ARTICLE IN PRESS

Journal of Environmental Management xxx (2017) 1–8

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Development of videogrammetry as a tool for gas-particle fluidization research

S. Anweiler

Faculty of Mechanical Engineering, Department of Environmental Engineering, Opole University of Technology, Poland

ARTICLE INFO

Article history:
Received 13 December 2016
Received in revised form
7 March 2017
Accepted 14 March 2017
Available online xxx

Keywords:
Fluidization
Visualization
Flow pattern
Dynamic image analysis
Videogrammetry

ABSTRACT

Many industries use fluidization of solid particles for energy efficiency or environmental friendly process development, and this paper introduces research techniques developed for investigating gas-particle systems At present there is plenty of room for refining gas-particle fluidization process. With the rapidly rising application of mathematical modelling, real time visualization of processes will be widely used for validation of those models in the near future. In presented research, photogrammetry, as a part of close range vision metrology, has been expanded to allow dynamic space and time analysis of the phase concentration distribution inside fluidization devices. A novel videogrammetry method was created with additional stochastic process analysis for detailed frequency and amplitude characteristics. Videogrammetry was used for the assessment of flow regimes, which were held in various types of fluidization apparatuses. Classic bubbling, jet-spouted and fast circulating fluidization processes were explored under the investigation. Videogrammetry is non-invasive flow regime recognition method, which enables detailed research of gas-particle fluidization phenomena. Until now, there were no comparative studies for three different types of fluidization processes with the use of one complex approach. Developed videogrammetric method consists of the flow structure visualization and dynamic image analysis. The analysed feature is the grey level of the image in time domain, and grey level signals were analysed with the use of autocorrelation function and power density function. The results are presented as images, plots and a flow map. Efficiency of the method was tested by comparison of real observed flow structures to the reconstructed flow structures and the recognition accuracy reached 92%.

1. Introduction

Fluidization is a result of solid particles suspension in a stream of gas. This phenomenon can be observed in many industrial processes, such as coal, biomass and waste combustion or gasification, renewable energy production, chemical, petrochemical and metallurgical processes, granulation and drying (Di Maio et al., 2013). Fluidized bed technology appears to be effective, especially in municipal waste treatment systems (Peng and Lin, 2014). Deliverance of therapeutic agents to the lungs and airways in the pharmaceutical industry is also a part of fluidization technology (Pasquali et al., 2015). Electronic parts has just become serious environmental problem to solve. Therefore another up to date fluidized bed technologies for printed circuit board decomposition were reviewed by (Marques et al., 2013). Significant role of fluidized bed reactors in CO_2 mineral sequestration was recently researched by (El-Naas et al., 2015). Recent environmental difficulties with the polychlorinated biphenyls (PCBs) in contaminated soils and wastes are solved by destruction using circulating fluidized bed combustion (CFBC) technology, which was studied by (Desai et al., 2007). It has been demonstrated that the reaction efficiency, heat transfer and energy consumption during fluidization process depend on solid mixing and solid–gas contact (Yurong et al., 2004). Major advantages of gas-fluidized bed reactors, such as efficient bed-to-surface heat transfer and temperature uniformity, derive from the motion of the particles, largely induced by interactions between voids and the dense phase (Tebianian et al., 2016). Solid mixing and solid-gas contact depend on solid/gas flow structure or solid/gas flow pattern (Li et al., 2014). For the reason it is essential to characterize the two-phase flow behaviours in gas-solid fluidized beds and monitor the fluidization processes for further control and optimization (Sun and Yan, 2016). Intensive research has been conducted to investigate the fluidization behavior experimentally (Cloete et al., 2013) and numerically (Gómez-Barea and Leckner,

E-mail address: s.anweiler@po.opole.pl.

http://dx.doi.org/10.1016/j.jenvman.2017.03.040
0301-4797/

2010), and many models have been developed for optimizing reactor design and bed scale up. This includes even such unusual techniques like stereology (Masiukiewicz and Ulbrich, 2004). Shi et al., (2011) proposed the energy minimization multi-scale model (EMMS) to characterize the meso-scale structure of fluidization process. Still, gas-particle fluidization process is not fully described and there is plenty of room for refinement. Solid flow pattern is an important factor which affects the fluidized bed characteristics, such as the rate of heat and mass transfer, chemical reaction intensity, as well as the particle attrition and internal erosion. Therefore, understanding the mechanism, and knowing the rate of solid mixing are vital to control the product quality and heat flow (Askarishahi et al., 2015). Although computational fluid dynamics (CFD) has become a popular and efficient tool for process design in the past decades, development has been slower for multiphase processes the than for single phase processes. This is due to theoretical complications related to phase interactions and the greater requirements for computational capacity. The large size of industrial facilities further complicates application of multiphase CFD. Fluidized beds are no exception and only recently simulation of large industrial fluidized beds has become feasible. CFD algorithms which couples the macroscopic governing equations for gas phase and the second law of motions for individual particles have been done recently by (Koralkar and Bose, 2016). Computation times in simulations with the most accurate models are still too long however, and modifications and adaptations to the modelling approaches are therefore needed to apply them at commercial scale (Kallio et al., 2015). Numerical approach is expected to give new information on fluidization process and leads to improved on-line reactor diagnostics (Ramirez et al., 2017). With the rapidly rising application of mathematical modelling, visualization of real processes will be, in the near future, widely used for validation of numerical models. Non-intrusive measurement techniques and the current state of knowledge and experience in the characterization and monitoring of gas-solid fluidized beds was fully reviewed by (Sun and Yan, 2016). Due to latest advancements in high accuracy of CCD/CMOS devices, and commonly accessible digital technology of high processor capacity, many research centres take an interest in vision metrology. That causes appearance of wide range of methods and techniques for visualization, and analysis of many various processes.

