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Influence of nozzle design on flow, mixing, and fluidisation in a bubbling bed fluidised by a single nozzle

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ABSTRACT

In this paper we apply, for the first time, positron emission particle tracking (PEPT) to a fluidised bed in which gas is injected through a nozzle-type distributor. The detailed, three-dimensional data obtained provide direct insight into how the angle of the orifices through which gas is injected affects the fluidisation, mixing, and flow patterns observed within the bed. Our results show that the fastest and most consistent recirculation of material – an indicator of good mixing – as well as the most complete fluidisation may be achieved by using a nozzle with horizontal- or near-horizontal outlets.

1. Introduction

Air may be injected into fluidised beds through a variety of different types of distributor. Perforated or porous plate distributors [1] – both forms of flat, horizontal plates with multiple orifices across their faces – are commonly explored in the scientific literature. However, nozzle-type distributors – typically comprising a vertical duct with one or a small number of outlets at or near the top (as depicted in Fig. 1) – are somewhat less-commonly studied. Networks comprising multiple such nozzles are widely used in industrial fluidised beds, because they are simple to construct and are less prone to solids back-flow than other types [1]. They also allow solids to flow around them and leave the bed under gravity, which is required in some applications such as pyrolysis and gasification [2,3]. In the present study we consider the behaviour of a single nozzle so as to provide detailed insight into the dynamics thereof. It is hoped that such a study might provide indirect insight into how a multi-nozzle network might function, as well as direct insight into the smaller number of chemical processes where single distributors are used [4]. Larger-scale studies investigating networks of multiple nozzles will be reported in a future publication.

As noted above, while there has been some past research into the design and effectiveness of such nozzles, despite their longstanding use in industry [5] such research has, to date, been limited in comparison to studies of other distributor types. Nonetheless, there has been some valuable work in the area: Shen et al. [6] used photodiodes to study the dynamics of a jet produced by a single nozzle in a two-dimensional fluidised bed. Guo et al. [7] used optical imaging to study the effects of gas velocity on jet formation, jet coalescence, pressure fluctuations and voidage profiles for a two-dimensional bed with double nozzles. Lim et al. [8] explored the influence of the number and configuration of nozzles on the pressure profiles, pressure fluctuations and bed expansion of a three-dimensional jetting fluidised bed. Mirek and Klajny [9] used pressure drop and gas flow measurements to test the effectiveness of a novel distributor design, with a particular focus on the prevention of the backflow of solids – a common problem in systems using such nozzles. Perhaps of greatest relevance to the present study, Materazzi et al. [10] used high-speed X-ray radiography to study and compare the jet behaviour of a number of industrial nozzles in a comparatively large, three-dimensional system. They also prototyped a number of new designs to alleviate operational issues observed in the real reactors being modelled in their study.

While the above studies use diverse techniques to gain insight into various important properties regarding the jets and bubbles formed in the systems explored, they provide comparatively little direct information regarding the dynamics of the particulate phase. In this study, we use positron emission particle tracking (PEPT) [11,12] to study the flow produced by nozzles, functionally similar to those used in the fluidisation of novel waste-plastic recycling systems [2], in a laboratory-scale system. Specifically, we explore how the angle of the orifices through which gas is injected affects the fluidisation, mixing quality, and flow patterns of particles within the bed, thus allowing an assessment of the suitability of each design for processes (such as pyrolysis) where good fluidisation and strong mixing are requisite.

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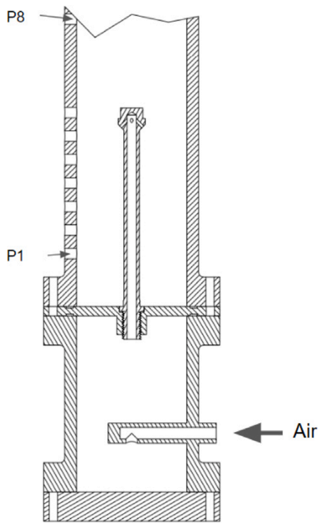

Fig. 1. Schematic of the experimental setup, consisting of a 94 mm diameter fluidised bed with a height of 1 m. The nozzle is located at the horizontal centre of the vessel. Holes for pressure measurements on the left side, P1 to P8 visible and two more points available towards the top of the bed. Pressure drops were measured using the difference between P1 and P10.

