Second International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
6-8 December 1999

COMPUTATIONAL AND EXPERIMENTAL STUDIES OF TUBE EROSION IN A FLUIDISED BED

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ABSTRACT

The paper presents the results of a computational model of erosion in a fluidised bed and a corresponding erosion experiment. The experiment has been simulated using the CFX (1995) code with computational models of hydrodynamics (hydrodynamic model A and kinetic theory model) and erosion (Finnie and kinetic theory). The experiment has been conducted at room temperature using a horizontal acrylic tube immersed in a rectangular fluidised bed for a total of 126 hours of run. Erosion measurements were made every 14 hours at eight equally spaced positions around the tube. The results show an induction period of 42 hours. Most of the wear occurred around the bottom of the tube with the maximum at an angle of about 45° from the tube bottom. The kinetic theory model predictions are in good agreement with the experimental results.

INTRODUCTION

Tubes immersed in a fluidised bed subjected to the solid particle impact may suffer severe erosion wear. The factors affecting erosion may be classified according to the particle characteristics (size, size distribution, hardness and chemical composition), mechanical design (air distribution, tube bundle geometry and solids feeder location) and operating conditions (fluidising velocity, temperature and gas and solids composition). An important factor is the velocity distribution of the particles as they strike the surface. However the actual effect of these factors is not well understood in any particular system. Stinger et al. (1987) reported that systems which appear to be similar in design and operating conditions may have significantly different erosion rates. Also, Zhu et al. (1990) stated that the procedures to minimise the incidence of wear are not widely accepted or well understood. There are only a few detailed published physical model studies of mechanisms of in-bed wear (Yates, 1987; Gansley and O'Brien, 1990) and recent published results have shown that a fruitful approach to solving the problem is to use modern computational fluid dynamics codes (Achim et al., 1996). With suitable refinement and validation, they can make an important contribution to the design, optimisation and operational analysis of fluidised beds. The experiment and computational models described in this paper were developed to assist the understanding of erosion in a fluidised bed.

COMPUTATIONAL MODELS

Computational models of wear in fluidised beds used in this paper are based on hydrodynamic models, which are referred to in the literature as multiphase continuum models. These models have been chosen rather than Lagrangian particle tracking models (Nesic and Postlethwaite, 1991) because of the high concentration of particles in a fluidised bed. (Witt et al., 1998). Bouillard et al. (1989) and Lyczcowski et al. (1987, 1989) have used computational models in fluidised beds based on hydrodynamic model A and B, which are essentially two-phase continuum models. They implemented empirical models for solids viscosity and solids stresses in the computer codes to improve the erosion prediction. As these computational models could only consider rectangular geometry, they used square tubes to represent the experimental round tubes. Various erosion models have been implemented to numerically model a two-dimensional idealisation of the I.E.A. Grimethorpe tube bank 'CI' configuration (Parkinson et al., 1985). In previous work Achim et al. (1996) used a CFX4 based hydrodynamic model A with a Finnie erosion model with angular dependence to calculate erosion rates around square and round tubes in two and three dimensions. The results were compared against published experimental data and other computational results. There was an order of magnitude agreement with physical experiments, which proved the capabilities of the computational models to predict erosion rates. Results computed for the hydrodynamic model A plus Finnie erosion model show that the model over-predicts erosion. In the circumstances represented by Finnie (1960), who studied erosion by single particle impacts over a plate, his model greatly under-predicts erosion for particle impact angles over 45°. We believe that hydrodynamic model A with the Finnie erosion model over-predicts erosion in a fluidised bed mainly because the shear stresses of the flow are not accurately represented.

Boemer et al. (1995), Ding et al. (1992) and Rogers and Boyle (1993) implemented more complex models for the solids phase based on the kinetic theory of granular flow. The kinetic theory equations describing the processes in a fluidised bed are the equations of conservation of mass, momentum and energy for transient isothermal two-phase flow (Gidaspow, 1994).

In this work a 2D and a 3D kinetic theory hydrodynamic model together with the kinetic theory erosion model has been implemented in the CFX4 code by extending the previous hydrodynamic model A implemented by Witt et al. (1995). An additional kinetic energy conservation equation has been added in an algebraic form based on the work of Syamlal et al. (1993). The new implementation follows the formulation of Gidaspow (1994) and differs in detail from the algebraic formulation of Boemer.

