Computational Fluid Dynamics Study of the Effects of Secondary Flows in 90-degree Pipe Elbow Erosion

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Abstract

Computational fluid dynamics (CFD) of particle-laden fluid flows through a 90-degree pipe elbow at Reynolds numbers 1,000 and 10,000 were completed; for different dimensionless elbow curvature ratios of 1.0, 1.5, and 2.5; and for particles with different Stokes numbers of 0.01, 0.1, 0.5, 1.0, 5.0, and 10.0. There were two scenarios in the study. For the first, the particles felt drag from the primary (or the axial) flow as well as from the secondary fluid flows in the elbow. For the second, the secondary fluid flow in the 90-degree bend was suppressed from the particle drag, thus the particles only felt the flow in the axial direction of the flow. These simulation scenarios were made to analyze how suppressing the secondary flow could cause less erosion in the 90-degree bend of the pipe when compared to the particles feeling both the primary and secondary flows of the fluid. The results show that secondary flows do not affect much the erosion when the particle Stokes number is high (close to 10). On the other hand, when the Stokes number is less than one, a significant 20% to 50% reduction on the erosion is observed after secondary flows were removed.

Introduction

There are many processes in industry where a fluid transported through pipelines carries particles within it. The particle interactions with pipe walls might create excessive erosion in the pipe that could cause major financial losses. Even though it is an important problem, current state of the knowledge is still far from having a full picture of the erosion phenomena in pipelines and even farther from having a robust erosion prediction model. Erosion prediction studies can be classified in three groups: erosion model developments, experimental investigations, and numerical simulations (Badr *et al*., 2005). Several theoretical erosion models have been developed experimentally over the years and they have served as the backbone of numerical studies. The most famous models date over more than 40 years (and are still currently in use) (Finnie, 1958; Bitter, 1963; Tilly, 1973). There are more recent correlations but are basically modifications of the old ones (Nesic, 1991; Chase *et al*., 1992; Jordan, 1998; Shirazi, 2000). In those models, the erosion rate depends on the particle and wall material characteristics, and the angle and speed of the incident particle. Although it has been recognized that the fluid-particle interactions play an important role in understanding particle impact erosion, the authors of the models focused almost exclusively in the material properties (Humphrey J.A.C, 1990). Furthermore, there are recognized limitations in the experimental techniques and the numerical techniques to study erosion, which in turn have not allowed for a fully fundamental study of the erosion mechanism including the fluid motion effect (Humphrey J.A.C, 1993).

In an effort to start untangling the complex fluid-particle interactions that lead to erosion in 90-degree pipe elbow, in this paper we present the results of a CFD study of particle-laden fluid flows through a 90-degree pipe elbow with different dimensionless elbow curvature ratios; and for particles with different Stokes numbers. Recognizing that the flow in a pipe elbow is composed by and axial flow (along the elbows centerline) and secondary flows (perpendicular to the elbow centerline), two simulation scenarios were made to analyze how suppressing the secondary flow could cause less erosion in the 90-degree bend of the pipe when compared to the particles feeling both the primary and secondary flows of the fluid.

Physical and Numerical Model

The physical domain consists of a circular pipe with 3 sections (as shown in figure 1). The first section consists of a straight part with a length long enough to allow the flow to fully develop, then a section of elbow of 90° with a radius of curvature r_o and finally the last section as straight square pipe of same length as the inlet pipe (long enough to eliminate any outlet boundary condition effect on the elbow flow). The dimensionless radius of curvature (ratio of r_o and D) were varied as 1.0, 1.5, and 2.5.