2. Materials and methods

2.1. Materials

Our experimental system consists of a cylindrical, gas-fluidised bed of inner diameter $D = 94$ mm, (depicted in Fig. 1) containing a bed of near-spherical, Geldart group B particles ($\Phi = 0.917 \pm 0.03$) composed of silica sand ($\rho = 2800$ kg m^{-3}, $\bar{d} = 393$ μm, $d_{10} = 329$ μm, $d_{90} = 456$ μm), representative of those used in the aforementioned waste-plastic pyrolysis process. The (count basis) particle size distribution of the bed material, measured via optical imaging using a Sympatec QicPic, is shown in Fig. 2. The minimum fluidisation velocity, U_{mf}, of the material has been measured experimentally as 14.5 cm s^{-1}, a value agreeing with the value predicted theoretically from Wen and Yu [13,14]. A volume of material is used such that the orifices of the nozzles used are covered by a height $H/D = 1$ of particles, again in line with values used in the industrial processes we intend to model.

The bed is fluidised using room temperature air through a single, 3D-printed nozzle, possessing four equally-spaced, 1 mm, circular orifices, which is located at the horizontal centre of the system (see Fig. 1). A schematic showing the basic nozzle design is provided in Fig. 3. A total of 7 different nozzle designs were created, all identical other than the angle at which the orifices are oriented. The orientations, θ, tested range from $\theta = 0°$ (vertically upward) to $\theta = 180°$ (vertically downward) in increments of 22.5°. The naming convention is demonstrated visually in Fig. 3.

PEPT measurements were conducted for each θ at a constant multiple of the measured incipient velocity, $U = 1.75U_{mf}$, chosen to be representative of the flow rates used in the aforementioned waste-plastic pyrolysis process.

2.2. Data acquisition: Positron emission particle tracking

Experimental data were acquired using Positron Emission Particle Tracking (PEPT), a technique capable of tracking the full, three-dimensional motion of a radioactively-labelled particle through the bulk of even dense, optically-opaque systems with sub-millimetre spatial resolution and sub-millisecond temporal resolution [11,12]. In order to perform PEPT, a single ‘tracer particle’ is labelled with a positron-emitting radioisotope, here Fluorine-18. The positrons emitted by the ^{18}F rapidly annihilate in the tracer medium, emitting pairs of gamma rays whose trajectories are collinear and antiparallel. By placing the system of interest within the field of view of a suitable detector system (here an ADAC Forté dual-headed positron camera [15]), these gamma photons can be detected, and their straight-line trajectories reconstructed. For suitably high tracer activities, several such reconstructed trajectories can be used to triangulate the position of the particle multiple times per second, thus allowing its trajectory to be recorded [16].

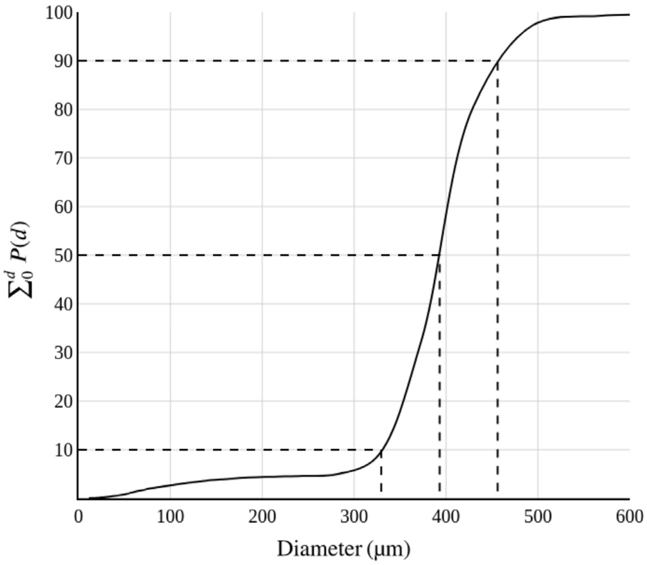

Fig. 2. Cumulative particle size distribution for the bed silica sand used in experiment.

