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Gas jet penetration lengths from upward and downward nozzles in dense gas–solid fluidized beds

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The penetration lengths of a jet issuing from upward and downward injection nozzles were measured in a dense fluidized bed of Geldart A to Geldart B particles, operated at superficial velocity well beyond the minimum bubbling velocity. Nozzle orientation, injection velocity and injected gas density were found to be the parameters having the most influence on the jet penetration lengths. Three distinct jet penetration lengths were determined for the upward nozzle: L_{min}, L_{max} and L_b, in accordance with Knowlton and Hirsan's (1980) definition [1], while for the downward nozzle, only L_{min} and L_{max} were observed. The jet penetration lengths were correlated with respect to dimensionless groups in a systematic approach in an effort to identify the most important terms. For each nozzle orientation, the analysis yielded unique correlation format which could be applied to each characteristic jet length by changing the correlation parameters. Fundamental distinctions between the upward and downward nozzles were uncovered. The mechanism responsible for the jet momentum dissipation was found to be gravitational forces acting on the jet volume for the upward nozzle and drag forces exerted on the entrained particles for the downward nozzle. Five new correlations were derived for the prediction of the characteristic jet lengths for upward and downward nozzles. The correlations retained for the upward nozzle were also found to be in good agreement with data from a high pressure fluidized bed.

1. Introduction

In industrial fluidized bed reactors, the injection of gas-phase reactants through nozzles located downstream from the main distributor is common practice to avoid potentially explosive conditions and promote selectivity [2,3]. The injection of high velocity gas through these nozzles can lead to the formation of so-called jets which are characterized by enhanced momentum, heat and mass transfer rates [4]. Entrainment of gas and solids from the fluidized bed into the high velocity jet can lead to the premature failure of the reactor due to particle attrition or erosion of bed internals [1]. Jets can play a key role in the performance of the reactors, thus nozzle design requires serious consideration.

The jet penetration length is one of the key nozzle design parameters and several correlations have been proposed for its prediction [5–14]. However, due to limitations in the experimental approaches, these correlations are often limited to a narrow validity window (e.g. near minimum fluidization velocity) and most have been developed for upward and horizontal nozzles. Furthermore, the jet length predicted by most correlations corresponds to L_{max}, a distance which is not sufficient to prevent jet erosion of bed internals. Knowlton and Hirsan [1] have shown that high momentum bubbles originating from the jet structure can penetrate the bed beyond L_{max} up to L_b, for which very few data and correlations have been reported. None of the correlations gathered from the literature and very few data targeted L_{min}, a distance of importance to the momentum, heat and mass transfer in the jet region, since it corresponds to the region with the greatest velocity difference between the jet and the fluidized bed.

Despite limitations in predicting the jet length from correlations, several studies have explored the impact of nozzle design and operating conditions. Every study encountered reported that the jet penetration lengths increase with the injection velocity and the orifice diameter. The impact of nozzle orientation has seldom been investigated systematically within a single study, but Zenz [14] showed that downward and horizontal nozzles yield jets of similar length, typically three times shorter than for upward nozzles. Benjelloun et al. [5] and Wang et al. [15] have shown that the injection of denser gases yields longer jets, which is consistent with trends observed on pressurized fluidized beds [1,16]. Systematic investigation of particle properties on the penetration length is rare due of the difficulty in obtaining particles differing only in the studied aspect. Hirsan et al. [9] have shown that increases in particle density and diameter result in shorter jet lengths. It is generally reported that in excess of minimum fluidization velocity, an increase in superficial velocity results in shorter jet lengths [1,9,15–19]. Guo et al. [8] recently showed that for FCC particles (Geldart A), an increase in superficial velocity, with U_g/U_{mf} between 1 and 2, presumably below U_{mb}, resulted in an increase in jet penetration length. Hong et al. [10] and

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Zhong and Zhang [20] have shown that lowering the position of the injector relative to the bed surface and the initial bed height, even in laboratory-scaled fluidized beds, resulted in noticeably shorter jet lengths.

The impact of bed scale has seldom been investigated when dealing with the study of jets in fluidized beds. None of the research papers consulted have firmly concluded to an influence of the bed diameter on the jet penetration length. In their work, Vaccaro et al. [4] examined the influence of bed diameter on the upward jet penetration by pressure signal analysis. They concluded that the bed diameter had a negligible effect on the jet penetration in the range of 0.2 to 0.35 m. In their study, Berruti et al. [21] addressed the impact of scale on the penetration of a horizontal gas–liquid jet in a gas–solid fluidized bed using a triboelectric sensing array. The small-scale system had a rectangular cross-section with a 0.3 m thickness and 1 m width; the large scale system had a trapezoidal cross section with a thickness varying between 0.2 near the nozzle inlet and 1.2 m at the opposite wall and a width of 3.5 m. Their experimental results for both scales agreed with the predictions using the correlation of Ariyapadi et al. [22]. Given that the correlation does not account for bed scale, it can be concluded that bed scale effects, if any, only play a minor role on the jet penetration length in the range considered by the authors. The correlation of Zhong and Zhang [20] contains a height-to-hydraulic bed diameter ratio term; however their study was conducted a 2D jetting-fluidized bed with a unique bed geometry and scale, thus a unique hydraulic bed diameter. The hydraulic bed diameter merely acts as a false constant in their proposed correlation. Caution should be exerted when applying their correlation for beds with significantly different bed geometry and/or hydraulic bed diameter. The correlation of Rees et al. [23] and the condition for jetting derived by Roach [24] suggest a dependency of the jet phenomenon with respect to the bed diameter in the form of a grid open area ratio. These correlations are not intended for isolated jets with background fluidization but rather for grids with multiple orifices.

