Global Journal of researches in engineering
Mechanical and mechanics engineering
Volume 12 Issue 1 Version 1.0 January 2012
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 Print ISSN:0975-5861

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GJRE-A Classification : *FOR Code: 030103*

TWO-PHASE GASLIQUID-SOLID FLOW MODELLING IN 90 BENDS AND ITS EFFECT ON EROSION

Two-phase Gas/Liquid-Solid Flow Modelling in 90° Bends and Its Effect on Erosion

M. R. Ansari [α], S. Mohammadi [Ω], M.Khalaiji Oskouei [β]

Abstract - Sand particles present in the fluid flows extracted from oil wells causes many problems for oil and gas production companies. Collision of sand particles to the wall of oil transfer pipes and process equipment reduces wall thickness which is considered as a cause of erosion. One of the consequences of this problem is frequent failures and loss of valuable production time. Bends installed in the path of oil and gas pipelines are at risk of such erosion as mentioned. This paper is a study of computational fluid dynamics to predict erosion in the bend geometry. It uses Lagrangian approximation which includes modeling of continuous flow of fluid, Lagrangian particle tracking and calculation relating to erosion. In this work, the effect of various parameters such as flow velocity, particle diameter, and bend geometry and particle-fluid density ratio on the particle motion and consequently erosion resulting from the collision of particle to bend wall is studied.

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I. Introduction

Erosion relates to the details of particle moving before and after the collision, accurate prediction of erosion is a very complex problem. Flow transmission and pipeline systems are not always straight; they include bends, T-junctions, joints and connections. This is apparent and problematic in design and application of Heat Exchangers, heaters, boilers, condensers and oil and gas transfer pipelines. Predicting erosion is a combination of fluid flow modelling, Lagrangian particle tracking and application of empirical correlations can be obtained by numerical methods. Flow modelling is used to obtain the flow field geometry and the particle tracking model is applied in order to obtain released particle path in the fluid flow. Particle collision data obtained from the empirical equations presented results in estimates of wall erosion. The above description including numerical and experimental data presents a prediction of erosion in pipes and fittings.

Eulerian and Lagrangian approaches for solid particle tracking have been conducted by some researchers [1 ~ 3]. Durst and et al. analyzed two approaches and then compared them with each other [4]. They found that the Lagrangian approach has many benefits on particle tracking in high velocities in compare to Eulerian approach. The particle tracking calculation has been conducted by several investigators [5 ~ 11]. Different forces act on a solid particle during its movement in the fluid. These forces determine the particle course in the fluid. Machaelides presented basic equation for hydrodynamic force acting on a spherical particle accelerating from a stationary state inside a fluid [6]. This equation is valid for low velocity and high acceleration; however it was not applicable for a restricted Reynolds numbers of a particle. There is a general method to overcome this restriction. This could be conducted by defining experimental coefficient especially for drag at steady-state condition. Hamilton and Odar defined these coefficients [6].The mentioned equation can be only used for a particle in the stationary liquid. There are other forces affected on particle moving through fluid. They used the force generated from the pressure gradient as a required force for accelerating the equal volume fluid substituted with particle during its absences. Clift and et al. presented this force in the general form [7]. Two lift forces effect on a particle in the fluid. Magnus force forms from particle rotation at low Reynolds number can be resulted from the non linear terms of Navier-Stokes equations. Jayanti and Hewitt presented the related Magnus force formula [11]. Saffman declared that a small sphere in a laminar shear flow senses a lift force in perpendicular direction to the flow field that is known Saffman force [8]. The other forces effect on a particle are volumetric forces related to gravity and buoyancy forces. Some of the mentioned forces can be neglected in some conditions with acceptable accuracy. Meng and Van der Geld studied on mentioned forces and compared their numerical values. They concluded that the Saffman force can be neglected because of its small value [9]. The added mass force can be included in the calculation when the particle is big. In the present article, the Saffman force was not included in the erosion calculation because of its small value.

Recently, some research has been conducted on erosion in pipe bends. Edward et al. used the commercial CFD code of CFX for erosion prediction due to a particle impact by applying appropriate procedure [12]. The erosion model of Ahlart and its extension by McLauray (1996) was used for prediction of erosion for Aluminum [13]. Also, they used LDA method for measurement of flow in the bend in order to validate

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their theoretical obtained results. Comparison of the model results with experimental results shows a reasonable agreement.