The viscosity and density of the gas phase are specified while the solids phase stress, with the solids pressure and viscosity terms, are calculated from the granular temperature, which represents the fluctuating kinetic energy component of the solids phase. The granular temperature is calculated from the kinetic energy conservation equation. The implementation of the solids phase variable viscosity in the kinetic theory based model gives a more realistic representation of the shear stresses near the wall. One advantage of the kinetic theory based model is that it reduces the need to use fine cells near the wall of the obstacle.

Ding et al. (1992) and Rogers and Boyle (1993) used kinetic theory hydrodynamic models together with kinetic theory erosion models. The kinetic theory erosion model of Ding et al. (1992) was implemented in the CFX code.

The erosion rate caused by particle impacts, $\dot{E}$, was calculated by integrating the probability of finding particles near the surface within the range c to $c+dc$ per unit volume times erosion caused by one particle impact in the Finnie erosion model (1960) over all impact velocities in the range of $(-\infty, \infty)$.

$$\dot{E} = \int_{\mathbf{c}_w \cdot \mathbf{n} > 0} (\mathbf{c}_w \cdot \mathbf{n}) B_F m c_w^2 f(a) f_w(r,c,t) dc_w ,$$

where f_w is the Maxwellian particle velocity distribution function, $\mathbf{c}_w$ is the particle's instantaneous velocity near the wall and B_F is a model constant. This proved to be a good approach since Ding et al. (1992) computed erosion rates of tube surfaces in two and three-dimensional fluidised rectangular beds which were in better agreement with experimental data than previous computational models predictions.

Early codes allowed only for a square tube geometry to be modelled. The CFX4 code has body fitted coordinates and therefore is suitable for investigation of a complex geometry. The experimental geometry has been modelled in 2D and 3D with the tube represented as round. In the 2D model, 39 cells are used across the bed in the x direction and 140 cells in the y vertical direction for a total of 5460 cells. The 3D computational model geometry has the same number of cells in the x and y directions and 4 cells in the z direction for a total of 21840 cells. The mesh allows for the edges of 8 cells to represent the outer tube surface. In both cases symmetry is assumed at the bed centre to reduce computational work. The boundary conditions at the plane of symmetry are zero normal gradients of all variables. The assumption of symmetry applied here to a transient calculation. However, because the geometry is symmetric the time averaged solution must be symmetric and in our case the end result is the time averaged erosion rate. A no-slip boundary condition is applied for the solids velocity in the vicinity of the walls, which is appropriate for small particles and for high solids concentration near a wall. The 2D and 3D models were run with both the kinetic theory hydrodynamic model coupled to the kinetic theory erosion model and with the hydrodynamic model A coupled to the Finnie erosion model.

PREVIOUS EXPERIMENTAL WORK

Experimental studies of wear have shown that the rate of material loss depends on the particle impact velocity and direction, particle mass flow rates and particle properties, tube size and material properties. The passage of bubbles over tubes, the type of distributor plate and the distance between the inlet and the tubes were also important.

Parkinson et al. (1985), Wood and Woodford (1983) and Zhu et al. (1990) have carried out wear tests on small scale fluidised beds and have found that more than 95% of the material loss occurred over the lower part of the tube. The maximum wear occurred at 40°-60° from the tube bottom. The wear dropped dramatically between 60° and 120° and was almost zero between 120° and 180°. The results showed that the overall average wear rates were approximately one third of the maximum local erosion rate.

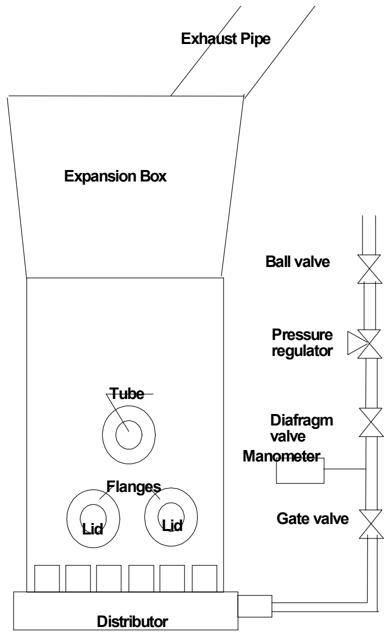

Figure 1. Sketch of the experimental rig.

