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Gas mixing study in freely bubbling and turbulent gas–solid fluidized beds with a novel infrared technique coupled with digital image analysis

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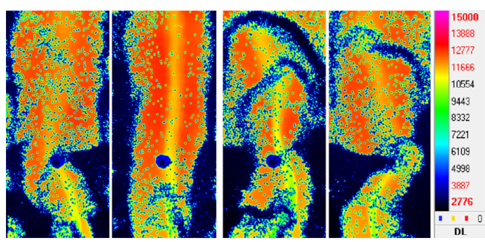
HIGHLIGHTS

- A new IR/DIA technique is applied for tracer gas detection.
- Gas dispersion increases as the superficial gas velocity increases and then decreases.
- Results obtained with IR/DIA are consistent with the mechanism proposed in literature.
- The new technique allows whole field, fast non-invasive measurements.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel experimental technique using a high speed Infrared (IR) camera combined with an improved Digital Image Analysis (DIA) method for non-invasive concentration measurement with high spatial and temporal resolution has recently been developed by Dang et al. (2013). This paper reports the extension of the IR technique to freely bubbling and turbulent fluidization regimes to investigate and quantify lateral gas mixing characteristics in gas–solid fluidized beds. The mechanism of lateral gas mixing in the bubbling regime studied with the novel technique is in good agreement with values reported in the literature. The experimental results, interpreted with a plug flow model with superimposed dispersion for a homogeneous flow, show that the lateral gas mixing coefficient first increases with the increase of superficial gas velocities from the bubbling to the turbulent flow regime and then decreases for even higher velocities, which is consistent with earlier literature studies. The dependency of the lateral gas mixing coefficient on the Reynolds number using Amos' correlation (Amos and Mineo, 1993) has shown large discrepancies at low gas velocities (where the equation was extrapolated), while a good match was obtained at higher gas velocities. The experimental findings reported in this paper indicate that the novel IR/DIA technique can successfully be applied for mass transfer and gas mixing studies in gas–solids multiphase flows.

1. Introduction

In fluidized bed (membrane) reactors, gas–solids contacting is one of the most important aspects which determine the conversion and efficiency of the process. Extensive research on fluidized bed reactors has been focused on hydrodynamic studies (amongst

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many others Müller et al. (2007), Mudde et al. (1999), Laverman et al. (2008), De Jong et al. (2011) and Dang et al. (2014)); however, not many studies concentrate on the important gas mixing characteristics. In fluidized bed systems the rapid mixing of solids can result in virtually uniform temperature profiles, even in very large industrial scale fluidized bed reactors for very exothermic reactions, but may also result in lateral (and axial) gas back-mixing. The deviation from the ideal plug-flow behaviour clearly influences the concentration profiles and significantly influences the conversion and possibly the product selectivities and, in case of submerged membranes, the permeation rates of the components in fluidized bed membrane reactors (Gallucci et al., 2013). Three coefficients of the fluidized bed have usually been used to quantify the gas (back)-mixing behaviour: axial dispersion, radial dispersion and gas back-mixing coefficients (Du et al., 2002). Experimental works carried out by Werther et al. (1992) and Gayán et al. (1997) indicate that the axial dispersion in the fast fluidization is negligible due to the convection dominated flow. It was found that it was very difficult to measure the back-mixing coefficient, because the tracer gas is quickly diluted by the fresh flow from the distributor, and its concentration drops below the detection limit of standard analysers.

