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Horizontal secondary gas injection in fluidized beds: Solid concentration and velocity in multiphase jets

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A B S T R A C T

High speed gas injection through nozzles is used in fluidized bed technology for controlling particle size or adding a reactant. Experiments were carried out to investigate the flow field of glass beads ($x_{1,2} = 92$ µm) in multiphase jets (with respect to the applied pressure). Particle image velocimetry (PIV) was used in a semicircular fluidized bed with optical access, to analyze the particle movement. It was found that higher gas pressure at the nozzle inlet initially leads first to higher particle velocities but decreases the particle degree of mixing. In subsonic conditions the trend of the measured data could be predicted by a simple force balance model. Additionally, the transition from subsonic to choked flow conditions inside the nozzle could be distinguished by analyzing the jet opening angle. The fluidization velocity showed no significant influence in these investigations. It was also proven by solid concentration $(1 - \varepsilon)$ measurements with capacitance probes: Increasing kinetic gas energy at the nozzle inlet leads to lower solid concentration at the jet axis. At very high gas pressures there were almost no particles in the jet. Finally, a relatively new measurement technique was used for flow analysis. A fast gantry X-ray CT was used to analyze the turbulent flow without disturbing it. Thanks to a calibration the solid distribution could be made visible. This showed an entrainment zone close to the nozzle exit. The results showed that the kinetic energy of solids can be increased by applying higher gas velocities. However, very high gas velocities lead to reduction of solid entrainment into the jet.

1. Introduction

In many industrial applications, secondary gas injection into fluidized beds is used to control particle size [1] or to introduce an additional reactant gas into the system [2]. A special case is the fluidized bed opposed jet mill, where the size reduction effect is used to grind particles into the submicron range [3].

In a highly expanded gas jet particles are entrained and accelerated to a focal point. If opposing jets are used, particles collide with each other and if the impact energy in the opposed jet is high enough, breakage occurs [4]. Therefore, one main goal in optimization of breakage processes in jet mills is to achieve very high particle velocities. Nozzle design as well as its number or array has been a focus of several publications [5–8]. Another important parameter is the solid concentration inside the gas flow. As a matter of fact, increasing the number of particles causes more particle-particle collisions, but an overloading could lead to lower impact energy. In the jet, there are two main possibilities for collision processes: First two particles can be accelerated from two opposed jets and collide at the focal point. The other possibility is the collision of two particles with different velocities, resulting in lower kinetic energies than in the first case. This leads to different modes of size reduction, namely abrasion by attrition and fracture by intense collisions [9]. Vogel and Peukert [10] showed for different materials that the breakage probability can be increased by the impact velocity or the number of impacts. The latter is increased with the solid concentration inside the jet and therefore the multiphase flow would be highly interesting. Access to the jet presents a challenge for measurements: The solid concentration in the surrounding region is very high and disturbs most optical methods. Furthermore, inside the jet fast particles can cause damage to measurement equipment. There are some examples in literature where indirect measurement techniques have been used e.g. regarding solid entrainment into jets [11]. Other authors have used a so-called 2D fluidized bed with optical access to investigate the flow pattern [12]. Another method is the use of electrical capacitance volume tomography [13] or optical fibers [14]. The drawback of these methods is the invasive disturbing of the flow, which can be overcome with the use of X-ray tomography [15,16] or positron emission particle tracking [17,18]. Another approach is the numerical simulation of jets in fluidized beds and is described by various authors [19–22]. The challenge of extremely high velocity gradients combined with dilute and dense phases is handled with either strong simplifications or long

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computational time. Another problem is the validation of results since experimental data are rare.

However, no literature is known where the full flow behavior of high speed jets in fluidized beds has been investigated. For this reason, the objective of this study is the experimental analysis of the fluid mechanical behavior of multiphase jets. For this purpose, three different setups were applied to gain information about particle velocity and solid concentration. The flow field was analyzed by particle image velocimetry (PIV) in a semicircular fluidized bed with optical access. Furthermore, solid concentration was determined with self-made capacitance probes. Additionally, a relatively new fast gantry X-ray computed tomography was employed to image the jet structure without disturbing the flow. The investigations were performed with glass beads and compressed air was introduced through simple cylindrical nozzles. Variables studied during this work were the injected gas pressure as well as the fluidization condition.

2. Material and methods

2.1. Particle velocity

The determination of particle velocities was carried out in a column of semi-circular cross section with a 190 mm inner diameter. On the front side, a fixed glass plate enabled optical access to apply particle image velocimetry (PIV). The secondary gas was induced by a horizontal attached semi-circular cylindrical nozzle with an exit diameter d_0 of 3 mm, which was glued to the glass plate. The whole setup with its dimensions is shown in Fig. 1.

