TURBULENT PARTICULATE PIPE FLOW AT CONSTANT REYNOLDS NUMBER

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Summary The effect of the pipe diameter in particulate turbulent cylindrical pipe flows has been numerically investigated at constant Reynolds number. The method used is based on a 2-D RANS. Results were obtained for the effects of pipe diameter, solids mass loading and particles size on the radial and longitudinal velocity profiles, on the turbulence modulation and on the particle concentration profiles.

MODEL APPROXIMATION

Particulate flows in pipes have numerous engineering applications ranging from pneumatic conveying systems to coal gasifiers, chemical reactor design and are one of the most thoroughly investigated subjects in the area of multiphase flows. These flows are very complex and influenced by various physical phenomena, such as particle-turbulence and particle-particle interactions, deposition, gravitational and viscous drag forces, particle rotation and lift forces.
The purpose of the present study is to focus the research on the effect of variation of pipe diameter for constant Reynolds number applied for vertical particulate turbulent pipe flows. The numerical study examined in details the effects of direct and indirect particle-turbulence interaction, gravity and inter-particle collisions for various flow mass loadings and particle sizes.
The presented numerical model utilizes the following assumptions: two-fluid model and the Reynolds-averaged Navier-Stokes (RANS) approach and it employs the closure equations, simultaneously considering both the particle-turbulence interactions [1] which is as the most relevant to allow a turbulence modulation caused by particles, since it includes both a turbulence enhancement and attenuation and the inter-particle collisions [2], that is one of its advantages. In order to consider the polydispersity of solid admixture, the inter-particle collisions were allowed by the model [2]. Thus, these two models enables the comprehensive mathematical simulation of two-phase upward pipe flow.
The presented model allows to cover 100 and more calibers of a pipe flow with unlimited predictions for Reynolds numbers obtained by two-phase RANS modeling.

MODEL DESCRIPTION

The governing equations written for the time averaged 2D RANS method are as follows:

Continuity, momentum and turbulent energy equations for the gas phase:

$$\frac{\partial u_i}{\partial x_j}=0\,,\;\; \frac{\partial u_i u_j}{\partial x_j}=-\frac{\partial p}{\rho\partial x_i}+\frac{\partial}{\partial x_j}\tilde{\nu}_t\frac{\partial u_i}{\partial x_j}+-\sum_{k=1}^{3}\alpha_k\left\{\frac{u_{ri,k}}{\tau'_k}+\left[(-1)^{i\pm1}C_{LR,k}\Omega_k+(1-i)F_{s,k}\right]u_{r(i\pm1),k}\right\},$$

$$\frac{\partial k u_j}{\partial x_j}=\frac{\partial}{\partial x_j}\tilde{\nu}_t\frac{\partial k}{\partial x_j}+P+\sum_{k=1}^{3}\frac{\alpha_k}{\tau_k}\left[u_{ri,k}^2+u_{r(i\pm1),k}^2+k_{s,k}\right]-\bar{\varepsilon}_h\,, \qquad (1)$$

where i,j=1, 2 and $i\pm1\equiv\begin{cases}2 & \text{for} \quad i=1\\ 1 & \text{for} \quad i=2\end{cases}$, $\tilde{\nu}_t=\nu_t+\nu$ is sum of the turbulent and laminar viscosities; k is the turbulent kinetic energy; p is the pressure; α is the total mass concentration, $\alpha=\sum_{k=1}^{3}\alpha_k$. Three fractions of particulate phase are considered with change of the fractions index $1\le k\le 3$. $(u_i-v_{i,k})$ is the particles relative velocity; τ_i is the particle response time; C_D is the drag coefficient; $\Omega_k=\omega_{s,k}-0.5rot(\vec{u})$ is the angular velocity slip with $\omega_{s,k}$ being the angular velocity of the k-th particle fraction. The coefficient of the Magnus lift force C_{LRk} in Eq. (1), is determined by [3]; $k_{s,k}$ is the collisional energy of the particulate phase [2]; P is the production of the turbulent energy of gas-phase; $\bar{\varepsilon}_h$ is the dissipation rate of turbulent energy calculated by the hybrid length scale as the harmonic average of the integral length scale and inter-particle spacing according to $k-L$ model [1].

