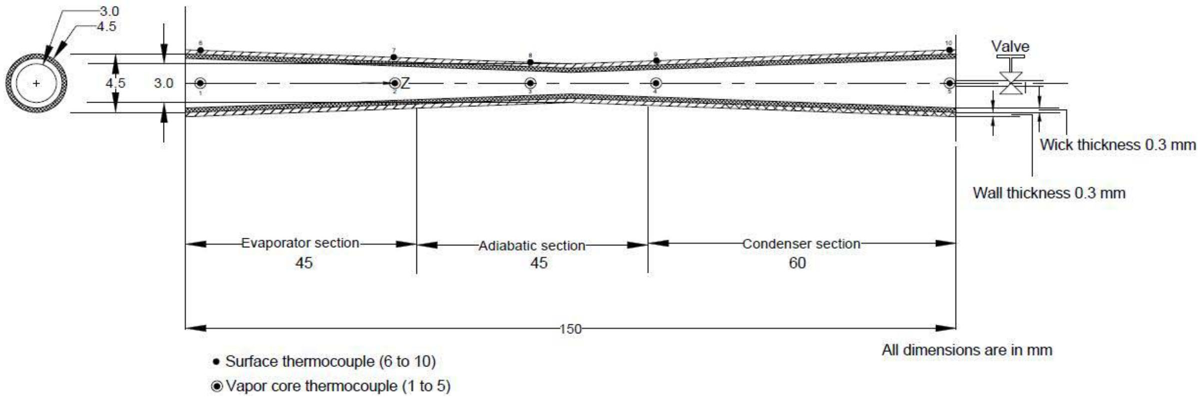


Figure 2 : Positions of thermocouples along the TMMHP

At the evaporator, a fire and electric shock proof tape has been laid around and then SGW36 electric heater wire has been coiled out at a closer pace possible without clinging to each other. To avoid the dispersion of heat produced by the heater in view to keep the heat input value significantly unaltered, the coil was insulated by the asbestos rope by many folds and was extended up to the end of adiabatic section. Finally, another strip of insulating tape was wrapped around to avoid getting soaked by the splash of water. Now the condenser-end of the TMMHP is wrapped up with cotton and inserted into a plastic container which has two outlets. Then the outlets are connected with flexible water tube—upper one is fitted with the valve of the coolant (water) reservoir and the lower one is dipped into an empty bucket to collect the used coolant.

The whole setup is then mounted on a rig which is placed on a wooden table. All the thermocouples have been calibrated and found with ±0.1 degree Celsius variations. Then the thermocouples have been connected with a digital thermometer through a selector switch. The coolant reservoir is filled with the supplied water which is placed above the level of TMMHP. To produce the variable heat input for the heat pipe, a Variac has been introduced, which is then monitored by one ammeter and one precision voltmeter to record the current and voltage simultaneously.

III. TEST PROCEDURES

At first the coolant flow is opened to run through the condenser end to ensure the condenser jacket is soaked and fully immersed in water. Then the Variac is connected with the AC power source to produce controlled heat by the heater. The power range is chosen from 2W to 16W producing heat flux ranging 1.9 kW/m^2 to 15.1 kW/m^2 simulating the generated heat in a laptop computer processor and similar electronic equipment [6]. It can be noted, before wrapping the heater coil, its red-hot power limit is checked and found to be 24W. Thus, the upper limit of 16W is quite safe for the experimental purposes. Initially, the TMMHP is inclined at 0° (horizontally), and the time and temperature at the evaporator are recorded until the system reaches steady state. The experiment is continued by keeping the setup at 45° and 90° (vertically) with evaporator uphill position. To attain steady state, a minimum coolant flow rate of 400 ml/min or 70 ml/s has been found to be reasonable to find the used coolant temperature equal to ambient. Although the initial steady-state for 2W is achieved not until ten minutes; however, the subsequent steady-states takes only less than two minutes.

IV. RESULTS AND DISCUSSIONS

Using collected data in this investigation various curves are plotted as shown from Fig. 3 to Fig. 22. Figure 3 shows time required for reaching steady state temperature for different working fluids. It is found that ethanol takes the least time out of four while the other three delayed approximately the same period of time. Methanol and iso-propanol are almost overlapped in terms of temperature rise as well as attaining steady-state condition—this may occur because of their proximity of boiling points (BP). On the other hand, water took longer to reach the BP but at a higher temperature range than the other three. It is observable that although the methanol's boiling is low, still it took the same time period of iso-propanol. This indicates the earlier boiling and condensation of methanol and iso-propanol than other two, which becomes chaotic within the narrow space of the micro heat pipe. Consequently, methanol takes longer period of time to reach thermal equilibrium thus to attend steady state than that of other two hydrocarbons. However, water took the same time but at a higher temperature than the other three because of water's higher latent heat. Therefore, the heat capacity of a fluid not only depends on its thermophysical properties (i.e. density, SG etc.) but also on its chemical bonding (i.e. hydrogen bonding for water).

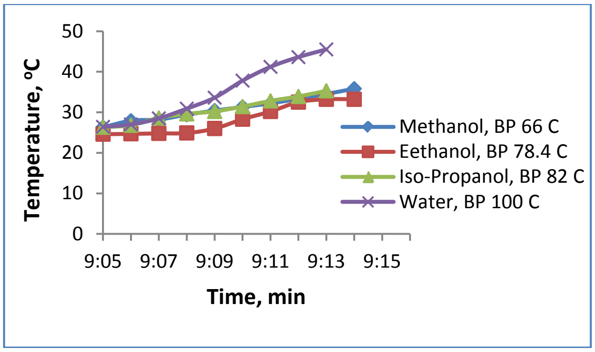


Figure 3 : Time required for reaching steady-state of different fluids

The trends of temperature rises (meter reading minus the ambient, 25°C) at the evaporator section for using different fluids in TMMHP are shown in Figure 4. Other than water, all three are nonlinear. This may happen because of the three are organic compounds and have similar chemical bonding, and the water as an inorganic compound is made up from hydrogen and oxygen's covalent bond. Again it supports the phenomenon that the heat capacity of a fluid is not simply based on thermo physical property (i.e. density, boiling point, SG etc.) rather mainly on its bonding.

V. EVAPORATOR OF TMMHP AS A SUPER HEATER

Distributions of temperatures along the length of the TMMHP for different working fluids, for different heat inputs, and also for different inclinations are shown from Figure 5 (a) to 12 (b). It is observed from these figures. That in each case of fluid used in TMMHP, there is a temperature rise in the evaporator from T_1 to T_2. Annamalai A. S. *et al.* [7] has reasoned that "In the evaporator zone heat is supplied by an electric coil and the coil surface area density is very high in the middle of the evaporator portion and hence the temperature of the vapor in the middle of the evaporator is high". Authors here disagree with Annamalai that there should be no reason to windup the heater coil densely in the middle of the evaporator rather wrapping must be uniformly done so the produced heat flux remains constant throughout the evaporator. Based on this work and the work of Sakib [6] and Sreenivasa [4], the working liquid should be filled only equal to or less than the empty space (vapor core) of the evaporator of the heat pipe. However, a lot more space in the heat pipe is still vacant to travel during operation. Soon after the MHP goes on operation, boiling starts at the beginning of the heat pipe—part of the fluid evaporates—that leaves a significant room empty within the evaporator which is fully wrapped up by the heater coil. Therefore, when the saturated vapor advances, it continuously receives heat from that part of heater to become superheated, and then it enters the adiabatic section. That's why we notice the temperature rise at point $T_{2,}$ hence this end of the evaporator act as a *super heater*. Regarding the rise of temperature in the evaporator, a comparative relationship between the fluids in the TMMHP and in the SMMHP [6] is shown in Figure 13 (a-c). At the initial steps, the trend for temperature rise for all the fluids are quite similar at 0° inclination; however, they get dispersed at moderately higher heat inputs (i.e. 12W) as the heat pipe is raised to 45° and 90°. This may happen from the "dried out" situation meaning poor capillary pumping of condensate back to the evaporator that leads uniform heating of evaporator. It becomes obvious that the orientation of the TMMHP plays an important role in superheating quality of the fluids. On the other hand, in the case of SMMHP [6, 7] the trend is always negative.

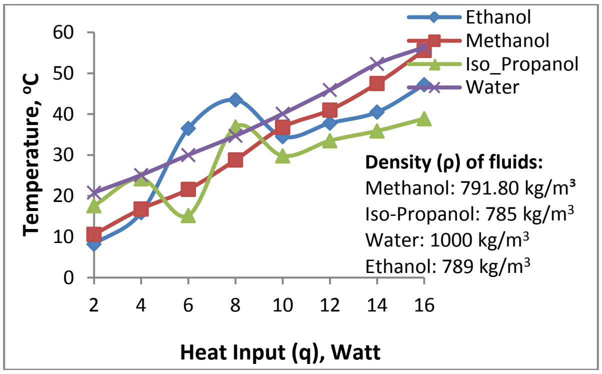


Figure 4 : Rise of fluid temp. vs. heat input at the evaporator

VI. Condenser of TMMHP as an Exothermic Port

It is also noticeable from Figure 5 to Figure 12; there is a rise of temperature of the condensate within the condenser section of the TMMHP. Its convergent-divergent geometry creates a variable pressure gradient throughout the heat pipe that results in a quick pressure drop at the condenser port. Thus the inherent kinetic energy of the condensate increases the terminal temperature which improves the heat transfer of the system. Such an increase of the liquid's temperature also enhances the capillary action which speeds up the rate of evaporation-condensation cycle.

