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Numerical investigation of convective heat transfer in pipeline flow of multi-sized mono dispersed fly ash-water slurry

Bibhuti Bhusan Nayak [a], Dipankar Chatterjee [b,*]

[a] Department of Mechanical Engineering, National Institute of Technology, Durgapur, Durgapur 713209, India
[b] Advanced Design and Analysis Group, CSIR-Central Mechanical Engineering Research Institute, Durgapur 713209, India

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ABSTRACT

A three-dimensional numerical investigation is performed to understand the influence of dispersed particles on the thermo-fluidic transport of liquid-solid slurry in a horizontal pipe. The study presents some new findings in regard to the heat transfer in a flow regime for a liquid-solid slurry that has not been studied in detail. A dimensional analysis is also carried out to understand the pertinent dimensionless quantities influencing the thermo-fluidic transport. The simulation is carried out by deploying an Eulerian multiphase model incorporated with kinetic theory of granular flow. Spherical coal fly ash particles of five different median diameters: 4, 8, 13, 34 and 78 μm, suspended in water for a mean flow velocity ranging from 1 to 5 m/s and particle concentrations within 0–50% by volume for each velocity are considered as the dispersed phase. The pipe wall is kept at an isothermal condition of 400 K whereas the slurry enters the pipeline at a temperature of 300 K. The results illustrate that for all particle sizes, heat transfer ratio is found to increase with particle concentration up to 3% and then gradually decreases with increased particle concentration and mean velocity of flow. Moreover, the heat transfer ratio and the relative pressure drop increase with the particle size at higher concentrations and mean velocities.

1. Introduction

A slurry is essentially a multiphase system where dispersed solid particles are suspended in a continuous liquid phase. The presence of the solid particles in the carrier phase can cause suppression or augmentation of heat transfer depending on the particle distribution and size, their concentration in the liquid phase, temperature and viscosity of the carrier phase, level of turbulence and the size of the conduit. The influences of the aforementioned controlling parameters are crucial for the optimum design of slurry pumps, heat exchangers, driers, fluidized beds and slurry pipeline reactors. Solid-liquid mixtures (particularly, the fly ash and the bed ash slurries) have also gained popularity in mine void filling because of the recent advances in hydraulic conveyance. Fly ash in bulk quantity can be utilized in stowing of underground mines in lieu of sand and filling up of abandoned open cast mine voids. The filling of mine voids using fly ash is an environmentally sound process and is the most feasible option of bulk utilization. It saves enormous land requirement for the disposal of the ash produced from the thermal power plants. It fills well into the void/cavity as it can flow easily and additionally the water holding capacity of it, in turn can facilitate the afforestation [1]. For the disposal of the fly ash produced by the combustion of the coal in the thermal power plants it is essential to estimate its heat transfer and pressure drop characteristics.

Quite a few numerical and experimental studies exploring the fluid dynamic aspects of the liquid-solid suspension is available [2–6]. For the numerical studies, the selection of the multiphase and the turbulence models has always been a topic of contention among the researchers. Ling et al. [7] deployed a three-dimensional algebraic slip mixture model (ASM) to obtain the numerical solution for the sand-water slurry flows in a horizontally straight pipeline. Rhee [8] followed the same route for modeling sand particles of concentrations up to 40%. Cornelissen et al. [9] used the multifluid Eulerian model with granular flow extension to simulate the gas-solid flow. Capecelatro and Desjardins [10] computationally investigated the complex multiphase flow dynamics in horizontal pipes using the large eddy simulation technique combined with the Eulerian-Lagrangian particle tracking. Chen et al. [11] investigated the flow characteristics of super dense coal-water slurries in horizontal pipelines using Eulerian multiphase approach based on the kinetic theory of granular flow. Ozbelge and Eraslan [12] developed a computational model to estimate the hydrodynamic and thermal characteristics of turbulent up-flows for dilute water-feldspar slurries through a concentric

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* Corresponding author.
E-mail address: d_chatterjee@cmeri.res.in (D. Chatterjee).