The gas mixing behaviour in fluidized beds have usually been quantified using the injection and sampling (a stimulus-response) technique, which is invasive and has a very low temporal (due to the analysis time) and spatial (only few points) resolution. The invasive probes disturb the flow path of both gas and solids and inevitably disturb the bed operation. Recent developments are based on techniques like X-ray and MRI Müller et al. (2007), which have allowed non-intrusive and fast measurements of the flow characteristics. Pavlin et al. (2007) applied an MRI technique to measure the mass transfer from the bubble to the emulsion phase in gas–solids fluidized beds by injection and tracing of laser-polarized xenon (^{129}Xe). However, the application of MRI techniques is limited by an extremely high investment cost, the fluid needs to contain MR-sensitive nuclei and the size of the apparatus under investigation is very limited by the magnet bore size. Moreover, the technique does not provide an instantaneous, whole-field measurement of the tracer gas, but rather time-averaged gas–solids information based on measurements of the solids. A qualitative description of gas flowing through a bubble in a gas–solids fluidized bed was already given in the early work by Rowe et al. (1964), who injected bubbles of nitrogen dioxide (visible brownish gas) into pseudo-2D beds. A novel experimental technique, using a high-speed IR camera with a proper optical filter centred on the IR absorbing wavelength of a tracer gas has recently been developed by Dang et al. (2013) to measure the bubble-to-emulsion phase gas exchange rate in a gas–solids fluidized bed. The technique has shown several advantages compared to the conventional techniques, viz. non-invasiveness, with high temporal and spatial resolution with high sensitivity. However, the optical technique using the IR camera is hardly applicable to measure the concentration in the emulsion phase, due to the non-transparency of the particles used, thus only the gas mixing behaviour in the dilute phase has been discussed, and only single bubble injection has been studied so far.

This study investigates the gas mixing behaviour in a micro-structured fluidized bed operated in different fluidization regimes by extending the developed novel infrared technique coupled with the Digital Image Analysis for tracer gas detection in bubbling and turbulent fluidization regimes. First, the experimental setup and calibration are described. Subsequently, the new DIA algorithm with a high pass filter to account for the influence of scattering and self-reflection of the particles is discussed. Finally, the gas mixing study for different fluidization flow regimes is described and the determined gas mixing coefficients are compared with literature.

2. Experimental section

2.1. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. A heater plate (430 ± 5 °C) is used as an IR emitter and simultaneously provides a good background for the IR camera. The temperature of the IR source is well controlled at 430 ± 5 °C and the plate is put in a holder for a good insulation with the

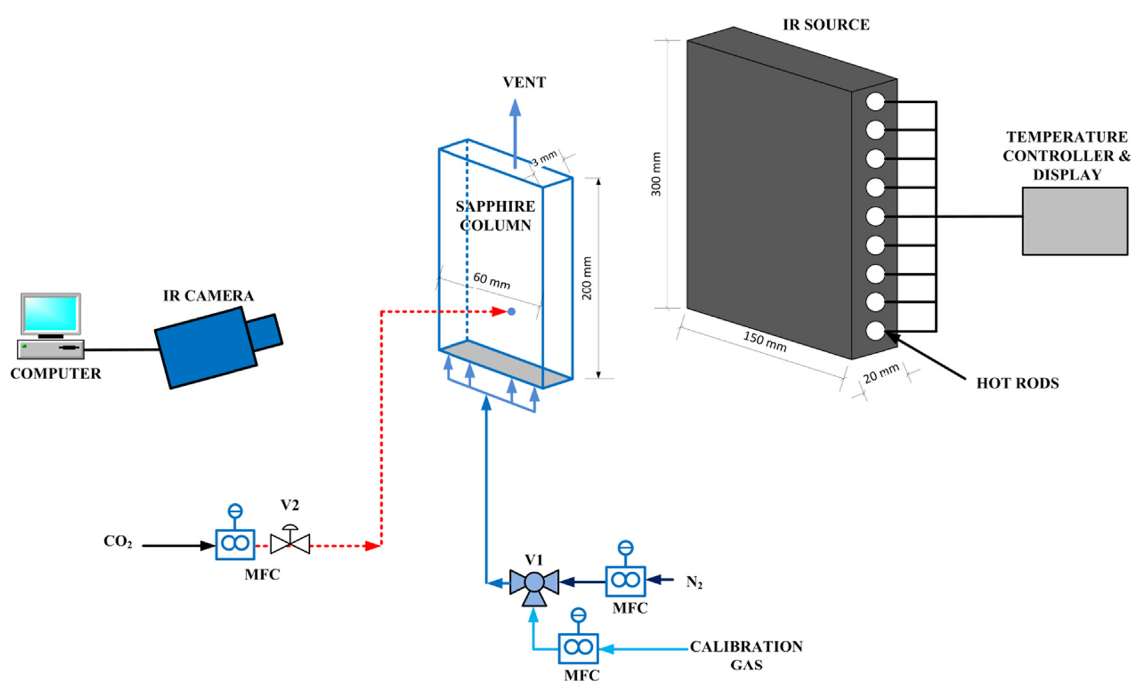

Fig. 1. Process flow diagram of experimental setup.