COMSOL Multiphysics was the commercial software used in this work, specifically the fluid flow and particle tracing modules were used. As in any computational fluid dynamics study, the governing equations are based in the three fundamental principles: conservation of mass, conservation of momentum and conservation of energy. Throughout this study, no energy balance was considered as isothermal conditions were assumed. The mathematical model consists of the set of Navier-Stokes equations and continuity equation. Two cases were studied, one laminar (Re=1,000) and one turbulent (Re=100.000). For the turbulence model, a k-ε model was used. At the inlet, a predetermined velocity value was imposed (that matched the Reynolds number). A prescribed value of 0 Pa was set at the outlet. Given that the flow in a pipe is symmetrical, only half of the geometry was simulated and a symmetry boundary condition was imposed.

A mesh sensitivity analysis was performed regarding to the size of the elements and the wall mesh resolution to minimize mesh numerical error. The selected mesh produced differences up to 4% when compared to a coarser mesh. The distribution of the domain elements and the wall elements were adjusted to achieve a y+ less than 11 (viscous units).

Particle transport modeling was performed through the Particle Tracking interface, which provides a Lagrangian

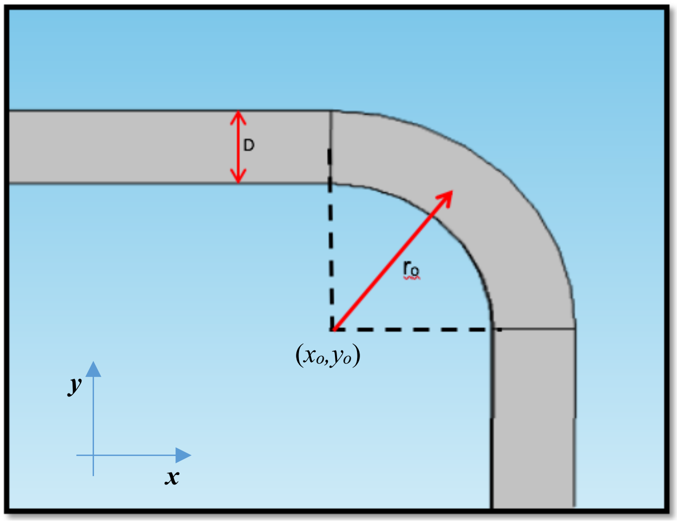

Figure 1. Typical Domain in the Study.

description of the dispersed phase by solving a set of differential equations based on Newton's second law. The drag model used was the Schiller-Naumann. The coupling of the particles of the sand was one-way coupling, which implies that the dispersed phase does not displace the volume that should occupy the fluid.

The particle characteristics were varied by adjusting the particle Stokes number (St). This value allows to obtain a general idea of the advection tendency of the particles with a flow. The smaller the number of Stokes, the more the particles will exhibit a behavior closer to the perfect advection by the fluid flow. The Stokes number was calculated by the following relationship:

$$\mathrm{St} = \frac{\tau_p V}{L} \tag{1}$$

where L is the characteristic length of the flow of interest, for the present study it was chosen to be the elbow arclength since the particles feel the secondary flows along the elbow. V is the average fluid velocity. The ratio L/V represents the characteristic time of the fluid relevant to the phenomena, while τ_p is the characteristic time of the particles, which can be calculated by:

$$\tau_p = \frac{\rho_p d_p^2}{18\mu_f} \tag{2}$$

ρ_p and d_p are the density and the diameter of the particle, and μ_f is the fluid viscosity. The particle density was the modified value to match the Stokes number of interests.

Gravitational forces were neglected and thus also buoyancy forces. At the outlet, the condition was set to make the particles disappear and the wall of the pipe was set to freeze (required COMSOL condition to compute erosion). As for the symmetry plane, a pure rigid-body bounce condition was used. The particles were introduced at the fluid inlet but through a 50% concentric reduced area. This was done to minimize the number of particles touching the inlet pipe walls as the objective was for the particles to reach the elbow before hitting any wall. The particle mass flow rate small enough for the one-way coupling assumption to be valid. The inlet velocity of the particles was set to the same as that of the fluid.

