Chemical Engineering Science 64 (2009) 43 – 51

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Direct numerical simulation of particle clustering in gas–solid flow with a macro-scale particle method

Jingsen Ma[a,b], Wei Ge[a,*], Qingang Xiong[a,b], Junwu Wang[a,b], Jinghai Li[a]

[a]State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, P. O. Box 353, Beijing 100190, China
[b]Graduate School of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 18 March 2008
Received in revised form 2 September 2008
Accepted 6 September 2008
Available online 20 September 2008

Keywords:
Clustering
Fluidization
Hydrodynamics
Multiphase flow
Simulation
Smoothed particle hydrodynamics

ABSTRACT

Particle clustering has long been a focus in the study of gas–solid flow. Detailed flow field information below the particle scale is required to understand the mechanism of its formation and the statistical properties of its dynamic behavior, but is not easily obtained in both experiments and numerical simulations. In this article, a meshless method is used to reveal such details in the destabilizing of a suspension with hundreds of particles. During the process, doublets, quadruplet and larger clusters are seen to form and disintegrate dynamically, showing a tendency to minimize local voidages. At the same time, single vertical streams, pairs of parallel streams and many irregular streams appear and disappear between particle clusters alternatively, exhibiting a tendency to suffer lowest resistance. Globally, the spatio-temporal compromise between these two tendencies results in a configuration of large clusters separated by fast flow streams. In the clustering process, the inter-phase slip velocity is seen to increase long after the forces on each phase have stabilized, suggesting that inter-phase friction is not a function of local voidage and Reynolds number only, as commonly considered. The article concludes with prospects on the sub-grid scale models for continuum description of gas–solid flow that can be established upon such simulation results.

1. Introduction

Evidences of natural particle clustering in both gas–solid and liquid–solid systems can be dated back to more than half a century ago (Wilhelm and Kwauk, 1948). The heterogeneity thus produced has significant effect on the transport and reaction properties of the system, and complicates the sub-grid scale models for its macro-scale hydrodynamic description.

To understand the origin of clusters, detailed information on the motion of individual particles is necessary, since clustering starts with the formation of doublets (Chen et al., 1991). Furthermore, according to the energy minimization multi-scale (EMMS) model (Li and Kwauk, 1994), clustering is shaped by the compromise between the minimization of particle gravitational potential and the resistance to gas flow (Li and Kwauk, 2001, 2003). Therefore, simultaneous visualization of both individual particle motion and the surrounding fluid flow is favorable to an extensive exploration on clustering mechanism. Though many experiments on the direct visualization of cluster formation have been reported (Fortes et al., 1987; Chen et al., 1991; Liu et al., 2005), such pictures were experimentally unattainable until recently (Martin et al., 2005). However, the number of particles that can be visualized is quite limited (with 8 and 16 particles in the whole system up to now), and accurate measuring of the flow field in the wakes of the particles was still considered to be difficult for very few PIV particles were observed to enter this region (Martin et al., 2005), whereas the wake effect is usually taken as an important inducement for clustering (Fortes et al., 1987; Chen et al., 1991).

In comparison, computer simulation can provide a more flexible and exhaustive alternative for this purpose, and the dramatic leaping in computational capability provided by parallelization has ranged simulations of fairly large systems into reasonable time. Several direct numerical simulations (DNS) of "large-scale" liquid–solid systems have been reported (Hu, 1996; Potapov et al., 2001; Pan et al., 2002; Cho et al., 2005; Nguyen and Ladd, 2005; Derksen and Sundaresan, 2007). And flow structures below the particle scale in fixed beds have been obtained also (Cate and Sundaresan, 2006; Beetstra et al., 2007 and the references therein). However, to our knowledge, few publications (e.g., Tang et al., 2004; Ma et al., 2006) have addressed high-resolution simulations on the more heterogeneous gas-solid suspensions where dynamic clustering is inherent.

* Corresponding author. Tel.: +86 10 82616050; fax: +86 10 62558065.
E-mail address: wge@home.ipe.ac.cn (W. Ge).

0009-2509/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2008.09.005

In this article, a gas–solid suspension with 389 solid particles is simulated with a macro-scale particle method (Ma et al., 2006), based on smoothed particle hydrodynamics (Gingold and Monaghan, 1977; Lucy, 1977), macro-scale pseudo-particle modeling (MaPPM, Ge and Li, 2001, 2003b) and moving particle semi-implicit (Koshizuka et al., 1995; Koshizuka and Oka, 1996). The whole destabilizing process from a uniform particle configuration is presented numerically, and the mechanism of clustering is explored based on qualitative description and quantitative analysis of the flow field around the particles gradually involved in the clustering and disassembling process. A correlation between the average slip velocity and clustering degree is discussed, which are of great interests to higher level simulation approaches such as Eulerian two-fluid models (TFM, e.g., Murray, 1965; Gidaspow, 1994) and Eulerian–Lagrangian discrete particle models (DPM, e.g., Tsuji et al., 1993; Hoomans et al., 1996).

