Powder Technology 268 (2014) 19–37

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Computation of fluid–particle interactions with high-speed compressible flows and multiple particles with deformation, plasticity, and collisions

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ARTICLE INFO

Article history:
Received 24 April 2014
Received in revised form 3 July 2014
Accepted 6 July 2014
Available online 15 July 2014

Keywords:
Fluid–structure interaction
Computational fluid dynamics
Soft collision model
Particle flow
Plasticity
Deformation

ABSTRACT

Two phase direct particle-high speed compressible gas flow simulation techniques developed by the author are extended to include the effects of particle deformation and plasticity with a focus on high speed impact of metallic steel particles moving in high speed air. The first part of the study involves the development of the necessary modeling techniques. Using the results of fluid independent finite element analyses, normal force functions were devised to simulate the effect of a collision of two 1.5 mm radius steel particles over a range of relative impact velocities from 12.5 to 200 m/s with an elastic and then an elastic perfectly plastic material model. Methods were introduced to model the deformation of the particles/objects. Use of the collision force model and the inclusion of deformation in a simulation of the collision between two particles in air replicated the appropriate short term post collision velocities of the corresponding finite element analysis. The parametric studies conducted during this model development demonstrated the importance of utilizing the proper material model in predicting the motion of the particles. A longer contact time and increasingly comparable post collision velocities for the two colliding particles develop with an elastic perfectly plastic based collision model, with the differences from the elastic based model results growing with collision velocity. The modeling techniques were then applied to analyze the motion of fourteen steel particles placed ahead of a gas driven piston in a flow channel 19.5 mm in width for three different piston driving pressures of 50, 75, and 100 MPa, implementing the elastic and then the elastic plastic based collision force models. The results clearly indicate that the incorporation of plasticity and particle deformation causes the particles to remain closer together both inside and outside of the flow channel. The modeling methods developed provide the ability to incorporate the plasticity/deformation effects of multiple interacting particles together with the local flow induced force to simulate the coupled gas flow and particle motion. The techniques developed offer a tool to capture more of the physical phenomena occurring in the two phase flow regime of interest, extending the capabilities to simulate the motion of gas-particles to a wider range of particle and flow velocities and providing information to assist in the understanding of particle motion and interaction characteristics.

List of symbols

Vectors		
ξ	Normal relative velocity measure (m/s)	Eq. (13)
E	Quaternion	Eq. (A.1)
$\dot{E}$	Time derivative of quaternion	Eq. (A.5)
F	Net force (N)	Eq. (27)
F_n	Normal force vector due to collision (N)	Eq. (14)
F_t	Tangential force vector due to collision (N)	Eq. (12)
M	Net moment (N/m)	Eq. (A.2)
n	Unit normal vector	Eq. (8)
Q	Quaternion	Eq. (22)
θ	Angular position (rad)	Eq. (A.8)

(continued)

Vectors		
r	Particle center of gravity location Fig. 2 (m)	Eq. (6)
$\dot{s}$	Tangential relative velocity measure (m/s)	Eq. (16)
t	Unit tangential vector	Eq. (11)
v	Fluid velocity (m/s)	Eq. (24)
V	Solid body velocity (m/s)	Eq. (27)
vr	Relative velocity of object 1 to object 2 (m/s)	Eq. (5)
ω	Angular velocity (rad/s)	Eq. (5)
$\dot{\omega}$	Angular acceleration (rad/s^2)	Eq. (5)
X	Solid body translation (m)	Eq. (28)
Scalars		
a	Particle spacing Fig. 1, exponent in Eq. (14) (m)	Eq. (14)
b	Particle spacing Fig. 1, exponent in Eq. (14) (m)	Eq. (14)

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http://dx.doi.org/10.1016/j.powtec.2014.07.012
0032-5910/Published by Elsevier B.V.

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Scalars		
c	Particle spacing Fig. 1 (m)	Eqs. (26a)–(26b)
C,G,Y,S	Turbulence parameters	Eqs. (26a)–(26b)
d	Particle spacing, Fig. 2 (m)	Eq. (7)
D	Particle diameter (m)	
k	Spring constant (may vary)	Eqs. (14) and (15)
m	Mass (kg)	
p	Pressure (N/m^2)	Eq. (24)
R	Particle radius Fig. 3 (m)	
S	Particle safety zone thickness Fig. 3 (m)	
s	Net displacement in the tangent direction (m)	Eq. (17)
T	Temperature (K)	Eq. (25)
t	Time (s)	
Greek		
ξ	Measure of spacing between the particles/objects (m)	Eq. (12)
γ	Damping coefficient (kg/s)	Eqs. (14) and (15)
κ,ε	Turbulence parameter	Eqs. (26a)–(26b)
ρ	Particle density, fluid density (kg/m^3)	Eq. (23)
τ	Stress tensor (N/m^2)	Eq. (24)
μ	Frictional coefficient	Eq. (19)
Notation		
n	Associated with normal	
t	Associated with tangential	
R^{xG}	Rotational matrix from local csys x to global	Eqs. (5) and (A.1)
r_x^{xy}	Vector to cg of object x in csys y	Eq. (5)
P1, P2	Associated with particle 1 and particle 2	
$ZZ_y{}^x{}_q$	Variable notation, related to object x, coordinate system y, time q	Eq. (27)

