Chemical Engineering Science 167 (2017) 297–316

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Experimental measurements of particle collision dynamics in a pseudo-2D gas-solid fluidized bed

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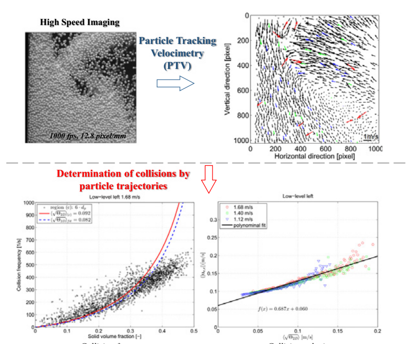
HIGHLIGHTS

- Particle-particle collisions are identified by particle trajectories obtained from optimized PTV measurements.
- Detailed comparison is conducted between experiments and the theoretical collision model in terms of collision frequency.
- Granular temperature is analyzed at microscopic and macroscopic scales.
- Particle impact velocity correlates linearly with the square root of granular temperature

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 December 2016
Received in revised form 20 March 2017
Accepted 12 April 2017
Available online 17 April 2017

Keywords:
Collision frequency
Impact velocity
Granular temperature
Fluidized bed
PTV

ABSTRACT

Based on particle tracking velocimetry (PTV) measurements by Hagemeier et al. (2014), the particle tracking approach is further optimized to accurately measure complex granular flows in a pseudo-2D fluidized bed. The particle granular temperature, particle collision frequency and impact velocity are systematically investigated under various operation conditions. Collision events are identified by a self-developed algorithm based on the variation of individual particle trajectories obtained from PTV measurements.

The circulation pattern of particles in the fluidized bed can be well represented using the time-averaged volumetric flux of particles. The evaluation of granular temperature depends on the size of the investigation region. The value of granular temperature and the corresponding anisotropy significantly decrease as the size of the investigation region varies from 45 times particle diameter to 6 times particle diameter. Compared to the collision model of the kinetic theory of granular flow, the experimental collision frequency tends to be relatively constant or even decrease after exceeding a critical solid volume fraction. This is a result of competing contributions of increasing solid volume fraction and decreasing granular temperature. The average impact velocity correlates linearly with the average square root of granular temperature. The slope of this linear equation depends on the location within the fluidized bed.

1. Introduction

Fluidized bed spray granulation, coating and agglomeration are widely utilized in the industry to produce, for example, food,

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http://dx.doi.org/10.1016/j.ces.2017.04.024

Nomenclature

A, B	constants in relaxation method [–]
d_p	particle diameter [mm]
$\boldsymbol{d}$	displacement vector between two particles [pixel]
f_c	particle and average particle collision frequency [1/s]
g_0	radial distribution function [–]
$I, \bar{I}$	intensity and mean intensity in the matrix of raw image [–]
L_c	distance of two particle centers [m]
L_i	distance to the front wall [m]
n	particle number concentration [1/m^3]
$\boldsymbol{n}$	unit vector between two particles [pixel]
$\dot{n}_c$	particle collision rate [1/(m^3·s)]
m_c	total number of candidate particles [–]
N_c	number of particle collisions [–]
N_p	number of particles [–]
$P_{ij}, \tilde{P}_{ij}$	normalized matching probability, non-normalized matching probability [–]
Q_{ij}	contribution of neighboring particles to matching probability [–]
R_r	recovery ratio [–]
$s, \bar{s}$	intensity and mean intensity in the matrix of template particle [–]
S_f	scale factor [pixel/mm]
St	Stokes number [–]
St_v	viscous Stokes number [–]
T	searching radius in relaxation method [pixel]
$t, \Delta t$	time, time step size [s]
u_c	magnitude of impact velocity (scalar) [m/s]
$\boldsymbol{u}_f$	fluctuation particle velocity (vector) [m/s]
$\boldsymbol{u}_p$	particle velocity (vector) [m/s]
$\boldsymbol{u}_{r,c}$	impact velocity (vector) [m/s]
U_{mf}	minimum fluidization velocity [m/s]
U	superficial gas velocity [m/s]
x, y, z	Cartesian coordinates [m]