DESCRIPTION OF THE EXPERIMENT

Our erosion wear experiment was conducted at room temperature in a rectangular fluidised bed, illustrated in figure 1, with dimensions 600 x 100 x 1130 mm. Wear on an acrylic tube target with 50 mm diameter and Vicker's hardness 38 kg/mm^2 located in the centre of the bed was measured over a period of 126 hours. The distributor consisted of six bubble cap tuyeres, 50 mm diameter each, evenly distributed across the inlet. The fluidising gas was nitrogen and the particles were zircon sand with a density of 4600 kg/m^3 and a particle diameter of 120-140 µm. The initial bed height was 0.5 m. Gas inlet velocity was 0.8 m/s and the superficial velocity was 0.4 m/s. The upper face of the rectangular fluidised bed was connected to an atmospheric expansion box. From there, an exhaust fan extracted the gas together with the very fine particles entrained by the flow. The pressure drop and hence the flow rate of nitrogen were constant. Hourly readings of the pressure during the experiment showed that a constant flow rate was maintained. The front glass of the experimental fluidised bed was designed to allow for the tube to be inserted and extracted at various times without any additional damage of the tube surface. During the experiment the tube was removed and measured every 14 hours.

MEASUREMENT PROCEDURE

The erosion on the tube surface was measured using a talysurf (1980). This measures the surface texture by traversing a stylus across a surface to produce a surface profile or an average reading of the surface roughness. The measurement precision of the talysurf is 0.012 μm.

Before the experiment, the roughness of the tube surface was measured to determine the surface without erosion. Two circular areas of the tube, 15 mm wide and 50 mm apart, were covered by tape to provide reference areas. The measurements were made along the tube at the eight equally spaced positions marked around the tube after every 14 hours. The positions are shown in figures 2 and 3 together with experimental results.

RESULTS AND DISCUSSION

The net material loss was calculated by subtracting the average roughness readings of the initial surface. The experimental measurements of roughness averaged along the tube have been plotted as a function of time in figure 2. The experimental readings of roughness were converted to a rate of material loss in µm/100 hours. The resulting erosion rates are shown in figure 3.

Figures 2 and 3 indicate that the first 42 hours were an incubation period for the sides and the bottom of the tube while there was a longer induction period for the top of the tube.

Figures 4, 5 and 6 compare computational results using the CFX4 kinetic theory model and the hydrodynamic model A and Finnie erosion model in 2D and 3D, with

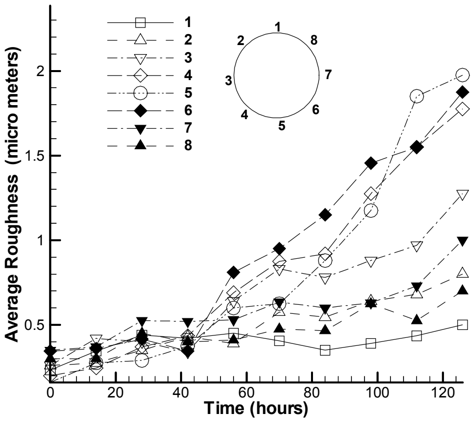

Figure 2. Averaged tube roughness as a function of time

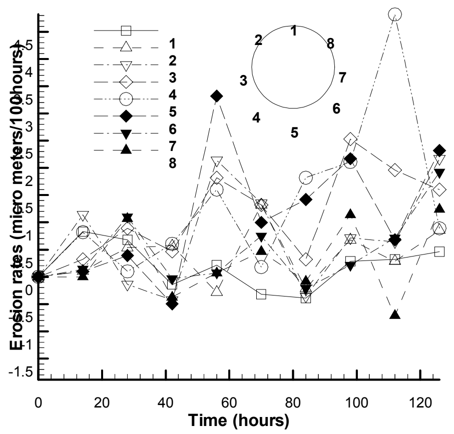

Figure 3. Experimental averaged erosion rates around the tube.