Keating and Nesic were studied a 180-degree bend using the commercial CFD code PHOENICS with a separate code for tracking a particle by Lagrangian method in 2000 [14]. They compared their results for flow field with experimental results and showed that their results are valid. However, they used the upgraded model of Finnie, but no comparison or suggestion was given. Hansen and Petal used PHOENICS code to study erosion in bends of air lifting channels [15]. Their work is somehow different with the other recent studies. They also investigated the scratch shape by erosion. Zhong and Hengshuan worked on rectangular cross section bends, two dimensional non viscous flow with and without secondary flow in 1990 [16]. They also used the Finnie model for erosion prediction. Wang and Shirazi studied erosion on 90° bends in 2003 [17]. They compared their numerical results with the experimental result of Eyler conducted for penetration rate in 1987. Even though their results have enough accuracy, however, they showed that their analysis differs from experimental results. They found the reason behind this, is that the particle flow rates is high in most of the experiments. They also found in long radius bends the erosion rate reduces as the main flow is gas. In the case of liquid flow, they showed that the squeeze film, secondary flow and an oscillation generated from turbulence flow has important role on the erosion rate. In addition, the authors presented a 1st order approximate correlation based on CFD analysis for engineering calculation to estimate the bend radius effect on erosion in long-radius bends.

Fashami worked on particle motion at outside of a pipe and its effect on erosion at outer surface of the pipe [19]. The objectives of this paper is a single particle trace in a two dimensional bend, determining of velocity and impact angle with bend wall and finally prediction of erosion rate by using an erosion model. A statistical study of the most probable impact location in the bend will be presented. With respect to the fore mentioned points, the solution procedure will be as follows:

- Obtaining the flow field in the bend
- Particle tracking in the flow field of the inside of the bend obtained from the previous part
- Obtaining the required information of the particle impact on the wall and erosion probability rate calculation.

II. The Governing Equations

a) The continues phase

For modelling of incompressible steady-state flow in the polar coordinate system in the radial and tangential directions, the mass and momentum conservation equations are as [20]:

$$\frac{1}{r}\frac{\partial ru}{\partial r}+\frac{1}{r}\frac{\partial v}{\partial \theta}=0 \tag{1}$$

$$u\frac{\partial u}{\partial r}+\frac{v}{r}\frac{\partial u}{\partial \theta}-\frac{v^2}{r}=-\frac{1}{\rho}\frac{\partial P}{\partial r}+\nu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial ru}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial v}{\partial \theta}\right] \tag{2}$$

$$u\frac{\partial v}{\partial r}+\frac{v}{r}\frac{\partial v}{\partial \theta}+\frac{uv}{r}=-\frac{1}{\rho r}\frac{\partial P}{\partial \theta}+\nu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial rv}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial u}{\partial \theta}\right] \tag{3}$$

u and v are the velocities at radial and tangential direction, respectively.

b) The discrete phase

The particle velocity equation at tangential direction is:

$$\frac{dv_P}{dt}=F_k\left(v_f-v_P\right)-\left(1-\frac{\rho_f}{\rho_P}\right)g_\theta-\frac{u_P v_P}{r_P} \tag{4}$$

The last term of the RHS of the above equation is the quasi coriolis force caused by the curvature effect of polar coordinate system on the particle.

The particle velocity on radial direction is:

$$\frac{du_P}{dt}=F_k\left(u_f-u_P\right)-\left(1-\frac{\rho_f}{\rho_P}\right)g_r+\frac{v_P^2}{r_P} \tag{5}$$

The last term of the RHS in the above equation is the centrifugal force effecting on the particle at the radial direction. F_k is the momentum transfer coefficient between the particle and fluid and can be obtained from:

$$F_k=\frac{18\mu}{\rho_P d_P^2}C_D\frac{Re_P}{24} \tag{6}$$

To calculate the drag coefficient, Wang and et al. declared an equation as presented by the following in 2003 [21]:

$$C_D=\begin{cases}\dfrac{24}{Re_P} & Re_P\le 1\\[2ex] \dfrac{24\left(1+0.15Re_P^{0.687}\right)}{Re_P} & 1<Re_P\le 1000\\[2ex] 0.44 & Re_P>1000\end{cases} \tag{7}$$

In the above equation, the drag coefficient is a function of the particle Reynolds number and is defined as:

$$Re_P = \frac{\rho_f d_P \left|\vec{V}_f - \vec{V}_P\right|}{\mu_f} \qquad (8)$$

c) Erosion model

At the present work, the model suggested by Wallace and Peters for erosion estimation is selected. They declare their equation by using the formula found experimentally by Neilson and Gilchrist in 1968 as [10]:

$$\begin{cases} E\times 10^{-6} = \dfrac{1}{N_P}\left[\dfrac{(1/2)\left|\vec{V}_P\right|^2 \cos^2\alpha \sin 2\alpha}{\gamma} + \dfrac{(1/2)\left|\vec{V}_P\right|^2 \sin^2\alpha}{\sigma}\right]; \alpha \le 45^o \\ E\times 10^{-6} = \dfrac{1}{N_P}\left[\dfrac{(1/2)\left|\vec{V}_P\right|^2 \cos^2\alpha}{\gamma} + \dfrac{(1/2)\left|\vec{V}_P\right|^2 \sin^2\alpha}{\sigma}\right] \quad ; \quad \alpha > 45^o \end{cases} \qquad (9)$$

In this equation, E is the erosion rate and its unit is mm3/gr. γ and σ are the cutting wear and deformation wear coefficient and are related to material properties or the body material specification. For carbon steel, their values are 33316.9 and 77419.7

III. Numerical Solution Procedure

To solve continuous phase equations, the solution domain is divided to a large number of control volumes and then discredited equations are solved using the finite volume method. The details of the solution process have been presented by Patankar [22]. It should be noted that SIMPLE algorithm is used for decoupling of pressure and velocity. The grid size becomes finer near the bend wall as shown in Fig. 1.

