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The effects of wall roughness on erosion rate in gas–solid turbulent annular pipe flow

M. Jafari [a], Z. Mansoori [b,*], M. Saffar Avval [a], G. Ahmadi [c]

[a] Department of Mechanical Engineering, Energy and Control Center of Excellence, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran
[b] Energy Research Center, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran
[c] Department of Mechanical and Aeronautical Engineering, Clarkson University, P.O. Box 5725, Potsdam, NY 13699-5725, USA

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ABSTRACT

In the present study, the effects of wall roughness on erosion rate for gas–solid flows in horizontal annular pipes for different ratios of inner to outer radii and also for different values of solid particle concentration are investigated. The results are compared with earlier studies, and the effect of various parameters is discussed. The impingement angles and impact velocities of solid particles, which are needed for using the comprehensive erosion model, are evaluated using a four-way coupled Eulerian–Lagrangian simulation approach of gas–solid flows. The turbulent gas phase flow is solved using the k–ε model. For the simulation of particle movement, the fluctuations of gas phase velocity are evaluated by the eddy interaction method. The numerical results indicate that the solid particle induced erosion rate at the outer wall of annular pipes is considerably larger in comparison with a simple circular pipe with the same outer radius, and the erosion rate further increases as the radius ratio increases. The results also show that the erosion rates at both inner and outer walls increase as wall roughness increases and are much higher compared with those for smooth walls or walls with a small roughness.

1. Introduction

Annular flows are widely used in heat exchanger systems, and there is considerable interest in increasing the efficiency of heat transfer. One of the passive heat transfer enhancement methods is to add solid particles to the fluid media [1]. Many studies have reported the effects of solid particles on the heat transfer rate in gas–solid flows [2–5]. Accordingly, the heat transfer is enhanced by the addition of micron-size solid particles into gases or liquids at small volumetric fractions due to the thinning of the viscous sublayer and increase of effective thermal conductivity [6].

A major concern of the use of gas–solid flows in the double pipe heat exchanger is the erosion of the inner and outer walls of the annulus. Impact of solid particles with the flow passage walls is the main cause of the removal of material from the surface [7]. Due to the serious damage caused by particle erosion in industrial applications, 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 gas–solid flows and the material properties of particle and target surfaces. Earlier studies were concerned with erosion in slurry flows, and researchers tried to develop the relationship of the erosion rate to particle impact velocity. Typically, power law dependence for the erosion rate was reported, where different values for the exponent of the particle velocity were suggested.

Many investigators have carried out numerical modeling of the erosion of pipe bends, elbows, tees and related geometries. Since the early nineties, computational fluid dynamics (CFD) has been used for predicting the solid particle erosion in curved pipes and ducts, and various analytical, semi-empirical and empirical models were developed [8]. Edwards et al. [9] used a commercial CFD code to model fluid–solid flows and added subroutines for predicting erosion due to particle impacts. Wang and Shirazi [10] performed their simulations on the erosion of 90° elbows and bends with circular cross-section. They used a simple modified mixing-length model for the fluid turbulence. They reported that the effect of the squeeze film, secondary flows and turbulent flow fluctuations may all play important roles in predicting the erosion rate when the carrier fluid is a liquid. Keating and Nesic [11] used a commercial CFD code coupled with an in-house particle tracker to predict fluid–particle flow in a full 180° bend. Zhang et al. [12] investigated a particle motion in the near-wall region using a commercially available CFD code, and modifying the code to account for particle size effects in the region before and after particle impact. Wallace et al. [13] also used an Eulerian–Lagrangian approach, coupled with a semi-empirical erosion equation, to predict erosion due to a slurry flow in choke valves. Li et al. [14] applied a Eulerian–Lagrangian approach with particle–particle interaction and a particle erosion model to simulate wall erosion characteristics of a solid–liquid two-phase flow in a choked flow. They used the standard k–ε model, the hard sphere

* Corresponding author. Tel.: +98 21 66405844; fax: +98 21 66419736.
E-mail address: z.mansoori@aut.ac.ir (Z. Mansoori).

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model to analyze inter-particle collisions, and semi-empirical correlations for erosion due to particle impact. Njobuenwu and Fairweather [8] developed a three-dimensional computational fluid dynamic model to investigate the erosion of both the concave and convex walls of square cross-section ducts for different bend configurations and orientations due to particle collisions with the walls. Jafari et al. [7] investigated the erosion rate numerically in a horizontal pipeline carrying a gas–solid two-phase flow using a four-way coupled Eulerian–Lagrangian approach. They implemented the Huang et al. [15] erosion model, which is a new phenomenological model for the rate of erosion that includes the properties of abrasive particles and surface material. In particular, they included the important effect of particle size, density and hardness, as well as the strength of surface material. This model accounts for two removal mechanisms — deformation damage removal and cutting removal.