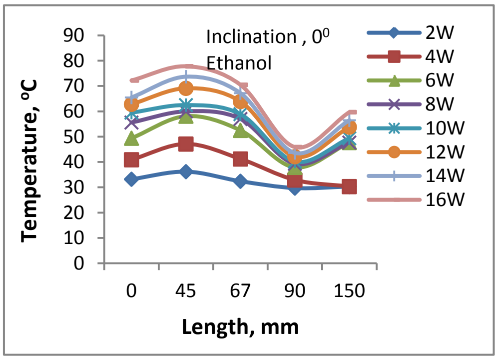


Figure 5 (a) : Fluid temp. distribution along the TMMHP

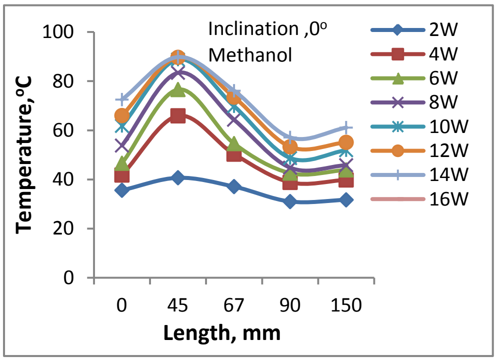


Figure 5 (b) : Fluid temp. distribution along the TMMHP

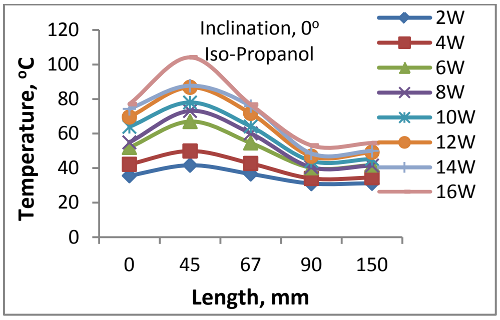


Figure 5 (c) : Fluid temp. distribution along the TMMHP

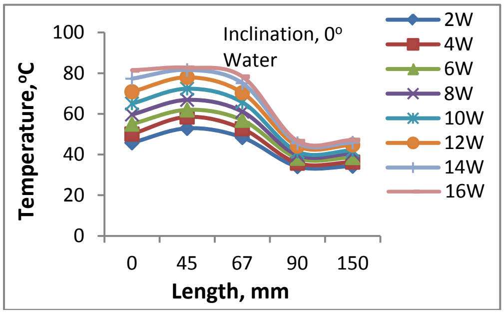


Figure 5 (d) : Fluid temp. distribution along the TMMHP

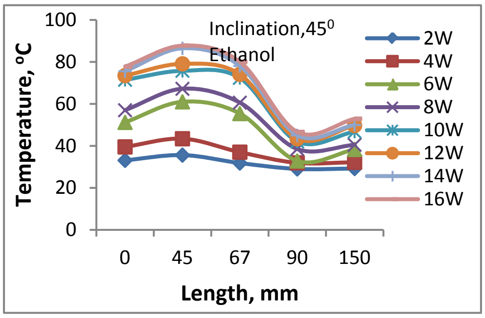


Figure 6 (a) : Fluid temp. distribution along the TMMHP

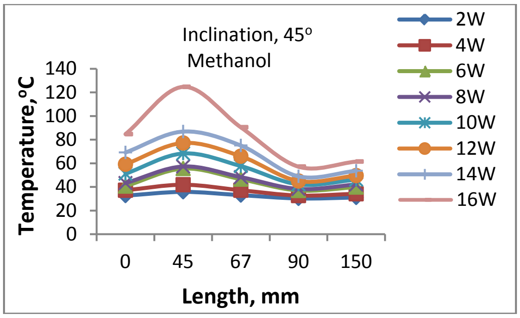


Figure 6 (b) : Fluid temp. distribution along the TMMHP

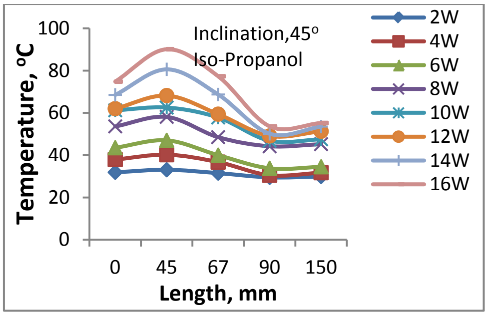


Figure 6 (c) : Fluid temp. distribution along the TMMHP

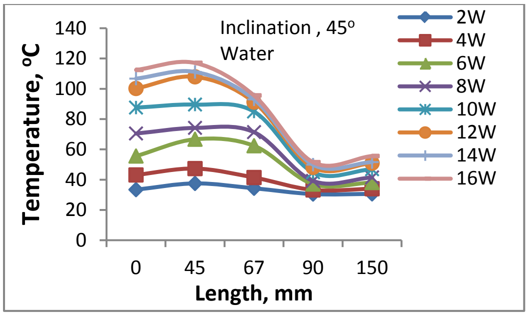


Figure 6 (d) : Fluid temp. distribution along the TMMHP

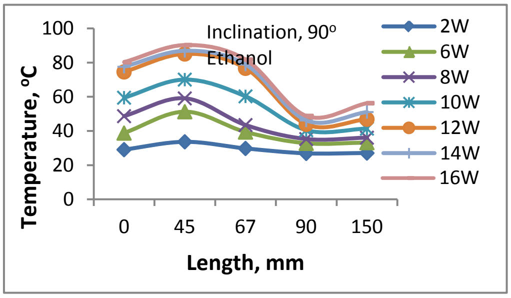


Figure 7 (a) : Fluid temp. distribution along the TMMHP

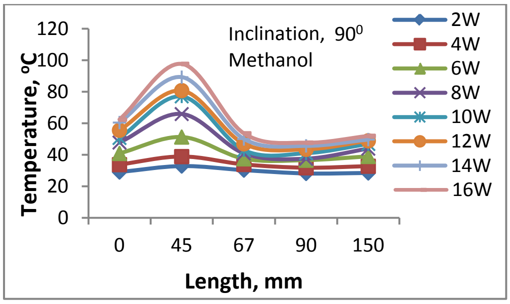


Figure 7 (b) : Fluid temp. distribution along the TMMHP

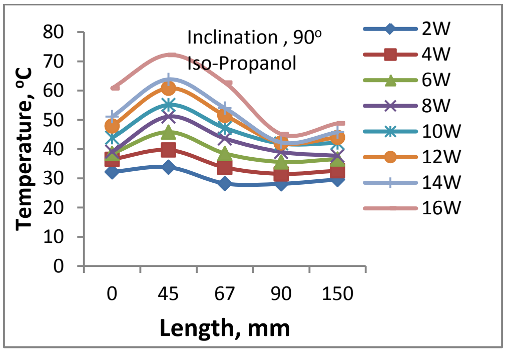


Figure 7 (c) : Fluid temp. distribution along the TMMHP

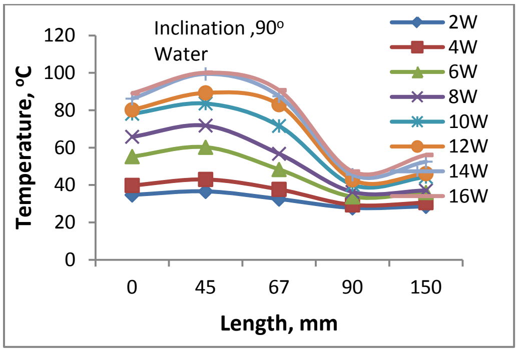


Figure 7 (d) : Fluid temp. distribution along the TMMHP

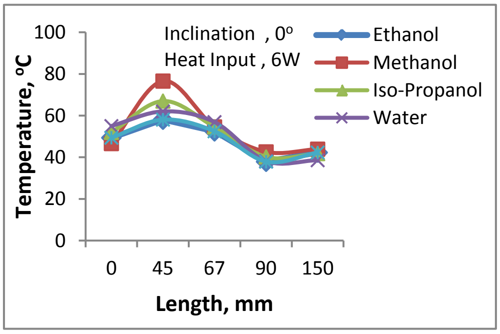


Figure 8 (a) : temp. distribn along the TMMHP

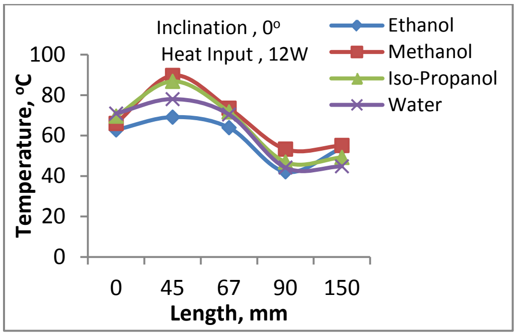


Figure 8 (b) : temp. distribn along the TMMHP

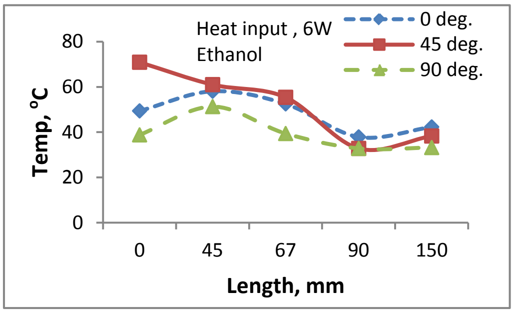


Figure 9 (a) : temp. distribn along the TMMHP

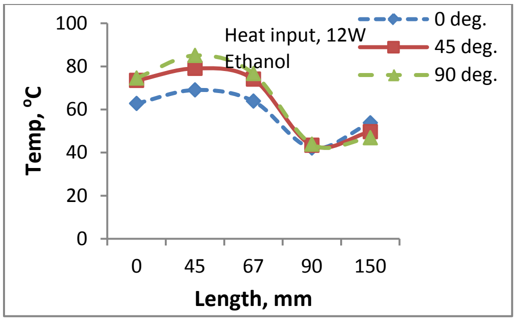


Figure 9 (b) : temp. distribn along the TMMHP

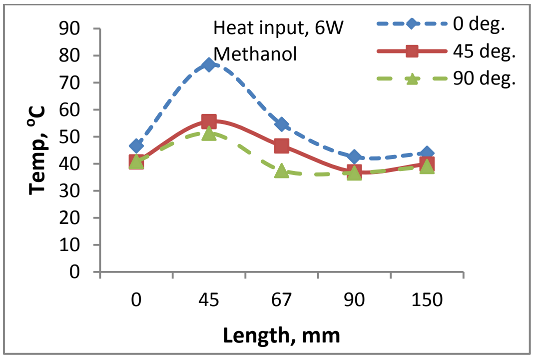


Figure 10 (a) : temp. distribn along the TMMHP

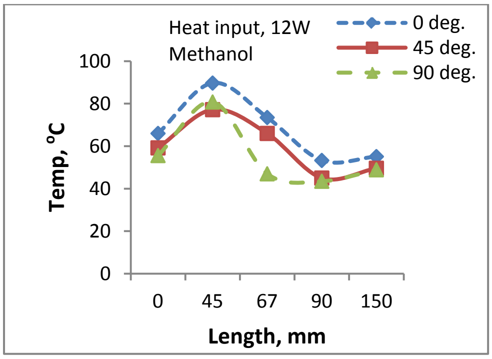
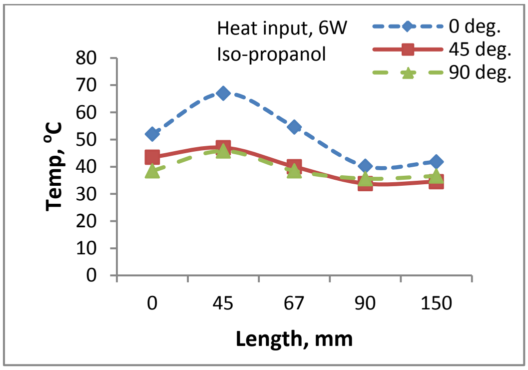