Greek symbols

γ	normalized cross-correlation coefficient [–]
δ	contact threshold value [pixel]
ϵ_s	solid volume fraction [–]
$\epsilon_{s,max}$	maximum solid volume fraction [–]
θ	angle between two velocity vectors [°]
Θ	granular temperature [m^2/s^2]
ρ_p	particle density [kg/m^3]
τ_p	life time of particle [s]
χ	collision model parameter [1/s]
Φ	volume flux of solid particles [m^3/(s·m^2)]

Subscripts

1, 2	different particles, or time steps
2D	two dimensional space
c	imaginary collision moment
i, j, k	indices
p	particle
fit	fitting curve

Abbreviations

CFD	computational fluid dynamics
CV	coefficient of variation
DEM	discrete element method
FOV	field of view
KTGF	kinetic theory of granular flow
MPT	magnetic particle tracking
PEPT	positron emission particle tracking
PIV	particle imaging velocimetry
PTV	particle tracking velocimetry
PBM	population balance model

pharmaceuticals, fertilizers, powder catalysts and cosmetics. In typical applications, particles are fluidized by hot gas through the bottom distributor, which mainly controls the global circulation and particle formulation process. Meanwhile, a spray zone containing solid material is formed by the atomization process, and particles are wetted in the spray zone. The shape and location of the spray zone depend on the specific sub-process and the apparatus configuration. Obviously, in a fluidized bed, the motion of particles is not only influenced by aerodynamic transport and turbulent effects, but is also significantly affected by particle-particle interactions (Crowe et al., 2011). In agglomeration processes, for instance, primary particles randomly collide and may stick at wet spots due to the formation of liquid bridges that are subsequently solidified by evaporation, whereas the global motion of all particles is governed by the macroscopic aerodynamic transport effect.

As a well-established macroscopic approach to describe product quality, population balance models (PBM) are usually used to investigate particle formation processes in industrial scale (Ramkrishna, 2000). Additionally, the Monte-Carlo method is another useful approach to model particle formation based on micro-scale events and processes (Turton, 2008; Tsotsas, 2015). Nevertheless, the accuracy of both approaches relies on model parameters associated with microscopic particle dynamics and collision dynamics, such as the residence time, the impact velocity and the collision frequency. For example, the so-called viscous Stokes number St_v (Ennis et al., 1991), strongly depending on the impact velocity, can be used as the coalescence criterion and provides the critical condition for the dissipation of kinetic energy by a given thickness of viscous layer (Iveson et al., 2001; Terrazas-Velarde et al., 2011a). The particle collision frequency, a main parameter in the aggregation kernel of the population balance models, dominates the agglomeration process (Hussain et al., 2013, 2015). Therefore, a sound understanding of microscopic particle dynamics and collision dynamics in gas-solid fluidized beds is important in order to design and scale-up new equipment, as well as to control the product quality.

Due to the industrial significance and experimental difficulty of microscopic particle dynamics and collision dynamics, the accurate measurement of these quantities has been the objective of many experimental studies of particulate flows in different configurations. In order to obtain microscopic particle dynamics, three particle tracking techniques are widely used to reconstruct individual particle trajectories in different configurations, including particle tracking velocimetry (PTV) (Capart et al., 2002; Spinewine et al., 2003; You et al., 2004; Hagemeier et al., 2014), magnetic particle tracking (MPT) (Mohs et al., 2009; Buist et al., 2014; Idakiev and Mörl, 2015), and positron emission particle tracking (PEPT) (Stein et al., 2000; Wildman et al., 2001; Parker and Fan, 2008; Li et al., 2015). The MPT and PEPT techniques, with limited number of tracer particles (one for MPT; up to three for PEPT), are able to achieve a relative long tracking period in three-dimensional configurations, which is a benefit in evaluating the cycle time and the residence time in various processing zones (Li et al., 2015). In addition, the MPT technique has the advantage to measure the rotation speed of particles (Idakiev and Mörl, 2015). Based on elaborate particle segmentation and particle tracking algorithms, the PTV technique