To demonstrate mesh independency of the numerical results, the tangential velocity at the radial cross-section of the bend is shown in Fig. 2.

The figure shows that the developed code mostly behaviour independent of grid and mesh 40*40 is used because of formation of a complete curvature in the bend area.

Also, Fig. 2 can be applied for validation of continuum phase solution that needs to solve of Navier-Stokes PDEs. It has been observed that velocity in the centre line of channel reaches to 1.5 times of fluid average velocity (Fluid input velocity). This result has a good agreement with presented analytical solutions in the flow solution references [20]. See Fig. 3 for the bend curvature grid configuration.

For equations solution of the particle, the Range-Kutta of fourth order is applied.

IV. Results and Discussion

Since Stokes number is used in the solution method, a brief definition is given as ratio of the particle response time to fluid time-scale characteristic. The Stokes number is related to three parameters as:

- Densities ratio
- Second order of the particle diameter to hydraulic diameter of channel ratio
- Reynolds number of fluid flow

In modelling of the particles motion the following assumptions are used:

- Particles have spherical shape
- The surface roughness is not included in the calculation

In this paper the collision probability of particle at different area of the bend is considered first and then obtained results are used for erosion estimation by particle. The particle track is presented for different Stokes numbers. The continuous phase is considered for two different fluids as water and air. The Reynolds numbers for the both air and water are kept same and in the laminar flow range. It should be mentioned that the density ratio is bigger than one for air and water cases. In all calculation cases the particle is started to move from the stationary condition and from the centre of distance between of the two side' walls and slightly before the bending start. See Fig. 4.

The results analysis show:

By comparing the particle path for the same Stokes numbers in air and water the results showed that the liquid cannot move (push) the particle in the flow direction and the particle changes its direction at the first half of the bend because of low flow velocity. Reynolds number is the same in both cases and assumed at laminar flow condition. It was concluded that the Stokes number is not a suitable parameter for comparison of a particle movement in two different fluids.

Comparison of particle collision location (point) in a fluid for different Stokes numbers showed that as Stokes number increases the particle impact at smaller angle of bend increases. To analyze this finding, it must be mentioned that the all three effective parameters of Stokes number have direct dependency with the particle inertia. In this paper the Reynolds number are kept constant and at the laminar flow area, thus the Stokes number change can be obtained by the change of two first parameters. So, by increasing Stokes number, the particle inertia increases and the particle have more tendencies to keep its movement direction without following the flow stream lines. This makes the collision angle reduces in the bend.

The other important parameter studied in this paper is the impact probability of particle at different location of bend. For this purpose change of the main three parameters of Stokes number as Reynolds number of the fluid flow, the particle diameter and the densities ratio were considered and presented in the following figures.

Fig. 5 shows the particle impact probability at different bend angle for different Reynolds number in the laminar flow field and density ratio of higher than one. With the mentioned conditions and knowing that the impact is in inner wall in density ratio greater than one, the most impact is happened between 0 up to 30°. The probability of not impacting in the bend wall and pass the bend is less than 10 percent.

Fig. 6 shows the particle impact probability at different location of bend for the different particle diameter from 50 to 500 microns. It shows that the particles with smaller diameter have higher probability to pass the bend without impact.

Fig. 7 shows the particle impact probability at different location of bend when the densities ratio changes from 100 to 700. The most impact probability happens at angles between 60 to 90°.

Finally, based on superposition of all probabilities and the final result for the particle impact probability at different bend location with respect to Stokes number it was concluded that the result for the all three location is almost similar. However, at 30 to 60° the impact is slightly lower than the other impact angles and the most impacts happens at the outer area of this zone, see Fig. 8. The velocity and the impact angle on the bend surface with respect to Stokes number were calculated and presented in Figs. 9 and 10 These figures show as the Stokes number which is particle inertia characteristic increases the impact velocity of the particle against the wall increases, but the impact angle (the tangent line direction at the same point on the bend wall) decreases. For the lower Stokes number (e.g. smaller diameter of a particle), the particle inertia is lower, so the particle can respond faster for velocity value changes near the wall that its result is lower impact velocity. On the other hand, the particle direction change in respect to wall will be delayed which cause the bigger impact angle.

The erosion rate by the particle impact, as mentioned before was estimated from Wallace and Peters' model declared in 2000. On this basis the volumetric erosion rate for a unit mass of eroded material (eroded carbon steel) was calculated by equation 9 and shown with respect to Stokes number in Fig. 11. The impact angle of particle at the bend was also shown on the same figure.

As it can be noticed from the figure, by increasing the Stokes number the particle inertia increases, so the particle deviate from its path at smaller angles and impacts the wall with higher inertia that means the erosion rate will increase.

