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MATHEMATICAL MODELLING OF EROSION IN A FLUIDISED BED

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ABSTRACT

This paper presents results of a study on erosion on immersed tubes in Fluidised Bed Combustors (FBC) with the purpose of predicting local erosion rates around single and multi square and round tube geometries in two and three dimensional fluidised bed combustors using hydrodynamic and erosion computer modelling.

A CFDS-FLOW3D hydrodynamic model together with a modified Finnie erosion model are shown to be capable of predicting flow patterns and erosion rates in fluidised beds and the calculated erosion rates agree reasonably well with physical experiments from cold model studies and other computational results.

INTRODUCTION

Fluidised bed combustion technology has developed as a means of burning high sulphur coal with great potential for the next generation of commercial boilers. However metal wastage is a problem which seriously affects the system reliability and availability and has become a critical issue for in-bed heat exchangers in bubbling FBC. Conditions under which erosion of internal FBC components occur are not completely understood (Stinger, 1987).

Tubes in some units have shown severe wastage, whereas there has been little material loss in other systems which appear to be similar in design and operation (Zhu et al., 1990). In some systems wastage occurs locally while in others it is widespread. Wear is most severe at the bottom of the tubes for some configurations, while in other cases the maximum material loss occurs at some other angle, eg. 20-40° from the bottom. Criteria or remedies to minimise the incidence of in-bed wastage are not well understood.

It is currently believed that the main factor that influences erosion of in bed components in fluidised bed combustors is solids motion around components, (Lyczkowski et al, 1994). Factors affecting erosion in FBC may be classified into feedstock characteristics (eg. size, size distribution, hardness and chemical composition), mechanical design (eg. air distribution, tube bundle geometry and solids feeder location) and operating conditions (eg. fluidising velocity, temperature and gas and solids composition). There are only a few detailed published physical model studies of mechanisms of in-bed wear and recent published results have shown that a fruitful approach to solving the problem is to use modern Computational Fluid Dynamics (CFD) codes which, with suitable refinement and validation, can make an important contribution to the design, optimisation and operational analysis of fluidised beds.

Physical Models

Published studies of mechanisms of in-bed wear show that the rate of material loss is found to be closely related to the particle impact velocity and direction, particle mass flow rates and particle properties, the passage of bubbles over tubes, the type of distributor plate or the inlet velocity distribution and the distance between the inlet and the obstacles. Wood and Woodford (1980) employed a 0.2 x 0.2m cold model fluidised bed operated with air at room temperature. Tests were performed on tubes of five elemental metals and five alloys. The superficial velocity was in the range of 1-4.8 m/s and the mean particle size was varied from 0.1-1.9 mm. Parkinson et al (1985) conducted wear tests with PVC tube banks in a 0.3 x 0.3m cold model pressurised fluidised bed. They also found that maximum erosion occurred at 35° from the tube bottom and that tubes placed close to the walls of the column suffered less material loss than tubes in the interior region. The experimental measured average erosion rate for aluminium tubes from above mentioned experiments was of order 0.1 to 0.3 mm/1000hours. Experiments by Zhu et al (1990) were undertaken in a cold three-dimensional rectangular column model with a cross section of 203 x 216 mm and the height of 1.5 m. The basic case was chosen for a gas superficial velocity of 1.87 m/s with silica sand of 1.0 mm mean diameter and a single target tube of diameter 32 mm containing rings of five materials. The static bed height was 320 mm for most tests. The bed height was not sufficient to permit a train of several slugs to form in series, therefore the bed was in the so-called apparent slug regime in which slugs do not have well established forms and where the large diameter voids resulting from bubble coalescence produce large bed oscillations and cyclic heaving of the bed surface. Measured erosion rates showed that erosion rate decreased slightly as the tube size increased. The presence of neighbouring tubes reduces the particle impact velocity and is clearly responsible for diminished erosion rates. For multiple tubes the spatial distribution of wear differed somewhat from that of the single tube.

with the maximum erosion rate occurring at the very bottom of the tube instead of about 40-50° from the bottom. The average erosion rates measured for brass square tubes were 1.12 and 1.14 µm/100h for the two sides of the square tube and 10.5 µm/100h for the bottom surface. The material loss for the top surface was very low.