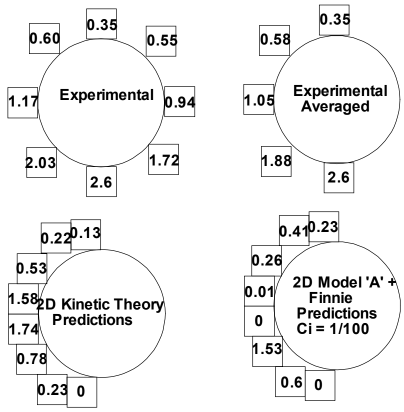

Figure 4. Experimental and computational 2D erosion rates (μm/100 hours).

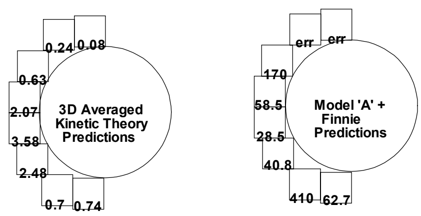

Figure 5. Computational 3D averaged erosion rates (μm/100 hours).

experimental results. They compare the experimental erosion rates averaged over the last 84 hours of run with the computational results time averaged over 2 seconds for each of the 8 cells around the periphery of the tube. Hence, only the rates for the last 84 hours of run were averaged along the tube for comparison with the numerical model.

The experimental results in figure 4 show that the flow in the fluidised bed displayed some asymmetry. This was

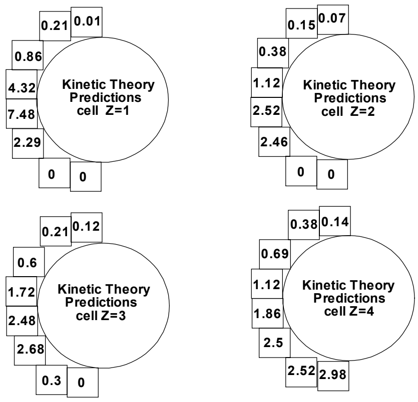

Figure 6. Computational 3D averaged erosion rates for every cell along the tube.

caused by the design of the distribution box and could not be avoided. Hence the readings for the left side and the right side of the tube have been averaged to compare with the results of the numerical model for validation. Figure 6 shows the 3D time averaged erosion rates calculated with the kinetic theory models for the 4 cells along the tube in *z* direction. They show that the highest erosion rate occurred under oblique angle from the tube bottom. The computational erosion rates are time averaged and averaged along the tube in order to compare with the

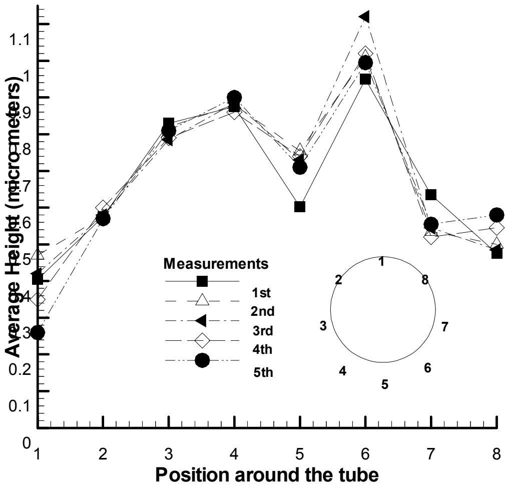

Figure 7. Repeated measurements of the tube roughness at 70 hours.

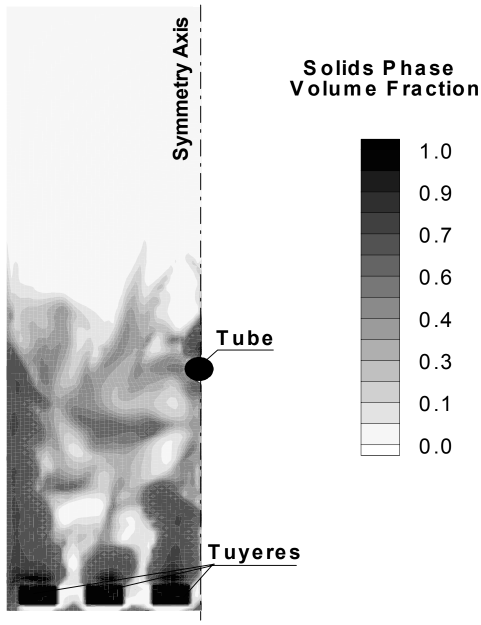

Figure 8. CFX4 kinetic theory model predictions at 1.05 sec.

experimental results. The computational results reflect the variation of the flow parameters due to the passage of the bubble. Also the experimental erosion rate showed some variation along the tube.

