CFD simulation and 2-D modeling of solid particle erosion in annular flow

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ABSTRACT

In oil and gas production, annular flow is a common flow regime found in wells and pipelines. Predicting erosion in multiphase flow is a challenging task as so many factors and phase interactions are involved. Computational Fluid Dynamics (CFD) offers a way to predict multiphase flow erosion. This present work shows how this state-of-the-art erosion model is applied to a 3 inch elbow to calculate erosion under annular flow conditions and how an improved 2-D model is developed for calculating erosion in annular flow for elbow geometries. The CFD predicted results are compared with experimental data and good agreement is observed. Flow solution from CFD and collected erosion data are also utilized to improve a 2-D model for annular flow application. It is shown that the combined CFD and 2-D model is a promising erosion prediction procedure for annular flows.

1. INTRODUCTION

Predicting solid particle erosion in multiphase flow is difficult as so many factors are involved in the problem. Currently, both experimental and numerical approaches can be applied to investigate the phenomenon of multiphase flow erosion. Several experimental studies were conducted at the University of Tulsa Ersoion/Corrosion Resesrch Center (E/CRC) to measure erosion in multiphase flow (Dosila, 2008; Vieira, 2015; Parsi; 2015; Fan, 2010). However, there are still many questions unanswered and especially modelling of multiphase flow erosion has not been extensively studied. This is especially the case for annular flow commonly found in oil and gas production.

Dosila (2008) found through experimentation that for annular flow the erosion rate can decrease when liquid flow rate increases above a critical value.[2] Fan (2010) also observed the same behavior even for large pipe diameters.[3] Vieira (2015) studied the effect of elbow orientation on erosion in annular flow. He found that erosion in a vertical-horizontal elbow was significantly higher than that in a horizontal-horizontal elbow. He improved a 1-D simplified model by increasing the initial particle tracking velocity. The factor was obtained empirically through flow experimental data[4].

Computational Fluid Dynamics (CFD) is another approach to investigate erosion in multiphase flow. But, the application of this approach to study annular flow erosion is relatively new and literature on this topic is extremely limited. A typical CFD-based erosion model can be divided into three parts: flow modeling, particle tracking and erosion calculation. Parsi (2015) investigated CFD erosion prediction for slug/churn flows. An Eulerian-Eulerian approach with Multi-Fluid VOF (Volume of Fluid) model was employed and multiphase flow particle tracking was achieved by utilizing local mixture velocity.[5] The CFD simulation demonstrated that sand concentration is proportional to local liquid hold-up. Also, the obtained erosion trend showed good agreement when compared with experimental data. In the present work, CFD is utilized to investigate erosion rates in annular flow and the results are used to obtain the necessary information and to improve a simplified 2-D model for predicting erosion rates in annular flow.

2. MATHEMATICAL MODEL

2.1 Flow Modeling

The available flow models in ANSYS Fluent for flow characterization of multiphase flow are the VOF model or Eulerian-Eulerian with Multi-Fluid VOF model. The VOF model tracks the volume fraction of each fluid $\boldsymbol{\alpha_q}$ throughout the domain. This is accomplished by solving continuity equations of one or more phases.[6] Assuming there are no source terms and mass transfer between phases, the formulation can be written as:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q\right) = 0 \qquad (1)$$

And, the primary phase volume fraction will be computed based on following constraints.

$$\sum_{q=1}^{n} \alpha_q = 1 \qquad (2)$$

When 0< $\boldsymbol{\alpha_q}$<1, it indicates cells contain the interface between the $\boldsymbol{q^{th}}$ fluid and one or more phases. So, in order to clearly resolve the interface between phases, plenty of cells need to be placed near the interface which results in a relatively fine mesh used in VOF modeling.

As for the velocity field, a single momentum equation is solved throughout the domain, and the velocity field from the momentum equation is shared by all the phases. The velocity field at a location is related to the local volume fractions of all phases through fluid properties. The mathematic formulation is shown below:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot [\mu(\nabla\vec{v} + \nabla\vec{v}^{T})] + \rho\vec{g} + \vec{F} \qquad (3)$$

$$\rho = \sum \alpha_q \rho_q \qquad (4)$$

$$\mu = \sum \alpha_q \mu_q \qquad (5)$$

Where, $\boldsymbol{\alpha_q}$ is the volume fraction of phase q, $\boldsymbol{\rho_q}$ is the density of phase q, and $\vec{v}$ is the mixture velocity shared by all the phases and determined by the local mixture fluid properties. $\vec{F}$ represents any other external forces.

