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Stagnant regions estimation in fluidized beds from bed surface observation

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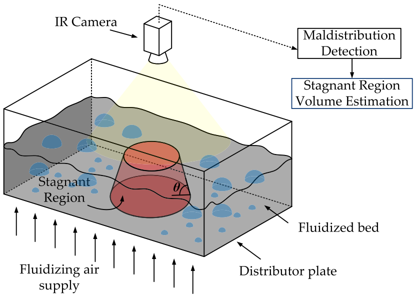
HIGHLIGHTS

- A method to estimate the size of dead zones in fluidized beds was developed.
- An induced maldistributed pseudo-2D bed was studied.
- Correlations were developed to relate the bubble phase with the defluidized zone.
- The results were extrapolated to a 3D fluidized bed.
- Dead zone volumes were estimated with a maximum 20% relative error.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel approach to estimate the size of stagnant regions in large-scale fluidized beds by means of experimental data obtained from images recorded on the bed surface was presented. For this purpose, the internal structure of an induced maldistributed pseudo-2D fluidized bed was first studied. Half of the total distributor area was covered to generate an induced stagnant region. The size and shape of this area was studied for several relative gas velocities and bed aspect ratios. The defluidized area was found to be almost independent of the bed aspect ratio, however, it was found to decrease for higher relative gas velocities. A solids recirculation zone was also found above the defluidized zone. The size of this zone increases with relative gas velocity, suggesting that it is strongly related to bubble motion. A correlation was developed to relate the visible bubble flow to the size of the defluidized zone. The results obtained in the 2D bed were extrapolated to a 3D cylindrical fluidized bed with a half-covered distributor plate to estimate the volume of the defluidized zone. The visible bubble flow in the 3D facility was estimated. Using the proposed correlation for the defluidized volume in the 2D bed was used to estimate the defluidized volume in the 3D bed. Finally, the calculated values of the defluidized volume were compared with the experimental values in the 3D facility, obtaining a maximum relative error of 20% in the estimations.

1. Introduction

Gas maldistribution is one of the most common problems related to distributor design and has an important effect on the performance of fluidized beds. Maldistribution is industrially undesirable: for dryers, because in the dead zones the drying rate drastically decreases, for reactors, because bypassing of reactants and uneven temperature in the bed are obtained, and in general, because it affects the heat and mass transfer capabilities and it may lead to defluidization and agglomeration problems. In most of the industrial processes carried out in fluidized beds, it is of crucial importance to prevent defluidization. When a defluidization problem is not detected and solved, major damage can be caused

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Notation

A_t	distributor cross-sectional area [m^2]
a_i	area of the ith bubble cut by the horizontal section defined [m^2]
$\overline{B}$	bubble concentration [–]
$\overline{C}$	black beads concentration [–]
d	penetration ratio [–]
D	bed diameter [m]
D_b	bubble diameter [m]
d_p	mean particle diameter [μm]
f_2	parameter of the Johnsson’s et al. correlation [–]
h	height over the distributor plate [m]
H	height of the 2D bed [m]
H_0	fixed bed height [m]
H_0/D	aspect ratio 3D [–]
H_0/W	aspect ratio 2D [–]
N	number of images in each video [–]
N_h	number of orifices of the distributor plate [–]
ΔP_{dist}	distributor pressure drop [kPa]
Q_b	visible bubble flow [m^3/s]
r	bed radius [m]
R	pressure drop ratio [–]
U_0	air superficial velocity [m/s]
U_b	rising bubble velocity [m/s]
U_M	superficial gas velocity at which all the distributor orifices became operative [m/s]
U_{mf}	minimum fluidization velocity [m/s]
U_r	relative fluidization velocity [–]
U_{vis}	visible bubble flow [m/s]
$\|V\|$	time-averaged dense phase velocity [m/s]
V_{def}	volume of the defluidized zone [m^3]
V_{rec}	volume of the recirculation zone [m^3]
V_t	total solids volume [m^3]
W	width of the 2D bed [m]
x	distance between the bed wall and the boundary of black beads [m]
x_f	distance between the centre of the bed and the boundary of defluidized zone [m]
Z	thickness of the 2D bed [m]