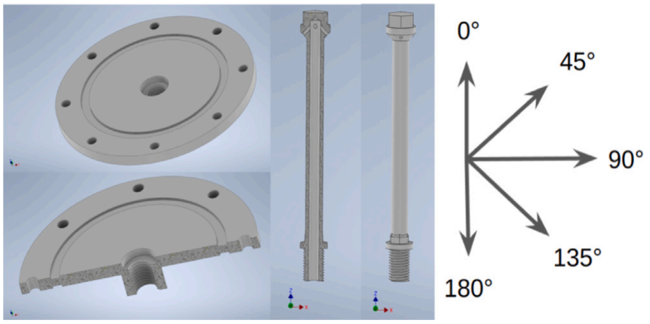

Fig. 3. CAD render of the basic nozzle design. The left-hand panels show the central plate into which the different 3D nozzles can be inserted. The middle panels show an archetypal nozzle, and a cutaway thereof illustrating the channel through which gas from the plenum is a able to flow into the bed. On the right hand panel the naming convention of the nozzles.

While typically in PEPT the tracer material used is the same as the bed material [12], in the present case said material was found to be unreceptive to the adsorption of ^{18}F ions, meaning that a suitably large amount of radioactivity could not be attached to the tracer. As such, it was necessary to use a surrogate material for the PEPT tracer. The main tracer used in experimentation was a spherical, borosilicate glass tracer whose size ($d_t = 300$ μm) and density ($\rho_t = 2700$ kg m^{-3}) providing a relatively close match to those of the bed medium, though still lying at the lower end of the measured particle size distribution. As such, to ensure the generality of our results, additional data were acquired using a spherical MCC particle of diameter 1 mm and density $\rho_t = 1300$ kg m^{-3}, intended to be representative of the plastic pellets used in the pyrolysis-based recycling systems which our experimental system was designed to model. Strikingly, the flow dynamics exhibited by both tracer types remained remarkably self-consistent other than

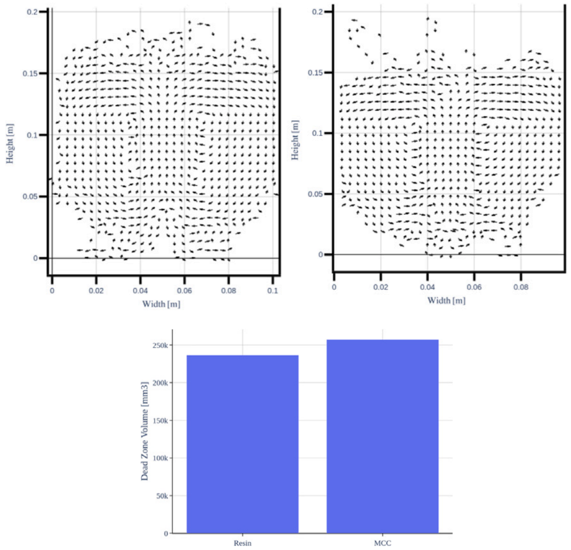

Fig. 4. Comparison of velocity vector fields (above) and dead zone volumes (below) produced by a nozzle with $\theta = 180°$ using both a 300 μm glass tracer (top left) and a 1 mm MCC tracer (top right). The choice of tracer is found not to significantly impact either the flow profile nor the size of the defluidised volume.

variations in the maximum height reached by the tracers during transits into the freeboard region (see Fig. 4) suggesting that the dynamics of our surrogate tracer can be safely assumed representative. The apparent independence of the tracer dynamics across a wide range of particle densities and diameters is likely due to the fact that we are, quite literally, operating in the tracer limit, where the tracer properties are not expected to impose a strong effect on the system behaviour.

For ergodic systems, such as those studied here, the time-averaged behaviour of a PEPT tracer can be used to determine a variety of important quantities and fields pertaining to the dynamics of the system, including three-dimensional particle velocity distributions [17], solids fraction distributions [18], and granular temperature distributions [19], as well as key scalar quantities such as self-diffusion coefficients [20] and, for binary or polydisperse systems, measures of segregation intensity [21]. In the present work, we are interested in particular in the determination of the velocity vector fields and circulation times of the systems explored, as these provide detailed insight into the quality of fluidisation and mixing experienced by particles within said systems [22,23]. Details of the manners in which these key quantities may be extracted from raw PEPT data can be found in Refs. [12,16]. Experiments are conducted, in all cases, for a period of 2 h, a period which has been shown to be sufficient in prior works using a similar geometry and operating conditions [23–25].