Computational Models:

In a CFD study, Lyczcowski et al (1994) varied the obstacle shape, fluidising velocity, jet velocity and distance of the tube above the distributor plate, and found these to have a strong effect on computed wear pattern and overall average erosion rate. Bouillard et al (1989) and Ding et al (1993) used the FLUFIX and IFAP codes. As these CFD models can only consider rectangular geometry, a square tube was used to model the experimental adopted round tube (this simplification was adopted by other users of the FLUFIX codes noted below). They found good agreement or at least an order of magnitude agreement with physical experiments. Ding et al (1993) modified the Argonne National Laboratory IFAP code by adding the kinetic theory granular flow model together with other features. The kinetic theory erosion model was used to compute erosion rates measured by Zhu et al (1990). Nonuniform grids were used in the computations; 10 cells in the X direction, 43 cells in Y direction for the two dimensional model, for a total of 430 cells, and another 4 cells in the Z direction, for the three dimensional computation. They found generally good agreement with the experiments and also that the three dimensional predictions were better than the two dimensional.

Bouillard et al (1989) used the FLUFIX/MOD2 computer program and a modified Finnie erosion model together with energy dissipation model to numerically model a two-dimensional idealisation of the I.E.A. Grimethorpe tube bank "CI" configuration studied by Parkinson et al (1985).

The FLUFIX model consisted of three square tubes displayed in two rows immersed in an FBC and five obstacle cells in each half of the bed deflecting the airflow. The computed erosion rates for aluminium tubes using the Energy Dissipation Model were compared with erosion rates for the Finnie Model and the wear pattern was quite uniform showing the same trend as the cold model physical experiment. The grid size chosen was $\Delta X=\Delta Y=1.7$ cm. The number of computational cells in the X direction was 9 with 48 in the Y direction, for a total of 432.

Unlike the above mentioned single tube model the superficial gas velocity was maintained, just above minimum fluidisation, for two seconds to obtain a reasonable initial condition for a bed at minimum fluidisation. The average aluminium erosion rate time-averaged over 2.0 s predicted by the dissipation model 0.35 mm/1000h, was of the same order as the physical data 0.1-0.3 mm/1000h. The average erosion rate predicted by the Finnie Model, 3.2 mm/1000h, was an order of magnitude higher.

DEVELOPMENT OF THE MODEL

Recent published results of Witt and Perry (1994) have shown that the modern computational fluid dynamics (CFD) code CFDS-FLOW3D can make an important contribution to the design, optimisation and operational analysis of fluidised beds. Unlike earlier codes noted above, this code includes body fitted coordinates enabling complex geometry to be considered. Square and round tube configurations were modelled to provide a comparison with available computational and experimental data. The Finnie Erosion Model with angular dependence has been coded into the computational engine CFDS-FLOW3D following the observation by Lyczcowski et al (1986) that average erosion rates computed with this model seem to agree more closely with experimental data. They further developed the model with the introduction of the erosion kinetic theory (Ding et al, 1993). We have developed a two dimensional model with single square tube geometry and a two dimensional model with single round tube geometry for comparison with the physical model of Zhu et al (1990) and the computational model of Ding et al (1993). A second model of a two dimensional multiple square tube geometry, and a two dimensional multiple round tube geometry is compared with the experiments of Parkinson et al (1985) and with the computational results of Bouillard et al (1989). Some changes in cell configuration have been adopted. The single square tube geometry uniform grid has 20 cells in the X direction and 86 in the Y direction for a total of 1720 cells. The single round tube geometry has 20 cells in the X direction and 240 in the Y direction for a total of 4800 cells. The multiple square model and the round square model have 18 cells in the X direction and 96 cells in the Y direction, for a total of 1728 cells. The latest CFDS-FLOW3D version developed for multi-phase flow within the CRC New Technologies for Power Generation from Low Rank Coal was adopted for this work.

RESULTS AND DISCUSSION

For the purpose of this paper hydrodynamic symmetry between the right and the left side of the FBC was assumed to reduce the required computational time. In reality there is some asymmetry in the physical field, which was emphasised by Lyczcowski et al (1994) in their study.

