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Original Research Paper

The impact of vertical internals array on the key hydrodynamic parameters in a gas-solid fluidized bed using an advance optical fiber probe

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A B S T R A C T

The effect of a circular configuration of intense vertical immersed tubes on the hydrodynamic parameters has been investigated in a gas-solid fluidized bed of 0.14 m inside diameter. The experiments were performed using glass beads solid particles of 365 μm average particle size, with a solid density of 2500 kg/m^3 (Geldart B). An advanced optical fiber probe technique was used to study the behavior of six essential local hydrodynamic parameters (i.e., local solids holdup, particles velocity, bubble rise velocity, bubble frequency, and bubble mean chord length) in the presence of vertical immersed tubes. The experimental measurements were carried out at six radial positions and three axial heights, which represent the three key zones of the bed: near the distributor plate, the middle of the fluidizing bed, and near the freeboard of the column. Furthermore, four superficial gas velocities (u/u_{mf} = 1.6, 1.76, 1.96, and 2.14) were employed to study the effect of operating conditions. The experimental results demonstrated that the vertical internals had a significant effect on all the studied local hydrodynamic characteristics such that when using internals, both the solids holdup and bubble mean chord length decreased, while the particles velocity, bubble rise velocity, and bubble frequency increased. The measured values of averaged bubble rise velocities and averaged bubble chord lengths at different axial heights and superficial gas velocities have been compared with most used correlations available in the literature. It was found that the measured values are in good agreement with values calculated using predicted correlation for the case without vertical internals. While, the absolute percentage relative error between the measured and calculated values of these two hydrodynamic parameters indicate large differences for the case of vertical internals.

1. Introduction

Gas-solid fluidized bed systems have been widely used in industrial processes. Many commercial applications can be found in the chemical, petroleum, pharmaceutical, biochemical, and food industries, heat transfer operations, and catalytic reactions. This is due to their excellent particle mixing, high heat and mass transfer rates, which can enhance chemical reaction conversions; and chemical process efficiency [1–3].

In general, there are two types of processes in the chemical industry that use fluidized bed contractors: catalytic fluidized bed and non-catalytic fluidized bed reactors. In catalytic fluidized bed reactors, the solid particles are not involved in the chemical reaction (e.g., chemical cracking of oil to produce different chemical substances). However, in gas-solid non-catalytic fluidized bed reactors, the particles undergo a chemical reaction (e.g., biomass combustion and coal gasification) [4]. In these types of chemical reactors, heat transfer is necessary to keep the operating reactor under desirable operating conditions and to regulate the reaction rate of these processes. Therefore, it is essential to control the

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Nomenclature

D	inside column diameter (m)
d_p	particle mean diameter or average particle diameter (μm)
H	axial height (m)
H_s	static bed height (m)
g	gravitational acceleration
r	radial position (m)
R	radius of the column (m)
u	superficial gas velocity (m/s)
U_B	bubble velocity (m/s)
u_{mf}	minimum fluidized velocity (m/s)
V_p	particle velocity (m/s)
ρ_p	solid particle density or solid density (kg/m^3)

Greek letters

ε_s	solid holdup
ρ	density (kg/m^3)
φ	sphericity factor

Subscripts and superscripts

B	bubble
mf	minimum fluidization
p	particle
f	fluid
s	solid

Abbreviations

$\overline{d_b}$	averaged bubble size
$\overline{V_p}$	cross-sectional average particles velocity
$\overline{\varepsilon_s}$	cross-sectional average solid holdup
$\overline{\text{BF}}$	cross-sectional average bubble rise velocity frequency
$\overline{\text{BMCL}}$	cross-sectional average bubble mean chord length
$\overline{\text{BRV}}$	cross-sectional average bubble rise velocity

temperature to ensure reliable efficiency, high yield, and the proper conversion rate. Consequently, immersed surfaces or internals of different types (e.g., plates, tubes, and baffles) and various configurations and methods of orientation inside fluidized bed reactors (e.g., vertical and horizontal) are required and have been employed [3,5–8].

