Particuology 22 (2015) 39–51

Contents lists available at ScienceDirect

Particuology

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

Estimation of particle dynamics in 2-D fluidized beds using particle tracking velocimetry

Thomas Hagemeier[a,*], Christoph Roloff[b], Andreas Bück[a], Evangelos Tsotsas[a]

[a] NaWiTec, Thermal Process Engineering, Otto-von-Guericke University Magdeburg, Universitaetsplatz 2, 39106 Magdeburg, Germany
[b] Fluid Dynamics and Technical Flow, Otto-von-Guericke University Magdeburg, Universitaetsplatz 2, 39106 Magdeburg, Germany

ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form 31 July 2014
Accepted 16 August 2014

Keywords:
Particle dynamics
Particle tracking velocimetry
Pseudo-2D
Fluidized bed

ABSTRACT

The experimental characterization of particle dynamics in fluidized beds is of great importance in fostering an understanding of solid phase motion and its effect on particle properties in granulation processes. Commonly used techniques such as particle image velocimetry rely on the cross-correlation of illumination intensity and averaging procedures. It is not possible to obtain single particle velocities with such techniques. Moreover, the estimated velocities may not accurately represent the local particle velocities in regions with high velocity gradients. Consequently, there is a need for devices and methods that are capable of acquiring individual particle velocities. This paper describes how particle tracking velocimetry can be adapted to dense particulate flows. The approach presented in this paper couples high-speed imaging with an innovative segmentation algorithm for particle detection, and employs the Voronoi method to solve the assignment problem usually encountered in densely seeded flows. Lagrangian particle tracks are obtained as primary information, and these serve as the basis for calculating sophisticated quantities such as the solid-phase flow field, granular temperature, and solid volume fraction. We show that the consistency of individual trajectories is sufficient to recognize collision events.

Introduction

In granular systems, knowledge of the individual particle and particle cluster velocities is essential for a model-based description of particulate processes. For instance, the classical two-compartment modeling approach of granulation processes used by Börner, Peglow, and Tsotsas (2013) relies on particle velocities. These are used to determine residence times within two characteristic zones, and the solid mass fluxes between them, under spraying and drying processes. This topic was addressed numerically by Fries, Antonyuk, Heinrich, and Palzer (2011), and a recent experimental treatment was reported by Börner, Hagemeier, Ganzer, Peglow, and Tsotsas (2014). Therefore, an accurate quantification of particle velocities within the process chamber is of enormous value to modern macroscopic modeling approaches.

There are numerous methods of gathering information concerning particle velocities in fluidized beds (Bhusarapu, Al-Dahhan, & Duduković, 2006). Various measurement devices can be used, such as fiber optical probe, laser-Doppler velocimetry, or particle image velocimetry, as summarized by Werther (1999). Each technique has advantages and limitations. In this paper, we apply particle tracking velocimetry (PTV) to dense particulate flows in a pseudo-2D fluidized bed. To date, the PTV technique has been used to measure particle velocities in vibrating beds, Couette flows in shear cells, rotating drums, or during hopper discharge. These contributions considerably improved the application of PTV in the field of granular flows. However, to the best of our knowledge, PTV has not previously been applied to the complex flows found in fluidized beds, where densely packed particle clusters exist alongside loose particles in large gas bubbles. An additional layer of complexity arises from particle trajectories in opposing directions, as well as through inter-particle and particle-wall collisions. These aspects have not been captured by other measurement devices for larger particle systems. Therefore, the objectives of this communication are to: (i) report the use of PTV for dense gas–solid two-phase flows in bubbling fluidized beds, and (ii) describe the particle trajectories measured by this method.

This proof-of-concept study is structured as follows. "Particle tracking velocimetry" section gives a general introduction to the methodology of particle tracking velocimetry, and discusses two

* Corresponding author. Tel.: +49 391 6712322.
E-mail address: Thomas.Hagemeier@ovgu.de (T. Hagemeier).

http://dx.doi.org/10.1016/j.partic.2014.08.004
1674-2001/

Nomenclature

d_p	particle diameter, m
f_r	frame rate, Hz
s_f	scale factor, pixel/mm
t, Δt	time, time step size, s
x, y, z	coordinates, pixel or m
I_A	interrogation area, m^2
$I_{1,2}$	images 1 and 2
$S_{i,j}$	Voronoi star i, j
T_{gran}	granular temperature, m^2/s^2
u_{mf}	minimum fluidization velocity, m/s

Greek symbols

ε_p	solid volume fraction,–
μ	fluid viscosity, kg/(m s)
ρ_p	particle density, kg/m^3
σ	standard deviation of particle velocity, m/s
τ	trajectory lifetime, s
τ_{corr}	corrected trajectory lifetime, s
τ_c	collision time, s
τ_v	particle response time, s

Abbreviations

FOV	field of view
PIV	particle image velocimetry
PTV	particle tracking velocimetry

approaches applicable to dense two-phase flows. In “Proposed PTV algorithm” section, we describe the PTV algorithm used in our investigations, including information on particle segmentation, tracking, and post-processing. “Experimental setup” section gives the experimental setup, with all operating conditions and hardware parameters, and “Results and discussion” section presents the resulting particle trajectories and derived quantities. More detailed results in the form of time series are given in Appendix A and as supplementary material (video sequences) online. In “Conclusions” section, we draw together some significant conclusions, and mention several open questions and ideas for future work.