Figure 10 (b) : temp. distribn along the TMMHP



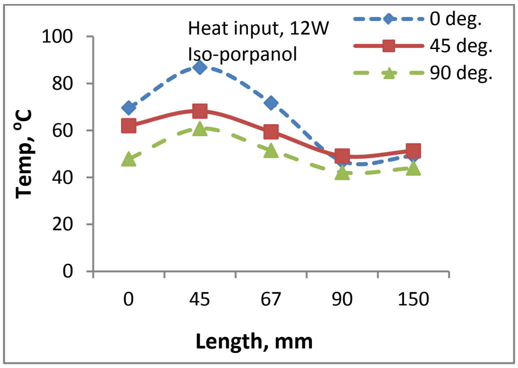
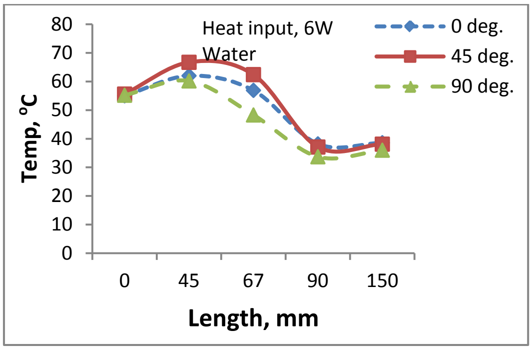


Figure 11 (a) : temp. distribn along the TMMHP

Figure 11 (b) : temp. distribn along the TMMHP



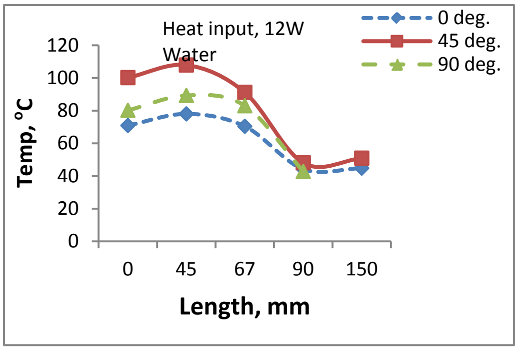


Figure 12 (a) : temp. distribn along the TMMHP

Figure 12 (b) : temp. distribn along the TMMHP

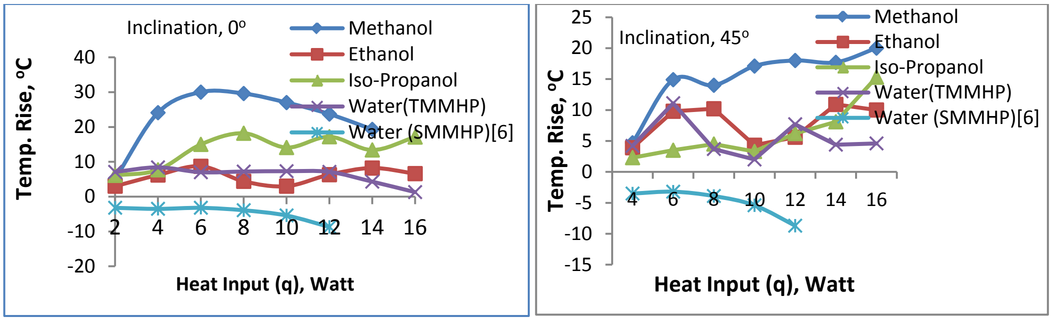


Figure 13 (a)

Figure 13 (b)

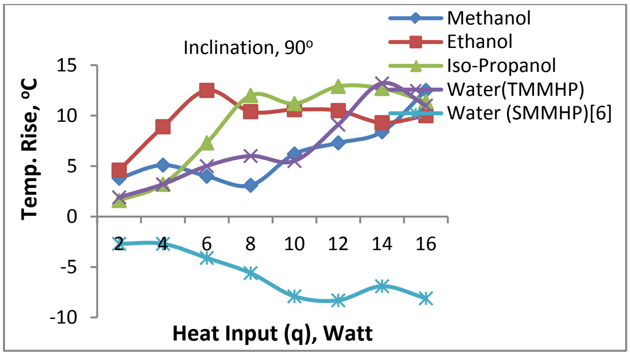


Figure 13 (b)

Figure 13 (a-c) : Comparison of temp. rise (T_2-T_1) of TMMHP with SMMHP [6] of diff. fluids at diff. inclinations

Figure 14 indicates that apparently methanol was condensed within the highest temperature band while water was condensed within the lowest. Such two different temperature bands were identified because of their lower and higher boiling point respectively. On the other hand, the sequence of bandwidth remains increasing for ethanol in all orientations.

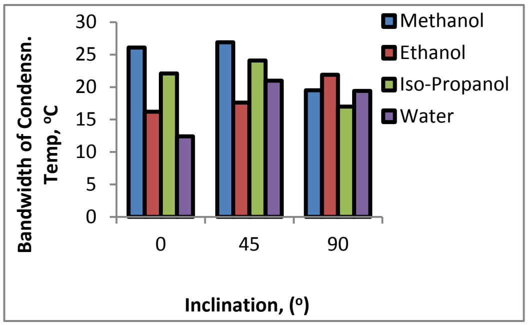


Figure 14 : Band-width of condensn. temp. ($T_{4,16W}$ - $T_{4,2W}$) of diff. fluids for diff. heat inputs applied to TMMHP at diff. inclns

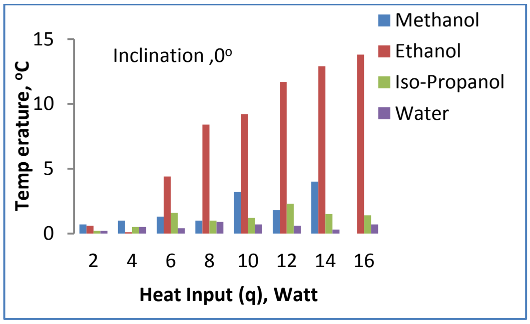


Figure 15 : Comparison of condensn. temp. (T_5-T_4) range of diff. fluids for increasing heat inputs to TMMHP

However, at 90° inclination, the values are scattered because of possible "dried out" situation. Capillary action of the water and hydro-carbons are quite different. As a result, the values of the three hydrocarbons are closely placed while the value of water is a bit apart from them. Thus it is proved again that the heat capacity of a liquid is not only depended on its physical property but also on its chemical property (i.e. structural bonding).

While being condensed, the internal working fluids were experiencing negative temperature gradient within the condenser at circular SMMHP [6], but the convergent-divergent is an exception with a positive gradient as shown in Figure 15. Such negative temperature gradient of fluids is due to continuous heat loss of the saturated liquid throughout the condenser [6]. However, the positive gradient at the convergent-divergent TMMHP is due to sudden pressure drop within its divergent condenser.

During this pressure fall, the inherent kinetic energy of the liquid is converted to heat, hence the temperature of the liquid increases. At the turning point, such a temperature increase of the liquid benefits the capillary action of the wick to drive back condensate even faster to the evaporator. A comparison of thermal performances between the single-metal and two-metal micro heat pipe has been established in the Table 2.

The efficiency of MHP is highlighted by its heat transfer capability at a lower temperature difference. A comparison between the TMMHP and SMMHP [6] is shown in Figure 16. As it is seen, the terminal temperature difference at TMMHP is only the third or even less than that of at SMMHP. This has become possible because of relatively higher conductivity of silver at the condenser port that accelerates the thermodynamic cycle of the working fluid within the heat pipe.

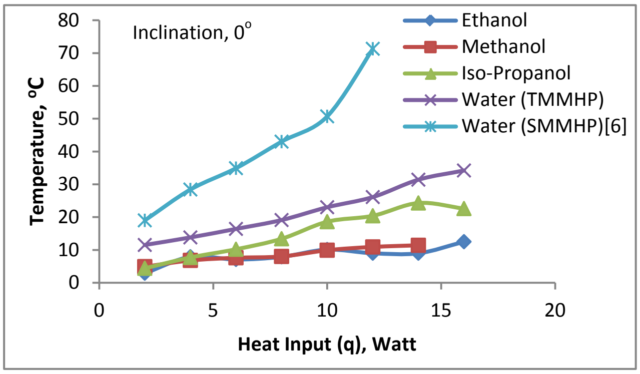


Figure 16 : Comparison of terminal temp. diffs. (T_1-T_5) of TMMHP with SMMHP [6]

a) Comparison of h for water between TMMHP and SMMHP

In Figure 17 and 18, *h* values of water at both SMMHP [6] and TMMHP for different inclinations can be compared. At 0°, the *h* values at TMMHP and SMMHP are almost the same. As the inclination is changed, the *h* values at TMMHP take a new shape which indicates the multiple times higher *h* at lower heat input than that of at SMMHP. However, as the heat input rises the *h* drastically goes down and then become constant. It is noticed, except at horizontal position, the pattern of *h* at both 45° and 90° are the same. If all the operating and test parameters remain the same at both single and two-metal micro heat pipe, then the variability of heat conductivity as well as their operating orientation in TMMHP is considered to be the only initiators for greater value of *h*.

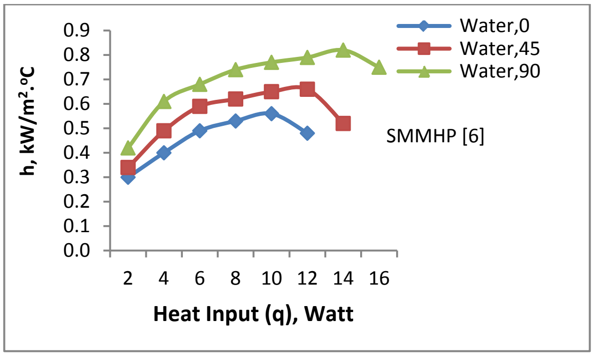


Figure 17 : Convec. HT coeffs. of water in SMMHP [6] at dif. inclns

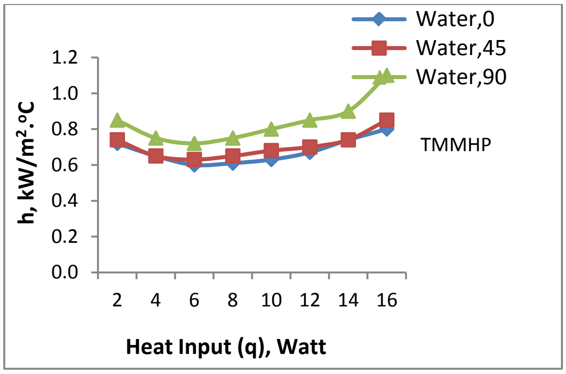


Figure 18 : Convec. HT coeffs. of water at TMMHP at dif. inclns

b) Comparison of h for all fluids between TMMHP and SMMHP

Figure 19 (a-c) shows the values of heat transfer coefficient of different fluids at inclinations of 0°, 45° and 90°. In all orientations, methanol possesses the highest '*h*' among all the fluids, and the highest value is attained at inclination 90°. Thus in respect to *h*, methanol is the most valuable working liquid out of the four for convergent-divergent TMMHP. Since the surface temperature of the TMMHP is depended on the heat input and heat rejection at the evaporator and condenser respectively, such high values of '*h*' become dependent only on overall thermo physical properties of the internal fluid. However, the sequence of '*h*' values for the four fluids in TMMHP does not keep the same trend as they do in the SMMHP at all three orientations. In Figure 19, the sequential rises of *h* of all four fluids in TMMHP at different angles are shown. In all cases, methanol gains the highest value of *h* whereas the lowest values are not for a particular fluid. According to Newton's law of cooling, *h of a system with constant heat input and surface area gets the highest value for the smallest terminal temperature difference within the heat pipe and vice versa.* This correlation can be authenticated by comparing Figure 16 and Figure 18 where water in TMMHP achieves the highest value of *h*. Consequently, at a small terminal temperature difference, the sharp decrease of pressure gradient leads to rapid condensation at the condenser port to increase the *h* value. The calculated h_{eff} values of all the fluids, based on the average temperature of the evaporator and condenser, for different inclinations are shown in Figure 20. It shows the water and three hydrocarbons are not producing the same pattern of *h* – all are nonlinear. Again it is proved; the value of *h* for any liquid is not only depended on its thermo physical properties but also on its chemical bond.

