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Numerical study of the erosion within the pulverised-fuel mill-duct system of the Loy Yang B lignite fuelled power station

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ABSTRACT

The quality of coal from a natural source can vary significantly as it is processed from the ground. Elevated sand loadings within the raw coal can significantly influence wear due to erosion within the mill-duct system of a lignite fuelled power station. A previous study [1] by the current authors investigated the gas and particle mass flow within the mill-duct system of a real-life operating power station both numerically and experimentally. This work extends the previous study by considering the wear of the mill-duct system caused by coal and varying levels of sand under normal operating conditions. At elevated levels of sand loading, the wear significantly increased in comparison with the coal only flow. Considering varying levels of sand loadings, the erosion wear at the highest sand loading case (30% by mass) produced slightly less than three times the total wear of the 10% sand loading case. This non-linear relationship can be attributed to the re-acceleration of the heavier sand particles after particle–wall collisions. The erosion patterns found within the swirl vane regions of the mill-duct confirm the findings of other researchers in the field of particulate roping. The findings suggested that the particle ropes twist around the circumference of duct when a series of bends is encountered. These findings were evident in the erosion distribution comparing the swirl vanes in the upper and lower legs of the mill-duct system. These differing erosion distributions were attributed to the rotational motion of the secondary gas flows and the difference in bend-to-swirl vane distance of the two legs. The predicted erosion wear on the upper leg swirl vanes was greater than those of the lower leg even though the particle mass flow was biased toward the lower leg. The upper and lower leg swirl vane geometry imparts an anti-clockwise rotation to the flow while the secondary flow created by the trifurcation geometry was anti-clockwise within the lower leg and clockwise within the upper leg. Thus the anti-clockwise motion created within the lower leg geometry actually aided the swirl vane motion, minimising the wear. The upper leg swirl vanes reversed the secondary flow resulting in a greater number of particle/swirl vane collisions, leading to a higher degree of wear.

1. Introduction

A majority of the electricity needs of Victoria, Australia are provided by the Latrobe Valley Lignite fuelled power stations. Typically the lignite fuelled power stations consist of a number tangentially fired furnaces [2,3] consisting of 8 circumferentially arranged mill-duct systems. These mill-ducts systems are responsible for grinding the raw coal and distributing the pulverised fuel to the furnace at appropriate concentrations to provide ideal combustion characteristics within the furnace. The current authors experimentally and numerically studied the distribution of the gas and coal phases within an operating real-life Lignite fuelled power station [1]. The mill-duct system consisting of a complicated series of large diameter-to-length ratio ducts coupled with numerous bends displayed a high level of non-uniformity in the distribution of Pulverised Fuel (PF) through the ducting. The findings of this work confirmed other researchers' findings on the study of particle roping downstream of a single or series of bends [4–9]. The non-uniform distribution of the solids loading within the ducting leads to regions of higher wear which results in costly mill shutdowns for maintenance. A more comprehensive review on PF flow in mill-ducts is available in Dodds et al. [1].

Surface erosion due to particle impacts is a topic that has been investigated by many researchers over the last century. Of these works numerous researchers have developed or refined erosion rate equations [10–15], of these the work of Finnie [10] is still a commonly accepted work for the basis of erosion even to this day. While the use of Computational Fluid Dynamics (CFD) to predict the erosion in coal power stations is certainly not new, the investigation of the influence of coal quality on the erosion within the mill-duct system would be of benefit to power station operators in general.

The aim of this research is to better understand the influence of coal quality (percentage of sand loading in raw coal) on the erosion

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of the mill-duct system of an operating real-life power station (Loy Yan B, Victoria, Australia) by numerical methods. CFD modelling of the erosion due to both coal and sand is considered in this work.

2. Material and methods

This section presents the numerical method used for the investigation of the erosion due to both coal and sand particles flowing through the mill-duct system of a real-life operating power station.

2.1. Numerical methods

The numerical methods presented here for convenience is a repetition from Dodds et al. [1], however the erosion modelling part is new. The low PF-to-gas ratio lends itself ideally to the Eulerian–Lagrangian approach. Under the Eulerian–Lagrangian approach, the gas and PF are treated as interacting phases. The AVL-Fire commercially available CFD software utilises an unsteady solution process which is deemed appropriate for the transient characteristics commonly associated with the complex mill-duct flows seen in industrial power stations. The process of grinding the raw coal within the rotating beater wheel mill leads to unsteady particle motion. Anagnostopoulos et al. [16] highlighted the unsteady motion of the beater mill due to the finite number of grinding blades. While the gas flow averaged over time provided a relative steady gas flow, the authors note that the particle distribution is predominately determined by the beater mill motion rather than the gas phase. The experimental and numerical study of two-phase flow through a bifurcation [17] also highlighted the unsteady characteristics of the two-phase flow downstream of the bifurcation. While the accepted method is to consider the two phase flow to be steady in nature to reduce computational requirements, it was decided that greater benefit and insight were to be achieved under transient simulated conditions. The time step used for the simulation varied from 0.005 s under initial simulation startup, up to 0.025 s once the simulation solution becomes more stable.