The multi-fluid VOF model couples the VOF and Eulerian multiphase models. This allows tracking both sharp and dispersed interfaces while still being able to offer different flow fields for each phase. Similar to the VOF model, the volume fraction equation may be solved either through implicit or explicit time discretization. The biggest difference is that the Eulerian-Eulerian with Multi-Fluid VOF model also solves momentum equation for each phase. The conservation equations solved are given below:

The continuity equation for phase q is

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q\right) = 0 \tag{6}$$

The momentum equation for phase q is

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) = -\alpha_q \nabla p + \nabla \cdot \overline{\overline{\tau_q}} + \alpha_q \rho_q \vec{g} + \sum_{p=1}^{n} \vec{R}_{pq} \tag{7}$$

Where, α_q is the volume fraction of phase q, ρ_q is the density of phase q, $\vec{v}_q$ is the velocity of phase q, p is the pressure shared by all phases, $\overline{\overline{\tau}}_q$ is the q[th] phase stress-strain tensor, and $\vec{R}_{pq}$ is an interaction force between phases. Thus, the benefit of applying this model is that velocity information for each phase can be extracted from solution and studied for erosion modeling. For the current study, both models are used to characterize the flow field. Comparisons will be made between the two models using a benchmark case.

2.2 Particle Tracking

Particle tracking is accomplished by integrating a particle equation of motion. It is an Eulerian-Lagrangian approach. The equation of motion for particles can be formulated as

$$\frac{d\vec{u}_p}{dt} = \frac{\vec{u}-\vec{u}_p}{\tau_r} + \frac{\vec{g}(\rho_p-\rho)}{\rho_p} + \vec{F} \tag{8}$$

Where, $\vec{u}_p$ is the particle velocity, $\vec{u}$ is fluid velocity, τ_r is particle relaxation time and $\frac{\vec{u}-\vec{u}_p}{\tau_r}$ represents the drag force per unit particle mass. ρ_p is particle density, ρ is fluid density, $\vec{g}$ is gravitational acceleration, $\frac{\vec{g}(\rho_p-\rho)}{\rho_p}$ represents the net gravity and buoyancy acceleration. $\vec{F}$ represents other additional force terms. (force/unit particle mass).

The current study only considers drag, gravity and virtual mass force in particle tracking and particle dispersion is modeled by a discrete random walk approach.

When DPM (Discrete Phase Model) is coupled with the VOF model, the fluid is treated as a mixture in which the primary phase and secondary phase share one set of momentum equations. Thus, flow velocity and fluid properties used in particle tracking are the mixture velocity and mixture properties. However, when the Eulerian model is used, the particle will only interact with the primary phase. In order to consider a secondary phase particle tracking, a UDF (User Defined Function) is developed to utilize the local mixture velocity and mixture properties.

2.3 Erosion Ratio Equation

There are many erosion ratio equations available in the literature. The latest one at E/CRC is developed by Arabnejad, et al.[7] This is a semi-mechanistic erosion ratio equation. It assumes that erosion damage is caused by two mechanisms cutting and deformation. The cutting erosion ratio ER_C is defined by Equation 9, and the deformation erosion ratio ER_D is defined by Equation 10. The total erosion ratio equals the summation of the cutting erosion ratio and deformation erosion ratio defined by Equation 11. The empirical constants in the equations are determined through direct impact tests in gas.[8]

$$ER_C = \begin{cases} C_1 F_S \frac{U_p^{2.41}\sin(\theta)[2K\cos(\theta)-\sin(\theta)]}{2K^2} & \theta \leq \tan^{-1} K \\ C_1 F_S \frac{U_p^{2.41}(\cos\theta)^2}{2} & \theta \geq \tan^{-1} K \end{cases} \quad (9)$$

$$ER_D = \begin{cases} C_2 F_S \frac{\left(U_p \sin(\theta) - U_{tsh}\right)^2}{2} & U_p \sin(\theta) > U_{tsh} \\ 0 & U_p \sin(\theta) \leq U_{tsh} \end{cases} \quad (10)$$

$$ER_{total} = ER_C + ER_D \quad (11)$$

Where, C_1, C_2, U_{tsh} and K are empirical constants. The deformation erosion is negligible for impacts with velocities in the normal direction less than the threshold velocity, U_{tsh}. F_S is the sharpness factor. F_S=1 for sharp particles, F_S=0.5 for semi-rounded particles, and F_S=0.2 for fully rounded sand particles. In this paper, the sand used in the tests is considered as sharp. Other empirical constants used for steel are shown in Table 1.

