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Positron emission particle tracking in fluidized beds with secondary gas injection

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ABSTRACT

We apply positron emission particle tracking (PEPT) to a gas–solid fluidized bed with injection of a secondary gas through a centrally arranged nozzle and present a method to compute stationary fluid-dynamic characteristics of the system from the trajectories of a test particle. In order to evaluate this non-invasive method we compare the field of density obtained by PEPT with the density obtained by a traditional, well-established and approved, yet invasive, measurement technique to find good agreement. Besides the penetration depth of the jet region and the opening angle of the jet which are inferred from the density field, we use PEPT to measure quantities whose measurement using traditional methods is rather sophisticated, including the residence time of particles in the jet region and the suspended phase, the coefficients of axial and radial dispersion and the material flux across the jet boundaries. We conclude that PEPT is a reliable and at the same time versatile technique to measure stationary fluid-dynamic properties of dynamical particle systems at spatial resolution only limited by the duration of the measurement.

1. Introduction

Fluidized beds with secondary gas injection enjoy great popularity in miscellaneous fields of process engineering. Their characteristic properties, such as intense mixing of solids, excellent heat and mass transfer conditions as well as easy solids handling, make them attractive for application in mixing and drying processes. Moreover they are implemented in power plant technology, but also as chemical reactors for heterogeneous catalysis or chemical vapor deposition [1,2].

The fundamental setup of a fluidized bed with secondary gas injection is composed of two subsystems. The first one consists of the actual fluidized bed, in which particles are fluidized at moderate superficial fluid velocities by feeding the primary process fluid through a distributor plate at the bottom of the plant. Apart from bubble formation, which is commonly observed in gas–solid fluidized beds, solids are distributed homogeneously in the first subsystem and particle motion therein is based on random. Hence the first zone is in many cases considered an ideally mixed system, which provides gradient-free conditions with respect to heat and material distribution. The second subsystem is induced by the injection of a secondary fluid, which is fed through the orifice of a nozzle. Depending on the velocity of the injected secondary fluid, a region with reduced solids concentration is formed at the top of the nozzle orifice. According to Merry [3] this region is termed the jet region. In contrast to the statistical particle motion observed in the suspension phase of the fluidized bed, the jet region is characterized by an oriented flow field.

Several studies have been undertaken in the past to describe the interaction of the jet region with particles of the suspended phase and to derive correlations and design criteria for the description of fluidized beds with secondary fluid injection [3–6]. A large number of the conducted studies aimed at the investigation of the physical dimensions of the jet region, namely its penetration depth into the fluidized bed and the jet opening angle, in dependence of the prevailing operating conditions [7–9]. For that purpose invasive measurement techniques were often applied. As alternative, two-dimensional replicas of the systems were constructed, which facilitate visual observation of the bed and the jet region. However, a drawback of previously applied procedures consists in their invasive nature. By changing the geometry of the bed or penetrating the bed with probes, the flow field is influenced, which has a detrimental effect on the significance of the obtained measurement data.

More recent studies focused on the effect of secondary gas injection on the bubble size and behavior in gas–solid fluidized beds. Using a fractal injector system, Kleijn van Willingen et al. found that the injection of secondary gas leads to a reduction of the average bubble size within the suspension phase of the bed, which leads to an improved gas–solid contact [10]. With regard to the implementation as a chemical reactor system the residence time behavior of the injected fluid was

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investigated and allowed to draw conclusions on the dispersion of the fluid within the bed [11,12].

The objective of the present article consists in the non-invasive investigation of a three-dimensional gas–solid fluidized bed with secondary gas injection through a single, centrally arranged nozzle. Apart from the determination of the jet characteristics an investigation of the behavior of single particles is aimed at for the first time. For that purpose a particle is randomly selected from the fluidized bulk material and labeled radioactively. By means of positron emission particle tracking (PEPT) the motion of the particle is analyzed with high temporal and spatial resolution. A method for PEPT-data evaluation is presented, by means of which the local solids hold-up in the bed can be inferred. The derived solids concentrations are juxtaposed to those measured invasively, using capacitance probes. In addition to that, the residence time behavior of the labeled particle in the jet region and in the suspended phase is analyzed. With regard to the flow characteristics of single particles in jetted fluidized beds the flux of particles across the boundaries of the jet region is determined and dispersion coefficients are derived.

2. Experimental setup

In the following sections the applied materials are introduced and the experimental setup of the fluidized bed with secondary gas injection is presented. Besides that, information on the operating conditions adjusted in the course of the measurements is given. Subsequently the applied measurement techniques are introduced and, in this regard, the measuring procedure is explained.

2.1. Setup of the fluidized bed with vertical injector nozzle and applied operating conditions

The fundamental setup of the applied fluidized bed with secondary gas injection is depicted in Fig. 1.

