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Experimental characterizing the residence time distribution of large spherical objects immersed in a fluidized bed

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A B S T R A C T

In many applications of fluidized bed, large objects are coexisting with small emulsion solids. The object motion patterns and residence time distribution (RTD) in the bed have a paramount effect in the performance of the reactor. In this paper, a series of experiments were conducted to study the influence of the superficial gas velocity and the constitutive properties of large spherical objects on their RTD in a fluidized bed with inclined air distributor using Electrical Capacitance Tomography (ECT) tracing technique. The objects were larger and denser than the fine particles of the dense phase, with the ratio of object diameter to bed characteristic length approximately 0.14 and the ratio of object density to static bed density ranging from 1.5 to 5.0. Experimental results show that the RTD curves of large objects have a relatively large discrepancy from the ideal normal distribution. As an object's size and density increases, the mean residence time (MRT) of the object decreases initially and increases subsequently. With the increasing of the superficial gas velocity, the MRT decreases with a trend of falling down fast at first then getting slow. Based on a mechanical model of the object on an inclined air distributor, the behaviors of the object were properly explained. Finally, an empirical correlation was derived for the MRT using some of experimental data and dimensionless analysis. The validations of the correlation by other independent experimental data show that the predicted values of MRT are well in accordance with the experimental values, and most of the relative errors are within $\pm 30\%$.

1. Introduction

Fluidized beds have been applied in many processes involving gasification, granulation, separation and combustion of a wide range of particulate materials including biomass, solid waste, sewage sludge and catalyst. Mixtures of dissimilar particles often exist in these processes, but the problems due to the presence of more than one particulate species that differ in their constitutive properties e.g. size, density or shape in the same unit remain less addressed.

Many attempts have been made to better understand the hydrodynamics of gas–solid flow in a multi-component fluidized system. Most of these studies focused on the overall mixing and segregation phenomena with analyses of the mixing and segregation progress, patterns and mechanisms under various conditions, [1–8] accepting that they are essentially driven by the action of bubbles. Other studies have focused on the motion behavior of single object with unusual constitutive properties (e.g. special shapes, large sizes or low densities) in a multi-component system, [9–15] since its motion patterns and ability to move throughout the bed are key factors influencing the performance of the bed. Sanderson et al. [12] studied the motion of a single large object in a 2-D bed, with characterization of cycles sinking down from the surface of the bed and rising back again. Similarly, Soria-Verdugo et al. [13] experimentally studied the effect of gas velocity, bed height, density and object shape on the motion of an object submerged in the bed with a rotating distributor. Takuya et al. [15] simulated the motion of a large sphere in a bubbling fluidized bed using DEM-CFD mesoscopic model combined with volume penalization method. However, their studies mainly concentrated on the low density objects and vertical motion in the dilute zone of a fluidized bed, rather than on the lateral motion behavior of large heavy objects next to the air distributor.

Several researchers [16,17] have noticed that large objects with large density may stop fluidizing in the bed and be captured in a stagnant zone over the distributor, therefore, investigation of their motion behavior within the dense zone in order to discharge them effectively is of significance for normal operation of fluidized bed. Uneven air distribution, such as inclined air distributor, induces an internal particle circulation inside the bed which can drive the large objects to the discharging hole [18,19]. Therefore, the residence time of objects in the uneven air distribution bed becomes one of the most important parameters. Some researchers[20–22] have studied the effect of operating parameters on the RTD of large objects, however, the investigations were all qualitative with few consistent conclusions; in addition, there have been few attempts on developing the mechanical model to depict the large object motion and explain the experimental results.

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Notation

C_D	drag coefficient
C_V	coefficient of variation
d_p	bed material diameter, mm
d_o	object diameter, mm
f	friction coefficient
f_s	static friction coefficient
$\mathbf{F}_d$	drag force, N
$\mathbf{F}_f$	friction force, N
$\mathbf{F}_G$	gravitational force, N
$\mathbf{F}_N$	normal force, N
$\mathbf{F}_P$	bed pressure difference force, N
g	acceleration of gravity, m/s
k	coefficient
L	bed length, m
N	repeated test times
s^3	skewness
t	residence time, s
t_m	mean residence time, s
t_{min}	the minimum residence time, s
V_o	object volume, m^3
v	velocity of gas–solid flow, m/s
v_{cr}	critical fluidization velocity, m/s
v_o	object velocity, m/s
v_t	turning gas velocity, m/s

Greek letters

α, β, γ	exponent
θ	inclined angle of air distributor
ρ	bed density during fluidization, kg/m^3
ρ_b	initial bulk density of bed materials, kg/m^3
ρ_p	skeletal density of bed material, kg/m^3
ρ_o	object density, kg/m^3
ρ_t	turning density, kg/m^3
ε	bed voidage
μ	dynamic viscosity of gas, N · s/m^2
σ^2	variance

Subscripts

$\perp$	direction normal to the air distributor:
$\parallel$	direction parallel to the air distributor:

The main objective of the present work is to examine the RTD of a large spherical object in a fluidized bed with an inclined air distributor and oriented caps. The emphasis is laid on the influence of the superficial gas velocity and the object properties (density, size) on their residence time. A dimensionless empirical correlation of MRT is proposed based on some of the experimental data. Along with the experiment, a mechanical model is established, trying to identify the fundamental principles controlling the RTD of the object in a multi-component fluidized system.