Particle tracking velocimetry

PTV is an image-based measurement technique to quantify flow velocities. It is mainly applied in the field of fluid mechanics, in particular to liquid flows (Adrian, 1991; Lloyd, Ball, & Standsby, 1995). However, some researchers have also described PTV measurements in particulate multiphase flows. Capart, Young, and Zech (2002) identified three aspects of granular flows that restrict an out-of-the-box application of PTV. These challenges arise because granular flows are: (i) highly dense particulate systems, with (ii) fluctuating particle motions due to particle-particle collisions, resulting in discontinuous path lines, and (iii) sharp velocity gradients. Consequently, the methodology of PTV cannot be applied to dense particulate flows, such as in fluidized beds, without suitable modifications. First, the particle system has to be accessible for the high-speed camera and the illumination source. These two devices observe and illuminate the scene through a transparent wall. The opaqueness of the particle system restricts the application of PTV to pseudo-2D configurations. Moreover, the high particle density leads to correspondence problems within the tracking algorithm. To avoid erroneous results, particles need to be identifiable. This can be achieved in two ways. The moving particle bed could be seeded with particles that have a different optical property to the majority of particles. This would involve tracer particles being colored using paint or a fluorescent dye (e.g., Natarajan, Hunt, & Taylor, 1995), which is also a common way to improve the PTV technique for gas flows (Bendicks et al., 2011). A standard tracking algorithm could then be applied, because the concentration of tracer particles is low enough to identify the same tracer particle on subsequent images. The second technique uses a specialized imaging method in which the particles are segmented and a certain type of bed structure can be identified. In particular, the Voronoi imaging method is used to generate a net of connection lines between neighboring particles, yielding a specific pattern in the particle bed. Particle assignment and tracking is linked to the properties of the Voronoi diagram. Jesuthasan, Baliga, and Savage (2006) provided a comprehensive review of PTV techniques together with the principles of PIV applied to granular flows. They also indicated the use of pattern matching algorithms to solve the correspondence problem in granular or densely seeded flows.

PTV with colored tracers

Colored tracers are commonly applied in PTV to enable particle identification in dense particulate flows. The dilute and dense regions of discrete multiphase flows, such as the gas–solid two-phase flows typically found in pneumatic conveying or fluidized beds, can be distinguished on the basis of a time scale analysis. If the collision time τ_c is larger than the particle response time τ_v, particles have enough time to adapt to the flow velocity before they come into contact with another particle. Hence, the two-phase flow can be described as a dilute system when $\tau_v/\tau_c < 1$. When $\tau_v/\tau_c > 1$, the collision time is smaller than the particle response time. This is characteristic of a flow that is dominated by particle interactions, and is consequently described as a dense multiphase flow.

Both the response time and collision time are functions of material properties such as the solid and fluid densities, fluid viscosity, and particle size. However, an explicit expression for the response time τ_v is only available for the Stokes flow regime (low particle Reynolds number).

$$\tau_v = \frac{\rho_p d_p}{18\mu} \quad (1)$$

In contrast, the collision time is the inverse of the collision frequency $\tau_c = 1/f_c$, where f_c is a function of the particle diameter, relative velocity, and particle number density of one size class. This quantity is commonly estimated on the basis of collision models, as by Sommerfeld (2001). More details on phase properties and phase interactions are given in various textbooks (e.g., Crowe, 2006; Crowe, Sommerfeld, & Tsuji, 1998). Hsiau and Jang (1998) measured particle velocity fluctuations in a Couette flow using 2% colored tracer particles among a majority of equally sized non-colored particles. They observed the particle motion while shearing the powder, and found anisotropic velocity fluctuation distributions. This contradicts the general assumption of the kinetic theory of granular flow, according to which fluctuations are random and isotropic (Lun, Savage, Jeffrey, & Chepurniy, 1984). Moreover, the overall particle motion should be almost deterministic, with no spontaneous changes of direction observed. Natarajan et al. (1995) used colored tracer particles to observe granular flow behavior in a hopper. They also used 2% (by weight) black tracer particles to seed the flow.

Colored tracer particles were used by Chung, Hsiau, Liao, and Ooi (2010) to estimate the translational and rotational velocities of non-spherical particles (two bonded spheres of identical size) in a vibrating bed. They used a cross-correlation algorithm that accounts for particle rotation and translation by shifting and rotating a control window in two consecutive images. The method was