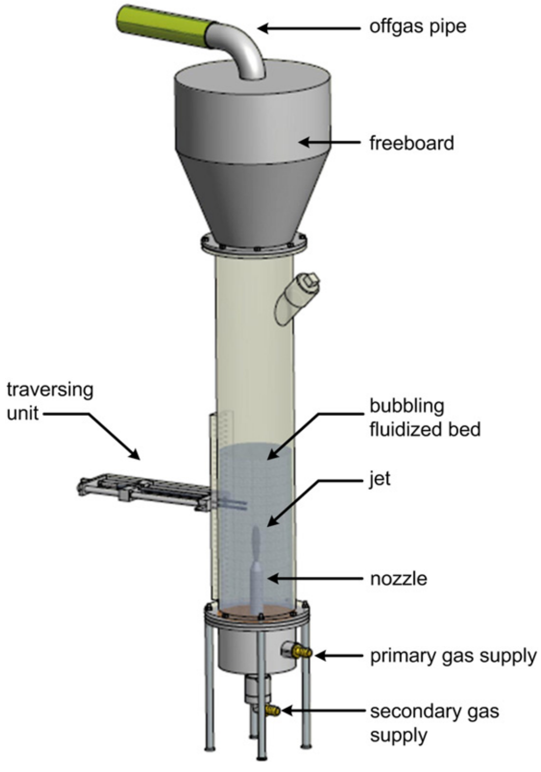

Fig. 1. Bubbling fluidized bed with secondary gas injection through a vertically arranged injector nozzle.

The section, in which the bubbling fluidized bed is located, is comprised by a hollow 1.4301 steel cylinder with an inner diameter of 0.190 m and its length amounts to 1.90 m. Prior to the start of an experiment a total mass of 30 kg of the bulk material to be fluidized is provided in this section. The primary process gas is supplied via a sintered metal distributor plate, which is located at the bottom of the plant. Due to its thickness of 0.010 m and an average pore diameter of 20 μm, the sintered metal base plate is presumed to distribute the primary process gas uniformly over the entire cross section of the plant. In the center of the distributor plate a nozzle is installed for the injection of a secondary process gas in vertical upward direction. The nozzle geometry consists of a cylindrical section with an outer diameter of 0.035 m at the bottom and a truncated conical section at the top. The nozzle orifice is located at an axial distance of 0.115 m above the distributor plate and the diameter of the orifice amounts to 0.010 m.

On passing the fluidized bed the process gas is conducted into a freeboard, in which entrained particles are separated from the gas and returned to the bed. After leaving the plant the process gas is lead to a filter.

In the course of all measurements presented in this work, the volumetric flowrate of the primary process gas was 47.6 $\mathrm{Nm^3\,h^{-1}}$, resulting in a superficial gas velocity of 0.5 $\mathrm{m\,s^{-1}}$. The secondary gas was injected through the nozzle orifice at a flow rate of 15.8 $\mathrm{Nm^3\,h^{-1}}$ and a velocity of 60 $\mathrm{m\,s^{-1}}$, respectively.

2.2. Materials

The experiments were carried out at room temperature and ambient pressure conditions. Air was used as the primary and secondary process fluid. The fluidized bulk material consisted of glass beads with a density of 2480 $\mathrm{kg\,m^{-3}}$ and a Sauter mean diameter of 732 μm. The point of minimum fluidization was determined on the basis of the pressure drop behavior of the bed in defluidization experiments, conducted at ambient conditions. Hence minimum fluidization occurs at a superficial gas velocity of 0.31 $\mathrm{m\,s^{-1}}$.

For particle tracking purposes single particles are randomly selected from the bulk of the glass beads. The diameter of the particle selected for the measurement series presented in this article was determined to be 700 μm.

2.3. Measurement techniques

The background of the applied measurement techniques is presented in the following. The main focus of the present article is on the investigation of the motion of single particles in a fluidized bed with secondary gas injection by means of position emission particle tracking. In order to verify the validity of the derived data, solids concentrations derived by PEPT are compared to those obtained from invasive measurements using capacitance probes.

2.3.1. Positron emission particle tracking

The essential principle, on which the PEPT-technique is based, consists in labeling the particle to be tracked with a radioactive marker. The radiation arising from the nuclear decay of the marker is used to spot the position of the labeled particle within the investigated system. According to Fan et al. [13,14] three different labeling techniques are distinguished, viz. direct activation, ion exchange and surface modification.

In this work, a single glass bead was selected from the bulk and labeled according to the direct activation method. For this purpose the particle was placed as a target in a Scanditronix MC40 cyclotron and bombarded by accelerated helium ions of the isotope ^{3}He at 33 MeV. Herein ^{18}O-oxygen isotopes contained in the tracer particle are converted to radioactive fluorine isotopes ^{18}F, with a half-life of 109.8 min [15]. The final activity of the particle was in the range of 20–40 MBq.