2. Experimental

2.1. Setup

The experiments were conducted in a rectangular-shaped fluidized bed setup with a length (L) of 0.28 m, a width (W) of 0.24 m, and a height (H) of approximately 1.4 m, as shown in Fig. 1. Fluidizing air enters the bed through a 5° inclined air distributor from a fan after passing through a rotameter and a valve. The distributor was made of plexiglass

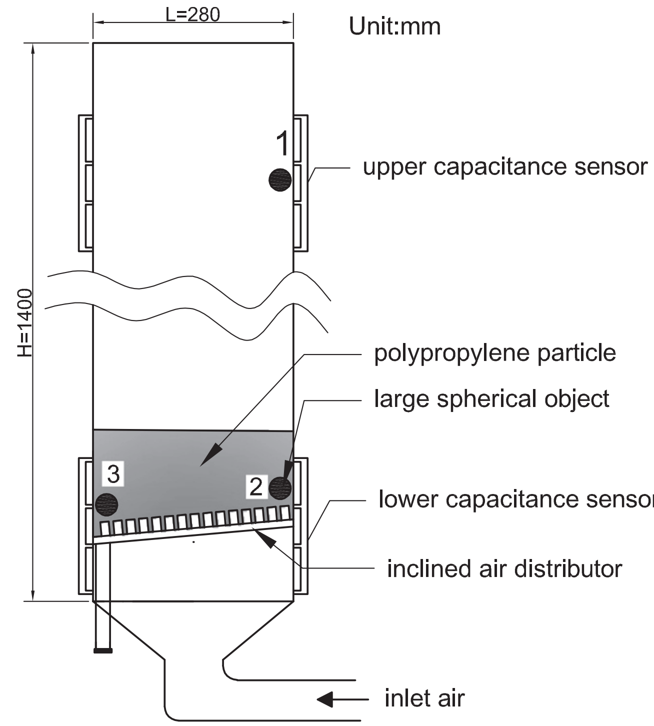

Fig. 1. Schematic of experimental setup.

and comprises of 194 equally spaced air caps, each of them consisting of six horizontal openings of 0.002 m in diameter, ensure the air flows in the downward direction parallel to the distributor, as detailed in Fig. 2.

2.2. Materials

Polypropylene particles with relative permittivity as low as 1.5 were used as the bed materials. They had an average diameter (d_p)

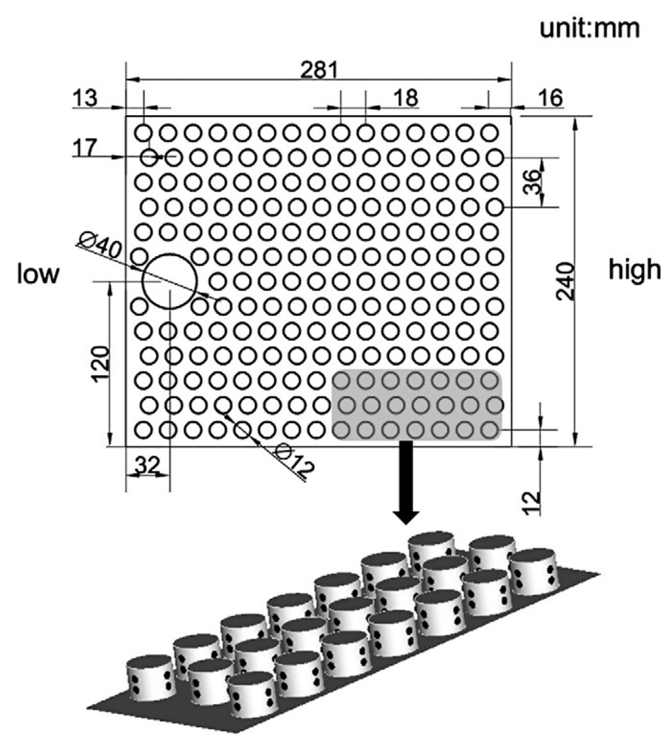

Fig. 2. Structure of air distributor and air caps.