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Maldistribution detection in bubbling fluidized beds

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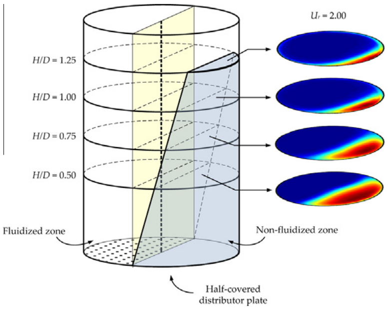
HIGHLIGHTS

- The onset of the maldistribution in fluidized beds has been studied.
- A half-covered distributor plate was employed in the experiments.
- Deep beds can overcome maldistribution at the bed surface.
- Standard deviation of pressure signals can be used to detect maldistribution.
- Online monitoring methods were successfully applied to maldistribution detection.

GRAPHICAL ABSTRACT



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ABSTRACT

A severe maldistribution problem was induced with a half-covered gas distributor plate. Videos of the bed surface were recorded and analyzed to study how the boundary between maldistribution and stable fluidization is affected by the gas velocity and the bed aspect ratio. It was observed that the visual inspection of the bed surface reports no information about the maldistribution at the bottom bed. Several cases of moderate maldistribution (i.e. different distributions of open orifices) were investigated by means of pressure fluctuation signal analysis to provide a criterion for maldistribution detection. The effect of the measurement position on maldistribution detection was also investigated. The attractor comparison test, the *S*-test, as well as the statistical process control of the standard deviation and wide band energy regions, were applied to test their capability of online detecting and monitoring gas maldistribution. The statistical process control methodology, based on standard deviation of pressure fluctuation signals, can be successfully applied to online detection of maldistribution when the pressure probe is located between 50% and 75% the total bed height. Finally, the rotation of the distributor was studied as a counteracting mechanism, showing good results overcoming maldistribution problems in fluidized beds.

1. Introduction

Gas maldistribution is one of the most common problems related to distributor design and has an important effect on the performance of the fluidized bed. When the gas velocity exceeds the value required for incipient fluidization, U_{mf}, gas bubbles appear in the bed; however there are zones, typically close to the distributor plate, called dead zones [1], where the bubbles are prevented to appear. The bubbling areas and the dead zones often move with time. Thorpe et al. [2] defined this state as the maldistribution state. These authors reported that when the superficial gas velocity is increased above a certain value, U_M, the distribution of bubbles through the bed became uniform and the bed is termed evenly fluidized. This value of U_M has been defined as the superficial velocity at which all the orifices or tuyeres of the distributor plate become operative, which usually means they are jetting [3,4]. Sathiyamoorthy and Rao [3] reported that the stable operation of a fluidized bed can be achieved when all the orifices or tuyeres of the distributor are operating at the same time (i.e. beyond

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Notation

$\overline{B}$	bubble concentration [–]
$\overline{C}$	black beads concentration [–]
D	bed diameter [m]
d_p	mean particle diameter [μm]
g	gravity acceleration [m/s^2]
H	height over the distributor plate [m]
H_0	bed height [m]
H_0/D	aspect ratio [–]
N	number of images in each video [–]
p_h	percentage of open orifices in zone 1 [%]
R	pressure drop ratio [–]
r	radial coordinate [m]
S	S statistic [–]
U_0	air superficial 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 [–]

Greek letters

α	polar angle [rad]
ε_{mf}	voidage at minimum fluidization conditions [–]
μ	air viscosity at ambient temperature [kg/m s]
ρ_{bb}	black beads density [kg/m^3]
ρ_g	air density at ambient temperature [kg/m^3]
ρ_s	particle density [kg/m^3]
ϕ	particle sphericity [–]
σ_{std}	standard deviation of the pressure signal [Pa]

Abbreviations

BFB	bubbling fluidized bed
DIA	digital image analysis
FSS	full-scale span
SPC	statistical process control

U_M) and, additionally, when a uniform distribution of gas and solids in the bed, without any channeling, is ensured. As previously reported by Whitehead [4], U_M 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 often 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 [5].