2.2. Gas phase

The continuous gas phase is calculated using the Navier–Stokes equations for which the general form can be written:

$$\frac{\partial}{\partial t}\left(\rho_g \phi\right) + \frac{\partial}{\partial x_i}\left(\rho_g U_i \phi\right) = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_i}\right) + S_\phi + S_{P\phi} \tag{1}$$

where ρ_g is the gas density, U is the velocity vector, ϕ is the variable quantity, Γ_ϕ is the diffusion coefficient, S_ϕ is the source term for the gas phase and $S_{P\phi}$ is the additional source term due to the interaction between the gas and the PF. Depending on ϕ, the above equation represents mass, momentum, species or energy conservation. For conservation of mass, $\phi = 1$ and when $\phi = U_i$ then the above equation becomes the momentum equation. The standard k-ε two-equation turbulence model was used to close the Navier–Stokes equations.

2.3. PF phase

The Lagrangian particle tracking method is used to calculate the individual trajectories of the dispersed PF phase. Equating the PF inertia with external forces, the momentum equations can be described by the following general equation:

$$\frac{d\vec{u}_p}{dt} = F_D\left(u_p - u_g\right) + \frac{\vec{g}\left(\rho_p - \rho_g\right)}{\rho_p} \tag{2}$$

The left side of the equation describes the inertia of the particle phase while the right side describes the external forces acting upon the particle phase whereby, F_D denotes the drag force between the particle and the gas phase where F_D is determined by the Schiller–Naumann correlation for a spherical particle. The second term on the right hand side denotes the gravitational force calculated based on the density difference between the PF and gas phase. Although other forces may also influence the particle trajectory, the drag and gravitational are the predominant forces acting on the PF in mill-duct flows. The typical volume fractions of coal fuelled power stations are in the range of less than 0.005. At such low volume fractions of solids, it is debatable about the degree of influence inter-particle collision modelling would provide. The shear number of representative particles required to simulate mill-duct flows would see a significant increase in the computational requirements without a justifiable increase in simulation accuracy. For this reason the influence of inter-particle collision has been excluded from this study. The particle–particle interaction was also ignored in similar study [18] involving roping. However, the interactions between gaseous eddies and the particles are taken into account by a stochastic procedure, referred to as the eddy life time concept. Particle diameter (Fig. 1) was set according to the particle size analysis measured in Ref. [1] and 20,000 particles/s were introduced through the inlet to represent the mass flow rate. Details of Eulerian–Eulerian gas-particle multiphase flows can be found in Refs. [19,20].

2.4. Heat and mass transfer

The heat transfer between the particle and gas is accounted for using the equation:

$$m_p c_p \frac{dT_p}{dt} = hA\left(T_g - T_p\right) + \frac{dm_p}{dt} h_{fg} \tag{3}$$

where m_p and particle properties for the mass and temperature respectively, A is the surface area of the particle, T_g is the local gas temperature and h the heat transfer coefficient calculated using the correlation of Ranz and Marshall [21]:

$$\mathrm{Nu} = \frac{hd_p}{\lambda} = 2.0 + 0.6\left(\mathrm{Re}_p\right)^{0.5} (\mathrm{Pr})^{0.33} \lim_{x \to \infty} \tag{4}$$

where Nu is the Nusselt number, Re_p is the particle Reynolds number, Pr is the Prandtl number and λ is the thermal conductivity. The radiative heat transfer has not been considered as part of this work as the influence was considered negligible within the mill-duct flows.

2.5. Erosion modelling

One of the simplest and most commonly used erosion model is that of Finnie [10]. The erosion modelling of this section is based on the Finnie work, with the Erosion rate calculated by the following relation:

$$E = km_p \left|v_p\right|^2 f(\alpha) \tag{5}$$

where E is the erosion rate, k is an experimental coefficient based on the particle/wall material interaction, m and v are the particle mass and velocity respectively and $f(\alpha)$ is a function of the impact angle between the particle and wall. The function of the impact angle, $f(\alpha)$ is defined by:

$$\begin{aligned} f(\alpha) &= \sin(2\alpha) - 3\sin^2(\alpha), & \alpha \le 18.4^\circ \\ f(\alpha) &= \frac{\cos^2(\alpha)}{3}, & \alpha > 18.4^\circ \end{aligned} \tag{6}$$

While mass, velocity and impact angle are calculated from the flow properties, coefficients of k_{sand} and k_{coal} must be determined.