V. Conclusion

In the present research, CFD simulation conducted on two-phase gas/liquid-solid flow in the bends by using two dimensional conservation equations at steady-state conditions. Different parameters of two-phase flow and the bend geometry and their effect on each other were considered by developing a computer code and finally the erosion rate on the wall were predicted. The following points were concluded:

- The main parameter for the study of particle motion within the fluid, which is the Stokes number, depend on flow Reynolds number, particle to fluid density ratio and the ratio of particle diameter to channel hydraulic diameter. As a result, with increasing Stokes number the particle inertia increases.
- As the Stokes number increases, the particle inertia increase will be resulted. So, the particle deviation from the flow direction and the probability of impact with wall will be increased.
- The angle of impact depends on the particle inertia and can be between 20° to 90°.
- The Stokes number for the condition that the particle can move through the bend without impacting the wall is different for the density ratio of bigger than one and smaller than one and should not be used for comparison basis.
- The erosion rate obtained from the particle impact with wall at higher Stokes number is bigger because of higher particle inertia and this happens mostly at smaller angles of the bend.
- The erosion increases with increasing the impact velocity and decreases with increasing the approach angle.

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Figures

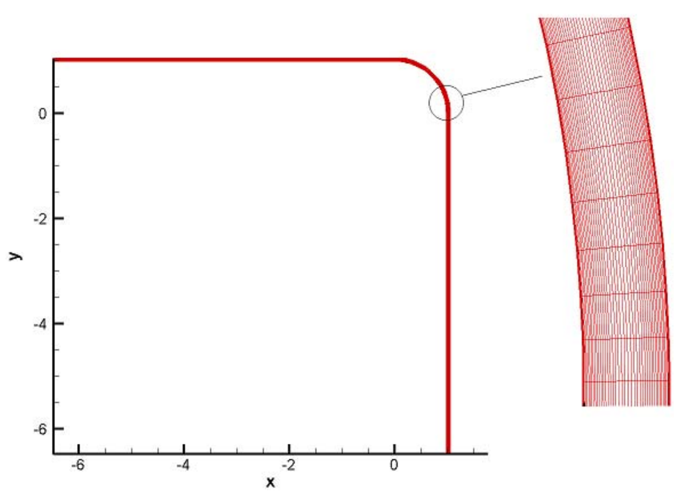

Fig. 1 : Grid configuration for flow field equations solution

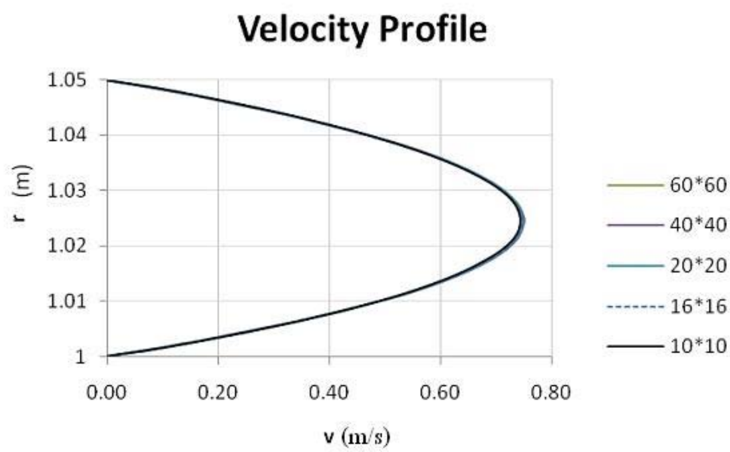

Fig. 2 : Velocity profile for grid independency study using different meshes

