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PARTIC-964; No. of Pages 9

ARTICLE IN PRESS

Particuology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Determination of particle exchange rates at over-flow weirs in horizontal fluidised beds by particle tracking velocimetry

Katja Meyer, Andreas Bück*, Evangelos Tsotsas

Thermal Process Engineering, Otto von Guericke University Magdeburg, Universitätsplatz 2, D-39106 Magdeburg, Germany

ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form
15 September 2016
Accepted 28 September 2016
Available online xxx

Keywords:
Particle tracking velocimetry
Horizontal fluidised bed
Axial dispersion
Granulation
Drying

ABSTRACT

Residence time distributions (RTDs) in horizontal fluidised beds have a huge effect on solid product properties and are influenced by the internal design of the apparatus, e.g. the separation into different compartments by weirs. Weirs can be passed in or against the overall solid transport direction, with the back-flow resulting in axial dispersion, which is a measure of the spread of the RTD. Therefore, the ratio of exchange rates at weirs under different fluidisation conditions provides information on axial dispersion. In this work, a methodology based on particle tracking velocimetry is presented to obtain information on the exchange rates of particles at weirs in horizontal fluidised beds. The internal recirculation is studied for over-flow weirs with respect to different fluidisation conditions, providing a first step towards determining the effects of weirs and fluidisation conditions on axial dispersion and RTDs in horizontal fluidised beds.

Introduction

Fluidised beds are a key technology in solids processing, with widespread application in the areas of food, feed, fine chemicals, and pharmaceuticals. Three major designs can be distinguished: cylindrical, conical, and horizontal (rectangular) apparatus. Whereas the first two usually perform a single operation, e.g. drying, cooling, layering, or agglomeration, horizontal fluidised beds can be used to combine more than one operation in a single apparatus, e.g. layering of particles with a solid-containing liquid followed by drying and cooling. To realise this, the apparatus is compartmentalised, i.e. it is sub-divided into compartments along the apparatus length, by the installation of weirs, as illustrated in Fig. 1.

Weirs are rectangular plates which are installed perpendicular to the solid transport direction. They can be divided into three groups (Fig. 2): over-flow weirs, which are installed directly on top of the distributor plate so that particles have to climb over the weir; under-flow weirs, which have a defined gap between the weir and the distributor plate; and side-flow weirs, which are similar to under-flow weirs, but the gap only exists over a certain portion of the apparatus width.

Compartmentalisation by weirs allows different processes to be performed in one apparatus by spatially dividing the solids, and also influences the residence time distribution (RTD). Particles have to pass the weirs, and their individual velocity depends on particle and fluidisation characteristics such as size, mass density, sphericity, fluidisation velocity, and bubble formation. Differences in these characteristics will yield different residence times in the compartments, and may eventually yield non-uniform product properties, e.g. during drying, some particles may still be too wet whereas others are already over-dried.

RTDs are generally characterised by the mean residence time and a standard deviation. Plug-flow behaviour corresponds to an RTD with zero standard deviation, i.e. all particles move through the apparatus with the same velocity. In practical applications, however, a non-zero standard deviation is observed, i.e. some particles may have a shorter residence time whereas others have a significantly longer residence time.

The occurrence of this non-zero standard deviation is usually attributed to particle motion against the transport direction, or the hindrance of a fraction of the particles to move with the dominant transport flow. In terms of RTDs in horizontal fluidised beds, the observed effect of developing a non-zero standard deviation is called axial dispersion. This goes back to the work of Levenspiel (2012), who used a convection–dispersion model to describe RTDs in horizontal fluidised beds. An ideal plug-flow can theoretically be achieved for an infinite number of compartments; practically, the number of weirs used is usually small, at the price of dispersion. Furthermore, in this concept, one has to distinguish between the number of theoretical stages and the number of geometric stages. It has been reported that these two numbers are rarely equal in

* Corresponding author. Fax: +49 391 67 18265.
E-mail address: andreas.bueck@ovgu.de (A. Bück).

http://dx.doi.org/10.1016/j.partic.2016.09.007

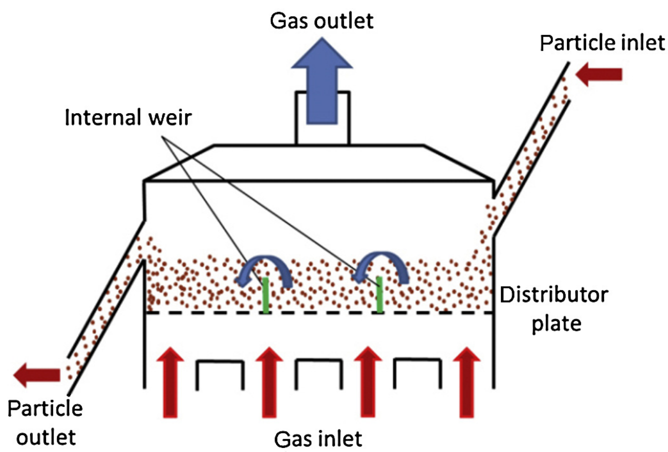

Fig. 1. Sketch of continuously-operated horizontal fluidised bed with internal weirs.