In this work, the erosion rate in a horizontal annular pipe carrying gas–solid two-phase flows with different wall surface roughness is studied. The RANS model is used to evaluate the mean velocity field and turbulence stresses in the passage. The discrete random walk model is used for evaluating the instantaneous turbulence fluctuating velocities. Using the detailed simulation of the gas–solid flows, the particle impingement angles and impact velocities are evaluated directly and used in the Huang et al. [15] comprehensive model to evaluate the erosion rate. The resulting erosion rates are compared with those available in the literature, and the effect of various parameters are discussed.

2. Turbulent gas–solid flow simulation

Turbulent gas–solid flows in a horizontal annular 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 Reynolds averaged Navier–Stokes (RANS) equations in conjunction with the standard $k - \varepsilon$ turbulence model. Solid particles are assumed to be rigid and spherical. Particle motions are analyzed by the Lagrangian tracking approach.

2.1. Gas phase modeling

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

$$\frac{1}{r}\frac{\partial}{\partial r}\left((1-\varphi)(\mu+\mu_t)r\frac{\partial U_g}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial \theta}\left((1-\varphi)(\mu+\mu_t)\frac{1}{r}\frac{\partial U_g}{\partial \theta}\right)- \\ -(1-\varphi)\frac{dP}{dx}-\rho(1-\varphi)g\sin\alpha+S_{pu}=0 \quad (1)$$

where φ is the particle volume concentration, U_g is the gas mean axial velocity, ρ is the gas density, and μ is the gas molecular viscosity. In Eq. (1), $\mu_t = C_\mu \rho k^2/\varepsilon$ is the (turbulent) eddy viscosity.

The cross section of an annular pipe configuration and coordinate system are shown in Fig. 1. The longitudinal direction of the pipe is along the x-axis, and the cross section of the flow shown in this figure is in the (r, θ) plane. It is also assumed that the pipe is horizontal. The transport equations for turbulence kinetic energy, k, and dissipation rate, ε, are given as

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

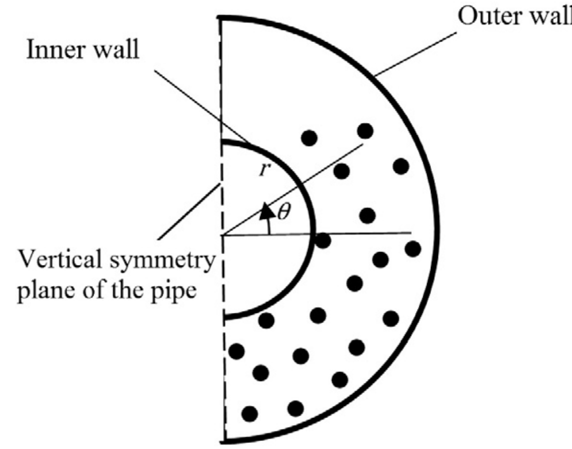

Fig. 1. A cross-sectional view of gas–solid flow in an annular pipe.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\left(\mu+\frac{\mu_t}{\sigma}\right)(1-\varphi)r\frac{\partial \varepsilon}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial \theta}\left(\left(\mu+\frac{\mu_t}{\sigma}\right)(1-\varphi)\frac{1}{r}\frac{\partial \varepsilon}{\partial \theta}\right)+ \\ +C_1(1-\varphi)\frac{\varepsilon}{k}\mu_t\left[\left(\frac{\partial U_g}{\partial r}\right)^2+\left(\frac{1}{r}\frac{\partial U_g}{\partial \theta}\right)^2\right]-C_2(1-\varphi)\rho\frac{\varepsilon^2}{k}+S_p=0. \quad (3)$$

The constant parameters of the turbulence model are those suggested by Launder and Spalding [16] and are summarized in Table 1.

In Eqs. (1) and (2), S_{pu} and S_{pk} are the source terms due to the presence of solid particles as proposed by Gouesbet and Berlemont [17] and are given as

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

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

Here the lower case symbols stand for fluctuating values. The dissipation source term in the ε equation was proposed by Lain and Sommerfeld [18]. That is,

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

where C_ε is a constant that varies in the range of 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 Model (DRW) (Hutchinson et al. [19]). In this model, a particle is assumed to be trapped by an eddy during its lifetime, which is given as $\tau_e = 2\tau_L$, where $\tau_L = C_l k/\varepsilon$ is the particle Lagrangian integral time scale. Here C_l is a constant (which is not quite universal). Sommerfeld [20] suggested using $C_l = 0.16$. The interaction between a particle and an 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

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

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