The Finnie model was used when calculating the resulting erosion in the elbow. As it has been mentioned, in order to study the effect of secondary flows in elbow erosion, there were two scenarios in the study. For the first (called "full flow" case), the particles felt drag from the primary (or the axial) flow as well as from the secondary fluid flows in the elbow. For the second (called "no secondary flow" case), the secondary fluid flow in the 90-degree bend was suppressed from the particle drag, thus the particles only felt the flow in the axial direction of the flow. For the former, the "fluid flow velocity components" felt by the particles (u_p, v_p, w_p) in the whole domain were set to be equal to the actual "fluid flow velocity components" (u, v, w). For the later, while the particles feel the full fluid flow in the inlet and outlet pipes, for region of the pipe elbow the "fluid flow velocity components" felt by the particles (u_p, v_p, w_p) follow this set of equations:

$$u_p = u\frac{(y-y_o)^2}{(x-x_o)^2+(y-y_o)^2} - v\frac{(x-x_o)(y-y_o)}{(x-x_o)^2+(y-y_o)^2} \tag{3a}$$

$$v_p = u\frac{(x-x_o)(y-y_o)}{(x-x_o)^2+(y-y_o)^2} - v\frac{(x-x_o)^2}{(x-x_o)^2+(y-y_o)^2} \tag{3b}$$

$$w_p = 0 \tag{3c}$$

They remove mathematically the secondary fluid flow presence from the particles' perspective and leaves the primary fluid flow only (in the axial direction of the pipe elbow).

Results and Discussion

Besides from the particle and pipe material, the erosion depends on the velocity and the angle of incidence of the particle at the moment of impact against the elbow wall. Thus, the results have been organized into three groups of graphs for different fluid Reynolds numbers, nondimensional elbow radius of curvatures, and particle Stokes numbers. Figure 2 presents the particle angle of incidence and in figure 3 the particle impact velocity is shown. The erosion was observed through the maximum erosion value occurring at an elbow location. Figure 4 shows the ratio of those maximum erosion values for the "no secondary flow" and "full flow" cases. This ratio provides the fraction of the total erosion that is due to the primary flow (axial flow) only. The reciprocal would be the fraction of the total erosion that is due to just secondary flows.

It is important to point out that it was intended to use low particle Stokes numbers (St), however for St less than 0.5 (and in one case for that specific value) the particles followed the fluid flow in a way that caused them to never contact the pipe elbow. Thus, no particle impact (therefore no erosion) was observed. Perhaps the reduced concentric particle release area is the reason for it. This will be further studied at a later time.

In figure 2, it can be observed that when the particles Stokes number is equal to unity or it is less than that, the angle of incidence reduces when the secondary flow is not felt by the particles. This indicated that the secondary flows clearly influence the particle trajectory once in the elbow. For large Stokes numbers, the particles are not affected by the secondary flow and their trajectory solely depends on the principal flow.