1. Introduction

Modeling the two phase flow involving multiple metallic particles moving at high speeds in high speed compressible flow must account for the fluid induced forces acting on the particles, the effects of the particle motion and their presence on the flow conditions, and the interactions between the particles or other objects as they collide. Direct particle modeling methods have been developed by the author [1,2] using customized algorithms to couple the particle motion with fluid flow within a standard computational fluid dynamics code with particles directly incorporated into the computational domain. Particle collisions are handled with a soft collision model and a safety zone technique. In these simulations, the particles remain rigid. However, for the flow and particle motion conditions of interest, particle deformation is likely, and this deformation can significantly influence the collision and post-collision motion of the particles. This study focuses on the extension of the direct particle two-phase compressible gas flow–solid particle flow modeling techniques to incorporate deformation and plasticity effects. Basic model development is carried out using binary collisions, and the methods are then applied to a multi-particle system driven by high speed gas flow. While the focus of this work is metallic particles and elastic and elastic–perfectly plastic material models, the approach used can be adapted for other deformable particles such as gels or even biological cells.

The ability to model the motion and interaction of particles in a fluid provides significant potential for enhancing the understanding of these multiphase flows and thus for using this knowledge to alter the operating characteristics to achieve a desired outcome. Particle-flow systems have wide ranging applications from chemical and industrial processes through natural phenomena. Advancing the methods of modeling these systems and expanding the scope of the phenomena and characteristics that are captured in the simulations thus provides a more effective and efficient means of harnessing these two phase flows for a given purpose.

In order to place the current work in perspective with the previous particle-flow model development, a brief summary of the initial direct particle motion–fluid flow coupling is needed. The origin of the direct flow–particle coupling with particle collision is simulations of rigid particles in incompressible flows in the 1990's by Tezduyar and Tezduyar and Johnson. These simulations utilize a space-time method [3] with advanced mesh moving methods [4] to allow the particles to move large distances through the fluid domain, relative to the particle size. Implicit coupling between the flow and the sold particles was implemented with a collision model based on the safety zone concept similar to that used in the current work. These methods were the first to provide direct three-dimensional computations by direct numerical simulation and matched experimental and theoretical data in 1996 [5]. By 1997, the methods were applied to capture the three-dimensional motion of 100 particles moving in the fluid, a first as well [6]. These models included collisions with container walls. By 1999, 1000 particles were included in the model, marking the earliest three dimensional simulations with this number of particles [7]. Remeshing was performed every 10 timesteps due to the advanced moving mesh techniques incorporated. Finally, by 2001, improvements for mesh generation and mesh motion techniques for spatially periodic domains allowed for the simulation of up to 128 particles in a periodic cell [8]. Hence, these direct modeling techniques for rigid particles set the basis for future development of simulation methods. A review of modeling methods and collision models is provided in [1].

Different numerical techniques have been developed to allow for the simulation of the motion of objects that change shape as they move through a fluid. Many studies involve a single deformable particle, focusing on methods to model the effects of the particle deformation. Yokoyama [9] successfully simulated the deformation of a fluid filled membrane where a thin membrane separating two fluids is replicated through a network of mass spring and dampers representing the mechanical characteristics of the membrane. Hosseini and Feng [10] reported on the use of smoothed particle hydrodynamics based techniques to study the shape change of a cell where a series of "particles" comprises the boundary of a deformable erythrocyte cell moving in a capillary. Nonlinear springs connect these "particles" to simulate the cell deformation. Ye and Lam [11] investigated the deformation of a cell in shear and Poiseuille flow using a level set method with Lagrangian tracker particles at the cell/fluid interface. The method was applied to model a system where the cell moves through a flow channel with a change in cross-section, causing substantial particle deformation, with results producing good correlation to other numerical models. Feng and Michaelides [12] report on the development of general techniques for particle motion in a fluid through the use of the combination of an immersed boundary condition method with tracking Lagrangian particles at the interface and a Lattice Boltzman model to counteract the fine mesh needed at the interface between the solid and the fluid for the immersed boundary condition method. Though deformation could be included, the work enforced rigid body motion. Swaminathan et al. [13] used an Arbitrarily Lagrangian–Eulerian method with a particle moving within a finite element mesh to study the deformation of a long elastic–plastic particle undergoing electrophoresis upon release into a quiescent fluid. Cleary [14] used a smoothed particle hydrodynamics method to simulate the deformations and interactions between a particle and a wall where limitations on large finite element deformation are removed since no computational mesh is involved, but acting fluid forces are not taken into account.

Other works have focused on the development of collision effect models that capture the effects of plasticity. A particle collision model proposed by Walton and Braun [15] assigns different spring constants for loading and unloading with a modified un-stretched spring length for unloading equal to the maximum particle overlap. The basic expression for the normal collision force in this work was:

$$Fn = \begin{cases} K_1 x \; (loading) \\ K_2 (x - x_{max}) \; (unloading) \end{cases} \tag{1}$$