In the presented research, the novel method – photogrammetry, as a part of close range vision metrology, has been expanded to allow dynamic space and time analysis of the phase concentration distribution inside fluidization devices. With addition of stochastic process analysis for detailed frequency and amplitude characteristics - the method of videogrammetry was created. Videogrammetry is non-invasive flow regime recognition method and enables detailed research of fluidization phenomena. Next videogrammetry was used for the assessment of flow regimes, which occur in various types of fluidization apparatuses. In particular – classic bubbling, jet-spouted and fast circulating fluidization processes were taken under the investigation. Until now, there were no comparative studies for the three different types of fluidization processes with the use of one composite approach. Developed videogrammetric method consists of the flow structure visualization and dynamic image analysis. The analysed feature is the grey level of the image in time domain. Grey level signals were analysed with the use of autocorrelation function (ACF) and power density function (PDF). The results were presented as images, plots and a flow map. The efficiency of the method was tested by comparison of real observed flow structure to the reconstructed flow structure.

Photogrammetry is the science and art of making precise and reliable measurements from images. While the term 'photogrammetry' may evoke the notion of 'photographic' images, the technique as such is by no means restricted to those but incorporates all sorts of non-photographic images as well. The term '*digital*' in '*digital photogrammetry*' emphasizes the use of digital images, in whatever form, be it from the X-ray, visible, near and far infrared range, or microwave portion of the electromagnetic spectrum. Even ultrasound and electron-microscopic images and the like could be included (Gruen, 1997). In pharmaceutic industry for example dry powder inhalers (DPI) deliver therapeutic agents to the lungs and airways in the form of a powder aerosol. To achieve efficient delivery of these agents to the lungs, studies of fluidization of the bulk of the powder are conducted (Pasquali et al., 2015). In the processes industry segregation of particles inside the reactors have significant impact on the reactions (Gilbertson and Eames, 2001). Segregated fluidization in atmospheric conditions occurs when a bed has a broad particle size range, forming a horizontal interface that separates the lighter (flotsam) and the heavier particles (jetsam) (Gilbertson and Eames, 2001). The bed thus fluidizes non-homogeneously with increase of flow rate (Kumar et al., 2014).

Regardless of the rapid development of numerical methods there is still need for experimental validation in process engineering, whether it is a dense phase of fluidized bed (Deen et al., 2007) or a dispersed phase in pneumatic conveying (Borsuk et al., 2016). Although industrial fluidized bed dryers have been used successfully for the drying of wet solid particles for many years, the development of industrial fluidized bed dryers for any particular application is fraught with difficulties such as scaling-up, poor fluidization and non-uniform product quality. Scaling-up is the major problem and there are very few good, reliable theoretical models that can replace the expensive laboratory work and pilot-plant trials (Daud, 2008).

Due to latest advancements in high accuracy CCD/CMOS devices, and commonly accessible digital technology with high processor capacity, many research centres are taking an interest in vision metrology, creating a wide range of methods and techniques for visualization and analysis.

2. Measurement setup

Investigations were carried out in three, so called, two-dimensional models of fluidization columns. Two-dimensional models of reactors were described by (Dyakowski and Jaworski, 2000) as an easy and useful, two-phase flow investigation method. Schematic view of such columns are shown in Fig. 1. Two-dimensional columns are often used for modelling and visualization of fluidization process in laboratory conditions. They are made of transparent materials, and filled with solid particles, which creates a bed of solid particles. Gas flows upwards, through the bed, causing appearance of gas bubbles, plugs and other turbulences, which are known as two-phase flow patterns, and sometimes are interchangeably called flow structures.

The overall view of the measurement stand is presented in Fig. 2 (Anweiler and Ulbrich, 2004). The measurement setup was developed to be flexible, which means that it is modal, so that different types of fluidization can be examined by modification of the side walls. With the use of different shaped side walls the desired kind of flow channel can be created by placing guide plates between two flat, transparent walls. In this way, any type of fluidization apparatus model can be build.

Three different fluidic apparatuses were put to the test. First – classical fluidization column – commonly used for bubbling fluidization, which is a rectangular chamber with perforated bottom, is shown in Fig. 1a. Second – jet-spouted fluidization column – which is a conical chamber with axially mounted riser, for the purpose of particle flow stabilization, is presented in Fig. 1b. Third – fast fluidization column – often called circulating fluidized bed,