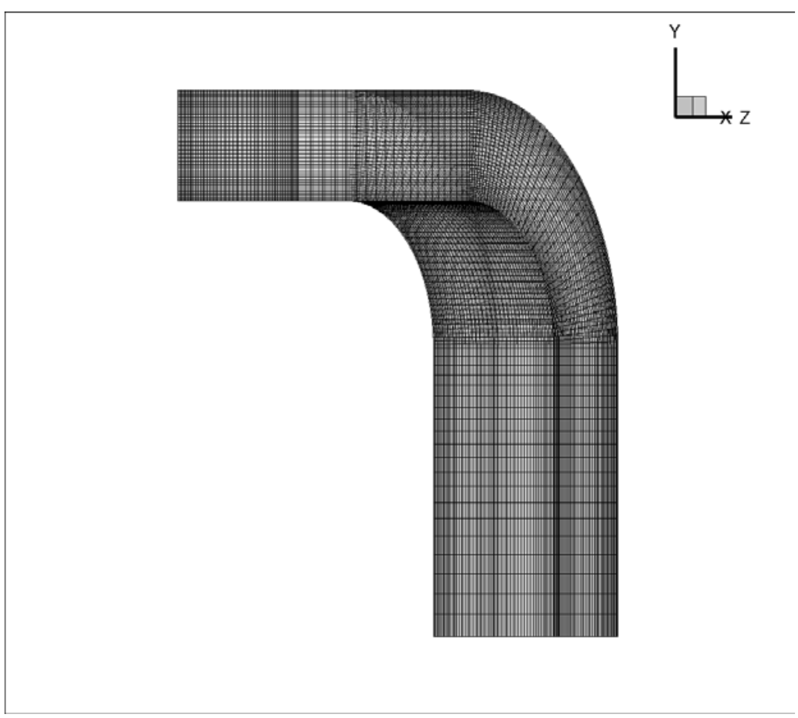

Fig. 3 : The bend curvature mesh configuration

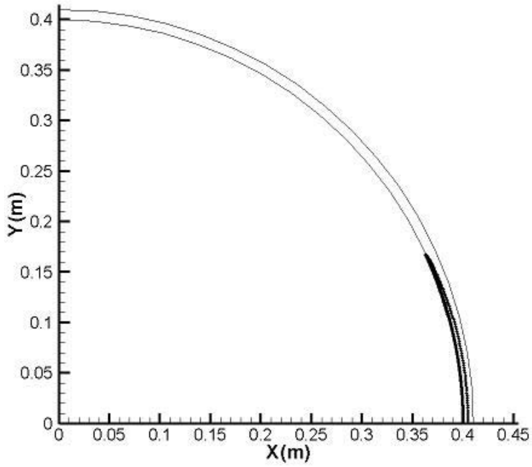

Fig. 4f, St=0.34

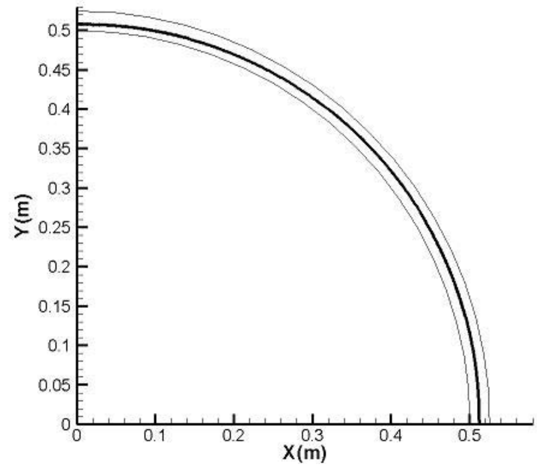

Fig. 4a, St=0.34

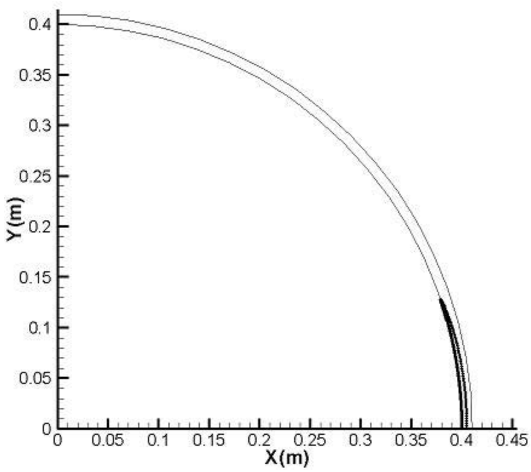

Fig. 4g, St=0.78

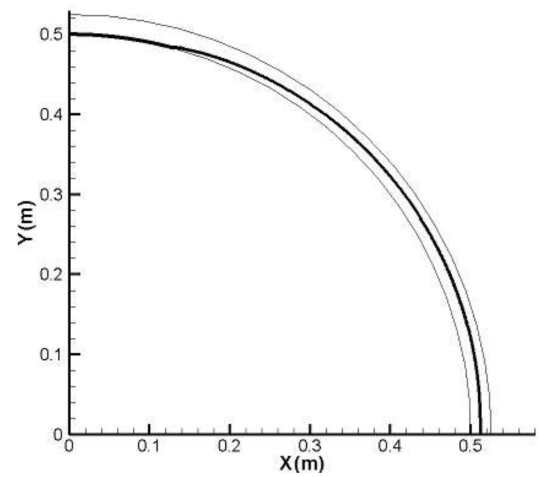

Fig. 4b, St=0.78

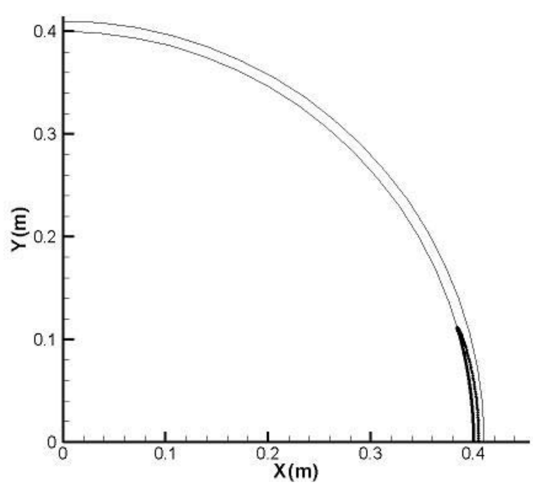

Fig. 4h, St=1.1

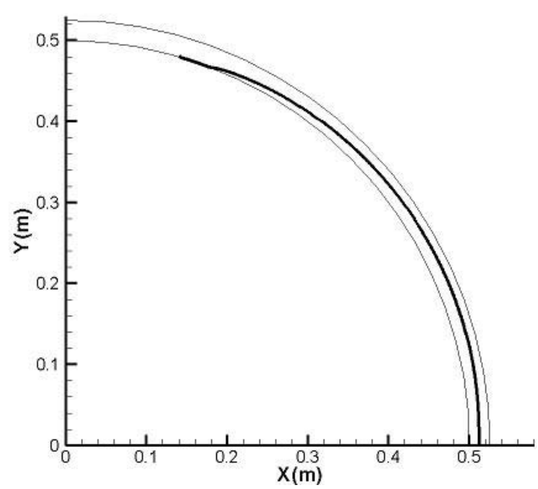

Fig. 4c, St=1.1

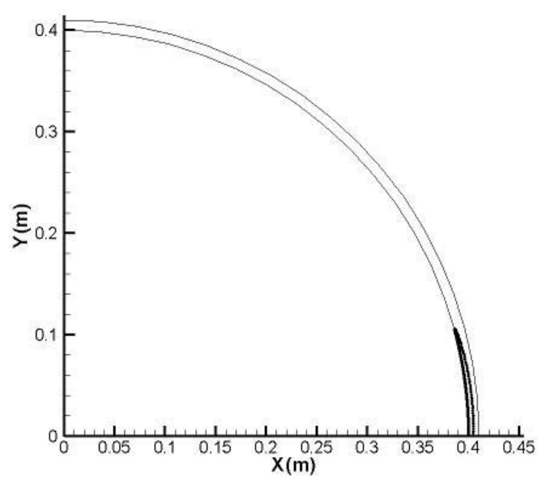

Fig : 4i, St=1.27

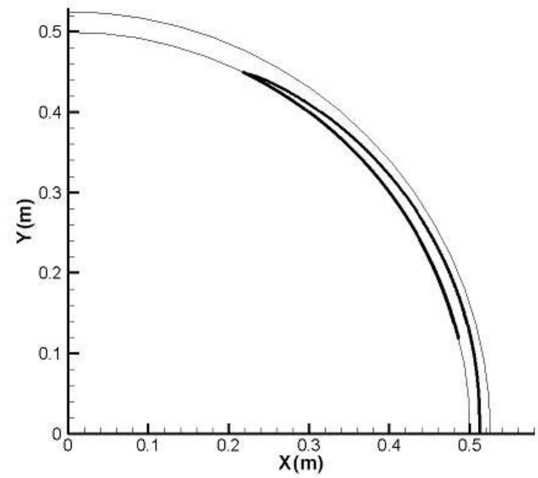

Fig : 4d, St=1.27

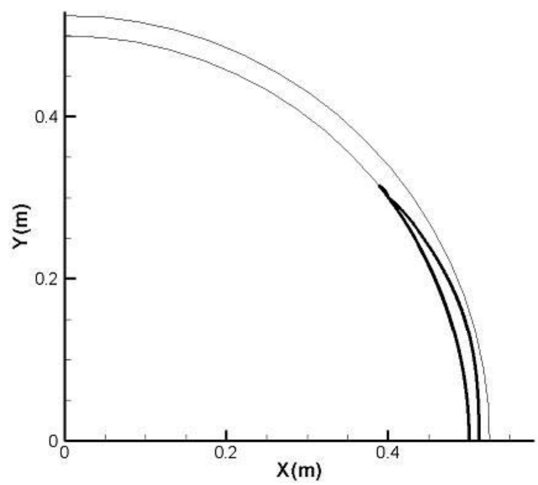

Fig : 4e, St=5

Fig. 4 : Particle movement path inside the bend for different Stokes number of 0.34, 0.78, 1.1, 1.27 and 5; a, b, c, d and e for air and f, g, h and i for water

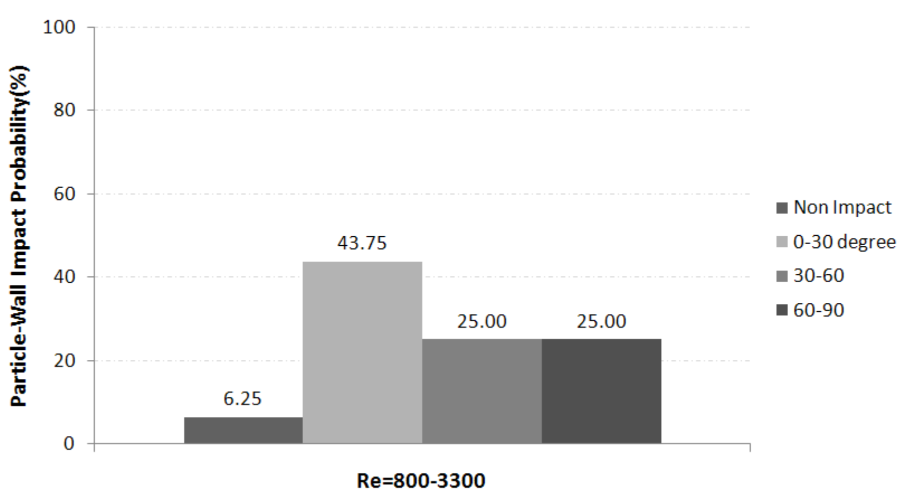

Fig. 5 : The particle impact probability at different area of bend wall by changing Reynolds number