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Nomenclature

C_D	drag coefficient
c_p	specific heat, J/kg K
C_{vf}	solid volume concentration, %
D	pipe diameter, m
d_s	particle diameter, μm
e_{ss}	coefficient of restitution of the particle-particle collision
e_{sw}	restitution coefficient of particle-wall collision
Ec	Eckert number
Fr	Froude number
g	acceleration due to gravity, m/s^2
g_0	radial distribution function
G	particle-particle modulus, N/m^2
h	heat exchange coefficient, W/m^3 K
$\hbar$	specific enthalpy, J/kg
k	turbulent kinetic energy, m^2/s^2
$k_{\Theta s}$	granular conductivity, W/m K
K	momentum exchange coefficient
L	pipe length, m
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Pr_t	turbulent Prandtl number
$\Delta P/\Delta L$	pressure drop per unit pipe length, Pa/m
q	heat flux, W/m^2
Ra	Rayleigh number
Re	Reynolds number
Re_s	relative Reynolds number
S	modulus of the mean rate-of-strain tensor, s^{-1}
t	time, s
T	temperature, K
u, v	velocity, m/s
V	mean inlet velocity, m/s
x	coordinate, m
y^+	dimensionless wall distance for the cell adjacent to the wall

Greek symbols

α	volume fraction
β_T	coefficient of thermal expansion, K^{-1}
Φ	dimensionless temperature
ε	turbulent kinetic energy dissipation rate, m^2/s^3
ϕ	friction angle
$\gamma_{\Theta s}$	collisional dissipation energy, m^2/s^3
κ	thermal conductivity, W/m K
λ_s	bulk viscosity of solids, kg/m s
μ	viscosity, kg/m-s
Θ_s	granular temperature of solid phase, K
ρ	density, kg/m^3
$\bar{\bar{\tau}}$	viscous stress tensor, Pa
ψ	specularity coefficient

Subscripts

eff	effective
f	fluid
in	inlet
m	mean
s	solid
t	turbulent
w	wall

Superscripts

$\bar{\ }$	non-dimensional quantity

annulus. Messa and Malavasi [13] used a commercial code PHOENICS to analyze the flow of solid-water slurry through an upward-facing step channel. Recently, Nayak et al. [14] used the ASM model in conjunction with the RNG k - ε turbulence model to analyze the convective transport of fly ash-water slurry through a horizontal pipe. Table 1 shows the contributions of various authors in a chronological order for the development of the numerical strategies for solving the liquid-solid/gas-solid slurry transport through closed conduits.

In the experimental category, Harada et al. [15] studied the fundamental characteristics of heat transfer from the wall to water suspensions of glass beads or ion exchange resin flowing through horizontal pipes for the operating range of Reynolds numbers and volume fraction of solid from 3000 to 50,000 and 0 to 0.1, respectively. Ku et al. [16] investigated the heat transfer coefficients of liquid-solid mixtures using a double pipe heat exchanger with suspension flows in the inner pipe. The experiment was carried out using spherical fly ash particles with mass median diameter ranging from 4 to 78 μm, volume concentration of solids in the slurry from 0 to 50% and the Reynolds number from 4000 to 11,000. The heat transfer coefficient of liquid-solid suspension to water flow was found to increase with decreasing particle diameter. A correlation for heat transfer to liquid-solid flows in a horizontal pipe was also proposed. Rozenblit et al. [17] showed through their experiment that the average heat transfer increases with particle concentration. Skudarnov et al. [18,19] performed experiment with five double-species composed of glass beads and water in a horizontal pipe for different species concentrations. The result showed that increasing the particle diameter gives higher pressure gradients for low flow velocities and a lower pressure drop for high flow velocities. An experimental study of Verma et al. [20] predicted the pressure drop across a 90° horizontal circular pipe bend for fly ash slurry flow at high concentration of 50–65% by weight. They observed that the relative pressure drop across the pipe bend increases with increase in the concentration at low velocity and is independent of the velocity for any given concentration. Ravelet et al. [21] conducted experimental study for the hydraulic transport of very large solid particles (above 5 mm) in horizontal as well as vertical pipes. The pressure drop was observed smaller for large particles in the horizontal pipe as compared to the vertical pipe. It is imperative to say that reproducing all of the above experiments numerically are too difficult or too

Table 1
Summary of numerical development.

Authors	Contributions in numerical development
Rhee (2002) and Ling et al. (2003)	Three-dimensional algebraic slip mixture model (ASM)
Ozbelge and Eraslan (2006)	Computational model based on a continuum approach. Prandtl's mixing length model is used to obtain the closure equations of turbulence
Cornelissen et al. (2007)	Multifluid Eulerian model with granular flow extension
Chen et al. (2009)	Eulerian multiphase approach based on the kinetic theory of granular flow
Capecelatro and Desjardins (2013)	Large eddy simulation technique combined with the Eulerian-Lagrangian particle tracking
Messa and Malavasi (2013)	Commercial code PHOENICS
Nayak et al. (2015)	ASM model in conjunction with the RNG k - ε turbulence model of Ansys Fluent