Table 1. Constants in Equation 9 and Equation 10 Obtained from Arabnejad et al. Erosion Model

Material	C_1	C_2	K	U_{tsh}(m/s)
Steel	3.96e-8	3.375e-8	0.4	7.3

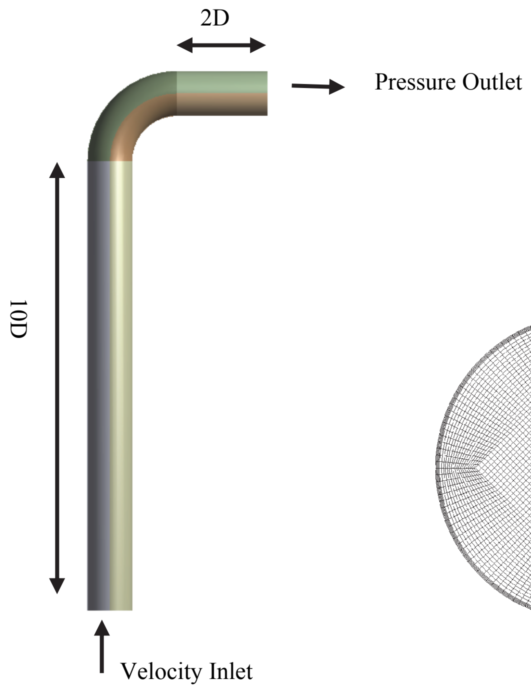
3. CFD STUDIES

In the present work, a commercial software package, ANSYS Fluent, is employed for computational modelling. Due to the high computational cost for multiphase flow modeling, only a portion of the experimental test section has been simulated.

3.1 Computational Domain and Mesh Generation

The geometry studied is a 3 inch (0.0762 m) standard vertical-horizontal elbow. Air-water-sand multiphase flow enters from the inlet vertically and exits from the horizontal outlet. The simulated vertical straight pipe is 0.762 m in length and the horizontal pipe is 0.1524 m. The elbow has a radius of curvature of 1.5. Figure 1 shows the schematic of the geometry.

A structured meshes is generated for this geometry. The inlet face is split into several parts. To facilitate simulating annular flow, a liquid film region is defined around the pipe wall and a gas core region is defined to the center of the pipe. The face meshes are then swept through the whole domain generating a structured mesh for the vertical elbow. Figure 2 shows the face mesh generated for the inlet of the elbow.



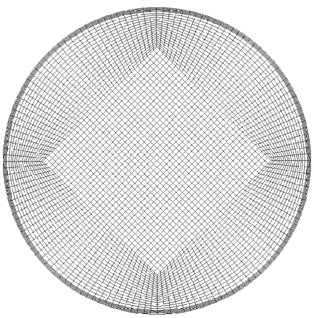


Figure 1. Simulated Vertical Elbow **Figure 2. Mesh Generated on the Inlet Face**

3.2 Model Setup

To facilitate the formation of desired flow regime, separate gas and liquid injection regime are defined at the inlet. The superficial gas and liquid velocity are converted to injection gas and liquid velocities. For all the cases simulated, air and water are used as the fluids which were also used in the experiments. The settings for various numerical schemes and models are listed in Table 2.

Table 2. Numerical schemes and Model Setup in Simulations

Variables	Settings
Turbulence Model	Realizable k-ϵ
Wall Treatment	Enhanced Wall Treatment
Interface Tracking	Geo-Reconstruct
Pressure-velocity Coupling	Phase Coupled SIMPLE
Spatial Discretization	First Order Upwind
Variable Time Step	Courant Number<1.00
Volume Fraction Formulation	Explicit
Interface Modeling	Sharp

3.3 Flow Solutions

Three cases with measured erosion data listed in Table 3 are simulated using the Eulerian-Eluerian Multi-Fluid VOF model while one case (V_{sg} =49 m/s, V_{sl}=0.46 m/s) is also simulated with the VOF model. The flow regimes of these three cases are predicted by FLOPATN software developed by Pereyra et al[9] are shown in Figure 3.

Table 3. Flow Cases Studied

Case No.	V_{sg}(m/s)	V_{sl}(m/s)	$d_p(\mu m)$	Sand Rate (kg/s)	Exp. ER (mm/kg)
1	27	0.1	300	0.004552	8.74e-4
2	49	0.46	300	0.02094	7.13e-4
3	31.1	0.47	300	0.021395	2.33e-4

