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Modeling and numerical investigation of erosion rate for turbulent two-phase gas–solid flow in horizontal pipes

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ABSTRACT

A modified model for prediction of erosion rate in pipe flows is presented based on the simulation of the fluid fluctuating velocities with the Discrete Random Walk model. Turbulence modulation of gas–solid flow in a horizontal pipe is investigated numerically using a four-way coupled Eulerian–Lagrangian approach. The particle impingement angle and impact velocity are evaluated and used for predicting the erosion rate by the available and newly developed models. The gas–solid flow simulation results are validated by comparison of the model predictions with the earlier experimental data for two-phase pipe flows. A modified model for erosion was developed that accounts for the effect of particle size to simulate the wall impact velocity caused by fluid turbulence. It is demonstrated that, when compared to the previous simplified erosion models, the new model can estimate erosion rate more accurately, especially for small particles in gas–solid flows.

1. Introduction

Erosion of ducts is an important issue in many industrial facilities such as gas pipelines, oil production and power plant equipment. Erosion causes serious damage to industrial equipment and reduces their life. Collision of solid particles with the inner wall of flow passages is the main cause of the removal of the material from the surface.

A major concern in the natural gas transmission industry is the presence of the solid particles called black powder. Black powder is composed mainly of iron sulfides and iron oxides, which can create wear on pipelines. These particles not only reduce the flow efficiency and clog the filters but also cause some operation and maintenance issues. Due to the serious damage caused by particle erosion, many researchers have studied the mechanism of erosion and tried to develop relationships for prediction of erosion rate in terms of the properties of the flow, particles and target.

Earlier studies were concerned with erosion in slurry flow, and most researchers have focused on the relationship of the erosion rate with particle velocity, where different values for the exponent of the particle velocity were reported. Finnie [1] developed a model for ductile material and reported a range of 2.05–2.44 for the particle velocity exponent. Hutchings [2] indicated that the power of particle velocity is different from the previously suggested values; and he obtained 3.0 for the velocity exponent. The majority of the erosion predictive models indicate that erosion rate is independent of the particle size and hardness. Finnie [1] showed that increasing hardness of the 1045 steel doesn't influence the erosion rate. Truscott [3,4] found a similar range of exponents on the flow velocity in pipeline erosion. More detailed experimental investigation by Karabelas [5] showed different exponents for the flow velocity around the pipe periphery.

Huang et al. [6] developed a new phenomenological model for rate of erosion that includes the properties of abrasive particles and surface material. In particular, they included the important effect of particle size, density, hardness and strength of surface material. Their model accounts for two removal mechanisms: deformation damage removal and cutting removal. Huang et al. [7] stated that some factors lead to particle lateral movement, such as flow turbulence, gravitational, buoyant and centrifugal forces and the particle's momentum of inertia. In straight and slightly straight pipelines, the effects of the last two factors are neglected. Some researchers indicated that the impingement angle in straight pipelines will be small if the particle size is small. Wellinger et al. [8] reported an impingement angle less than 5°. Due to the small impingement angle, Huang et al. [7] neglected the deformation damage removal. They balanced the gravitational, buoyant and drag forces, and derived a relation for the particle's lateral velocity. They also neglected the boundary layer effects on the particles. It is critical to apply the appropriate model for simulating fluid fluctuating velocities which are important for the accurate analysis of a particle transport process.

In this work, the erosion in a horizontal pipeline carrying a gas–solid two-phase flow was studied. The RANS model was used to evaluate the mean velocity field and turbulence stresses. The Discrete Random Walk model was used for evaluating the instantaneous turbulence fluctuating

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velocities. The presented model provides an improved estimate for the particle impingement angle needed in the Huang et al. [7] erosion model for slurry flows. The new improved erosion model was validated by comparison with the available experimental data for sand/water slurry flow. The simplified model's predictions were also compared with comprehensive numerical results for gas–solid turbulent flows in horizontal pipelines.

2. Turbulent gas–solid flow simulation

Turbulent gas–solid two-phase flows in a horizontal pipe are analyzed using a four-way coupled Eulerian–Lagrangian approach. The gas phase flow is assumed to be steady, incompressible and fully developed. The gas hydrodynamic field is simulated by the RANS equation model together with the standard $k-\varepsilon$ turbulence model. Solid particles are assumed to be rigid and spherical. Particle motions are analyzed by the Lagrangian tracking method.

2.1. Gas phase modeling

For fully developed, incompressible pipe flows, the time-averaged steady-state axial momentum can be written as,

$$\frac{\partial}{\partial y}\left((1-\varphi)(\mu+\mu_t)\frac{\partial U_g}{\partial y}\right)+\frac{\partial}{\partial z}\left((1-\varphi)(\mu_m+\mu_t)\frac{\partial U_g}{\partial z}\right) \\ -(1-\varphi)\frac{dP}{dx}-\rho(1-\varphi)g\sin\theta+S_{pu}=0 \qquad (1)$$

where φ is the volume concentration of the particles, U_g demonstrates the mean axial velocity, ρ is the gas density, and μ is the gas molecular viscosity. In Eq. (1), $\mu_t=C_\mu\rho\cdot k^2/\varepsilon$ is the (turbulent) eddy viscosity. Pipe configuration and coordinate system are shown in Fig. 1. In this paper, θ is considered to be zero and a horizontal pipe is studied. The transport equations for turbulence kinetic energy k and dissipation rate ε are given as,