2. Simulation

2.1. Methods

This work adopts a Lagrangian–Lagrangian scheme which combines macro-scale particle methods (MaPM) for the gas flow and

Table 1
Simulation and physical parameters.

	H (m)	W (m)	ρ (kg/m^3)	v (m^2/s)	d (m)	h (m)	ΔP (Pa)	F (m/s^2)
Dimensional	7.68e−3	7.72e−3	1.225	1.46e−05	6.54e−6	7.27e−6	3.403	3.617e2
Dimensionless	352	354	11.11	5.0e−04	0.3	1/3	1.717e−5	4.39e−9
	m (kg)	R_1 (m)	R_2 (m)	g_s (m/s^2)	m_s (kg)	ρ_s (kg/m^3)	Δt (s)	e
Dimensional	1.142e−15	1.20e−4	1.09e−4	−9.8	1.306e−10	160.49	1.627e−08	
Dimensionless	1	5.5	5	−1.19e−10	114348.47	1455.93	1	0.8

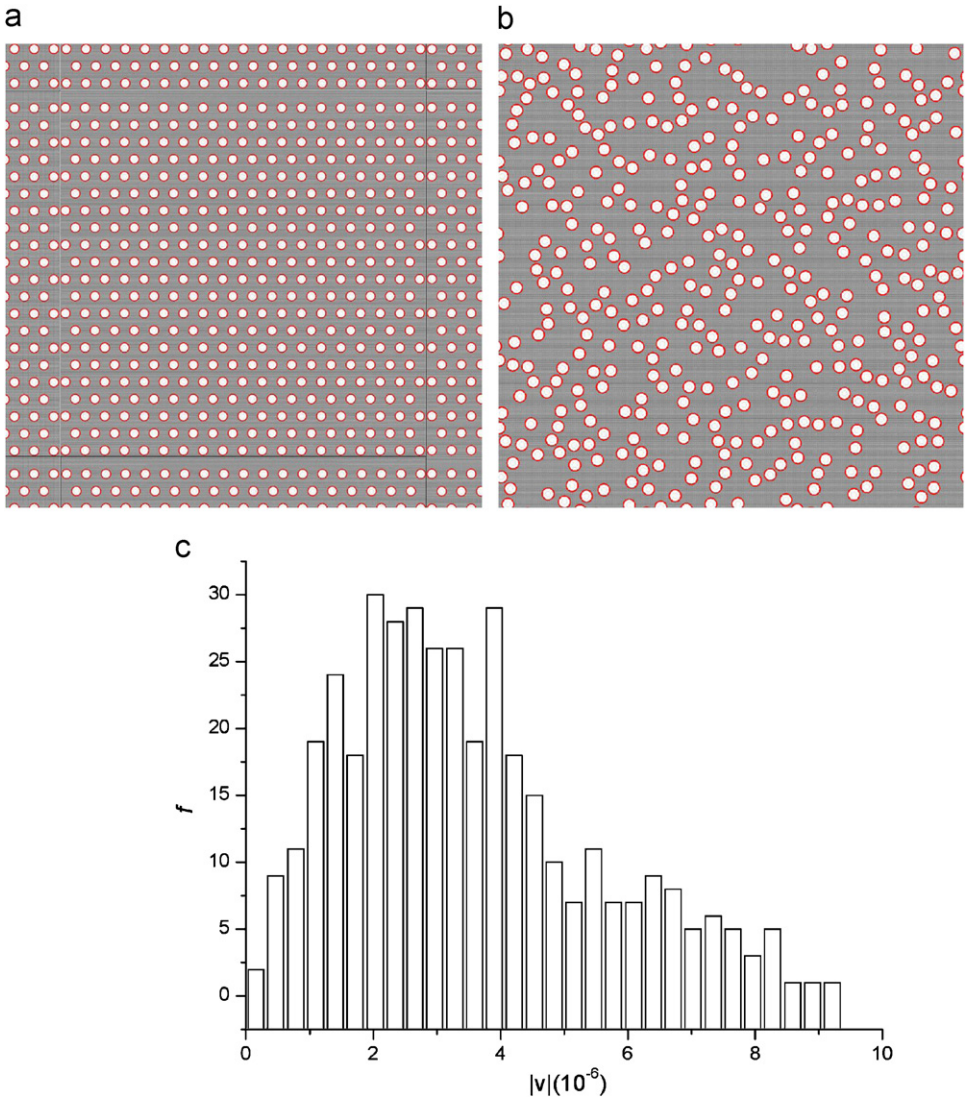

Fig. 1. Initial solid distribution in both cases. (a) Initial solid distribution in the "regular" case (the white lines and the repeated parts outside of them represent periodic boundaries), (b) initial solid distribution in the "random" case (periodic boundaries are omitted for simplicity) and (c) initial solid velocity vector values distribution in the "random" case.