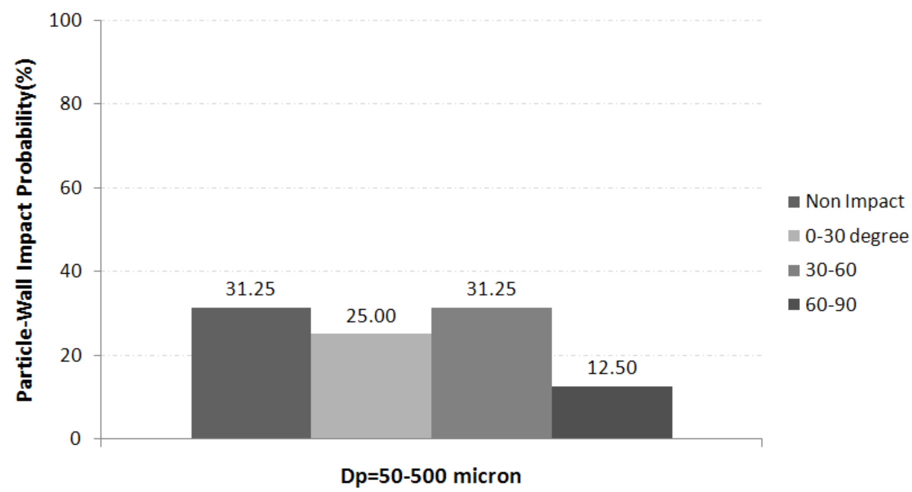

Fig. 6 : The particle impact probability at different area of bend wall by changing the particle diameter

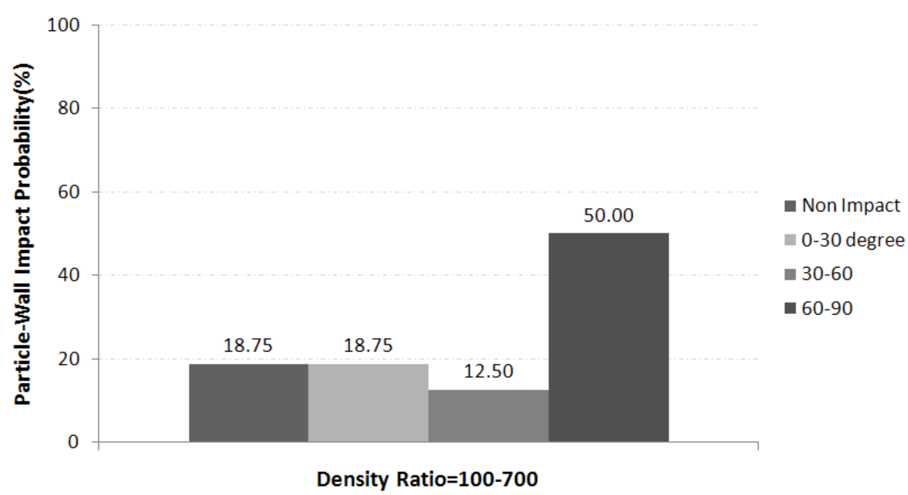

Fig. 7 : The particle impact probability at different area of bend wall by changing the density ratios

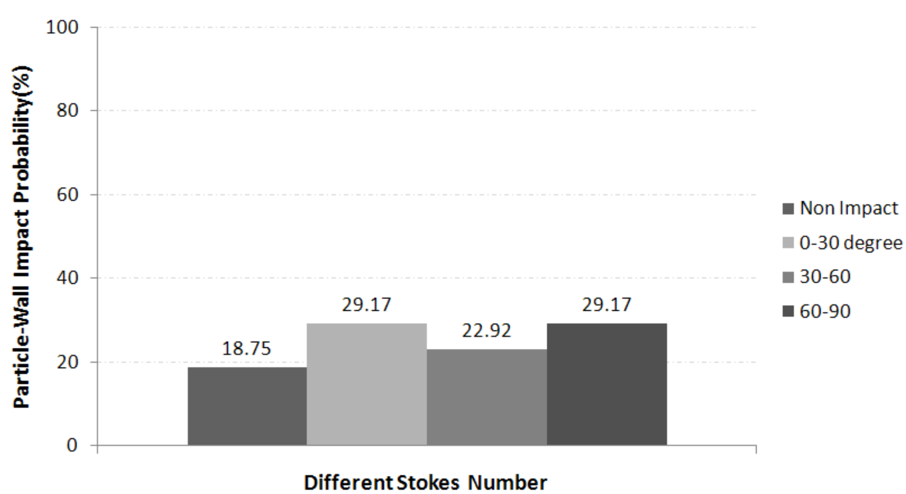

Fig. 8 : The particle impact probability at different area of bend wall for different Stokes number