The particles can be fluidized by pressurized air through a metal sintered plate at the bottom of the column. In this work beds are operated at minimum fluidization (and bubble free) and at fixed bed conditions.

Two pulsed ND-YAG lasers expose the region of interest (ROI) whereupon a diffusor plate causes expansion of the laser beam. A fast image recording CCD-camera (PCO 2000) with high resolution (2048 × 2048 pixels) took 2 consecutive pictures, which were evaluated via cross correlation. Therefore, the time between two laser pulses Δt_{piv} was used to visualize the particle movement clearly. Since no laser sheet optics can be used here, the ROI is located right behind the glass plate. Time management between the laser and the camera is regulated by a synchronizer. With these experiments the particle velocity field in and around the jet can be analyzed. Therefore, the consecutive images are divided into grids with a cell size of 16 × 16 pixels. In these grids the dislocation l_x of particles in one direction is analyzed by a cross correlation algorithm VidPIV [23].

$$v_x = \frac{l_x}{\Delta t_{piv}} \tag{1}$$

As a result, the velocity vector v_x for the grid is obtained. The time distance Δt_{piv} was adapted to the gas velocity and was varied between 4 μs and 20 μs. For a higher light yield 4 pixels was binned together and a ROI of 30 × 30 mm was chosen. Hardware and software were from ILA GmbH in Jülich, Germany.

2.2. Particle concentration

The solid concentration was determined in a fluidized bed with an inner diameter of 190 mm. This can be seen in Fig. 2. Here the nozzle is horizontally fixed to the bottom of the column, while a mount for capacitance probes is welded-on at a 90° angle. The investigated area is in the axial direction to the nozzle exit ($d_0 = 4$ mm) and is defined by the bore holes through the mount. The holes were in 25 mm distances to each other and started at 4 mm from the nozzle exit. The radial position can be regulated freely by a screw connection, which also works as a sealant.

The measurement setup consists of the self-made capacitance probes and a two-channel capacitance amplifier which is connected to a computer. Solids in the measurement volume affect the electromagnetic field at the tip of the needle probes and cause a change of the capacitance, which is then converted to a voltage signal. For each probe a calibration was made to allocate the measured voltage to a respective solid concentration $(1-\varepsilon)$. The solid concentration corresponds to the

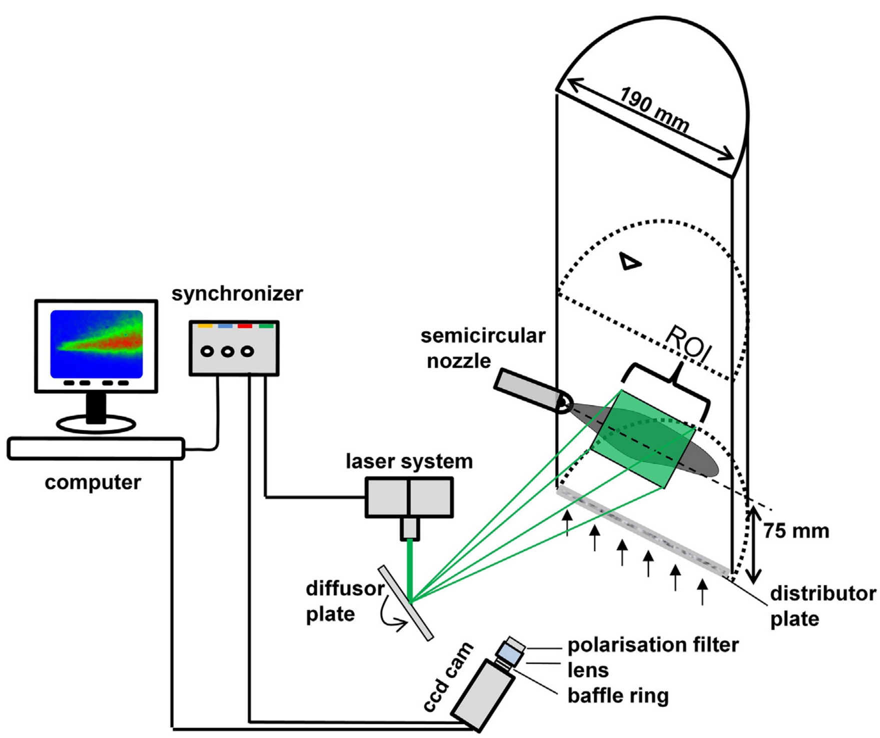

Fig. 1. Setup for flow visualization and particle image velocimetry (PIV) measurements.

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