3. Results and analysis

3.1. Flow patterns

Fig. 5 shows two-dimensional, depth-averaged flow fields for each of the 7 nozzle angles explored in experiment. Even without analysing the flow patterns themselves, Fig. 5 provides valuable insight into the quality of fluidisation produced, in that several of the nozzle designs tested show ‘empty’ regions, indicative of the presence of defluidised zones within the bed [25]. In the depth-averaged images presented, a fully-fluidised bed would be expected to show data (i.e. arrows) across the full horizontal width of the bed at all heights within the bulk of the system, as is the case for the horizontal nozzle ($\theta = 90$). An absence of data in the horizontal extremities at low heights (as strikingly evident for $\theta = 0$ and $\theta = 180$, for example) demonstrates that the PEPT tracer has not been able to penetrate these regions, thus being indicative of defluidisation. Visual observations can also confirm the presence of defluidised zones in these cases. However, unlike through visual observations, our PEPT measurements can also be used to provide *quantitative* insight into the *extent* of defluidisation, which correlates with the size of the observed ‘blank’ regions [25]. The nature of the two-dimensional, depth-averaged data in Fig. 5 means that it is possible that some degree of defluidisation has in fact been ‘averaged out’ providing an impression of more complete fluidisation than is actually present. In order to avoid this issue and thus better quantify the degree of defluidisation within the system, the experimental volume is subdivided into a three-dimensional grid, and the number of empty grid cells computed. In order to distinguish between defluidised regions and unoccupied space above the bed, only data below the system’s static bed height are considered. The number of empty grid cells can thus be used to estimate the ‘dead zone volume’. The calculated dead zone volumes for all nozzles tested can be seen in Fig. 6.

From Fig. 6, we can see that a nozzle angle of 90 degrees (parallel to the horizontal plane) produces near full fluidisation, while deviations from the horizontal (in either direction) produce greater defluidisation. Based on this observation – and considering exclusively the matter of defluidisation – one may infer from the above that distributors with nozzle angles closer to the horizontal ($\theta = 90°$) are preferable.

Of course, the degree of defluidisation exhibited by a system is not the only consideration when designing a distributor. As is well known from the literature [1,5], the flow patterns exhibited by a system can be used to give insight into the expected quality of mixing facilitated by a given system. The nozzles oriented at $\theta = 135°$, $\theta = 180°$ and $\theta = 0°$ produce clear, well-defined double-roll convection patterns, with particles (on average) rising up through the centre of the bed and down at the walls, as expected for a normal, well-fluidised bed, suggesting good mixing [23,25]. Nozzles oriented at $\theta = 45°$, $\theta = 67.5°$, $\theta = 90°$ and, to a lesser extent, $\theta = 112.5°$, indicate the presence of multiple rolls, with the former two nozzle designs also exhibiting the somewhat unusual case of particles travelling *downwards* at the centre of the system.

An interesting, and initially somewhat counter intuitive observation from the above is that the *downward facing* $\theta = 180°$ and $\theta = 135°$ (centrally-placed) nozzles produce *upward* flow at the centre of the system, while the *upward*-facing $\theta = 45°$ and $\theta = 67.5°$ nozzles produce *downward* flow at the system’s axial centre. It is thought that this is due to the formation of a bubble cap surrounding the downward-facing distributors. This phenomenology can be sharply contrasted with that observed for the sideways-facing distributors, which can be observed to form high-velocity jets (regions of relatively low particle concentration but a high particle flux, conveying large amounts of material) such as those depicted in Fig. 7.

3.2. Circulation rates

Having discussed in the previous section the flow patterns of the various nozzle designs explored and their possible implications for mixing within the system, we discuss in the present section a more direct indicator of mixing quality: the circulation rate of material within the bed.

To determine the circulation rate, we use a specific method, which involves measuring the time taken for a particle to pass through two set boundaries in the x-y plane of the system, five times over. A timer starts when a particle crosses either of the two boundaries (upper or lower), and a series of events is tracked: passing the second boundary, going back across the second boundary, crossing the first boundary, and finally touching the first boundary again. This series of events marks one full circulation, at which point the time is reset and the circulation timer restarts. Circulations that do not follow this pattern are ignored by resetting the timer for that particle. The boundaries were placed at 25% and 75% of the static bed height, as proposed in the original work in which this methodology was developed [26].

