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Application of the MP-PIC method for predicting pneumatic conveying characteristics of dilute phase flows

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ABSTRACT

This study investigated the applicability of the multiphase particle-in-cell (MP-PIC) method for predicting pneumatic conveying characteristics. Three-dimensional computational particle fluid dynamics (CPFD) simulations were performed to assess the dilute-phase pneumatic conveying of plastic pellets in a horizontal circular pipe. The pellets were 80–500 μm in diameter and 1000 $\mathrm{kgm^{-3}}$ in density. The air velocities ranged from 6 to 15 $\mathrm{ms^{-1}}$, and the solids-to-air mass flow ratios (solids loading ratios) ranged from 1 to 3. The predicted pressure drops and solids and air velocity profiles were compared with experimental data from the existing literature. A parametric study was carried out to investigate the effects of model collision parameters on pneumatic conveying characteristics. Moreover, the importance of including new collision terms developed by other researchers in the MP-PIC method for the prediction of dilute phase flows was emphasized.

1. Introduction

The practical applications of the pneumatic conveying of particulate materials are extensive [1]. Depending on the materials to be handled, operational conditions and system geometry, transportation can occur in different flow regimes that can be essentially categorized as dilute or dense [2]. Despite wide applications, efficient pneumatic system design remains challenging [3]; it is complicated by interactions between the particulate phase and the turbulent carrier flow as well as particle-particle and particle-wall interactions [4,5]. Because of these complications, a fundamental understanding of the complex physics involved in gas-solids flows is crucial for the proper design, control and optimization of any pneumatic conveying system [6].

With the recent development of computer technology, computational fluid dynamics (CFD) has gained importance in investigating different multiphase flows [7]. Two basic approaches are available for gas-solids multiphase flow modelling: the Eulerian-Eulerian approach (Euler-Granular model) and the Eulerian-Lagrangian approach [8]. Under the Eulerian-Lagrangian approach, available models include the Lagrangian discrete phase model (DPM), the dense discrete phase model incorporated with kinetic theory of granular flow (DDPM-KTGF), the CFD-discrete element method (CFD-DEM) and the computational particle fluid dynamics (CPFD) numerical scheme incorporated with the multiphase-particle-in-cell scheme (MP-PIC) [8,9]. More information on the merits, limitations and applications of these models is available elsewhere [8].

The computational particle fluid dynamics (CPFD) numerical scheme incorporated with the multiphase-particle-in-cell (MP-PIC) method is a recently developed model for gas-solids flows. To date, this method has been used to predict certain processes; however, to the authors' best knowledge, published information is unavailable on the application of this model in pneumatic conveying. Previous applications of the MP-PIC method include bubbling and circulating fluidized beds [10–32], fluidized bed gasifiers [33–40], fluidized beds for carbon capture [41–45], gas/liquid/solid fluidized beds [46–48], Rayleigh-Taylor mixing layers [49], sedimentation [49,50], downer reactors [51–53], dryers [54], 3-D particle jets [49], hopper flows [55,56], disk-donut fluid catalytic cracking (FCC) strippers and FCC regenerators [57,58], dense spouted bed [59] and particle flows in U-tubes [55].

As in all other Eulerian-Lagrangian approaches, the MP-PIC method treats the gas as a continuous phase and the particles in a discrete manner. Solving a transport equation called a Liouville equation for

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Abbreviations: BGK, Bhatnager Gross and Krook; CFD, computational fluid dynamics; CFD-DEM, CFD-discrete element method; CFL, Courant-Friedrichs-Lewy; CPFD, computational particle fluid dynamics; DDPM-KTGF, dense discrete phase model incorporated with kinetic theory of granular flow; DPM, Lagrangian discrete phase model; FCC, fluid catalytic cracking; LES, large eddy simulation; MP-PIC, multiphase particle-in-cell; PDC, partial donor cell; PDF, particle distribution function.