In a prior work, an experimental approach using a reflective fiber-optic probe to determine the local structure of a gas jet was proposed [25]. The approach was suitable for dense fluidized beds operated at superficial velocities in excess of the minimum bubbling velocity (U_{mb}) and allowed for the determination of L_{min}, L_{max} and L_b. The present effort builds on this prior knowledge and attempts to highlight the impact of operating conditions on the jet penetration length for upward and downward nozzles.

The intrusiveness of probe based measurements in fluidized beds has often been raised and in some cases, spectacular discrepancies have been reported. Recently, Liu et al. [26] found that average bubble size determined by intrusive fiber-optic probe was greater than that determined by non-intrusive pressure fluctuation by a factor 2–5. They explained this difference by the fact that freely rising bubbles of small size are not as likely to be captured by the intrusive probe. On the other hand, a comparative study conducted by Dubrawski et al. [27] has shown that intrusive fiber-optic probe measurements are in agreement with those from non-intrusive techniques such as electrical capacitance tomography, X-ray tomography and radioactive particle tracking when determining the time-averaged solid holdup in fluidized beds. The experimental approach used herein is based on the semi-quantitative evolution of time averaged solid holdup measurement with respect to injection velocity and thus is not as sensitive to the intrusiveness of the fiber optic probe as is the determination of bubble sizes and bubble rise velocities. Furthermore, as opposed to freely rising bubbles, the impact of the probe's intrusiveness is expected to be lower due to the higher momentum carried by the jets and ensuing bubbles and by relying on probes with small impact surfaces.

2. Experimental setup and procedure

The experimental procedure used in the present study was developed in earlier work [25]. For a given fiber-optic probe measurement position, located at a distance L downstream from the injector along the injection axis, plots of the average local solid holdup against injection velocity exhibit transition velocities indicative of one of four jet impact zones: 1) no impact; 2) intense bubbling; 3) pulsating jet; 4) permanent jet. To these transition velocities correspond a characteristic jet length: L_b, L_{max} and L_{min}.

The experimental apparatus consisted of a 152 mm ID by 1.5 m tall Plexiglas column mounted on a perforated plate distributor with 160 holes with a diameter of 0.8 mm. The column was topped by a vertical acceleration section feeding into a cyclone which returned the entrained solids near the top of the column. The column was divided into three sections, 0.6, 0.6 and 0.3 m tall from bottom to top respectively. The middle section could be removed to allow direct access to the injector and fiber-optic probe located in the bottom section. The bottom section was equipped with an array of ports located along the axis with a 50 mm pitch.

The injector depicted in Fig. 1, consisted of an 80 mm long threaded shaft with a 8 mm ID. The shaft was welded near its top onto a 150 mm long 6.35 mm OD feeding tube. An 80 mm long sleeve with a 10 mm OD was screwed onto the shaft. Three interchangeable injection tips with 10 mm OD and 2.4, 4.9 and 7.2 mm orifices could be mounted onto the tip side of the sleeve. The sleeve could be adjusted so that the distance between the feeding tube and the injection tip covered a 75–140 mm span. This span was sufficient to cover the distance between two consecutive column ports, thus allowing a wide range of effective injection locations and measurement distances. The sleeve position was held in place with a lock nut. Adjustment of the injector location relative to the probe tip was made by first positioning the injector tip in contact with the probe tip either directly or indirectly by way of two calibrated gauges of 30 and 80 mm. From the point of contact, sleeve rotations were added or removed to achieve the desired distance. A distinct marking on the sleeve body allowed for an easy assessment of the number of rotations, with each rotation corresponding to a tip displacement of 1.06 mm. The injector could be mounted with the nozzle in the upward or downward orientation and was positioned along the centerline of the column. The tip of the injector was typically located between 0.15 and 0.30 m from the distributor.

Single bundle reflective-type fiber-optic probes were used for the local solid holdup measurements (also shown in Fig. 1). The probe body was a 6.35 mm OD tube and the probe tip consisted of a 50 mm long 0.9 mm OD needle which was press-fit into the end of the probe body. A 2 mm OD protective sheath was affixed to the tip of the needle to provide support for a 1 mm-thick window which minimized the impact of the blind region on the solid holdup measurements [28]. Despite the presence of a sheath, the more abrasive particles, coupled with the vicinity of a strong jet, could cause significant erosion of the sheath after as little as a week of continuous operation. A replacement probe was always available to limit the down time. The effective measurement location was considered to correspond to the axis of the fiber-optic probe and thus the distances were corrected to account for the sheath radius. The tip of the fiber-optic probe was positioned 1 mm short of the injection axis so that its effective measurement volume coincided with the injection axis.

The solids used for the investigation were intended to cover heat carriers (Geldart B) used in homogeneous combustion systems as well as common catalysts (Geldart A) and are summarized in Table 1. The bed height at rest was varied between 0.2 and 0.75 m. The main fluidization gas, which consisted of dry air, was monitored by one of two rotameters covering a range of superficial velocities from 0.015 to 0.7 m/s. The injected gas consisted of air, helium, CO_2 or argon. CO_2 was used during the first series of runs, but difficulties in maintaining constant flow at the higher injection rates, due to the evaporative cooling of the CO_2, resulted in argon being preferred. The injection flow rate was monitored by one of four rotameters