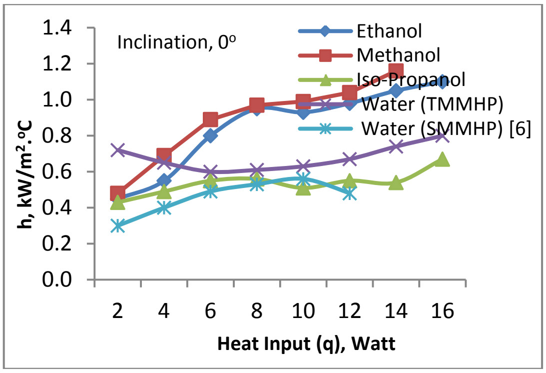


Figure 19 (a) : Convec. coeff. of fluids vs. heat input in TMMHP

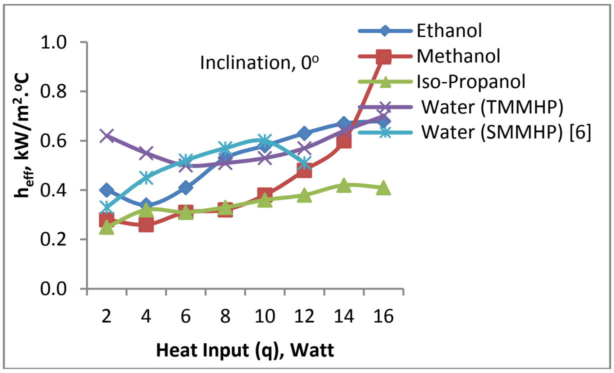


Figure 20 (a) : Eff. convec. coeff. of fluids vs. heat input in TMMHP

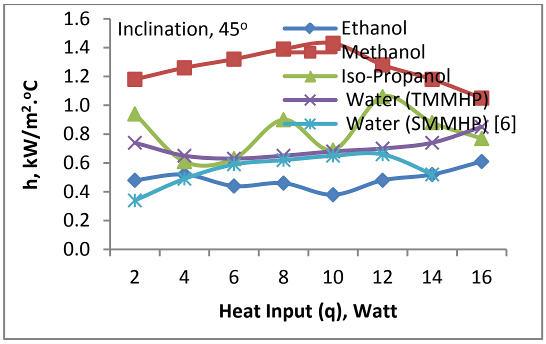


Figure 19 (b) : Convec. coeff. of fluids vs. heat input in TMMHP

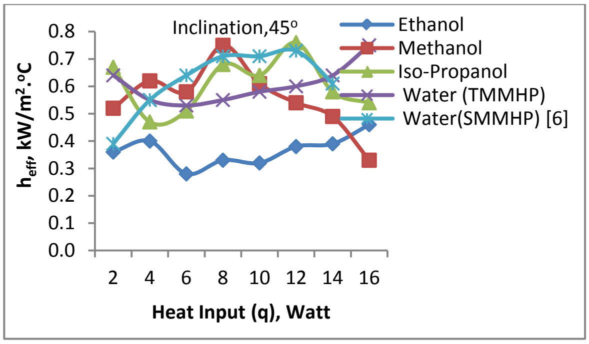


Figure 20 (b) : Eff. convec. coeff. of fluids vs. heat input in TMMHP

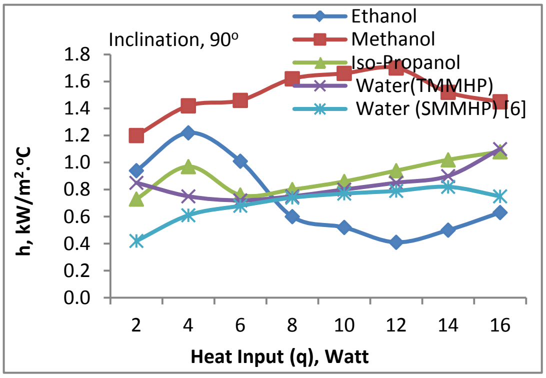


Figure 19 (c) : Convec. coeff. of fluids vs. heat input in TMMHP

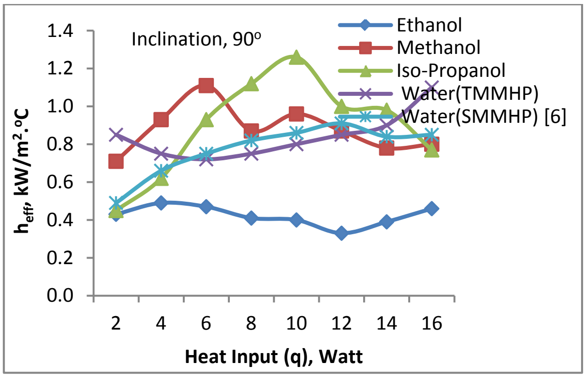


Figure 20 (c) : Eff. convec. coeff. of fluids vs. heat input in TMMHP

Density is a thermo physical property of a fluid. Therefore, when the vapor becomes liquid at the condenser; the density of the fluid therein goes many folds high. Nevertheless, *h* keeps no direct relationship with the density alone which reflects in both Figure 19 and Figure 20. Rather it is found that *h is compositely related with the fluid's density, pressure drop and heat input.* This relationship can be expressed by $h = f(\rho(p(q)))$. Then the authors have developed the dimensionless correlations from this relationship presented later. In Figure 21(a-b), all the fluids' dimensionless heat transfer coefficients are shown including the water's h/h_{eff} at SMMHP [6]. The maximum value of methanol is seen both at 0° and 45° which is quite in match with its *h* value (Fig.19 a-b). However, a little deviation at 90° for methanol indicates the experimental error that spikes up the value of iso-propanol.

However, comparing the water's h/h_{eff} value at TMMHP is higher than that of at SMMHP [6]. Thus, the two different thermal conductivities at the two ports of the TMMHP initiate the quicker heat removal than it does in the SMMHP, hence improves the *h* so greatly.

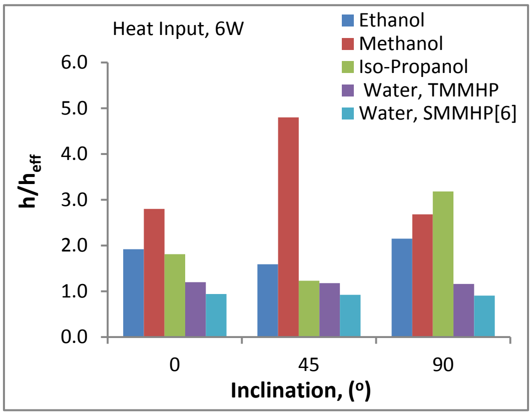


Figure 21(a) : Comparison of h/hef between TMMHP and SMMHP [6]

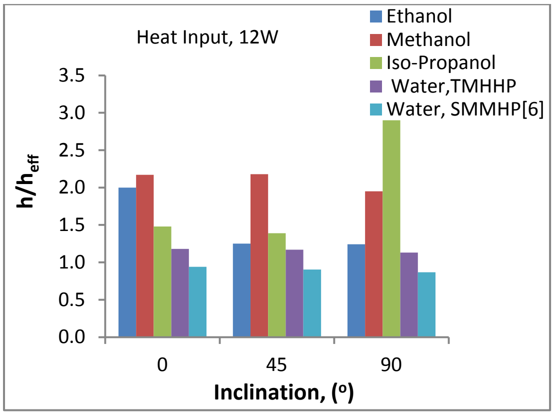


Figure 21(b) : Comparison of h/hef between TMMHP and SMMHP [6]