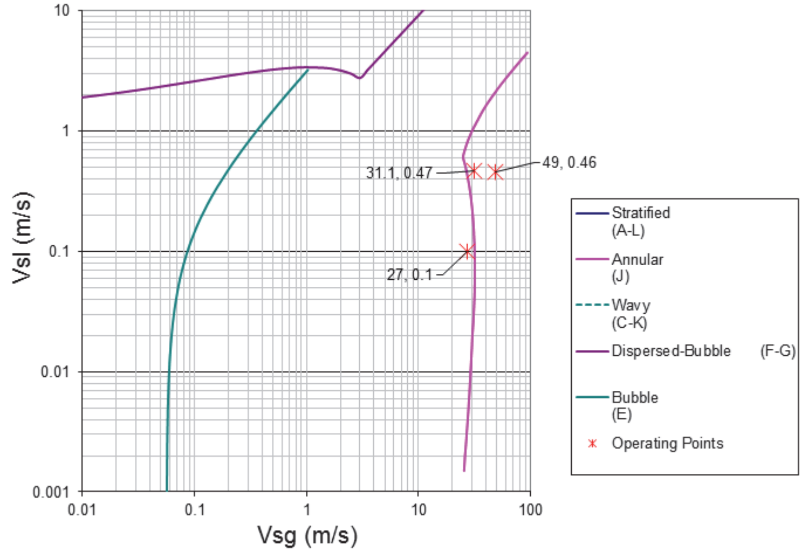
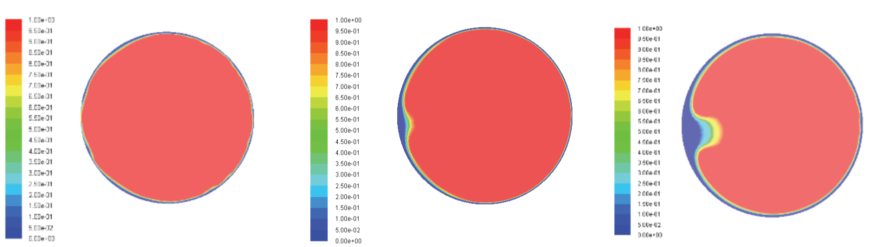


Figure 3. Flow Regime Prediction for Investigated Cases

The V_{sg} =27 m/s, V_{sl}=0.1 m/s case is very close to the predicted annular flow boundary and can be viewed as unstable annular flow. The condition also has lower gas and liquid superficial velocities which will affect erosion profile. The selection of these three conditions are to investigate the effect of liquid/gas ratio on erosion profile.

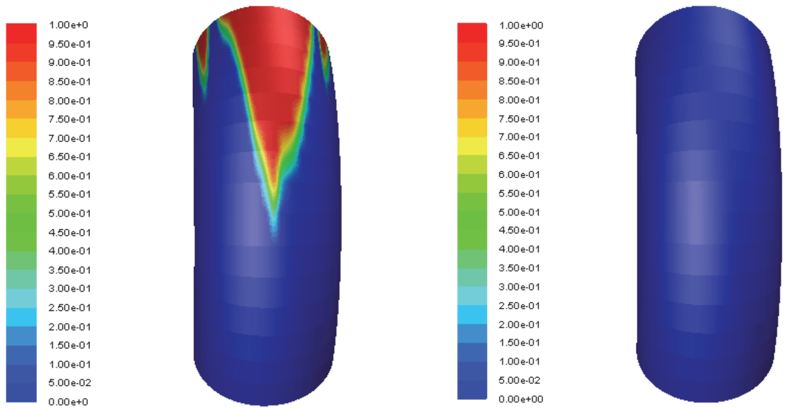
First, liquid information located at the 45 degree position of the elbow (this is the location where the maximum erosion typically takes place for annular flow) is extracted to evaluate the differences of liquid film when passing through the elbows. The following figures show the liquid film for each case.



$V_{sg} = 27m/s, V_{sl} = 0.1m/s$ V_{sg}=$49m/s, V_{sl} = 0.46m/s$ $V_{sg} = 31.1m/s, V_{sl} = 0.47m/s$

Figure 4. Liquid Film Distribution at 45° of the Elbow (Outer Radius)

It is observed from these three cases that as liquid flow rate increases, the local liquid film thickness becomes thicker at the at 45º position of the elbow. The liquid film can act as a buffering layer to protect the elbow from erosion. As observed from Table 3 and Figure 4, erosion reduces as film thickness increases. This effect is highlighted by comparing the third case V_{sg}=31.1m/s, V_{sl}=0.47m/s to the other two cases. The liquid film for Case 3 is much thicker than the previous two cases. This explains why the measured erosion for the other two cases are 3-4 times higher than this case. A comparison can also be made for the first two cases. The first case has a lower gas velocity which would cause less erosion; however, Case 1 also has a thinner film thickness which would cause more erosion. These effects cancel each other and result in comparable erosion. It is noted that for the V_{sg}=27m/s, V_{sl}=0.1m/s case, at the 45 degree position the liquid film is drying out. Figure 5 demonstrates this behaviour.



$V_{sg} = 27m/s, V_{sl} = 0.1m/s$ $V_{sg} = 31.1m/s, V_{sl} = 0.47m/s$

Figure 5. Liquid Distribution over the Elbow (Red Represents Air and Blue Represents Water)

In order to compare results from the Eulerian-Eulerian Multi-Fluid VOF and the VOF model, one case V_{sg}=49m/s, V_{sl}=0.46 m/s is simulated with the VOF model. Figures 6 shows the results obtained with the VOF model, and Figures 7 shows the results obtained with the multi-fluid VOF approach.