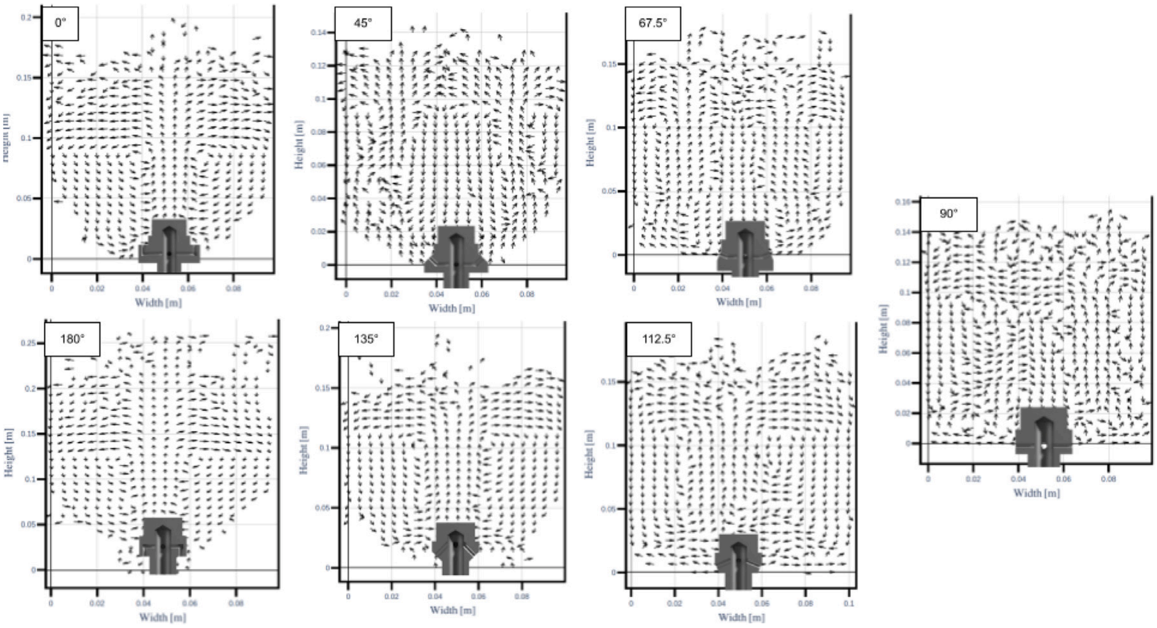

Fig. 5. Two-dimensional, depth-averaged flow patterns produced by nozzles with orifices inclined at varying angles to the horizontal. All images correspond to a constant gas flow rate of $U = 1.75U_{mf}$ and a constant depth of material above the nozzle . Note that, for clarity, the arrows indicating the velocity have been normalised such that they all possess the same length.

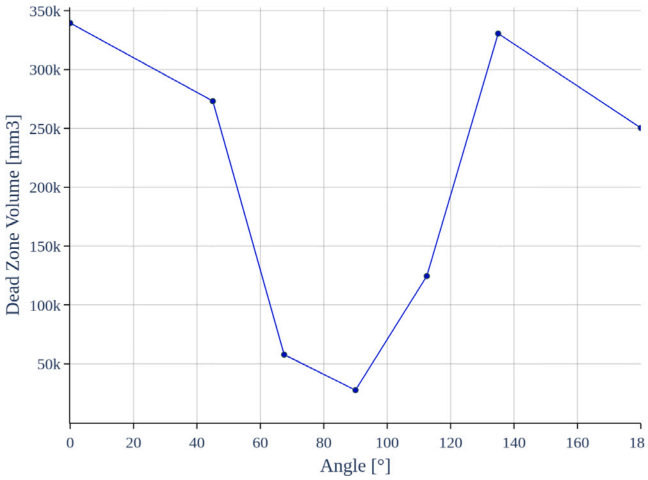

Fig. 6. Variation of the extent of defluidisation with nozzle angle.

