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Three dimensional heat transfer modeling of gas-solid flow in a pipe under various inclination angles

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ABSTRACT

The turbulent heat transfer in gas-solid flows through an inclined pipe under various inclination angles is studied with constant wall heat flux. The hydrodynamic $k - \tau$ and $k_\theta - \tau_\theta$ thermal two phase model is used in a lagrangian/Eulerian four way approach. The numerical results agreed reasonably with available experimental data in vertical and horizontal pipe flows. The effects of inclination angles on the flow patterns are reported. The pressure drop and Nusselt number are enhanced significantly as the inclination increases up to a certain angle. The mass loading ratio has influence on the optimal inclination angle. With increasing loading ratio, the optimal inclination angle of maximum pressure drop shifts to the lower amount.

1. Introduction

Turbulent gas-solid flows have considerable applications in industry and environmental processes. Evaporation of droplets, thermal energy conversion systems, air pollution control, coal processing systems and fluidized bed combustion are some examples which illustrate the importance of these systems. Turbulent gas-solid flows in inclined pipe have received little attention in the literature in accordance with vertical and horizontal pipe. In order to achieve optimum design of these systems, it is essential to analyze the flow dynamics and evaluate the critical pipe angle that is the angle at which the maximum pressure gradient for a given solid flow rate is achieved.

In spite of a large number of research works on gas-solid flows and heat transfer in horizontal and vertical pipes, less attention has been paid to gas-solid flows in inclined cases. Levy et al. [1] compared the pressure drop in an inclined pipe to that of a horizontal pipe in a series of experimental and numerical studies. They showed that a critical pipe angle case exists giving the maximum pressure drop for a given solid flow rate different from the vertical. This angle is completely different for the case of two-phase flow, comparing to single-phase one. Cao et al. [2] analyzed the gas-particle two-phase turbulent flows at various loadings in horizontal and inclined ducts. They concluded that particles affect significantly the dynamics of the flow near the lower wall for both horizontal and inclined duct flows. Hirota et al. [3] studied the effect of mechanical properties and the inclination angle of pipe on the pressure drop in their experimental study. Zhu et al. [4] reported the influence of inclination angle on flow patterns of 0.3 mm particles in a pipe. They predicted the asymmetries in the mean flow quantities (gas velocity, solids velocity, and solid volume fraction).

In order to simulate non-isothermal gas–solid flow, a variety of different numerical modeling tools are being employed over the past decade (Simonin [5], Louge [6], Han [7], Avila [8], Boulet [9], Mansoori [10]). Analysis of turbulent gas-solid flows showed that some factors have influence on the heat transfer between the wall and the suspension. The loading ratio, the particle characteristics, the inter-particle collisions, the particle-turbulence interactions, and flow regimes have been distinguished as the affecting factors. For example, Jepson et al. [11] reported that the heat transfer coefficient decreases at low loading ratios and increases at higher loading ratios and the rate of changes is also affected by particle diameter. The role of particle collisions in heat transfer of gas–solid pipe flow was introduced for the first time by Louge et al. [6] A new $k_\theta - \tau_\theta$ model for two-phase flows with heat transfer was developed by Saffar-Avval et al. [12] which illustrated the presence of particles source terms. Mansoori et al. [10] extended the model and studied the effects of particle interactions and collisions on the particle thermal fluctuations. Mansoori et al. [13] proposed a new four way interaction model and reported that the level of thermal turbulence intensity (which is equal to $1/2\overline{t't'}$) and the heat transfer are strongly affected by the particle collisions. They introduced the source term due to the presence of the solid phase in the $k_\theta - \tau_\theta$ transport equations and showed that inter-particle collisions reduce the temperature fluctuations near the wall

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Nomenclature

A_p	Particle surface, m^2
c_p	Specific heat, $Jkg^{-1o}C^{-1}$
c_d	Drag coefficient
D	Pipe diameter, m
d_p	Particle diameter, m
F	$6Nu_pK_fd_p^{-2}$
$f\mu$	Damping function
$f\lambda$	Damping function
g	gravity acceleration, ms^{-2}
h_p	heat transfer coefficient, $Wm^{-2o}C^{-1}$
k	Turbulent kinetic energy, $m^{-2}\,s^{-2}$
k_θ	temperature variance, $°C^2$
K_f	gas heat conductivity, $Wm^{-1o}C^{-1}$
Nu	Nusselt number $= Dh_p/K_g$
P	pressure, Nm^{-2}
Pr	Prandtl number $= \mu c_p/K_g$
Pr_t	turbulent Prandtl number $= v_t/\alpha_t$
Q	heat flux, Wm^{-2}
Re_p	particle Reynolds number
S	source term due to particle phase
T	mean temperature, °C
t'	temperature fluctuation, °C
u	Velocity, ms^{-1}
u'	Velocity fluctuation, ms^{-1}
U	gas mean axial velocity, ms^{-1}
x	axial coordinates, m
y	distance from the wall, m
y^+	non-dimension distance from the wall, $=y/y^*$
z	loading ratio, solid mass flux/gas mass flux
X,Y,Z	coordinate system

Greek letters

α	thermal diffusivity, $m^2\,s^{-1}$
α_t	thermal eddy diffusivity, $m^2\,s^{-1}$
σ	constant number
τ	turbulence time scale, S
τ_θ	thermal turbulence time scale, S
μ	Viscosity, $kgm^{-1}\,s^{-1}$
v	kinematic viscosity, $m^2\,s^{-1}$
v_t	eddy viscosity, $m^2\,s^{-1}$
ρ	density, kg/m^3
φ	particle volume concentration

Subscripts and superscripts

f	Fluid
p	Particle
X	(capital letter) average quantity
x'	fluctuating quantity
θ	thermal property

and amplify in the pipe core region. Studies of the effect of inclination angle on heat transfer in gas-solid flows are rather rare, so it will be interesting to investigate the performance of gas-solid two phase flows in inclined pipes.