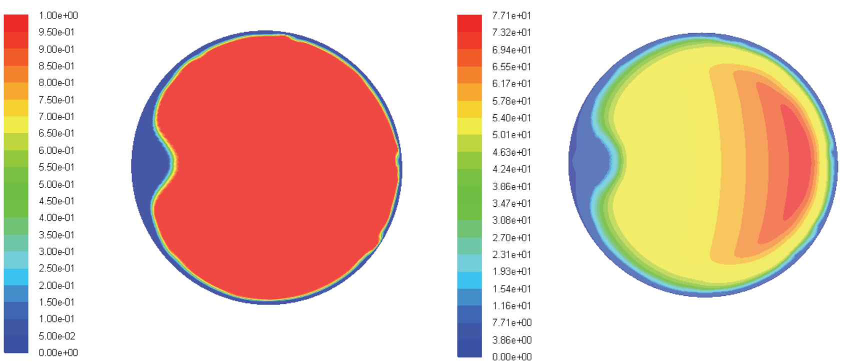


Figure 6. Liquid film Distribution and Velocity Contour at 45º (VOF)

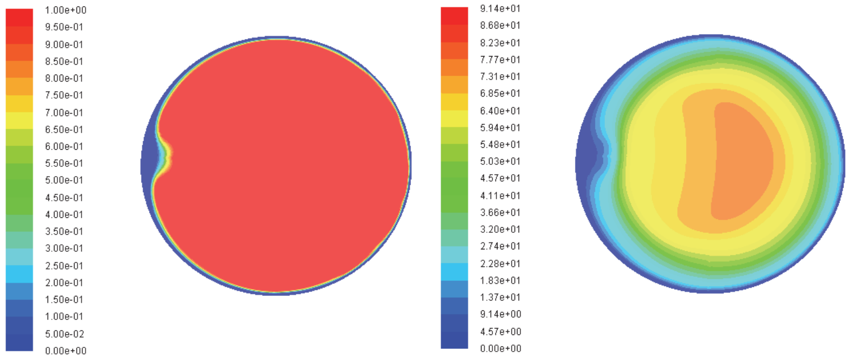


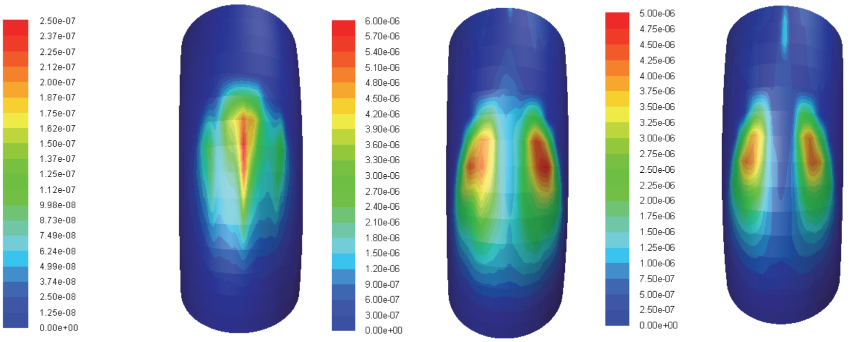
Figure 7. Liquid Film Distribution and Velocity Contour at 45º (Eulerian)

It is observed from this comparison that the VOF model gives a larger liquid film thickness at 45º as compared with the Eulerian-Eulerian with Multi-Fluid model. This may be due to the difference in the formulation of the governing equations for the two models. The VOF solves only one set of momentum equations, so there is no interaction between the two phases which means it treats the air and water as a mixture such that the effect of interfacial drag is removed. However, the Eulerian-Eulerian with Multi-Fluid VOF model solves continuity and momentum equations for each phase. And, the interaction of the two phase is reflected by the drag force implemented in the governing equation for each phase. So, for the Eulerian-Eulerian with Multi-Fluid model, the interfacial shearing effect may prevent the liquid film from growing at the 45 degree position in the elbow.

For the velocity field, it is observed that the Eulerian-Eulerian with Multi-Fluid model offers more information near the gas-liquid interface. And, liquid velocities from the VOF model are higher. This could be the limitation of the VOF model that a shared momentum equation for both phases results in inaccurate prediction of velocities near the interface.

3.4 Erosion Results

As previously discussed, particle tracking is conducted to provide input for erosion calculations. There is no special treatment for particle tracking in the VOF model, since it is essentially applying a mixture flow field. There is only one flow field in the domain since two phases share the same momentum equation. However, for the Eulerian-Eulerian with Multi-Fluid VOF model, this is not the case. Each phase has a flow field, but the particle tracking only interacts with the primary phase. Thus, in order for particles to be able to interact with the secondary phase as well, a UDF is developed to combine local secondary phase information to formulate volume fraction averaged mixture properties and velocities to track particles. This approach is implemented for annular flow applications, and the following figures show the erosion patterns for the investigated cases.