Figures (1) and (2) show the CFDS-FLOW3D 2D numerical results of the square and the round tube geometry based upon the experimental conditions and geometry set by Zhu et al (1994). A comparison of the predictions of time averaged two dimensional slice-averaged porosity contours, figure 1 with IFAP predictions (Ding et al 1993) show good agreement. The predicted brass tube erosion rates using CFDS-FLOW3D/modified Finnie Erosion Model are compared to those of Ding et al (1993) using the IFAP/Kinetic Theory Erosion Model. The two codes compare reasonably well in their prediction of wear about the circumference of the tube but the CFDS-FLOW3D model predicts higher erosion rates than that from IFAP particularly for the side of the tube. The average predicted erosion rate of 12.1 µm/100h at the bottom of the single square tube compares well with the average erosion rate of 10.1 µm/100h for the single brass tube measured by Zhu et al (1990). The average predicted erosion rate of 20 µm/100h for the round brass tube compares well with 14.1 µm/100hours the average measured erosion rate. The predicted distribution pattern was improved using a round tube geometry and agrees with the finding that for a single tube geometry in a FBC the maximum erosion rate is expected to be at an angle of 40-50° from the tube bottom, and has very low values on the top of the tube (Zhu et al, 1990).

Figures (3) and (4) present the numerical results for the multiple tube case and follow the experimental conditions considered by Parkinson et al (1985). The CFDS-FLOW3D computer generated porosity contours at 2.7 and 3.9 seconds show similar trends with those presented in Bouillard et al (1989). For the FLUFIX computed erosion rates the top number in each square being the solution for the Energy Dissipation Model and the bottom number for the modified Finnie Erosion Model. The average erosion rate predicted by the CFDS-FLOW3D model for the multiple square tube geometry upper obstacle was 0.05 mm/1000hours and 0.14 mm/1000 hours for the lower obstacle. For the multiple round tube geometry the prediction was 0.12 mm/1000hours for the upper obstacle and 0.14 mm/1000 hours for the lower obstacle, with the distribution pattern improved for the multiple round geometry. The measured aluminium average erosion rate was of order 0.1 to 0.3 mm/1000hours. The CFDS-FLOW3D model appears to be in agreement with the measured data.

CONCLUSIONS

The modified Finnie erosion model has been coded into the computational engine CFDS-FLOW3D and shown to be capable of analysing the erosion rates in a FBC. For single and multiple square and round tubes immersed in the bed the calculated erosion rates are consistent with the experimental findings and earlier computational models.

The influence of the grid size on the computed results has been investigated by Ding et al (1993). The CFDS-FLOW3D computations also show that the grid size can strongly influence the results. Therefore a full convergence study may be required when choosing the grid for the problem of interest.

The multiple round tube model computational results show better distribution patterns around the obstacle compared with the multiple square tube results, and are in good agreement with the physical measurements.

This is the first time to our knowledge that round tube geometry has been simulated with the purpose of predicting local erosion rates in a cold model fluidised bed combustor.

More comprehensive physical modelling data is required to support the further development of these models.

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REFERENCES

Bouillard, J. X., Lyczkowski, R. W., Folga, S., Gidaspow, D. and Berry, G. F., (1989), "Hydrodynamics of Erosion of Heat Exchanger Tubes in Fluidised Bed Combustors", The Canadian Journal of Chemical Engineering, Vol 67, pp. 218-229.

Ding, J. R., Lyczkowski, R. W., Burge, S. T. and Gidaspow, D., (1993), "Three-Dimensional Models of Hydrodynamics and Erosion in Fluidised-Bed Combustors", A.I.Ch.E. Symposium Series, Fluidised Processes, Vol. 88, No. 289, pp. 85-98.

Lyczcowski, R., W., Bouillard, J., X. and Berry, G., F., (1986), "Erosion Calculation in a two dimensional fluidised bed", Report of the U.S. Department of Energy, Morgantown Energy Center, USA.

Lyczkowski, R. W., Bouillard, J. X., Chang, S. L. and Folga, S. M., (1994), "Mechanistic Modelling of Tube Erosion in Fluidised Bed Combustors", Energy Systems Division, Argonne National Laboratory, Contract W-31-109-ENG-38, USA.

Parkinson, M. J., Napier, B. A., Jury, A. W. and Kempton, T. J., (1985), "Cold Model Studies of PFBC Tube Erosion" Proceedings of 8th International Conference on Fluidised Bed Combustion, Vol II, pp. 730-745, National Technical Information Service, USA.

Stinger, J., (1987), "Current Information on Wastage in Fluidised Bed Combustors", Proceedings of the 1987 International Conference on FBC, J. P. Mustonen, Ed., Vol 2, pp 685-686., American Society of Engineers, NY.

Witt, P. J. and Perry, J. H., (1994), "Application of Multiphase Modelling to the Hydrodynamics in Circulating Fluidised Beds", The 2nd CFDS International User Conference, Pittsburgh, USA.