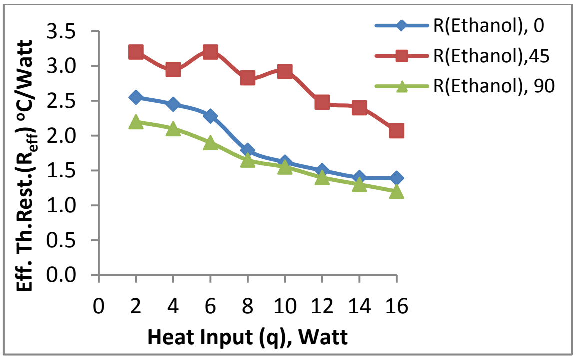


Figure 22 (a) : Thermal Resistance Vs. Heat input at TMMHP

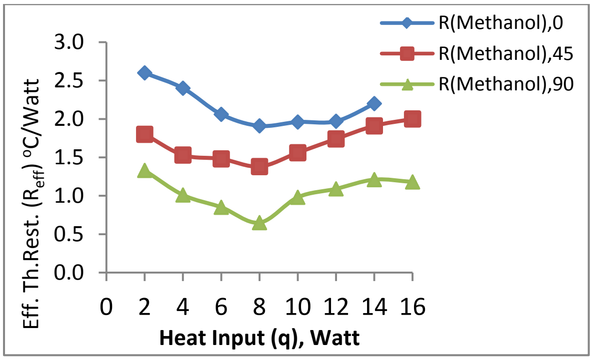


Figure 22 (b) : Thermal Resistance Vs. Heat input at TMMHP

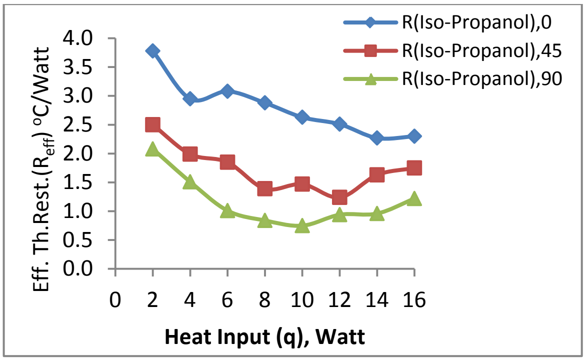


Figure 22 (a) : Thermal Resistance Vs. Heat input at TMMHP

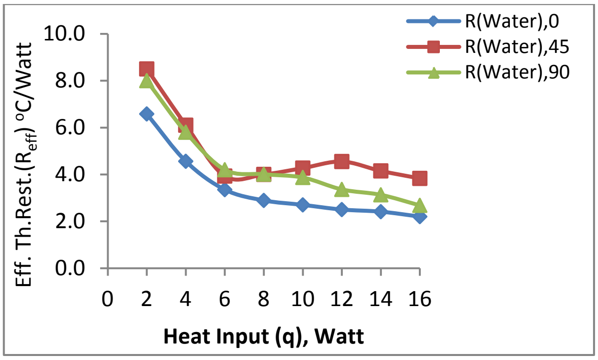


Figure 22 (b) : Thermal Resistance Vs. Heat input at TMMHP

In Figure 22(a-d), the effect of thermal resistances for all four fluids is shown. Except water, the rest three fluids keep almost the same pattern of resistance in the convergent-divergent TMMHP with respect to heat input. Again, the reason can be the difference of their chemical bonding—water is covalent compound and the other three are hydrocarbons. However, a variation of resistance in different fluids is obvious according to the inclination of the experimental setup. Another obvious thing is seen, as the heat input increases to the moderately higher value (i.e. 10W) the resistance goes higher in all four cases and in all inclinations. Since all other parameters are fixed, the geometry of the micro heat pipe is causing this upper trend. Still there are some irregularities between the heat input intervals; those are because of "dry out" situation in the evaporator. As it is noticed, the time required for evaporation-condensation is very low in the convergent-divergent TMMHP; the capillary pumping of the wick is not enough to reach the evaporator. In case of water, by comparing Figure 18 for h and Figure 22(c) for R_{eff}, it is seen the trend of the curves is almost alike. In respect to the heat input, it can be deduced that such decreasing-increasing path is maintained by the internal variability of the conductivity of the two different metals (Cu-Ag). In addition, the convergent-divergent geometry of the TMMHP which also guides the variability of pressure that induces variation of heat transfer. However, methanol poses the lowest thermal resistance 0.65 °C/Watt out of four fluids used in this study.

A comparison of thermal performance between single-metal (SMMHP) [6] and two-metal micro heat pipe (TMMHP) observed in this study is given in Table 2.

Table 2 : Comparison of thermal performances between SMMHP [6] and TMMHP for water

Sl. No.	Parameters	SMMHP [6]	TMMHP	Remarks
1	Thermal conductivity (k)	Constant	Variable	Rate of heat removal is increased in TMMHP.
2	Bandwidth of condensation temperature (Water, 0° incln.)	Small 3.6° C	Large 12° C	Condensation takes place at higher temp. in TMMHP than in SMMHP.
3	Overall temp. difference between two ends of MHP (Water, 0° incln.)	41.2° C	14.9° C	In TMMHP is much smaller, thus enhances cyclic order and rate of heat removal.

4	Temp. gradient at condenser for water	Negative	Positive	Positivity at TMMHP improves capillary action.
5	Time reqd. to complete cycle (Water, 0° incln.)	2 min	< 1 min	Because of thermal vacuum created in TMMHP for variable conductivity and variable pressure gradient.
6	h/h_{eff} (Water, 0°, 6W)	0.95	1.30	Higher TMMHP value because of super heater effect that makes average temp. high.
7	h_{max} (Water, 0° incln.)	0.48 kW/m². °C	0.80 kW/m². °C	At TMMHP h_{max} is almost *two times* high.
8	*h* with respect to increasing Q	~uniform	~uniform	At TMMHP mean value of *h* is higher than SMMHP.

VII. VALIDATION OF THE EXPERIMENTAL SETUP WITH KNOWN RESULTS

To validate the present experimental setup and results, four experiments are carried out in the IUT Lab with another setup following the test procedures applied to TMMHP. The setup contained a circular SMMHP made with copper which was tested by the experimenters Hossain et al. [18] for ethanol, methanol and acetone, and operated at 30°, 50°, 70° and 90° angles with the heat inputs of 0.61W, 1.56W, 3.67W, and 8.71W. Out of three fluids, ethanol is selected as the working fluid for the validation test. The specifications of the setup are given in Table 3.

Table 3 : Specifications of the experimental setup

Test Parameters	Dimensions (mm)
Outer diameter of the tube, d_o	2.0
Hydraulic diameter of the tube, d_h	1.8
Length of heat pipe, L	150
Length of evaporator section, L_e	50
Length of adiabatic section, L_a	30
Length of condenser section, L_c	70
Inclinations	30°, 50°, 70°, 90° (vertical)

The values of overall heat transfer coefficient, *U*, obtained from the source [18] are compared with those found from the validation experiment, which are within the proximity of 93% of TMMHP. Similarly, the thermal resistances, *R*, are also compared and found to be within 95% of the known values.

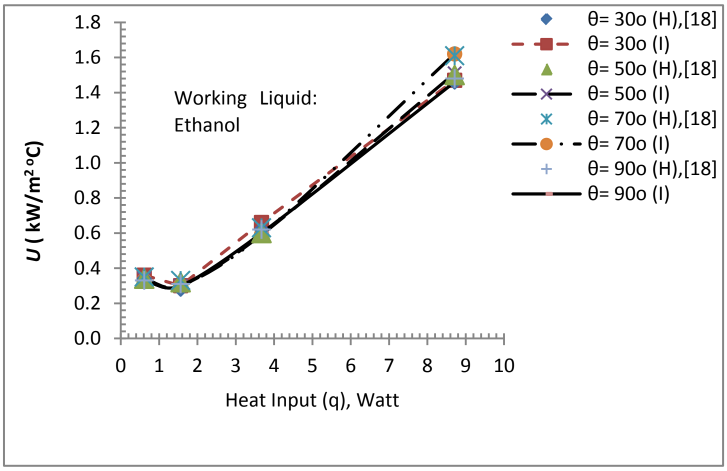


Figure 23 : Validation experiment with the known results [18]

The variation of overall heat transfer coefficient, *U*, at different inclinations are shown in the Fig. 23. In the legendry of the plots, H represents Hossain et al [18] and I for Iqbal (author).

VIII. UNCERTAINTY ANALYSES

A detailed analysis regarding the uncertainties within the equipment, measurements and results is carried out, which cumulatively is 8.90% with 95% confidence level, According to Kline and McClintock

[19] the total uncertainty propagation for $r = f(v_{j=1\ldots n})$ is summarized in *eqn. 1* which is commonly used in calculating the related uncertainties in any experiment.

$$u(r) = \sqrt{\Sigma_{j=1}^{n}[\frac{\partial r}{\partial v_j} u(v_j)]^2} \tag{1}$$

Here, *u* stands for the standard uncertainty, which is equivalent to the standard deviation, and v_j stands for the variables that contribute to the uncertainty in the result *r* that revolves around any data reduction equation. Thus finally, the relative uncertainties for *h* can be cumulatively expressed as in *eqn. 2*

$$\left(\frac{U_h}{h}\right)^2 = \left\{\left(\frac{U_{h_e}}{h_e}\right)^2 + \left(\frac{U_{h_a}}{h_a}\right)^2 + \left(\frac{U_{h_c}}{h_c}\right)^2\right\} \times 100\% \tag{2}$$

or, it can be re-written for standard uncertainty in the form of *eqn. 1* as shown in *eqn. 3*.

$$u(h) = \left\{\sqrt{\Sigma_{j=e}^{c} \frac{\partial h}{\partial q_j} h(q_j) + \Sigma_{j=e}^{c} \frac{\partial h}{\partial T_j} h(T_j) + \Sigma_{j=e}^{c} \frac{\partial h}{\partial A_j} h(A_j)}\right\} \times 100\% \tag{3}$$

where *j* = *e, a* and *c* which represents evaporator, adiabatic and condenser respectively.

IX. CORRELATION

A dimensionless correlation has been developed which correlates all the data collected in this study. It is mentioned earlier and shown in the graphs that a few common relations are found between heat transfer coefficient and other operating parameters. These common relations may be shown mathematically as $h = f(\rho(p(q)))$

In a dimensionless relation, the above function can be rewritten along with the calculated constants as follows.

$$\frac{h}{h_{eff}} = 0.468\left(\frac{q"_{e,eff}}{q"_{e,s}}\right)^{-0.041}\left(\frac{q"_{c,s}}{q"_{c,eff}}\right)^{0.076}\left(\frac{\Delta P}{\Delta P_{eff}}\right)^{-0.984}\left(\frac{\rho_c}{\rho_e}\right)^{0.081}\left(\frac{d_T}{d_H}\right)^{0.997}\left(\left\{\frac{l}{l_{eff}}\right\}^{sin\theta cos\theta}\right)^{1.366}$$

Graphical representation of all the correlated data is shown in Figure 23, and 98% of them are found to be within ±15% range of the regression line. Using the acquired data, the correlation produces *h* within the ±18% proximity of the experimental value.

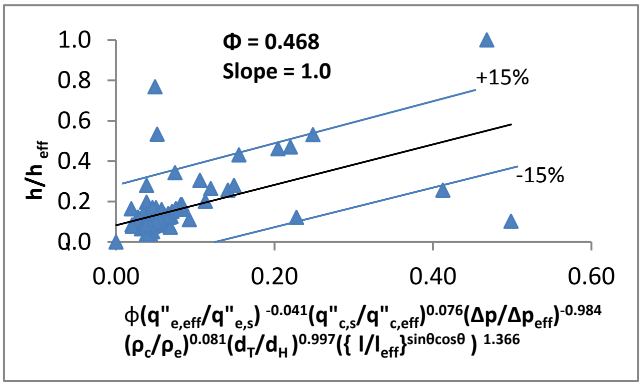


Figure 23 : Graphical representation of the developed correlation of TMMHP

X. CONCLUSIONS

From the study, the following conclusions can be drawn.

a) In SMMHP, the terminal temperature difference is very high for water comparing with that produced by TMMHP. As a result, the *h* of the water produced by the TMMHP is much higher than that by SMMHP.

b) Out of four working fluids, *methanol* has been found to provide the highest *h* in all three orientations, because of its low boiling point and density that enables quick completion of thermodynamic cycle.

c) It is proven that MHP made with the metals of variable thermal conductivity, i.e. TMMHP, of ascending order orientation, which initiates the super heater effect in the evaporator, indicates many folds better prospect of *h* value than that of made with constant conductivity, SMMHP [6].

d) While an assumption of single phase flow in SMMHP works well at lower heat inputs, but at moderately high heat inputs it becomes a two-phase flow. However, the super heater effect at the evaporator in TMMHP eliminates that complexity of the two-phase and instantly turns into a single phase flow of vapor which was not possible in SMMHP [6, 7].

e) In case of convergent-divergent TMMHP, the upper trend of temperature at the condenser terminal is uniquely different from that of other geometry. Such a condition demands the coolant flow of lower than the ambient temperature or a coolant of higher C_p. Eventually, this slightly increased temperature of the vapor condensate speeds up the capillary action of the wick.

f) The change of any specific physical property (i.e. density, specific gravity, viscosity) of a fluid singly cannot change the *h* of that fluid in an MHP, rather it is a compound value developed functionally from both of its physical properties and state variables as of $h = f(\rho(p(q)))$.

g) Since the evaporation-condensation cycle within the convergent-divergent TMMHP takes much small time, which causes the "dry out" situation in the evaporator, an attempt to improve the capillary pumping system within the heat pipe may be undertaken for further research.

h) Since the *h* values produced by organic and inorganic compounds are found to be characteristically different, non linear and linear respectively, an azetrope (content of mixed fluids at a certain ratio with no chemical reactions) may be used as a working fluid to check the improvement.