V_{sg}=27m/s, V_{sl}=0.1m/s V_{sg}=49m/s, V_{sl}=0.46m/s V_{sg}=31.1m/s, V_{sl}=0.47m/s

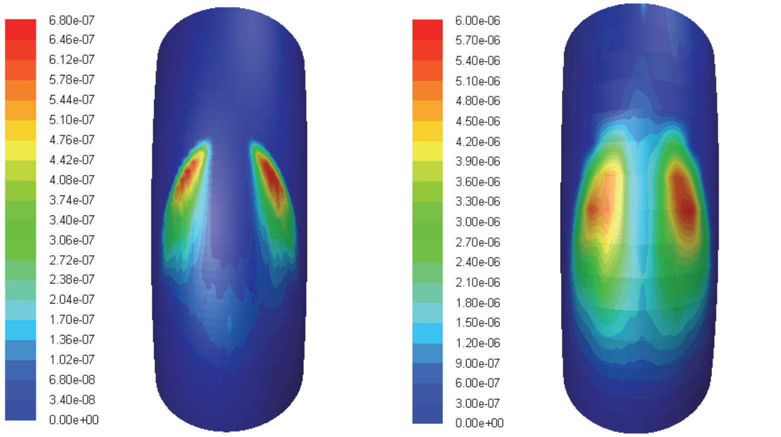
Figure 8. Erosion Pattern Obtained by Eulerian-Eulerian with Multi-Fluid VOF Approach

Figure 8 shows erosion pattern for the investigated cases. Erosion patterns are taken from different flow times, thus, they differ in erosion magnitude. The figures reflect difference in erosion profile due to different amount of liquid and gas. In line with flow solutions, Case 1 has dry region near 45º and with less liquid so that the maximum erosion is concentrated and located near 45º. However, there are thick liquid film formed at 45º for Case 2 and Case 3 and there are more liquid for the cases. These factors deflect location of maximum erosion to the sides of 45º location. Since Case 3 forms thicker liquid film at 45º of the elbow, erosion there is much less than Case 2. For unsteady particle tracking, the amount of material removal will grow with time, and the constant slope of material removal over time represents the steady erosion rate. These values are computed for each investigated case and are presented in Table 4.

Table 4. Comparison of CFD Erosion Prediction with Experimental Data (Eulerian Model)

V_{sg}(m/s)	V_{sl}(m/s)	d_p (μm)	Exp.ER (mm/kg)	E/CRC (mm/kg)
27	0.1	300	8.74e-4	1.29e-3
49	0.46	300	7.13e-4	7.57e-4
31.1	0.47	300	2.33e-4	3.04e-4

Following the same procedures, erosion results from the VOF model and Eulerian model are compared and given in the Figure 9 and Table 5. Erosion patterns from both models follow the same pattern with maximum erosion happened at the two sides of 45º location of the outer radius of the elbow. Figure 9 only shows the erosion pattern and it is shown that as the VOF model predicts a thicker liquid film at 45 degree of the elbow, erosion is much less severe than results from the the Eulerian model. But both models predicts same locations of maximum erosion. The magnitude of erosion is computed by taking the slope and is given in Table 5. As can be seen from the table, the VOF model and Eulerian-Eulerian with Multi-Fluid VOF model produce comparable erosion magnitudes. And, the slight different may due to difference in resolving the near interface region as discussed before.



VOF Model for V_{sg}=49m/s, V_{sl}=0.46m/s Eulerian Model for V_{sg}=49m/s, V_{sl}=0.46m/s

Figure 9. Comparsion of VOF model and Eulerian-Eulerian with Multi-Fluid VOF Model Erosion Prediction Contour

Table 5. Comparison of Eulerian Model and VOF Prediction with Experimental Data

Model	V_{sg}(m/s)	V_{sl}(m/s)	$d_p(\mu m)$	Exp.ER (mm/kg)	E/CRC (mm/kg)
Eulerian	49	0.46	300	7.13e-4	7.57e-4
VOF	49	0.46	300	7.13e-4	7.73e-4

4. THE 2-D MODELING OF ANNULAR FLOW EROSION

4.1 2-D Erosion Prediction Method

The 2-D erosion prediction method was first developed for predicting single-phase flow erosion with great advantage over predicting small particle erosion, erosion in viscous and high-pressure flows compared with its 1-D erosion prediction method counterpart.

The 2-D erosion prediction method is a hybrid CFD erosion prediction tool which utilizes flow solutions from CFD codes. The flow field needed for particle tracking is obtained by linear interpolation of stored flow solutions based on Reynolds number. The stored meshes are also interpolated with the change of pipe diameter. The in-house 2-D particle tracking was developed by Zhang et al. (2009) which considers turbulence fluctuations and offers the user versatile control over eddy scales and near wall treatment.[10]

In the 2-D method, particles are tracked in a 2-D domain with flow field information assigned to the attached mesh. The particles are released from the inlet and tracked along the flow domain. Figure 10 shows a schematic of a representative 2-D elbow geometry.