Wood, R. T. and Woodford, D. A., (1980), "Tube erosion in fluidised beds", ERDA Report 81-12 11/ET-FUC 179, USA.

Zhu, J., Grace, J. R. and Lim, C. J., (1990), "Tube Wear in Gas Fluidised Beds-I. Experimental Findings", Chemical Engineering Science, Vol 45, no. 4, pp. 1003-1115.

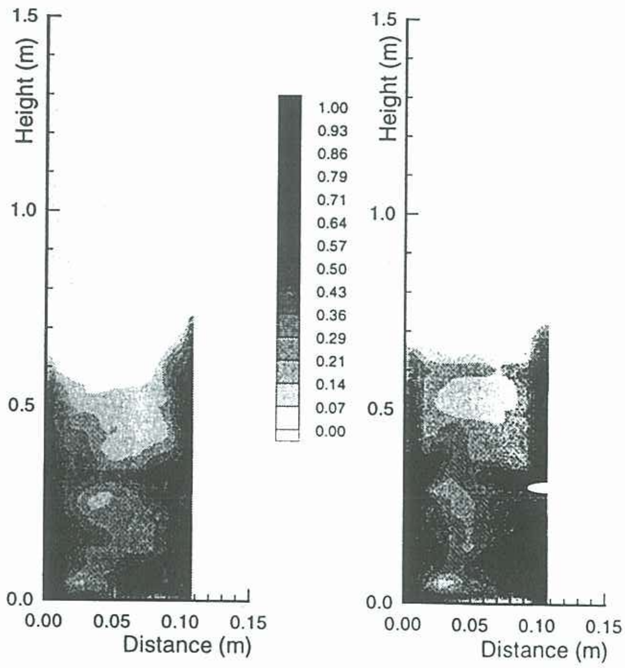

Figure 1 CFDS-FLOW3D predictions: time-averaged two dimensional slice-averaged porosity contours for a square and a round single tube geometry.

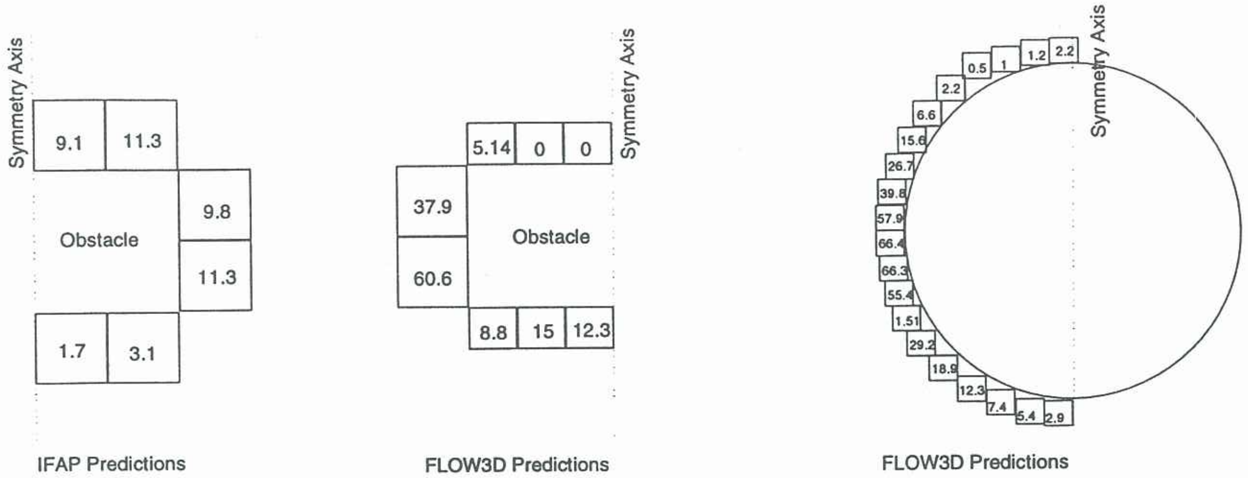

Figure 2 Comparison of time-averaged two dimensional slice-averaged IFAP predicted erosion rates (μm/100h) at the brass tube surface (Ding et al, 1993) with CFDS-FLOW3D predicted erosion rates for a single square and a single round tube geometry.