NOMENCLATURE

C_p,	specific heat at constant pressure, $kJ/kg.\,^0C$
d_H,	hydraulic diameter of the heat pipe, (m)
d_T,	profile height of the heat pipe, (m)
h,	heat transfer coefficient for terminal temperature difference of the fluid, $kW/m^2.\,^0C$
h_{eff} ,	effective heat transfer coefficient for terminal average temperature difference of the fluid, $kW/m^2.\,^0Cv$
l,	length of the heat pipe, m
l_{eff} ,	effective length of the heat pipe, m
p,	pressure of the fluid, $Pa\ (N/m^2)$
q,	heat input, *Watt*
Δp,	terminal pressure drop, kPa
Δp_{eff},	effective pressure drop at terminal average pressure, kPa
q'',	heat flux, kW/m^2
$q''_{e,\,eff,}$,	effective heat flux through the evaporator shell by conduction, kW/m^2
$q''_{e,\,s,}$,	heat flux at the evaporator surface supplied by heater, kW/m^2
$q''_{c,\,s,}$,	dissipated heat flux from the condenser surface by convection cooling, kW/m^2
$q''_{c,\,eff}$,	effective heat flux dissipated through the condenser shell by conduction, kW/m^2
R_{eff},	effective thermal resistance, $^o\,C/Watt$
T_1-T_5,	temperatures of the fluids in the micro heat pipe, ^0C
ρ ,	density of the fluid, kg/m^3
ρ_c ,	density of the fluid at the condenser, kg/m^3
ρ_e ,	density of the fluid at the evaporator, kg/m^3
φ ,	dimensionless correlation constant
θ ,	angle of inclination, degree (^{o})

Subscripts:

c,	condenser
e,	evaporator
eff,	effective
p,	constant pressure
s,	surface of the heat pipe
1-5,	positions of thermocouples

XI. Acknowledgement

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Water Resource Conflict in the Amazon Region: The Case of Hydropower Generation and Multiple Water uses in the Tocantins and Araguaia River Basins

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Abstract- The guarantee of multiple water use is one of the main objectives of the Brazilian system of managing water resources. However, it is still unclear how to reach these objectives regarding hydropower plants. This paper introduces a method for support of hydropower plants taking into account the compatibility with multiple water uses. It also introduces a computational tool based on the proposed method, which assesses energy generation and possible losses associated with meeting upstream water demand. A case study of the Tocantins and Araguaia basins (Amazon region) is presented. The results obtained corroborate the applicability of the proposed method.

Keywords: amazon region; SisUca; energy generation; water conflict.

GJRE-J Classification : FOR Code: 291899

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Mônica De Aquino Galeano Massera Da Hora [α] & Luiz Fernando Loureiro Legey [σ]

Abstract- **The guarantee of multiple water use is one of the main objectives of the Brazilian system of managing water resources. However, it is still unclear how to reach these objectives regarding hydropower plants. This paper introduces a method for support of hydropower plants taking into account the compatibility with multiple water uses. It also introduces a computational tool based on the proposed method, which assesses energy generation and possible losses associated with meeting upstream water demand. A case study of the Tocantins and Araguaia basins (Amazon region) is presented. The results obtained corroborate the applicability of the proposed method.**

Keywords: amazon region; SisUca; energy generation; water conflict.

I. INTRODUCTION

Y Water resource management involves a large number of variables and other uncertainties. The complexity increases when the objective is to combine multiple benefits arising from reservoir system operation (hydropower, irrigation, etc.) that frequently compete, together with reducing natural risks (flood control) and meeting environmental requirements. Management of large hydro-systems, especially when they cover more than one watershed, often raises conflicts between authorities or organizations with different interests [1].

There are many causes leading to conflicts over water use. Some arise from issues such as waste disposal, granting of licenses, restrictions on use and violation of agreed conditions [2]. When shortages or droughts are present, conflicts of course tend to become more critical.

A water license in Brazil is called a "grant" (outorga), defined as the "right to take and use water, subject to the terms and conditions of the grant" [3].

The grant of a water right to a user must take into account the estimation of the flow rate of the river that can be distributed among users without causing conflict. This estimation refers to a "low-flow or scarce period", which unfortunately is not precisely defined or regulated. Nevertheless, there are several flow indexes suggested by publications on the subject. Among them, the most mentioned indexes are: (1) Q7, 10, meaning the minimum 7-day average with a 10-year recurrence interval [4]; (2) Q95, the discharge that is equalled or exceeded 95% of the time [5]; and (3) QFERC, the minimum flow specified by the American Federal Energy Regulatory Commission (FERC) in the operational license of the Conowingo Dam [6]. Q95 flow index has been globally used by researchers with different uses [7].

In Brazil, the implementation of a water resource policy is intended to bring new approaches to the management, planning, and regulation of water use in river basins, while giving special attention to the instruments available for those tasks, such as water rights. The volume allowed to users is defined after an analysis of water availability, which maps the balance between supply and demand and indicates whether there is a situation of stress or abundance. The maximum surface water that can be withdrawn - usually defined as 70% of the Q95 discharge - corresponds to the allowed supply.

The complexity of the granting of water rights derives from the several issues it engenders. Among these, the following stand as the most pressing ones: the balance between present and future water demands; the different needs of distinct users; and the various dimensions involved - economic (industry and agricultural demands), social (drinking and recreation), and environmental (ecosystem sustainability).

In addition, in establishing riparian rights, policymakers have to consider quality levels and multiple water resource uses, e.g., navigation and especially hydropower. As for the latter, hydropower reservoirs act as huge stopcocks which interfere in the natural river flow, imposing a controlled amount of outflow to downstream users while inhibiting upstream withdrawals, in order to guarantee the amount of energy associated with the inflow. Hence, there is a clear

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conflict between the interests of the reservoir operator, who has to supply the required energy to meet demand, and the needs of multiple other water users.

In this paper, we discuss the compatibility between multiple water uses and hydropower generation. For this purpose, we propose a new method for reservoir operation, considering not only the additional water availability provided by the flow control from reservoirs, but also the multiple uses of water, which are limited to the maximum surface withdrawal. In addition, we present a mathematical model called SisUca (Sistema de Simulação de Usinas e Usos Consuntivos de Água, or System for the Simulation of Hydropower Plants and Consumptive Water Uses), a free program developed by [8] for such analysis. The method was applied in a case study of the hydropower reservoirs located on the Tocantins and Araguaia rivers, in Brazil's eastern Amazon region. The basin of both rivers - which has a drainage area of 767,000 km^2, or about 7.5% of Brazilian territory - is the most relevant for the implementation of water resource policies, because of its multiple economic, social and environmental conflicts.

II. Power Plant Operation Models

Nowadays, the simulation of power plant operation in Brazil is performed with the help of the MSUI (Modelo de Simulação a Usinas Individualizad as, or Model for Simulation of Individualized Power Plants)[9]. This model represents the characteristics of individual power plants and assumes the recurrence of the natural flows observed in the past. The model simulates the operation of a set of power plants in order to meet a specified energy demand, attempting to minimize costs by avoiding reservoir spillages. The main aspects considered in the model are: priorities for filling and emptying reservoirs; relationship among reservoir storage, water levels and surface areas (through estimated equations); minimum release policies; and maximum generation capacity of plant turbines.

However, the MSUI does not consider the possibility of water withdrawals or the existence of multiple uses. This is an important drawback, since the major objective of a water management system is to guarantee the correct distribution of water among its multiple uses and users. When hydropower plants are present, though, it is not clear how to ensure that the water management system will be effective. The reason is that water withdrawals from reservoirs or the reduction of inflows caused by multiple upstream water uses decrease hydropower generation potential and consequently lead to a decline in energy benefits derived from utilities, including possible financial losses.

Nevertheless, one cannot disregard the diverse uses of water. Thus, a new approach to the management of water resources needs to be implemented. Such an approach should take into account all of multiple uses of water, including hydropower generation. In this paper, we propose a new model for the simulation of hydropower operation, the SisUca, which includes a representation of water withdrawals, along with a new rule for reservoir operation that takes regulated discharges and their benefits to downstream users into account. In the remainder of this section, we describe the basic structure of this new model.

The simulation assumes the following hypotheses: (1) reservoirs are initially full; (2) the historical stream flow data are representative of future flows; (3) it is possible to build a reservoir with a storage capacity that would leave the reservoir empty just once over the period of historical stream flow data; and (d) the critical period corresponds to the time span between two successive full conditions, going through an empty condition [10].

The proposed reservoir operation considers the following release rules [8]:

- If the reservoir pool level at the end of period t-1 is between its maximum and minimum levels, then the reservoir is under a condition of drawdown or refilling, and the operating flow is equal to the regulated discharge during period t. Formally:

$$Qop_t = Qreg_t \rightarrow \text{if } PL_{min} \le PL_t \le PL_{max} \qquad (1)$$

where Qop_t is the operating flow at period t, in m^3s^{-1}; $Qreg^t$ is the regulated discharge at period t, in m^3s^{-1}; PL_t is the reservoir pool level at period t, in m; PL_{min} is the minimum pool level, in m, and PL_{max} is the maximum pool level, in m.

- If the reservoir pool level at the end of period t-1 is equal to its maximum level, then the reservoir is full and the operating flow is equal to the maximum operating flow during period t. Formally:

$$Qop_t = Qop_{max} \rightarrow \text{if } PL_t = PL_{max} \qquad (2)$$

The maximum operating flow can be estimated by:

$$Qop_{max} = \frac{PI \cdot 1000}{9.81 \cdot \eta \cdot h_{ref}} \qquad (3)$$

where Qop_{max} is the maximum operating flow, in m_3s_{-1}; PI is the total installed power, in MW; h_{ref} is the plant rated head, in m, and η is the efficiency of the turbine-generator-transformer system.