Greek letters

ψ	fraction of visible bubble flow [–]
ρ_{bb}	black beads density [kg/m^3]
ρ_s	particle density [kg/m^3]
θ	penetration angle [°]

Abbreviations

BFB	bubbling fluidized bed
DIA	digital image analysis
FSS	full-scale span
IR	infrared
PIV	particle image velocimetry

to bed internals, agglomeration of bed particles may occur and, as a consequence, the heat and mass transfer capabilities of the bed will be drastically reduced [1].

Maldistribution of gas and the design criteria to avoid it have been investigated by many researchers, such as [2–5]. Thorpe et al. [5] reviewed the existing literature concerning theoretical models used to estimate the boundary of maldistribution in fluidized beds. The authors determined U_M, defined as the superficial velocity at which all the orifices or tuyeres of the distributor plate become operative, which usually means they are jetting [6,7], with bed pressure drop measurements in a 3D fluidized bed and compared the experimental results with predictions of several models: the theory of Fakhimi and Harrison [3], the theory of Whitehead and Dent [2] and the theory of Yue and Kolaczwoski [4]. They found the best fit with the theory of Fakhimi and Harrison. They also found a good agreement with the theory of Yue and Kolaczwoski, however, this theory is an attempt to improve the theory of Fakhimi and Harrison by considering the effect of bed height. The authors concluded that the theory of Fakhimi and Harrison gives the best estimation, since it is a simpler theory than that of Yue and Kolaczwoski. These works were based on the study of U_M, which depends on the gas flow rate, the bed aspect ratio, the bed material and the open area of the distributor. All these variables have been studied in terms of the distributor to bed pressure drop ratio, R, since the onset of maldistribution seems to be directly related to this ratio [8].

A recent work of Sánchez-Prieto et al. [9] showed that gas maldistribution in fluidized beds can be detected using pressure signal analysis. The authors studied the onset of maldistribution with digital image analysis (DIA) of images of the bed surface and then, applied several monitoring methods to quantify the boundary between stable operation and maldistribution. However, nothing can be said about the internal structure of the maldistribution region generated inside the bed, since the pressure fluctuations signals were proven to detect if there is maldistribution present but could not identify the exact source of these changes in the dynamical behavior.

Visualization methods such infrared (IR) imaging are commonly used in industrial boilers and incinerators for monitoring and control purposes [10]. These methods are usually employed to obtain information about the combustion flame [11–14], since it is directly related to the combustion performance. IR imaging can also be used to determine temperature profiles of solid bodies such as the solid fuel particles, the reactor wall or, in case of a fluidized bed combustor, the bed material. Thus, the online monitoring of the bed surface of a fluidized bed combustor with an IR camera can help to detect dead zones caused by gas maldistribution or agglomeration.

In this work a new methodology is proposed to study the defluidized zone generated in an induced maldistributed pseudo-2D fluidized bed. These beds have shown to be of great importance for the understanding of fluidized beds. Two-dimensional beds typically have a transparent wall and possess a small thickness, so that optical access to the system is allowed and the behavior of the visualized particles is representative of the whole system [15]. The variables affecting the defluidized zone in a pseudo-2D fluidized bed were investigated to obtain a correlation for the size of this zone. The final aim of this work is the extrapolation of the 2D results to a 3D fluidized bed, in order to obtain a method capable of estimating the size of the defluidized zone in an industrial fluidized bed combustor, provided that experimental images of the bed surface are available.

2. Experimental setup

Two different experimental facilities were employed in this work: a pseudo-2D cold fluidized bed and a lab-scale cylindrical bubbling fluidized bed (BFB).