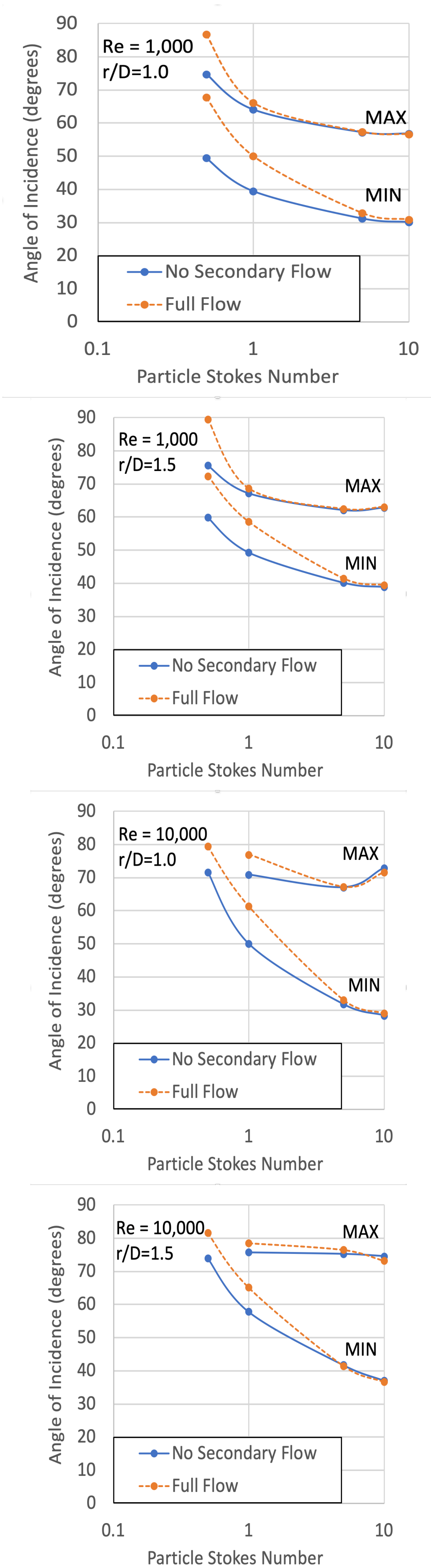

Figure 2. Angle of Incidence for the "No Secondary Flow" and the "Full Flow" Cases for Different Reynolds Numbers and Elbow Radius of Curvature. The maximum and Minimum Values of the Angle of Incidence are Shown. The Case for r/D=2.5 Shows Similar Behaviors.

Also note that the angle of incidence increases for lighter particles, which helps reducing the erosion. The erosion should be more pronounced for intermediate angles: at 0 and 90 degrees of angle of incidence, the particle does not tear pipe material at the moment impact, thus no erosion is supposed to happen.

As seen in figure 3, similar behavior is noted in figure 3 where the impact velocity reduces when the secondary flow is not felt by particles with Stokes number less than one. The reduction is more pronounced for the observed minimum impact velocity, from about 12% for r/D=2.5 to about 20% for r/D=1.0. When comparing the reductions in angle of incidence and impact velocity shown in figures 2 and 3, secondary flows seem to have a larger impact in the particle angle of incidence.

Finally, regarding the maximum erosion ratio shown in figure 4, it can be inferred that the secondary flows in elbows have a large impact in the erosion, especially for particle Stokes numbers less or equal to one. For large Stokes numbers the maximum erosion ratio is one within a 2% to 5%. Further studies will be carried on for the cases of larger Reynolds number and large elbow radius of curvature where the secondary flows seem to become important in the erosion.