As shown in Figure 1, the regulated discharge represents the average flow that can be continuously released during the critical period [8].

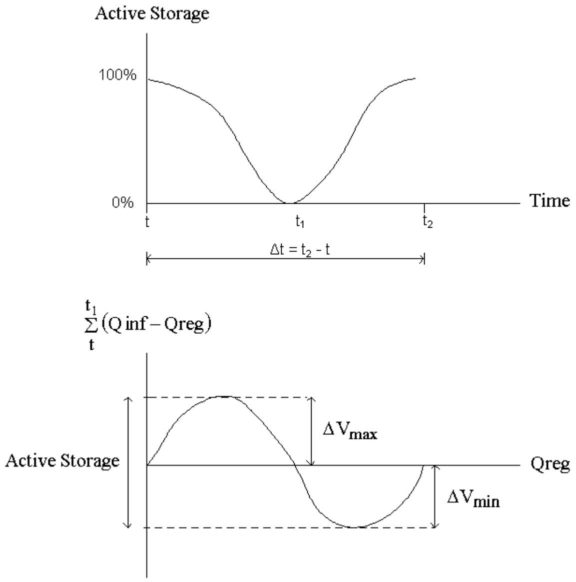

Fig. 1 : Regulated Discharge and Active Storage Capacity [8]

It can be calculated through an iterative process that acts by balancing both sides of Eq. (4) and (5).

$$\sum_{\tau=t}^{t_1}(Qinf_{\tau} - Qreg_{\tau}) = \Delta V_{max} + |\Delta V_{min}| \qquad (4)$$

$$\Delta V_{max} + |\Delta V_{min}| = C \qquad (5)$$

where t is the time period corresponding to the beginning of the critical period; t_1 is the time period corresponding to the empty condition (during the critical period); ΔV_{max} is the maximum accumulated difference between inflow and release, in m^3; $|\Delta V_{min}|$ is the modulus of the minimum accumulated difference between inflow and release, in m^3; $Qinf_{\tau}$ is the inflow during period τ, in m^3s^{-1}; $Qreg_{\tau}$ is the regulated flow during period τ, in m^3s^{-1}, calculated from the corresponding storage level of period τ -1, limited by Eq. (2) and (3); and C is the active storage capacity (corresponding to the volume of water that can be stored above the level of the lowest off-take, or the reservoir's total storage minus its dead storage).
The active storage in period t is given by [11][1]:

$$V_t = V_{t-1} + (Qinf_t \cdot ns) - (Qop_t \cdot ns) - Ve_t \qquad (6)$$

subject to $0 \le V_t \le C$

$$Qevap_t = \frac{Ve_t}{ns} \qquad (7)$$

where V_t is the storage at the end of period t, in m^3; V_{t-1} is the storage at the end of period t-1, in m^3; $Qinf_t$ is the inflow during the t^{th} time period, in m^3s^{-1}; Ve_t is the net evaporation loss during period t, in m^3 (the net evaporation loss, as defined by McMahon and Mein, is the difference between the evaporation from the reservoir and the evapotranspiration from the reservoir site); $Qevap_t$ is the net evaporation discharge during period t, in m^3s^{-1}, and ns is the number of seconds in a month (2.6298×10^6 seconds).

The reservoir pool level at period t is calculated by a simple extrapolation, as shown by the following equation:

$$PL_t = \left(\frac{PL_{t-2} + PL_{t-1}}{2}\right) \qquad (8)$$

where PL_t is the pool level at the beginning of period t, in m; PL_{t-2} is the pool level at the end of period t-2, in m, and PL_{t-1} is the pool level at the end of period t-1, in m.

The net evaporation loss is defined by the following equations [12]:

$$Ve_t = EL_t \cdot A \cdot 1000 \qquad (9)$$

$$EL_t = Ew_t - ETR_t \qquad (10)$$

where Ve_t is the net evaporation loss, in m^3; A is the reservoir surface, in km^2 (the reservoir surface is obtained from an estimated polynomial relationship between the area of the pool surface and pool level); EL_t is the net evaporation during period t, in mm; ETR_t is the real evapotranspiration during period t, in mm; and Ew_t is the pool surface evaporation during period t, in mm.

The model demonstrates the inflow discharge to hydropower plant i by the following relations:

$$Qinf_i = Qincr_i + \sum_{k \in M} Qrel_k - Quses \qquad (11)$$

$$Qinf_i = [Qnat_i - \sum_{k \in M} Qnat_k] + \sum_{k \in M}[Qop_k + Qspill_k]$$

$$-Quses \qquad (12)$$

$$Quses \le MSW \qquad (13)$$

where $Qinf_i$ is the inflow discharge to hydropower plant i, in m^3s^{-1}; $Qincr_i$ is the net incremental natural inflow between plant i and upstream plants, in m^3s^{-1}; $Qrel_k$ is the outflow of plant k, in m^3s^{-1}; $Qnat_i$ is the natural inflow to plant i, in m^3s^{-1}; $Qnat_k$ is the natural inflow to plant k, in m^3s^{-1}; Qop_k is the operating outflow of plant k, in m^3s^{-1}; $Qspill_k$ is the spillage outflow of plant k, in m^3s^{-1}; Quses is the water withdrawals between the sites of plant i and k, in m^3s^{-1}; MSW is the maximum surface water withdrawal, in m^3s^{-1}; and M is the set of plants upstream to plant i.

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[1] Eq. (6) is a particular case of the general equation introduced by [11], which considers the possibility of spillage. Eq. (6) applies during the reservoir's filling and drawdown phases (i.e., when the reservoir's active storage is in use). In this situation, the operating flow equals the regulated flow.

Finally, monthly energy generation is expressed in the model by:

$$E_i = 0.00981 \cdot \eta_i \cdot h_i \cdot Qop_i \cdot n_h \qquad (14)$$

where E_i is the average energy generation in plant i, in MWmonth; h_i is the net head in plant i, in m; Qop_i is the monthly operating flow in plant i, in m^3s^{-1}; η_i is the turbine-generator-transformer efficiency in plant i; and n_h is the number of hours in a month (730.5 hours).

III. THE TOCANTINS AND ARAGUAIA RIVERS' HYDROPOWER CASCADE

The energy losses caused by multiple water uses in the Tocantins and Araguaia rivers' hydropower cascade were evaluated in terms of increasing withdrawal scenarios. In these scenarios we attempted to present the demands for other uses and defined them as percentages of the maximum surface water withdrawal (25%, 50%, 75% and 100% of MSW). The natural inflow historical data (1931 to 2006) to each hydropower plant were obtained from [8]. The topological arrangement of the cascade took into account the following plants: Serra da Mesa, Cana Brava, São Salvador, Peixe Angical, Lajeado, Couto Magalhães, Santa Isabel and Tucuruí, as shown in Figure 2.

The Q95 discharges and the maximum surface water withdrawals (70% of the Q95 discharge) and the incremental maximum surface water withdrawals for the different plants in the cascade are shown in Table 1.

Table 1 : Q95 and MSW in Tocantins/Araguaia River hydropower plants

Hydropower Plant	Q95 (m^3s^{-1})	MSW (m^3s^{-1})	Incremental MSW (m^3s^{-1})
Serra da Mesa (SM)	150.0	105.0	
Cana Brava (CB)	179.0	125.3	20.3
São Salvador (SS)	200.0	140.0	14.7
Peixe Angical (PA)	347.0	242.9	102.9
Lajeado (L)	439.0	307.3	64.4
Couto Magalhães	44.6	31.2	
Santa Isabel (SI)	588.0	411.6	380.4
Tucuruí (T)	2,037.0	1,425.9	707.0

The simulation of hydraulic energy generation for the cascade took two initial conditions into account: the first condition corresponds to the lack of water withdrawals and the second one corresponds to an increasing water withdrawal, as percentages of the MSW (for the first plant in the cascade, Serra da Mesa) and of the incremental MSW (for the other plants in the cascade).

Table 2 shows the main features (physical, hydraulic and total installed power) of the plants in the cascade. The information shown was obtained from the database of hydropower potential in Brazil, developed by Centrais Elétricas Brasileiras (Eletrobrás).

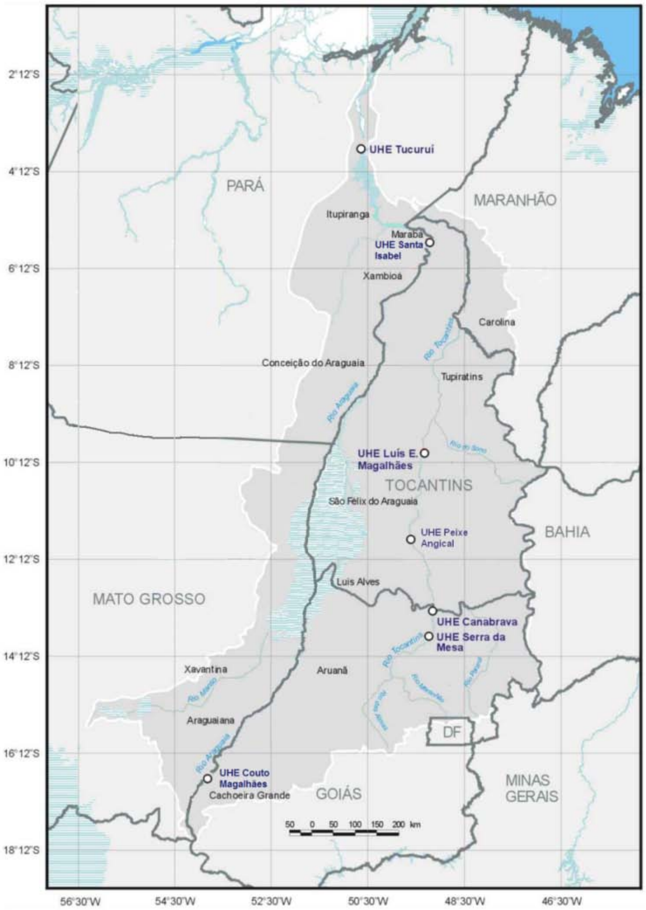

Fig. 2 : Hydropower plant cascade in the Tocantins/Araguaia rivers [8]

IV. THE SISUCA SIMULATION

The results of the simulation performed by SisUca were compared to those obtained by the current approach used by the Brazilian electric sector in order to evaluate whether specific requirements were satisfied and an accurate representation from the perspective of the intended use was achieved. For this purpose, a baseline scenario was defined by considering a period from April 1999 to December 2001. In addition, only the energy generated by Serra da Mesa and Tucuruí was considered, because the other plants were not yet built. In April 1999, the Serra da Mesa active storage represented 57.1% of its full storage capacity, corresponding to a pool level of 448.17 m, while Tucuruí was completely full. The first comparison, shown in Table 3, indicates that when there are no water withdrawals (Quses = 0), both models give roughly the same results.