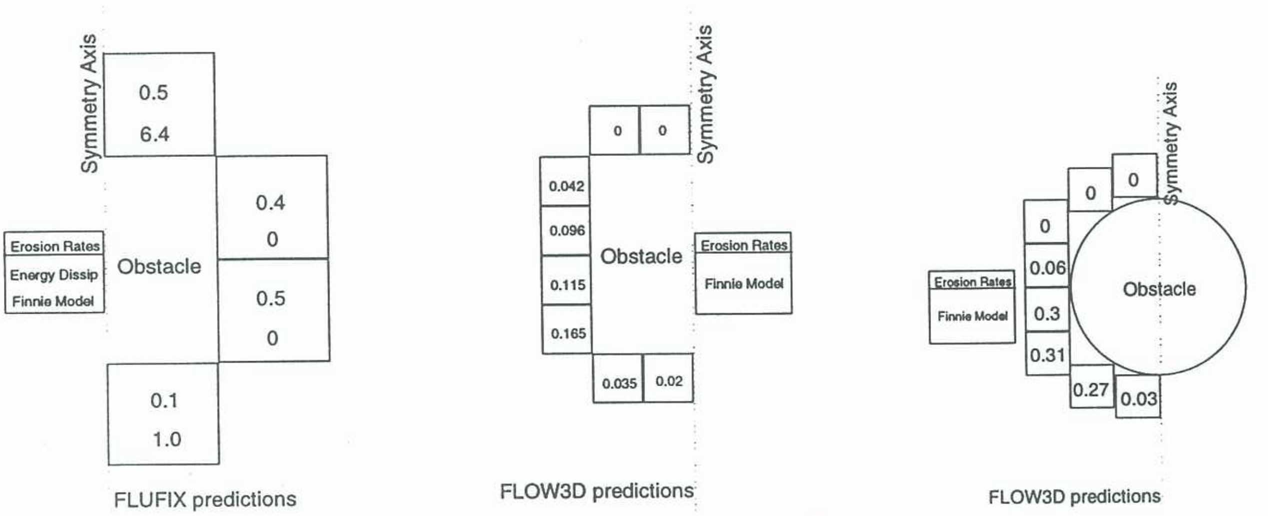

Figure 3 Comparison of time averaged two-dimensional slice averaged FLUFIX predicted erosion rates (mm/1000h) at each aluminium tube surface (Bouillard et al, 1989) with CFDS-FLOW3D predicted erosion rates for the multiple square and the multiple round tube geometry, upper obstacle.

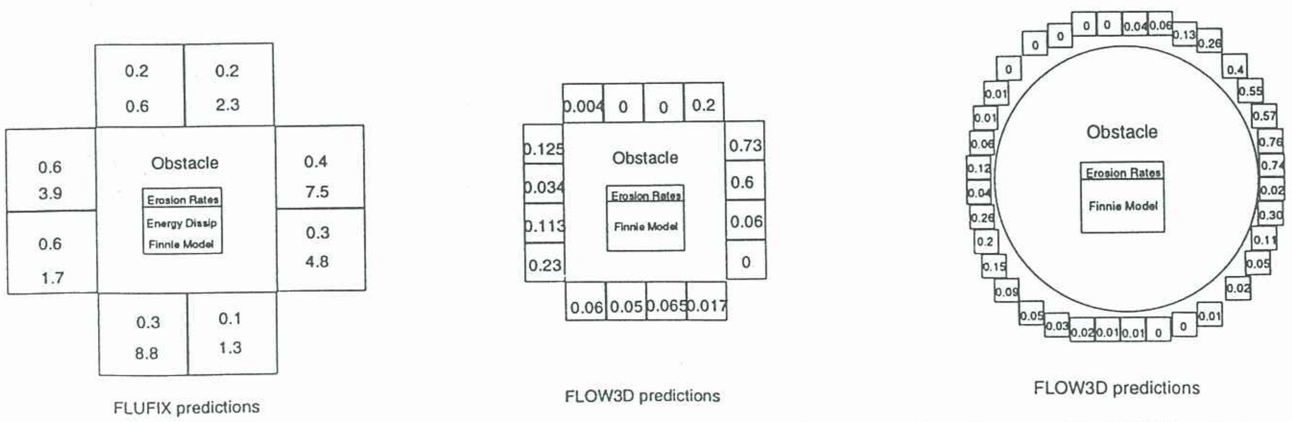

Figure 4 Comparison of time averaged two-dimensional slice averaged FLUFIX predicted erosion rates (mm/1000h) at each aluminium tube surface (Bouillard et al, 1989) with CFDS-FLOW3D predicted erosion rates for the multiple square and the multiple round tube geometry, lower obstacle.