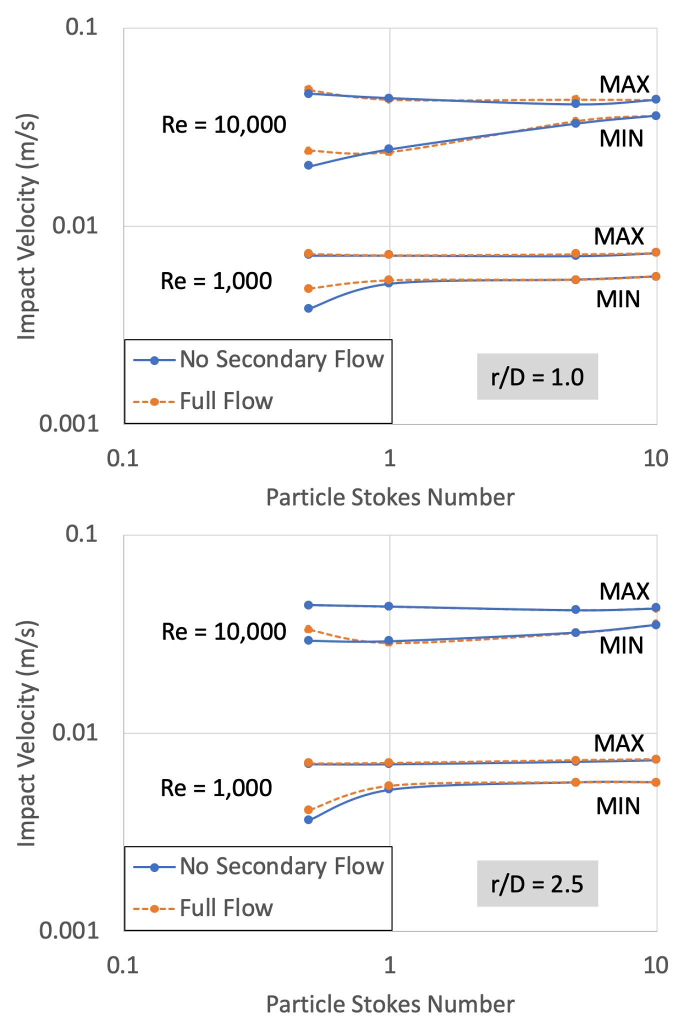

Figure 3. Impact Velocity for the "No Secondary Flow" and the "Full Flow" Cases for Different Reynolds Numbers and Elbow Radius of Curvature. The maximum and Minimum Values of the Impact Velocity are Shown. The Case for r/D=2.5 Shows Similar Behaviors.

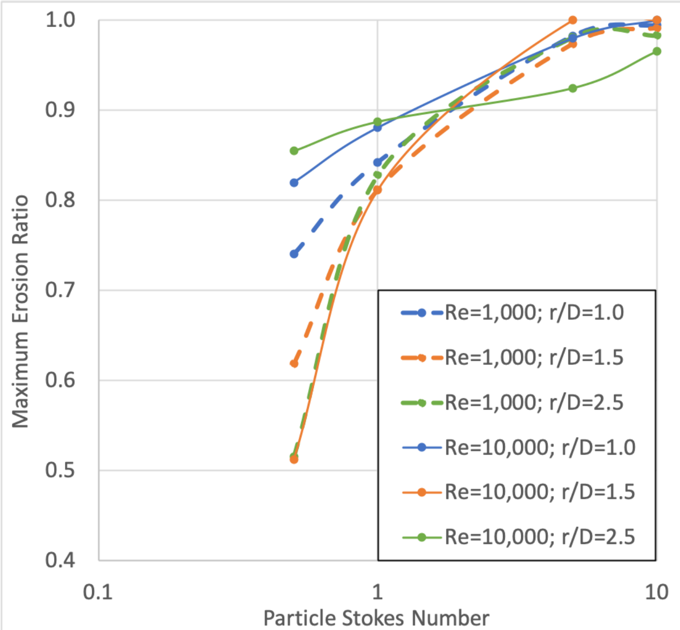

Figure 4. Ratio of the "No Secondary Flow" Case Maximum Erosion to the "Full Flow" Case Maximum Erosion.

In general, as the radius of curvature increases, the effect of secondary flow in the elbow erosion is stronger. This is because at larger r/D the principal flow is less effective at dragging the particle against the outer section of the elbow where the erosion occurs. On the other hand, as the Reynolds number is increased, the main flow does a better job at bringing the particles against the elbow wall.

As it was observed in all the results, the particle Stokes number equal to one is critical in the analysis of the effect of the secondary flows in particles erosion. This value is consistent with other studies of particle laden flows where phenomena such as particle clustering has been observed to pick at Stokes number equal to one.

Conclusions

The results show that secondary flows do not affect much the erosion when the particle Stokes number is high (close to 10). When the Stokes number is less than one, a significant 20% to 50% reduction on the erosion is observed and it seems to largely be due to the effect of the secondary flow on the angle on incidence. The magnitude of this erosion reduction depends on the Reynolds number and radius of curvature. This study serves as a preliminary insight to the effects of curvature ratio, Stokes number, and Reynolds number in relation to the significance of secondary fluid flow on erosion in a 90-degree pipe elbow.

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Acknowledgements

Acknowledgment is made to the donors of the American Chemical Society Petroleum Research Fund for support of this research.