Figures 4, 5 and 6 show that the computational results for hydrodynamic model A with the Finnie erosion model give qualitative agreement and the kinetic theory models give quantitative agreement. For the 3D kinetic theory models predictions, the overall predicted average erosion rate is 1.31 μm/100 hours. This compares well with the overall average experimental erosion rate of 1.29μm/100 hours. The average predicted erosion rate for the tube bottom 0.74 μm/100 hours does not compare as well with the average experimental erosion rate 2.6μm/100 hours. The average predicted erosion rate for an angle of 45° from the tube bottom 1.58 μm/100 hours, compares with the average experimental erosion rate 1.88 μm/100 hours. The average predicted erosion rate for the tube side 2.82 μm/100 hours compares with the average experimental erosion rate 1.05μm/100 hours. The average predicted erosion rate for an angle of 135° from the tube bottom 0.43 μm/100 hours compares with the average experimental erosion rate of 0.58 μm/100 hours. The average predicted erosion rate for the top of the tube 0.08μm/100 hours compares with the average experimental erosion rate 0.35μm/100 hours.

Some of the variability in the numerical results as compared with the experiment could be due to experimental error. The tube was marked and the readings were taken following the marks as close as possible at the same position. Errors may have occurred when fitting the tip of the talysurf over the marked position or when reading the scale of the talysurf. The readings after 70 hours were repeated 5 times in order to assess the repeatability of the measurements. Results in figure 7 indicate a high degree of repeatability.

The computational results show that of the kinetic theory hydrodynamic model reproduced the experimentaly observed flow pattern. Figure 8 shows a typical visualisation of the fluidised bed at 1.05 seconds with large diameter bubbles travelling towards the surface. There is a large accumulation of particles forming on top of the bubble cap tuyeres and along the walls. This behaviour is because of the particles being returned after reaching the upper surface of the bed. These characteristics have been observed in the physical experiment.

CONCLUSIONS

The experimental erosion rates show the expected distribution of wear rates around the tube with the maximum erosion rate at an oblique impaction angle and a very low value on the top of the tube. Comparison of the experimental data with the computational results obtained with a kinetic theory hydrodynamic model together with the kinetic theory impaction erosion model suggest that the main mechanism of erosion has been appropriately represented in the model. The wear rates are underestimated for the tube bottom in the 2D computational model. Since a zero velocity gradient is applied along the symmetry axis in both the 2D and 3D computations, the solids motion across the bottom of the tube is smaller than observed. This could reduce the predicted erosion rate.

The 3D time averaged kinetic theory results given in figure 5 show very good agreement with the experimental rates especially for angles of 45° and 135° from the tube bottom. For the top and the bottom of the tube the erosion rates are under-predicted as compared with the experimental erosion rates. This may be due to the symmetry condition in the computational model. However, there is better agreement with the experiment than the previous study of Ding et al. (1992). The greatest discrepancy occurs on the side of the tube where rates higher than the observed experimental rates were computed. Some of the difference may be due to the asymmetry of the distribution box located under the bubble cap tuyeres, which generated random blockage of the tuyeres during the experiment. Other causes, which may have influenced the experimental results, are attrition of the bed material and periodical replacement of a small quantity of particles lost through the exhaust pipe. Figure 5 also shows that the 3D averaged results, calculated with the hydrodynamic model A and Finnie erosion model, are significantly higher than the measurements.

A 3D model without a symmetry axis run over an extended period of time would give a more realistic representation of the flow conditions but would require significant additional computational time. Further improvement of the computational models is possible by solving in full the additional energy conservation equation and the introduction of a drag coefficient correction to account for multiple particle sizes. Further experimental work may be required to increase the confidence in the model predictions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial and other support received for this research from the Cooperative Research Centre (CRC) for New Technologies for Power Generation from Low Rank Coal, which is established and supported under the Australian Government's Cooperative Research Centre program. The assistance of Robert White from CSIRO Division of Minerals was greatly appreciated.

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