Once a particle hits the wall, the impacting speed and angle are recorded and averaged over each cell to serve as input for the erosion calculation module. The erosion calculation module utilizes an erosion ratio equation to convert the impacting parameters to erosion damage. The maximum erosion damage is selected and output.

The present work shows how this 2-D method is applied to predict annular flow erosion and discusses some improvements that will be made to the existing 2-D method.

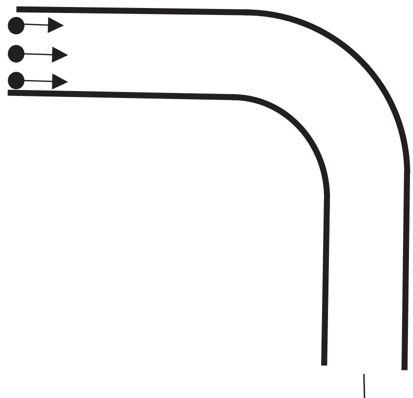


Figure 10. Schematic of 2-D Erosion Prediction Method for Elbow Geometry

4.2 2-D Mixture Model

The CFD approach essentially utilizes local mixture flow field properties to track particles for multiphase flow regardless of the model used (VOF or Eulerian-Eulerian with MultiFluid VOF). So, ignoring the complicated two-phase flow configuration, a simple modelling approach for annular flow or any other multiphase flow regime is to treat the two-phase mixture as a pseudo single-phase flow with average velocity and fluid properties. In this way, the complex multiphase flow particle tracking is simplified to track particles in this mixture, and the flow field is simplified to a single-phase flow field.

In application of this 2-D mixture model, the flow field is first obtained by interpolating from the database using the mixture fluid Reynolds number. The pseudo single-phase flow Reynolds number is calculated from the following formula:

$$Re_m = \frac{\rho_m v_m D}{\mu_m} \tag{14}$$

$$V_m = V_{sl} + V_{sg} \tag{15}$$

$$\rho_m = \frac{\rho_l V_{sl} + \rho_g V_{sg}}{V_m} \tag{16}$$

$$\mu_m = \frac{\mu_l V_{sl} + \mu_g V_{sg}}{V_m} \tag{17}$$

In this approach, the particle initial velocity V_o is set to be the fluid mixture velocity V_m. With this information prepared, 2-D particle tracking is performed and erosion is calculated whenever a particle hits the wall.

The mixture model can provide a rough approximation for all multiphase flow regimes, and it basically utilizes single-phase flow field. Experimental data are collected to examine the performance of the 2-D mixture model to predict annular flow erosion for various elbow sizes, particle sizes and flow conditions. The data was collected at E/CRC by various investigators. It includes 1, 2, and 3 inch elbow annular flow erosion data with two different particle sizes of 150 microns and 300 microns. Figure 11 shows the results.

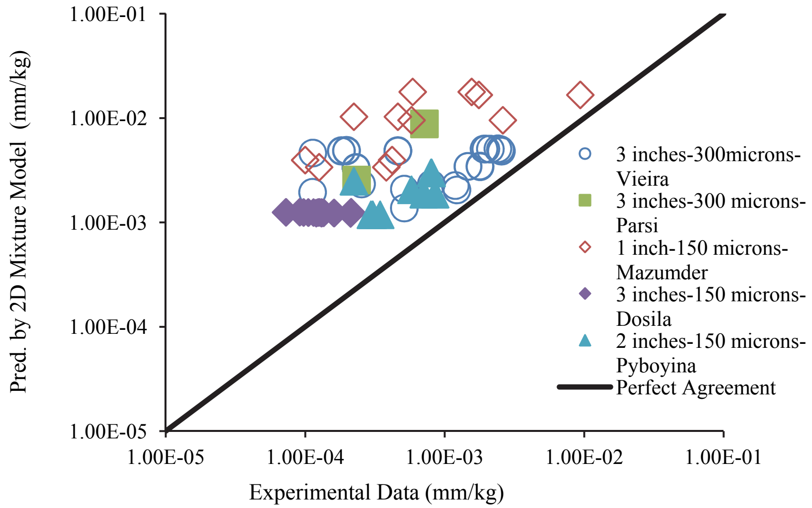


Figure 11. 2D Mixture Model for Annular Flow Erosion Prediction

It is observed that this approach for annular flow erosion prediction generally over-predicts erosion. For some cases, the over-prediction ratio can be over a factor of 20. Another drawback of this approach is that the predicted results commonly remain similar even if the experimental conditions were changing. This means that the mixture model is insensitive to the change of flow conditions. The mixture model usually can't capture flow characteristics when one of the superficial velocities changes. Setting the particle tracking initial velocity to the mixture velocity for the mixture model is also a rough estimation especially for annular flow regimes. However, this method is very simple and it is easy to use by engineers to provide a first estimate of the erosion propensity.