$$\frac{\partial}{\partial y}\left((\mu+\mu_t/\sigma_k)(1-\varphi)\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left((\mu+\mu_t/\sigma_k)(1-\varphi)\frac{\partial k}{\partial z}\right) \\ +(1-\varphi)\mu_t\left[\left(\frac{\partial U_g}{\partial y}\right)^2+\left(\frac{\partial U_g}{\partial z}\right)^2\right]-(1-\varphi)\rho\varepsilon+S_{pk}=0 \qquad (2)$$

$$\frac{\partial}{\partial y}\left((\mu+\mu_t/\sigma_\varepsilon)(1-\varphi)\frac{\partial \varepsilon}{\partial y}\right)+\frac{\partial}{\partial z}\left((\mu+\mu_t/\sigma_\varepsilon)(1-\varphi)\frac{\partial \varepsilon}{\partial z}\right) \\ +C_1(1-\varphi)\frac{\varepsilon}{k}\mu_t\left[\left(\frac{\partial U_g}{\partial y}\right)^2+\left(\frac{\partial U_g}{\partial z}\right)^2\right]-C_2(1-\varphi)\rho\frac{\varepsilon^2}{k}+S_{p\varepsilon}=0. \qquad (3)$$

The parameters in the turbulent model are those suggested by Launder and Spalding [9] and are summarized in Table 1.

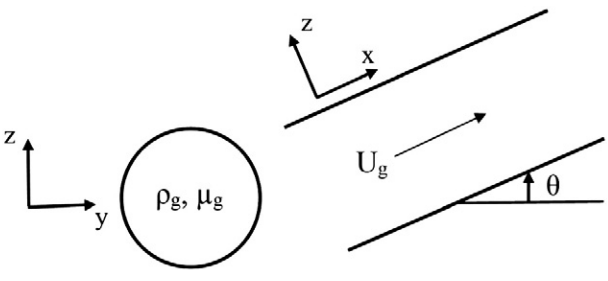

Fig. 1. Illustration of gas flow.

Table 1
Values for the turbulence model coefficients.

C_μ	C_1	C_2	σ_k	σ_ε
0.09	1.44	1.92	1.0	1.3

In Eqs. (1) and (2), S_{pu} and S_{pk} are source terms due to the presence of solid particles as proposed by Gouesbet and Berlemont [10] and are given as:

$$S_{pu_i}=\varphi\left\langle-\rho_p\left(\frac{dU_{p_i}}{dt}-g_i\right)\right\rangle \qquad (4)$$

$$S_{pk}=\left\langle s_{pu_i}u_{f_i}\right\rangle. \qquad (5)$$

Here the lower case symbols stand for fluctuating values. The dissipation source term in the ε equation was proposed by Lain and Sommerfeld [11]. That is,

$$S_{p\varepsilon}=C_\varepsilon\frac{\varepsilon}{k}S_{pk} \qquad (6)$$

where C_ε is not universal and can vary from 1.0 to 2.0. Here a value of $C_\varepsilon=1.80$ is selected. Gas velocity fluctuations are simulated by the Discrete Random Walk (DRW) model (Hutchinson et al. [12]). In this model, a particle is trapped by an eddy during its lifetime which is given as $\tau_e=2\tau_L$, where τ_L is the particle Lagrangian integral time scale and is given by $C_l k/\varepsilon$. Here C_l is a constant which is not quite universal. Sommerfeld [13] has suggested using $C_l=0.16$. The interaction between particle and eddy ends when the particle crosses the eddy boundary or the eddy lifetime is over. The particle eddy crossing time, τ_{cross}, is evaluated as:

$$\tau_{cross}=-\tau\ln\left[1-\left(\frac{L_e}{\tau\left|u-u_p\right|}\right)\right] \qquad (7)$$

where τ is the particle relaxation time, and $L_e=c_\mu^{3/4}(k^{3/2}/\varepsilon)$ is the eddy length scale. For small particles when the Stokes drag is applicable, $\tau=\rho_f d_p^2/18\mu_f$. For larger particles when nonlinear drag is used, the expression of particle relaxation is modified appropriately.

During the lifetime of the eddy, the instantaneous fluid velocity seen by a particle is given as

$$u'=\lambda_i\ u_{rms} \qquad (8)$$

$$v'=\lambda_j\ v_{rms} \qquad (9)$$

$$w'=\lambda_k\ w_{rms} \qquad (10)$$

where λ_i, λ_j and λ_k are zero mean Gaussian random numbers with a standard deviation of 1. For the $k-\varepsilon$ model, the RMS fluctuating components are given as:

$$u_{rms}=v_{rms}=w_{rms}=\sqrt{2k/3}. \qquad (11)$$

These expressions are applicable in the regions far from the wall when turbulence is nearly isotropic. For the near-wall region, turbulent fluctuations are strongly anisotropic. DNS simulations of duct flows were reported by Soltani and Ahmadi [14] and Matida et al. [15] among others. Here the expressions for RMS fluctuation velocities