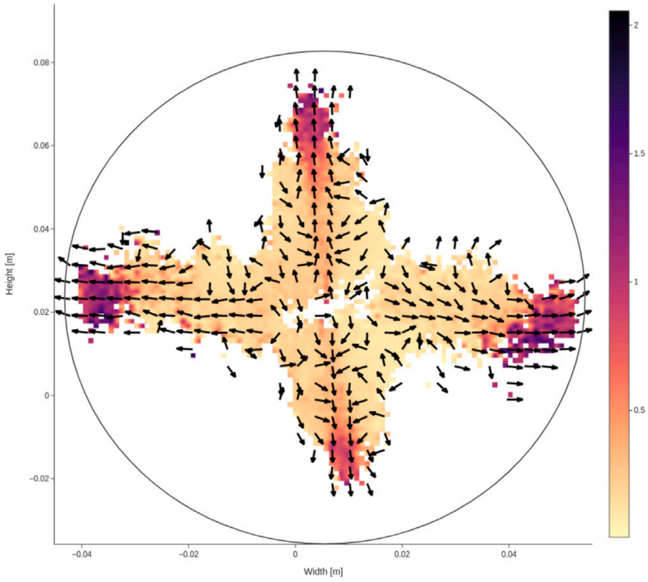

Fig. 7. Local velocities and directions of material motion in jets for a horizontally-pointing ($\theta = 90°$) nozzle; fluidised bed wall also depicted.

Fig. 8 shows the distribution of circulation times for all nozzle designs. Fig. 9 shows the means and standard deviations of these circulation time distributions representing, respectively, the characteristic circulation time and the variability of circulation rate for a given nozzle. The distributions for $\theta = 67.5°$, $\theta = 90°$, and $\theta = 112.5°$ show wide, seemingly multi-modal distributions. The apparent presence of multiple peaks within the distribution can likely be explained by the presence of multiple distinct convection rolls within the system, as can be observed in Fig. 4.

It is interesting to note that, despite their highly similar flow patterns (see Fig. 4), the $\theta = 0°$ (vertically upward) and $\theta = 180°$ (vertically downward) cases exhibit markedly differing circulation time distributions, indicative of strongly divergent mixing efficiencies. This observation thus calls into question the widely-held assumption [25] that flow pattern can be directly correlated to mixing quality for fluidised-bed systems. The difference in behaviour between the two systems can perhaps be explained by the fact that bubbles form lower in the bed in the downward-facing case than the upward-facing, allowing for greater bubble growth and thus stronger transport.

A second notable conclusion which may be drawn from a comparison of Figs. 6 and 9 is that – unlike the previous findings of [25] concerning perforated plate distributors – the distributors which here provide the best *fluidisation* also afford the best *mixing*, though the differences in mixing quality are somewhat less pronounced than the differences in dead zone volume, and the precise ordering of the three best is different: while the 90° nozzle clearly produces the best performance in terms of fluidisation, the 112° case produces faster circulation – though the difference in this case is marginal, and well within error margins.