In addition to the benefit of the immersed internals for temperature adjusted and control, they have many other advantages on the fluidization processes. The immersed tubes can modify the flow structure of the gas-solid patterns, which typically alters the hydrodynamic parameters. Generally, the internals inside gas-solid fluidized beds has the following many beneficial effects. First, it reduces the bubble size by controlling the bubble growth and minimizes the total amount of coalescence, which improves the contact between the gas phase and the dense phase [5,9]. In addition, a decrease in bubble size can reduce the carryover of the solids from the bed and make the fluidization "smoother," while also increasing the heat and mass transfer rates between the solid particles and the fluidizing gas [10,11]. Second, the internal tubes can suppress the cross-circulation patterns of the solids phase inside the bed [5]. Moreover, the back-mixing of the gas phase can be reduced [1]. Third, immersed internal tubes can divide the bed into many small fluidized bed sections, such that each can serve as an individual fluidization unit, which improves the chemical reaction conversion inside the fluidized bed reactors [11]. Fourth, using the internals can reduce the following: the pressure drop inside the bed, slugging behavior, fluctuations in bed height, and particle elutriation. Moreover, local solids circulation is improved [12]. It is worthy to mention that the reduction in pressure drop due to the presence of the internals can be explained by the effectively breakage of the bubbles which leads to make smaller bubbles with uniform size within the bed. In another word, the presence of internals can control the bubbles size and their growth inside the bed as mentioned by Mathew et al., [13].

Many types of research have been conducted experimentally and numerically to study the impact of different types and configurations of immersed surfaces on the hydrodynamics behavior in gas-solid fluidized beds [14]. Most of these works studied the effect of different shapes, sizes, and configurations of the internals on the global and some local hydrodynamic parameters such as gas holdup, bubble rise velocity, axial particle velocity, bubble size, and bubble frequency. The first work that studied the effect of internals on scale-up process in a fluidized bed was Volk et al. [9]. They reported that the problem of scale-up could be solved by employing vertical internals within the gas-solid fluidized bed reactor. Glass and Harrison [15] investigated the bubble sizes in fluidized bed with horizontal internals using a photographic approach. They concluded that the internals could enhance the fluidization quality by reducing the bubble size, which would lead to improving the heat transfer between the bed and the surface of the internals. Grace and Harrison [5] studied different ways to orient the internals (e.g., vertically, horizontally, and inclined) inside the fluidized bed. They reported that the vertical and horizontal orientations are valuable, but the inclined orientation has some disadvantages, such as excessive gas bypassing, heat transfer reduction, and short-circuiting of gas bubbles along the undersides of the inclined surfaces. Ramamoorthy and Subramanian [12], Yates et al. [10], and Olowson [1] used various sizes, orientations, and types of internals in beds of different solid particles. They found that using the internals can improve the fluidization process by reducing the size of the bubbles and enhancing the contact between the gas and dense phases as well as increasing the residence time of the gas phase inside the bed. Law et al. [11] studied the effect of vertical baffles on the drying and mixing of Geldart D powder inside a fluidized bed dryer. They deduced that the vertical baffles could modify the contact efficiency between the gas and solid particles and that the heat and mass transfer rates inside the fluidized bed dryer could be enhanced accordingly. Yurong et al. [2] investigated the gas and solid hydrodynamic parameters of fluidized beds with and without internals, using numerical simulation (computational fluid dynamics). They concluded that using horizontally immersed internals as heat exchange surfaces is necessary for absorbing the heat generated by the chemical reaction to keep the bubbling fluidized bed reactors working under desirable operating conditions. Different sizes, tube-to-tube spaces, and tube arrangements (i.e., square and triangular) to study the effect of vertical internals on the bubble hydrodynamic characteristics (i.e., bubble size, bubble rise velocity, bubble frequency, and bubble holdup) using different techniques have been investigated [7,8,14,16,17]. All of these researchers reported that vertical internals have a significant effect on the bubble hydrodynamic parameters, such as the reduction of the bubble size, improving the bubble frequency, and increasing or decreasing the bubble rise velocities.

Accordingly, harnessing the power of vertical internals in gas-solid fluidized beds has many advantages: (1) the difficulty of

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