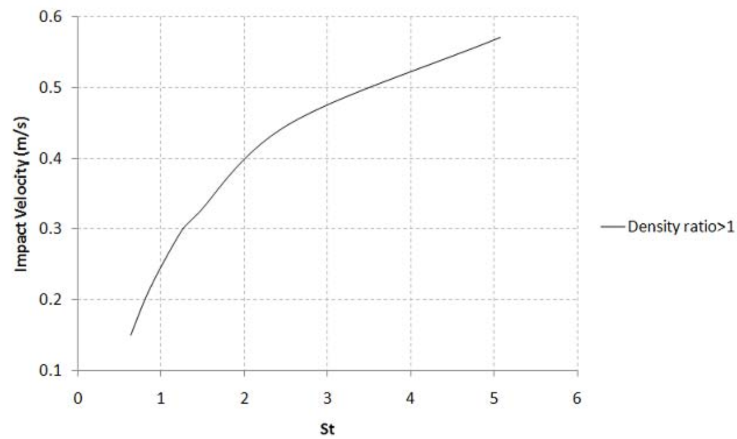

Fig. 9 : The particle impact velocity with the bend surface for different Stokes number considering the density ratio is bigger than one

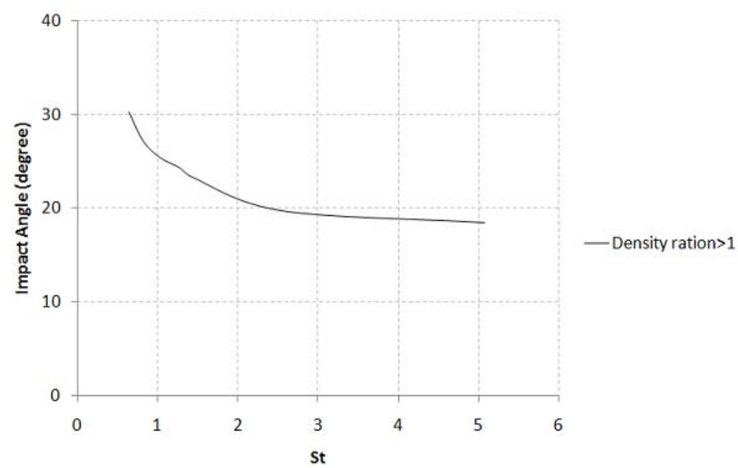

Fig. 10 : The angle between the particle impact direction and the tangent to surface at the bend wall during the particle impact for different Stokes number considering the density ratio is bigger than one

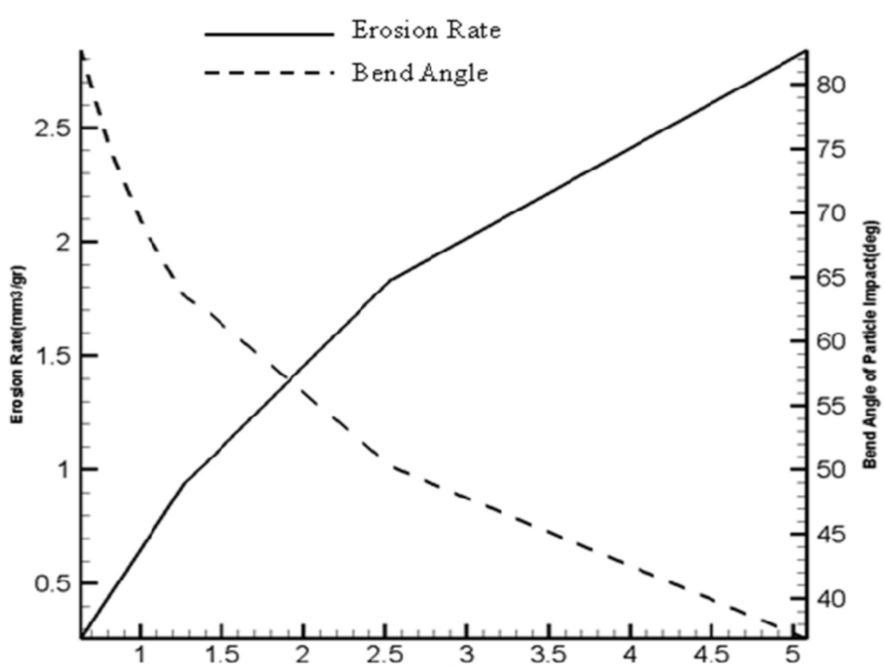

Fig11 : The particle impact angle and the erosion rate at the bend for different Stokes number