4.3 2-D Mixture Model with Ad Hoc Modification

Based on CFD simulations, it is observed that for some cases the liquid film will exist or even grow locally over the elbow which will have a damping effect to reduce maximum erosion. However, for some cases, the liquid film will not cover the whole elbow and leave a dry region. These situations are closely dependent on superficial gas and liquid velocity. So, to damp or not to damp the particle impact, the effect is modeled and reflected on the initial particle tracking velocity. An empirical correlation is proposed based on collected experimental data so as to determine a proper particle initial tracking velocity for different superficial velocity conditions.[11] Then, the new pseudo single-phase flow field will be determined by the following formulas:

$$Re_o = \frac{\rho_m V_o D}{\mu_m} \tag{18}$$

$$V_o = \lambda_1 V_{sl} + \lambda_2 V_{sg} \tag{19}$$

$$\rho_m = \frac{\rho_l V_{sl} + \rho_g V_{sg}}{V_m} \tag{20}$$

$$\mu_m = \frac{\mu_l V_{sl} + \mu_g V_{sg}}{V_m} \quad (21)$$

Where, V_o is the modified particle initial velocity from a weighted combination of V_{sl} and V_{sg} . λ_1, λ_2 are empirical values and change with V_{sl} and V_{sg} . The flow field is interpolated based on Reynolds number calculated from V_o . Figure 12 shows the application of this concept by changing the particle initial velocity.

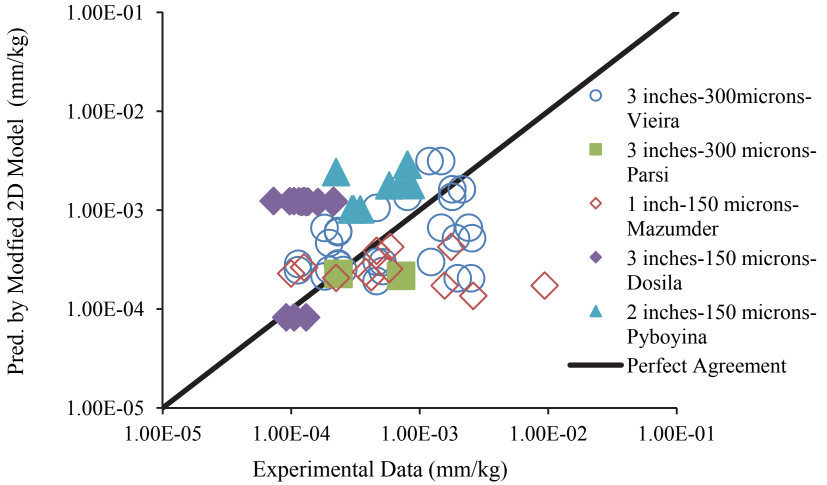


Figure 12. 2D Mixture Model for Annular Flow Erosion Prediction

It is shown in the figure that this ad hoc modification is able to avoid a significant over prediction of erosion and works well for most of the cases. However, since it is an empirical modification it is still unable to capture all the flow characteristics. This requires a more physical 2-D flow regime dependent model to be developed in future for multiphase flow erosion predictions.

5. CONCLUSIONS

An Eulerian-Eluerian with Multi-Fluid VOF model is successfully applied to model annular flow. Particle tracking in the resulting flow field offers good erosion prediction results. Compared to the VOF model, it is less time-consuming and can effectively resolve interfacial flow field. Both of the models can obtain comparable erosion results and show good agreement with experimental data.

Investigation of annular flow by the Eulerian-Eulerian with Multi-Fluid VOF model reveals that the liquid film can effectively reduce erosion for elbows. However, for all annular flow conditions, the liquid film does not always exist continuously over the elbow. It is dependent on superficial gas and liquid velocities and other factors. Further stability analysis can be carried out to determine the criteria for a stabilized continuous liquid film over the elbow which will shed more light on annular flow erosion modeling.

A 2-D mixture model is evaluated to predict erosion for annular flow conditions. Results show that the 2-D mixture model can significantly over predict erosion for some cases.

For the 2-D mixture model, the effect of liquid film on erosion is not considered which may be one of the reasons causing large deviations from experimental data.

Considering the effect of both superficial gas and liquid velocity, a 2-D ad-hoc model is implemented. It is an empirical model based on collected experimental data. Results from this 2-D ad hoc model show improvement compared with the mixture model but further refinement is desired for some cases.

Finally, even though CFD produces good results for erosion prediction, the flow modeling results are still not physical as no entrainment is observed in the gas core which needs to be further investigated. But, it can provide liquid film distribution information over the elbow which can be utilized to develop a flow regime dependent 2-D annular flow model.

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