Table 2 : Characteristics of hydropower plants and reservoirs

Plant	PI (MW)	η	h_{ref} (m)	PL (m)		Storage Capacity (hm^3)		Active Storage Capacity (hm^3)
				Minimum	Maximum	Minimum	Maximum	
SM	1,275	93.0	117.20	417.30	460.00	11,150.0	54,400.0	43,250.0
CB	471.6	91.0	43.60	333.00	333.00	1,906.1	1,906.1	0.0
SS	280.0	90.0	22.66	287.00	287.00	952.0	952.0	0.0
PA	452.1	92.3	27.71	261.00	263.00	2,223.7	2,223.7	0.0
L	902.5	93.3	29.00	212.30	212.30	4,711.1	4,711.1	0.0
CM	150.0	92.0	145.0	620.00	620.00	46.26	46.26	0.0
SI	1,080	93.0	26.20	125.00	125.00	1,850.0	1,850.0	0.0
T	8,365	93.6	63.35	51.60	74.00	11,292.8	50,275.2	38,982.4

Table 3 : Comparison between results of the Brazilian electric sector approach and SisUca

Year	SERRA DA MESA		Difference (%)	TUCURUÍ		Difference (%)
	Energy Generated (MWyear)			Energy Generated (MWyear)		
	Brazilian electric sector	SisUca		Brazilian electric sector	SisUca	
1999	4,578,685	4,992,026	9.03	18,880,344	19,634,464	3.99
2000	6,740,951	6,588,449	-2.26	27,260,754	29,498,730	8.21
2001	6,386,497	5,790,443	-9.33	27,863,160	29,098,968	4.44
Total	17,706,133	17,370,917	-1.89	74,004,258	78,232,162	5.71

It is important to note that while the individual differences shown in Table 3 reach ±9%, when one considers both plants in the cascade and the whole period of three years, the difference goes down to 4.07%.

Another important aspect is that SisUca simulations aim at equalizing the operating flow to the regulated discharge (or Qop = Qreg), while the Brazilian electric sector approach is intended to meet energy demand, thus causing the operating flow to be a function of demand. These results show that SisUca satisfies the energy requirements, despite employing an alternative formulation.

A second simulation was performed for the arrangement presented in Figure 2. Energy losses for the entire Tocantins and Araguaia cascade are shown in Table 4, for different percentages of MSW. The loss in terms of mean energy reaches 7,471 x 10^3 MWyear (12.10%) for a withdrawal of 100% of the MSW and 8,193 x 10^3 MWyear (16.67%) when measured in terms of firm energy.

Table 4 : Cascade energy losses for different amounts of water withdrawals

Percentage of MSW	Tocantins and Araguaia Cascade					
	Mean Energy			Firm Energy		
	Generated (x 10^3 MWyear)	Loss (x 10^3 MWyear)	Loss (%)	Generated (x 10^3 MWyear)	Loss (x 10^3 MWyear)	Loss (%)
0	61,729	0	0	49,148	0	0
25	59,940	1,789	2.90	47,103	2,045	4.16
50	57,979	3,750	6.07	45,046	4,102	8.34
75	56,081	5,648	9.15	42,979	6,169	12.55
100	54,258	7,471	12.10	40,955	8,193	16.67

The SisUca simulations also demonstrate that meeting increasing water demand arising from multiple uses has a direct impact on regulated flows, as Table 5 shows.

Table 5 : Impact of different amounts of water withdrawals on regulated flows

Percentage of MSW	Serra da Mesa			Tucurui		
	Regulated flow (m^3s^{-1})	Regulated flow reduction		Regulated flow (m^3s^{-1})	Regulated flow reduction	
		(m^3s^{-1})	(%)		(m^3s^{-1})	(%)
0	627.96	0	0	3030.65	0	0
25	601.47	26.49	4.22	2699.13	331.52	10.94
50	574.97	52.99	8.81	2367.61	663.04	21.88
75	548.48	79.48	13.82	2036.11	994.54	32.82
100	523.25	104.71	19.09	1706.19	1324.46	43.70

Only the regulated flows of Serra da Mesa and Tucuruí are presented because these are the only plants with reservoirs. The other plants in the cascade (Cana Brava, São Salvador, Peixe Angical, Lajeado, Couto Magalhães and Santa Isabel) are classified as "run-of-the-river", because of their insignificant active storage capacity. The reduction in Tucuruí especially is quite impressive, as it reaches 43.70% when withdrawals attain 100% of MSW.

V. Conclusion

One of the main objectives of water resource management is to assure that sufficient water is available for various uses, but it is not clear how to attain this goal, particularly in the case of hydropower reservoirs, because the withdrawal of water or reduction of inflows lowers the energy that can be generated. Therefore, it is necessary to investigate solutions for better sharing of water resources between power generation and other uses.

In this article, we presented a formulation to address this problem of sharing water among various uses, by introducing a new variable, represented by water withdrawals, limited to the total amount of water available at maximum flow. The aim of the proposed method and the application developed is to enable water resource managers and power sector planners to analyze the evolution of the possible generation losses in function of increased upstream consumption.

As shown, the SisUca model performs quite well in comparison to the traditional approach for operating hydropower plants, when there are no water withdrawals. This indicates that the model seems to be compatible to the reality it proposes to emulate.

For simulations where water withdrawals were allowed, there was, as expected, a reduction of the energy produced in the Tocantins and Araguaia rivers' cascade. Energy losses for the whole cascade ranged between 2.9% to 12.1% in terms of mean energy and 4.2% to 16.7% for firm energy. On the other hand, by prioritizing equality between operation flow and regulated discharge, during the refilling and drawdown phases of reservoirs, the approach presented in this paper attempts to ensure that downstream users get a constant water release from the reservoirs. Thus, there will be an additional amount of water in the downstream river stretch, which in principle could be allocated to various users and uses.

Therefore, SisUca proved to be a useful tool that can help governmental agencies during the process of analysis and granting water rights, providing a way to balance energy generation and multiple water uses, in order to benefit the largest possible number of users.

The model quantified the reduction in generated energy caused by withdrawals. The results show that agreements to meet energy demand can be jeopardized. Utilities should be previously informed of that fact so as to take preventive measures. In that sense, it is very important to establish clear rules, which should prevent penalizations for energy entrepreneurs and the advent of conflicts among users.

Finally, it is important to continuously monitor possible flow reductions or decreases in energy generation and the likely economic impacts - positive and negative - caused by water withdrawals.

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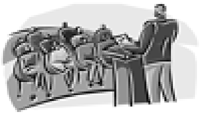

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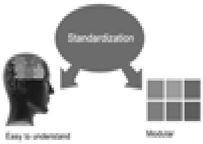

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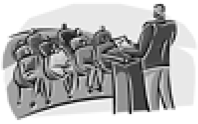

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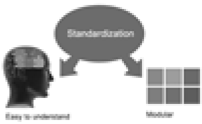

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The summary should be two hundred words or less. It should briefly and clearly explain the key findings reported in the manuscript--must have precise statistics. It should not have abnormal acronyms or abbreviations. It should be logical in itself. Shun citing 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 approach 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. Yet, use comprehensive sentences and do not let go readability for briefness. You can maintain it succinct by phrasing sentences so that they provide more than 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 maintain the initial two items to no more than one ruling each.

- Reason of the study - 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 quantitative data; results of any numerical analysis should be reported
- Significant conclusions or questions that track from the research(es)

Approach:

- Single section, and succinct
- As a outline of job done, it is always written in past tense
- A conceptual should situate on its own, and not submit to any other part of the paper such as a form or table
- Center on shortening results - bound background information to a verdict or two, if completely necessary
- What you account in an conceptual must be regular with what you reported in the manuscript
- Exact spelling, clearness 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 to comprehend and calculate the purpose of your study without having to submit to other works. The basis for the study should be offered. Give most important references but shun difficult to make a comprehensive appraisal of the topic. In the introduction, describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will have no attention in your result. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here. Following approach can create a valuable beginning:

- Explain the value (significance) of the study
- Shield the model - why did you employ this particular system or method? What is its compensation? You strength remark on its appropriateness from a abstract point of vision as well as point out sensible reasons for using it.
- Present a justification. Status your particular theory (es) or aim(s), and describe the logic that led you to choose them.
- Very for a short time explain the tentative propose and how it skilled 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 with every section. If you make the four points listed above, you will need a least of four paragraphs.

- Present surroundings information only as desirable in order hold up a situation. The reviewer does not desire to read the whole thing you know about a topic.
- Shape the theory/purpose 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 sound written Procedures segment allows a capable scientist to replacement 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 for the least amount of information that would permit another capable scientist to spare 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 object, mention the specific item describing a way but draw the basic principle while stating the situation. The purpose is to text 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:

- Explain materials individually only if the study is so complex that it saves liberty this way.
- Embrace particular materials, and any tools or provisions that are not frequently found in laboratories.
- Do not take in frequently found.
- If use of a definite type of tools.
- Materials may be reported in a part section or else they may be recognized along with your measures.

Methods:

- Report the method (not particulars of each process that engaged the same methodology)
- Describe the method entirely
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures
- Simplify - details how procedures were completed not how they were exclusively performed on a particular day.
- If well known procedures were used, account the procedure by name, possibly with reference, and that's all.

Approach:

- It is embarrassed or not possible to use vigorous voice when documenting methods with no using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result when script up the methods most authors use third person passive voice.
- Use standard style in this and in every other part of the paper - avoid familiar lists, and use full sentences.

What to keep away from

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings - save it for the argument.
- 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 a 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. Carry on to be to the point, by means of statistics and tables, if suitable, to present consequences most efficiently.You must obviously differentiate material that would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matter should not be submitted at all except requested by the instructor.

Content

- Sum up your conclusion in text and demonstrate them, if suitable, with figures and tables.
- In manuscript, explain each of your consequences, point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation an exacting study.
- Explain results of control experiments and comprise remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or in manuscript form.

What to stay away from

- Do not discuss or infer your outcome, report surroundings information, or try to explain anything.
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- Never confuse figures with tables - there is a difference.

Approach

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- 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 part.

Figures and tables

- If you put figures and tables at the end of the details, make certain that they are visibly distinguished from any attach appendix materials, such as raw facts
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- Make a decision if each premise is supported, discarded, or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."
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- You may propose future guidelines, such as how the experiment might be personalized to accomplish a new idea.
- Give details all of your remarks as much as possible, focus on mechanisms.
- Make a decision if the tentative design sufficiently addressed the theory, and whether or not it was correctly restricted.
- Try to present substitute explanations if sensible alternatives be present.
- One 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?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

- When you refer to information, differentiate data generated by your own studies from available information
- Submit to work done by specific persons (including you) in past tense.
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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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