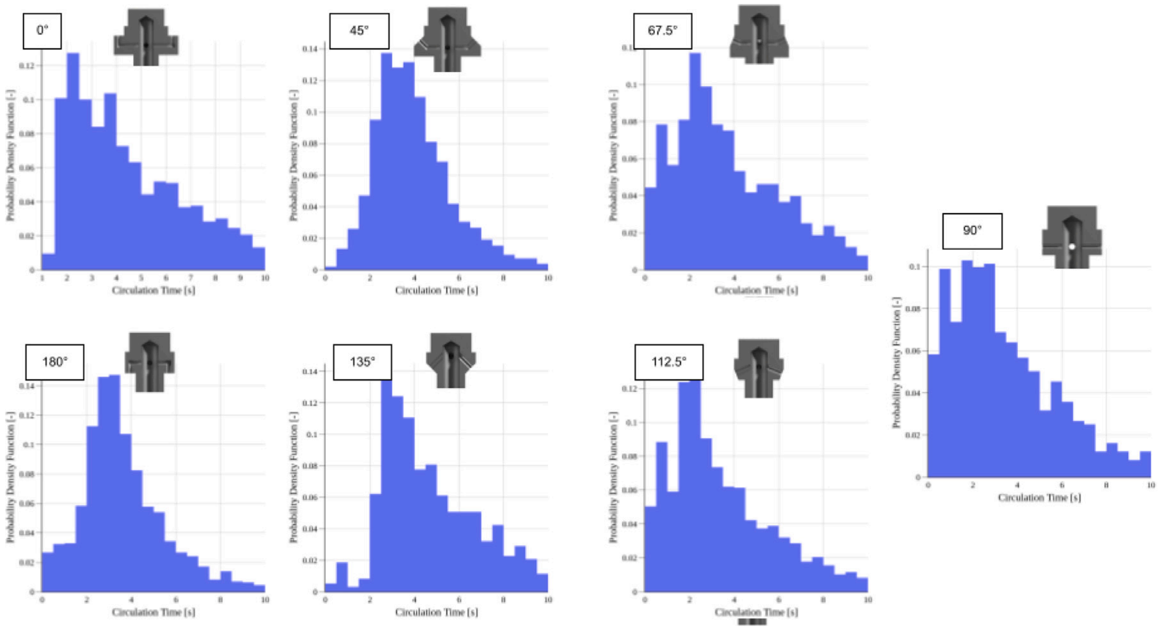

Fig. 8. Comparison of particle circulation times in a fluidised bed for seven different system setups with nozzle orientations varying from 0° (upward) to 180° (downward).

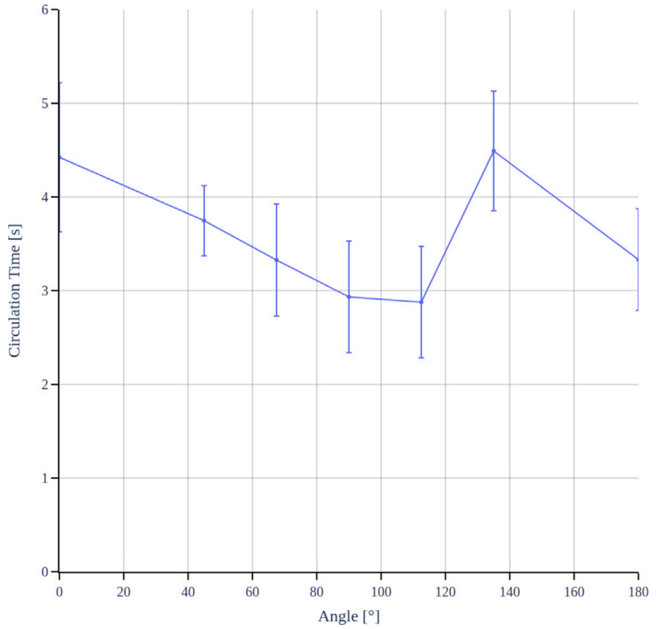

Fig. 9. Plot showing the means and standard deviations of the circulation time data presented in Fig. 8.

4. Conclusions

In this work we have used experimental data acquired using positron emission particle tracking (PEPT) to explore the influence of the gas injection angle of industry-relevant distributor nozzles on the resulting flow fields and circulation patterns within a laboratory-scale fluidised bed. Our results clearly demonstrate that simply varying the angle of inclination of the nozzle orifices, whilst holding all other relevant parameters constant, can significantly alter the flow dynamics of a fluidised bed, affecting both the extent of defluidised regions and the observed particle circulation rates.

The dual objectives of a distributor in most, if not all, industrial applications are to (a) provide uniform fluidisation (b) and to induce rapid mixing, thus providing the strong mass- and heat-transport for which fluidised bed reactors are known. Our results suggest that nozzles with orifices at or near the horizontal are more suitable to achieving both these goals, with the three best performing cases being those with their orifices aligned with the horizontal, and ±22.5° from the horizontal. In terms of real-world performance, the more downward-facing of these three cases would likely make the most suitable choice for industrial application, as it would carry the additional advantage of being the least prone to a ‘backflow’ of particles entering the distributor.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kit Windows-Yule reports financial support was provided by Engineering and Physical Sciences Research Council. Kit Windows-Yule reports financial support was provided by Royal Academy of Engineering. Kit Windows-Yule reports financial support was provided by The Royal Society.

Data availability

Data will be made available on request.

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