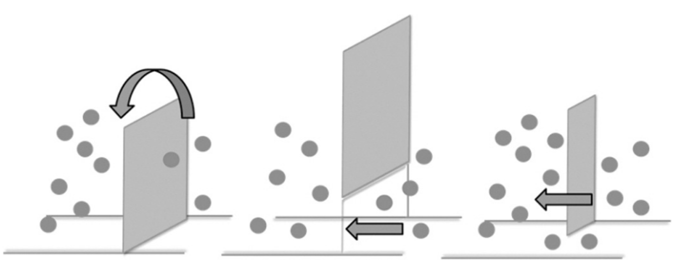

Fig. 2. Common weir designs: (left) over-flow weir, (middle) under-flow weir, (right) side-flow weir.

fluidised beds. For instance, Bachmann, Bück, and Tsotsas (2016a, 2016b) determined that the residence time behaviour in a horizontal fluidised bed with four geometric stages corresponds to a series connection of approximately two ideally stirred tanks without back-flow.

The connection between the standard deviation and the dispersion coefficient *D* has been investigated experimentally by Bachmann et al. (2016a), Nilsson and Wimmerstedt (1988), Reay (1978), and Satija and Zucker (1986). RTDs were obtained by tracer experiments, in which a well-defined amount of coloured tracer particles are injected at the inlet of the fluidised bed and the mass flow rate of tracer particles is measured at the outlet. Using various model assumptions, the mean residence time, standard deviation, and axial dispersion coefficient could be determined. Applied to weirs, the axial dispersion coefficient would provide a measure for the overall transport resistance introduced by the weirs, i.e. the effect of individual weirs and the connection to individual particle properties and fluidisation conditions can only be studied as a whole. However, no such studies have yet been reported in the literature. The knowledge of the effect of an individual weir parameterised with respect to particle properties and fluidisation conditions, however, would allow a number of important design questions to be answered. Foremost among these is how many weirs are required in an apparatus to obtain a desired spread of the RTD; other important questions concern the segregation of particle mixtures or preferential transport of certain particle sizes.

In this set-up, axial dispersion can be understood as a consequence of particles moving against the main solid transport direction at weirs, with the ratio of particle numbers moving along and against the dominating flow direction, i.e. the particle exchange rates, defining the value of the standard deviation of the RTD. To answer the questions raised, a robust methodology is required that allows the determination of particle exchange rates at weirs.

The most basic method of obtaining particle exchange rates is manual counting: After filling two adjacent compartments with differently coloured particles, with one colour in each compartment, the particles are fluidised for a certain time. After stopping the fluidisation and emptying the compartments, the number of particles of each colour in the two compartments is counted, giving a number- or mass-based measure of particle exchange. This setup can be extended to more than one chamber by a similar strategy, which in the limit (coloured particles in the first chamber and counting in the last) can be interpreted as the RTD of particles in the apparatus. The main drawbacks of this method are the very high labour cost and the determination of the exchange rates only as an integral measure, i.e. cumulative or net particle exchange.

Another way to study exchange rates and particle movement is by optical tracking, where a combination of high-speed recording and image analysis is used to capture and observe particle motion with the focus on particle velocities. By construction, optical tracking is usually limited to pseudo-2D set-ups, i.e. the planar motion of particles. The two main approaches are particle image velocimetry (PIV) and particle tracking velocimetry (PTV).

In PIV, first introduced by Adrian (1991), two images taken within a very short time interval are used to determinate the particle motion from one image to the next using an intensity-distribution-based cross-correlation. From the known time difference between the images, a velocity field can be determined (Bokkers, van Sint Annaland, & Kuipers, 2004; Börner, Peglow, & Tsotsas, 2013; Lim, Wong, & Wang, 2007; Liu, Li, Zhao, & Yao, 2008). However, no direct particle tracking takes place besides a tracking of intensities. Additionally, spatial and temporal averaging is performed in the evaluation, giving a space-time-average of the velocity field. This results in the preferential detection of dominant net transport behaviour, e.g. solids in the transport direction, and the potentially far smaller back-flow of particles is over-shadowed and cannot be detected.

PTV (see Bendicks et al. (2011), Capart, Young, and Zech (2002), Hagemeier, Börner, Bück, and Tsotsas (2015), Hagemeier, Roloff, Bück, and Tsotsas (2015), Jesuthasan, Baliga, and Savage, (2006) and You, Zhao, Cai, Qi, and Xu (2004) for details and successful applications) involves the identification of individual particles in images, e.g. using a sample particle (Bendicks et al., 2011; Capart et al., 2002; Hagemeier, Börner et al., 2015; Hagemeier, Roloff et al., 2015; Jesuthasan et al., 2006; You et al., 2004). The positions of these identified particles are then tracked from image to image using various algorithms to construct individual particle trajectories. From the known time difference between the images, the individual (Lagrangian) particle velocities can be determined. In principle, the detection of movement in any direction is possible. However, some problems occur in practice, such as particles leaving the observation plane, i.e. moving into the third dimension, or identification problems in dense particle flows. In recent years, significant progress has been made to overcome these issues, as summarised by Hagemeier, Roloff et al. (2015). The main advantage of PTV over PIV is that particles are tracked directly and individually, allowing the detection of small numbers of particles moving opposite to the dominant particle flow. This makes PTV highly suited to the investigation of exchange rates at weirs. However, by construction, optical methods like PIV or PTV are limited to 2D set-ups; their use always assumes some uniform extension of the flow in the unobserved third dimension.

A non-intrusive measurement technique that provides fully three-dimensional information on particle movement is positron emission particle tracking (PEPT). This has been successfully used to study the movement of dense particulate flows in a variety of apparatuses, e.g. twin-screw extruders, mixers, and spiral concentrators (Boucher et al., 2014; Laurent & Cleary, 2012; Lee, Ingram, & Rowson, 2012; Van de Velden, Baeyens, Seville, & Fan, 2008).