In this study, the hydrodynamic $k-\tau$ and $k_\theta-\tau_\theta$ thermal two phase models are used to analyze the steady, three-dimensional (*3-D*) two-phase gas-solid turbulent flow in horizontal and inclined pipes under various inclination angels. A four-way interaction Eulerian–Lagrangian model for two-phase flows is used in the analysis. Inter-particle collision is treated by the deterministic method. The computational model is first applied to simulate gas-solid turbulent flows in horizontal and vertical pipes. The model predictions are compared with available experimental data. It is shown that the model predictions are in good agreement with experimental ones. The model is then applied to gas-solid turbulent flows in inclined pipes under different inclination angles. The model predictions appear to be reasonable since similar behavior has been observed in our experimental investigation of gas solid flowing in a tube with adiabatic boundary condition at various positions.

2. Mathematical modeling

A turbulent gas–solid flow in a heated pipe with inclination angle α is considered. Moreover, spherical and uniform size particles are assumed. The gas flow is assumed to be steady, three-dimensional and incompressible. The numerical calculations are solved by the Eulerian/Lagrangian approach for the fluid and particle phases respectively. The gas phase is described by partial differential conservation equations in three-dimensional cylindrical (x, r, θ) coordinates and for the particle motion the Cartesian (x, y, z) coordinate system is accepted. The fluid phase calculations are based on the time-averaged Navier-Stokes equations for the mean velocity and temperature fields in connection with the two equation multiphase $k-\tau$ turbulent model for flow field and $k_\theta-\tau_\theta$ model for the thermal field. To take account the influence of the present particles in the $k_\theta-\tau_\theta$ equations, the additional source terms reported by Saffar Avval et al. [12] and Mansoori et al. [13] are used.

2.1. Gas phase flow field modeling

The general form of the elliptic differential equations for the gas phase is written as follows:

$$div((1-\varphi)\rho\langle v\rangle\langle\phi\rangle)-div\Big((1-\varphi)\Gamma_\phi grad\langle\phi\rangle\Big) = S_\phi + \Big\langle S_\phi'\Big\rangle \quad (1)$$

Where, S_ϕ is the source term of the gas phase, $\langle S_\phi'\rangle$ is for the dispersed phase, and Γ_ϕ is the effective viscosity in three dimensions. The gas-phase conservation equations are solved for different variables ϕ: three velocity component (U,V,W), temperature (T), turbulent kinetic energy (k), turbulence time scale (τ), temperature variance (k_θ) and thermal turbulence time scale (τ_θ). Table 1 presents the source term S_ϕ and variables ϕ for each equation.

The coefficients and the damping functions f_μ and f_λ as introduced by Schwab and Lakshminarayana [14] are listed below:

$$C_\mu = 0.09; C_\lambda = 0.2; C_{\tau1} = 0.92; C_{\tau2} = 0.44; C_{\tau\theta1} = 0.27; C_{\tau\theta2} = -0.07;$$
$$\sigma_k = \sigma_\tau = \sigma_{k\theta} = \sigma_{\tau\theta} = 1.0; \nu_t = C_\mu f_\mu k\tau; \alpha_t = C_\lambda f_\lambda k\tau_\theta;$$
$$f_\mu = \Big(1+3.45\mathrm{Re}_{t\theta}^{-1/2}\Big)\tanh\Big(y^+/70\Big); f_\lambda = \Big(1+2.4\mathrm{Re}_{t\theta}^{-1/2}\Big)\tanh\Big(y^+/120\Big);$$
$$C_{\tau\theta3} = \Big[1-\exp\Big(-y^+/4.8\Big)\Big]^2; C_{\tau\theta4} = (1.92-1)\Big[1-\exp\Big(-y^+/4.8\Big)\Big]^2$$

The various source terms due to the presence of particles are listed in Table 2.

Here, the turbulence Reynolds number is defined as $\mathrm{Re}_t = k\tau/\upsilon$, $\mathrm{Re}_{\tau\theta}$ is the turbulent Reynolds number based on k and τ_θ (thermal time scale), i.e., $\mathrm{Re}_{\tau\theta} = k\tau_\theta/\upsilon{\cdot}\tau_p$.is the particle dynamic relaxation time, c_d is the drag coefficient, u_{pi}', u_{fi}' are, respectively, the fluctuation velocities of gas and particle phases and φ' is the particle concentration fluctuation. The triple correlation in the <S_k> source term equation is neglected. Therefore, the first term in the right-hand side of the source term of turbulent kinetic energy involves the fluid–particle velocity correlation. The second term calculates the influence of particle and fluid mean velocity differences, along with the particle concentration and velocity correlation. Besides, the coefficient $c_{\tau3} = 2$ is used.