Several authors [6–8] have developed methods to detect if a fluidized bed is moving towards defluidization. The method proposed by Briens et al. [6] is based on the attractor comparison of pressure signals. The method is capable of detecting local changes in the fluidization behavior, but the main disadvantage is the requirement of too many measurements to be applied in a large-scale fluidized bed. More recently, van Ommen et al. [7] reported a new method for the early defluidization detection based on the standard deviation of pressure signals. They showed that pressure fluctuations measurement is suitable for a quick detection of defluidization caused by changes in the gas feed or pressure. The authors reported that just a pressure probe is sufficient to detect the defluidization, provided that it is more or less homogeneously spread over the bed. Nevertheless, the use of several measurement positions is essential when only part of the bed is moving towards defluidization (e.g. due to problems on the gas distributor). Gómez-Hernández et al. [8] developed a new statistical method to perform a frequency division of the power spectra of pressure fluctuations signals. The methodology was used in water-induced defluidization tests, showing its capability to detect the onset of the defluidization and when the bed is returning to the fluidization state.

In this work, the effect of the measurement position on the maldistribution detection is investigated. Thus, severe and moderate maldistribution conditions are induced in a lab scale fluidized bed by means of different orifice distributions in the distributor plate. First, the qualitative aspects regarding the effects of nonuniform gas distribution on the fluidized bed dynamics are studied by means of digital image analysis (DIA) of images of the bed surface. Complementarily, pressure fluctuation signals measured in the plenum chamber and at several locations inside the bed were analyzed in terms of the standard deviation and the autocorrelation function to confirm that neither increasing the gas velocity nor increasing the bed aspect ratio are able to mend the severe nonuniform gas distribution induced at the bottom of the bed. To provide with a criterion for maldistribution detection in gas fluidized beds, several online monitoring methods previously used in literature to detect defluidization problems, such as the attractor comparison test [9], the wide band energy division method [8] and the statistical process control approach [10] were applied to the measured pressure fluctuation signals. To do that, the pressure fluctuation signals were compared to the uniform case (i.e. with a proper distribution of the gas in the bed). It is assumed that defluidization problems might be accompanied or generated by gas maldistribution and consequently, similar monitoring approaches, successfully used previously to detect defluidization, can be also applied to maldistribution detection. Finally, a rotating distributor plate was employed as a counteracting mechanism to overcome maldistribution.

2. Experimental setup

The experiments were carried out in a lab-scale cylindrical bubbling fluidized bed (BFB), sketched in Fig. 1. The column is a transparent tube with an inner diameter of 0.192 m (D) and 1 m in height. The air flow was measured with a set of two flow meters, with ranges of 0–500 L/min and 150–3000 L/min providing an accuracy of 1% of full-scale span (FSS).

The bed material used was sepiolite (clay) particles (SG36) with a density of 1551 kg/m^{3}and 450 μm mean diameter, classified as type B according to Geldart's classification [11]. The main physical properties of the bed material are summarized in Table 1, including experimental values of minimum fluidization voidage, ε_{mf}, and minimum fluidization velocity, U_{mf}, at ambient temperature, which were determined using pressure measurements [5]. The particle sphericity, ϕ, was calculated by means of the Carman–Kozeny equation [12], taking into account the minimum fluidization velocity and voidage obtained experimentally (Eq. (1)):

$$U_{mf} = \frac{(\phi d_p)^2(\rho_s - \rho_g)g}{180\mu}\left(\frac{\varepsilon_{mf}^3}{1-\varepsilon_{mf}}\right) \tag{1}$$

Black beads of 6 mm in diameter made of a low-density material (ρ_{bb} = 36.20 kg/m^3) were used to produce a high contrast in the bed surface and to facilitate the recognition of bubbles during the digital analysis of the images recorded. When a bubble explodes in the bed surface, the black beads are ejected leaving a free space of the size of the exploding bubble.

Three piezo-electric pressure transducers (*Kistler type 5015*), with an accuracy of ±0.01% of FSS, were used to measure the pressure fluctuations in the plenum chamber and at several locations