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Continuity, momentum and angular equations for the particulate phase:

$$\frac{\partial(\alpha_k \tilde{v}_{j,k})}{\partial x_j} = 0, \qquad \frac{\partial(\alpha_k \tilde{v}_{i,k} v_{j,k})}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\alpha_k \nu_{s,k}^{i,v} \frac{\partial v_{i,k}}{\partial x_j}\right) + \alpha_k \left[\frac{u_{ri,k}}{\tau'_k} + \left[(-1)^{i\pm1} C_{LR,k} \Omega_k + (1-i) F_{s,k}\right] u_{r(i\pm1),k} - g\right],$$

$$\frac{\partial(\alpha_k \tilde{v}_{i,k} \omega_{s,k})}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\alpha_k \nu_{s,k}^{i,\omega} \frac{\partial \omega_{s,k}}{\partial x_j}\right) - \alpha_k C_\omega \frac{\Omega_k}{\tau_k}, \qquad (2)$$

where $\tilde{v}_{i,k}$ are the longitudinal or radial components of the drift particle velocity of the *k*-th fraction; they are given by $\tilde{v}_{i,k} = v_{i,k} - (D_{t,k} + D_{c,k}^i)\frac{\partial \ln \alpha_k}{\partial x_i}$; g is the gravitational acceleration; $\nu_{s,k}^{i,v}$, $\nu_{s,k}^{i,\omega}$ and $D_{c,k}^i$ are the pseudoviscosity and pseudodiffusity coefficients of the particulate phase used for closure of the linear and angular momentum and mass conservation equations of particulate phase due to the particles collision [2]; the coefficient of turbulent diffusion of particles $D_{t,k}$ is calculated using the PDF model [4]; C_ω is the torque coefficient [3].

RESULTS

Fig 1 shows the radial distributions of the normalized longitudinal velocity lag for various pipe diameters. The increase of the pipe diameter results in lower turbulence level at the constant Reynolds number, that in turn leads to the smaller velocity lag with less deviation from particles terminal velocity, and, in fact, to the weaker particles involvement into the turbulent motion.

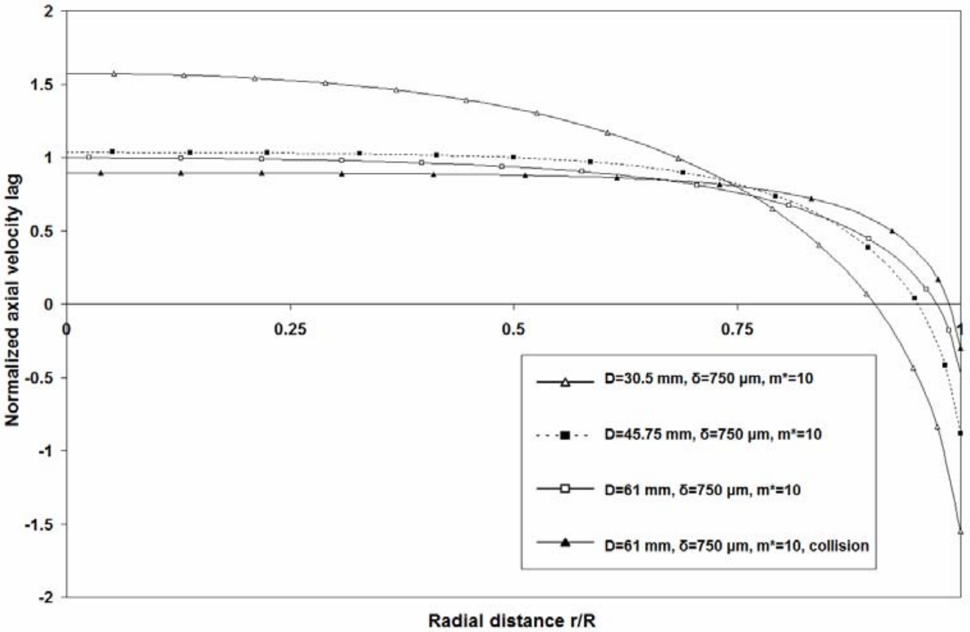

Fig. 1. Radial distributions of the normalized longitudinal velocity lag for the 750-μm coal particles for the pipes diameter D =30.5, 45.75 and 61 mm at the flow mass loading $m^* = 10$ and the Reynolds number $Re = 4.4 \cdot 10^4$.

CONCLUSIONS

Results show the effect of the pipe diameter, flow mass loading and particles size on the radial distributions of the velocity lag, turbulence modulation and particles concentration. In particular, increase of the pipe diameter at constant Reynolds number results in decrease of the relative velocity lag and flattening of the radial distributions of particles velocity and mass concentration as well as decrease of a turbulence attenuation rate.

References

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