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Nomenclature

$\boldsymbol{A}_p$	Particle acceleration, ms^{-2}
C_1	Model constant = 180
C_2	Model constant = 2
C_d	Drag coefficient
C_s	Smagorinsky constant = 0.01
D_1	Wen and Yu drag function, s^{-1}
D_2	Ergun drag function, s^{-1}
D_p	Drag function, s^{-1}
$\overline{D}_p$	Average particle drag function, s^{-1}
e_n	Normal-to-wall momentum retention (particle-wall restitution coefficient in normal direction)
e_{ss}	Particle-particle restitution coefficient
e_t	Tangent-to-wall momentum retention (particle-wall restitution coefficient in tangential direction)
$\boldsymbol{F}$	Momentum exchange rate per volume between the fluid and the solid phase, Nm^{-3}
f	Particle distribution function (PDF)
f_D	PDF obtained by collapsing the velocity dependence of f to a delta function centred about the local mass-averaged particle velocity
f_G	Equilibrium distribution
$\boldsymbol{g}$	Gravitational acceleration = 9.81, ms^{-2}
$g_1(\alpha_p)$	Blending function
$\boldsymbol{I}$	Unit tensor
m	Solids loading ratio (solids-to-air mass flow ratio)
m_p	Particle mass, kg
P	Static pressure, Pa
P_s	Pressure constant = 1, Pa
R	Pipe radius, m
Re	Relative Reynolds number
r	Vertical distance from pipe horizontal axis, m
r_p	Particle radius, m
t	Time, s
U_g	Velocity magnitude of gas phase, ms^{-1}
U_m	Superficial air velocity at inlet, ms^{-1}
U_s	Velocity magnitude of solid phase, ms^{-1}
$\boldsymbol{u}_g$	Gas phase velocity vector, ms^{-1}
$\boldsymbol{u}_p$	Solid phase velocity vector, ms^{-1}
$\hat{\boldsymbol{u}}_p$	Drag-averaged particle velocity vector, ms^{-1}
X_p	Modified acceleration due to contact stresses, ms^{-2}
$\boldsymbol{x}_p$	Particle spatial location, m
α_{cp}	Close-pack volume fraction = 0.6
α_g	Volume fraction of gas phase
α_p	Volume fraction of solid phase
β	Constant = 3
Δ	Subgrid length scale, m
$\delta x \delta y \delta z$	Product of dimensions of a cell, m^3
ε	Constant = 10^{-8}
μ_{eff}	Effective dynamic viscosity of gas phase, Pas
μ_g	Molecular viscosity of gas phase, Pas
$\mu_{t,g}$	Turbulent viscosity of gas phase, Pas
ρ_g	Density of gas phase, kgm^{-3}
ρ_p	Particle density, kgm^{-3}
$\overline{\rho}_p$	Mean particle density, kgm^{-3}
τ_D	Collision damping time, s
τ_G	Return-to-isotropy time, s
τ_g	Gas phase effective stress tensor, Pa
τ_p	Particle normal stress, Pa

the particle distribution function predicts the particle dynamics. The particle distribution function contains particle properties such as particle spatial location, particle velocity, particle mass, and time [10]. The MP-PIC method uses the concept of parcels (numerical particles) in order to reduce the number of particles involved in the computations; this provides a significant acceleration of simulation speed [6]. A parcel is a collection of several real particles with the same properties (species, size, density, temperature, etc.). Unlike DEM models that calculate particle-to-particle force with a spring–damper model and direct particle contact, the MP-PIC methodology models particle collision force for each particle as a spatial gradient. A particle normal stress model is developed from this concept to describe the particle collisions [17].

According to You et al. [60], inter-particle collisions play an increasingly significant role and are no longer negligible, even at particle volume fractions as low as 4×10^{-4}. As previously mentioned, only enduring contacts were originally considered through the particle normal stress model in MP-PIC; however, the models have undergone remarkable improvements. First, O′Rourke et al. included the Bhatnager, Gross and Krook (BGK) model in transport equations in order to model the collision term so that the particle distribution function relaxed to equilibrium distributions on a time scale proportional to the time between particle collisions [46]. Second, the BGK model for damping time was improved in order to include the effects of particle material coefficients of restitution and non-equilibrium particle velocity distributions [61]. Real collisions cause the particle velocity distributions to be more isotropic; they also cause scattering. This additional effect is included via the collisional return-to-isotropy term [62]—the third improvement made in the models. Finally, a new contact force model was developed that accounts for the inhibition of relative motion between the differing sizes or densities of particles [63]. This new model is called the “blended acceleration” model and is a blend between the particle acceleration of the original MP-PIC method for rapid granular flows and an average particle acceleration that applies to closely pack granular flows. Some cases, for example, rise of small particle in a packed bed, collision of gas-solid jets, sedimentation and fluidization of binary mixtures were computed to analyse the model improvements [61–63].

Compared to conventional Euler-Granular model, MP-PIC method is more realistic due to discrete treatment of particles. This can provide analysis of flows with a wide range of particle types, sizes, shapes and velocities. Moreover, compared to CFD-DEM, MP-PIC method is computationally efficient for large scale systems with high physical particle count, because the particle-particle interactions are concerned indirectly through the models and the method uses parcel concept [13]. Despite the success of the MP-PIC method in predicting various gas-solids flow applications, its validity in pneumatic conveying applications has yet to be proven. Especially, there was no much investigation of using MP-PIC method for predicting very dilute phase flows where the instantaneous binary contacts play a significant role. Moreover, the focuses were more on fluidized beds and less on horizontal flows where the gravitational settling of particles is important. Therefore, this work uses the MP-PIC method to perform three-dimensional simulations of the dilute-phase pneumatic conveying of plastic pellets in a horizontal circular pipe. The cases are similar to experimental cases carried out by Tsuji and Morikawa [64]. In addition to investigating the validity of the method for pneumatic conveying applications, we also investigate the importance of including novel collision models developed by O'Rourke and Snider for the accurate prediction of pressure drops and flow patterns in dilute phase pneumatic conveying. Moreover, some of the major model parameters deemed important in predicting pneumatic conveying characteristics, namely particle-particle and particle-wall collision parameters. Therefore, the sensitivity of these parameters in predicting conveying characteristics is also discussed. The CPFD numerical methodology incorporated in the commercially available Barracuda® 17.0.3 code is the platform used for the modelling and simulations in this study.