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RESEARCH & KNOWLEDGE

Research Article

Experimental investigation of solid holdup in twin-cyclone combustor

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Abstract- In this study, the hydrodynamics behaviors and solid holdup in a twin-cyclone combustor with a swirling fluidized bed were investigated under a wide range of cold–air operating conditions. Silica sand of three different particle size ranges: 600–710 μm, 710–1000 μm, and 1000–1700 μm, was used as the inert bed material at a fixed static bed height of 30 cm. The solid holdup was measured in the radial direction along the horizontal axis at levels of 40, 50, 60, and 125 cm above the air distributor system. From the radial solid holdup profiles at different axial positions, the distributions of the solid holdup were non-uniform with dilute and dense regions. The radial profile peaked at the center of the combustor and the solid holdup gradually decreased toward the combustor walls. The primary air velocity significantly influenced the solid holdup, while the effects of the ratio of the secondary air and the tertiary air flow rate to the primary air flow rate and the particle size of the bed material used for the air distributor seemed to be small. With the increasing ratio of the secondary air and the tertiary air flow rates to the primary air flow rate, the solid holdup slightly increased.

Keywords: Hydrodynamics, solid holdup, secondary air, tertiary air

1. Introduction

During the last two decades, hydrodynamic features, the characteristics of gas-solid bed flows, and the distribution of solid holdups have been studied mainly in circulating fluidized-bed combustors (CFBCs) by many researchers (Moraveji, 2001; Wang and Zhu, 2004; Ersoy *et al.*, 2004). This type of combustor can be operated for the wide range of solid holdup from 25 to 1000 kg/m^{2}s with a high superficial air velocity of 2.5–28 m/s. The radial solid holdup profile was strongly affected by the superficial gas velocity, orientation of secondary air injection, and the solid circulation rate. Among the different types of secondary air injectors, the tangential (swirl) injection accelerated the higher solid holdup in the riser, while the radial injection seemed to improve the radial gas mixing (more uniform of fluidization) (Koksal and Hamdullahpur, 2004).

The improved understanding of the flow behaviours in the fluidized bed combustion system enhanced the success of the modelling and prediction of the combustion characteristics as well as the emissions and heat transfer. From the literature, the operating conditions (particularly, excess air and air-staging), properties and particle size of the bed material, and the air distribution systems were reported to have significant effects on the gas-solid flow patterns inside fluidized-bed combustors (Kaewklum and Kuprianov, 2010; Kaewklum *et al.*, 2009; Chen *et al.*, 2008; Li *et al.*, 2004).

In a pioneer study on a conical swirling fluidized-bed combustor with annular spiral distributor using quartz sand as the bed material, the bed behaviour could be separated, according to the Δp-u diagrams, into four operational regimes as (1) fixed-bed regime, (2) partially fluidized-bed regime, (3) fully fluidized-bed with partial swirl motion, and (4) fully swirling fluidized-bed regime (Kaewklum and Kuprianov, 2010). The Δp-u diagrams in this study showed the apparent effects of the static bed height, sand size diameter, and swirl generator type. However, the axial and radial distributions of the solid holdup in the conical-bed combustor were unavailable. Therefore, the main objective of this work was to investigate the distribution of the solid holdup along the radial and axial directions in the combustor for a wide range of operating conditions and bed particle sizes.

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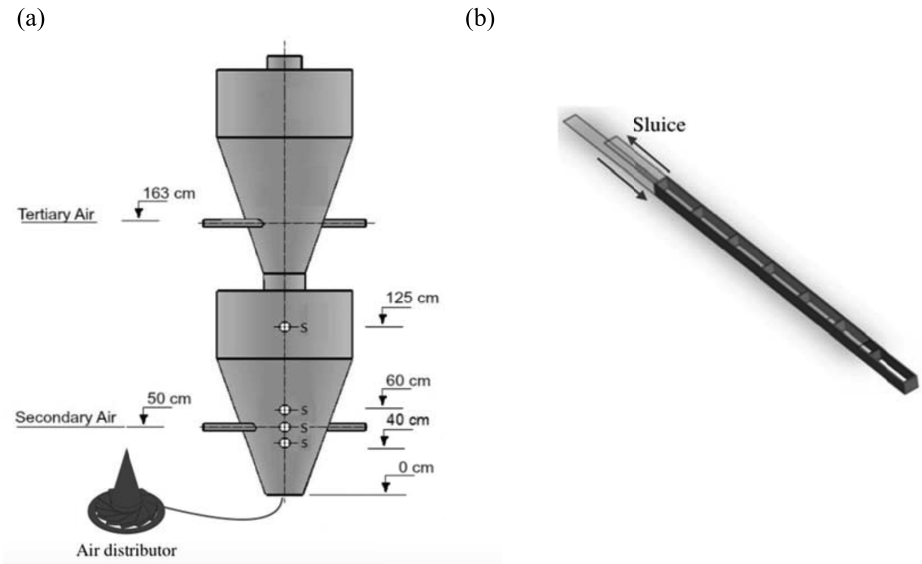

Figure 1. Schematic diagram of (a) twin-cyclone combustor with annular spiral distributor and (b) solid holdup measuring device.

2. Methodology

2.1 Experimental set-up and bed material

Figure 1 shows a schematic diagram of the "cold" experimental set-up: a laboratory scale twin-cyclone combustor with an annular spiral distributor as the swirl generator and the solid holdup sampling points (S). The combustor body consisted of two cyclonic combustors connected by a circular pipe along the centerline. The combustor was assembled with three air supply systems, namely the primary air (PA), secondary air (SA), and tertiary air (TA) injectors. The combustor consisted of two parts, a conical (bottom) section of 1 m height with a 0.25 m base diameter and 40^o cone angle and a cylindrical (upper) section of 1 m height with a 1 m inner diameter.

Silica sand of three different particle size diameter (d_p) ranges: 600–710 μm, 710–1000 μm, and 1000–1700 μm, was used as the inert bed material, and the bulk densities for each group of bed material were 1700, 1660, and 1640 kg/m^3, respectively. The bulk densities of the sand particles were determined using standard test methods for the density of compacted or sintered powder metallurgy (PM) products using Archimedes' principle ASTM B962−15.

2.2 Operating condition

To conduct the tests at the fixed static bed heights for different particle sizes and under a wide range of operating conditions, the loosely-packed sand bed was prepared by blowing the primary air in to the packed sand bed. After switching off the primary blower, the bed material was measured at 30 cm above the air distributor.

In the investigation of the solid hold up, the combustor was allowed to run for about 15 minutes to a steady state condition before inserting the measuring probe. To get valid and repeatable data, the sampling was repeated at least five times. For the adjustment of the primary air flow, the minimum fluidized velocities for each particle size were determined from Δp–u diagrams. From the analysis of the Δp–u diagrams for the different particles, it was found that the Δp_{mf} and u_{mf} were 2.84 kPa and 0.63 m/s, 3.09 kPa and 0.78 m/s, and 3.30 kPa and 1.27 m/s for particle sizes of 600–710 μm, 710–1000 μm, and 1000–1700 μm, respectively.

The effects of the operating conditions on the solid holdup were investigated at a primary air velocity range between u_{mf}–3u_{mf}, and the ratios of the secondary air flow rate (Q_s) and tertiary air flow rate (Q_t) to the primary air flow rate (Q_p) were 0, 0.3, and 0.5, respectively.

Table 1. Characteristic of solid hold up measuring device.

Sampling point	Grid dimension (mm)			Total length	Grid volume
(height above air distributor, cm)	Width	Length	Height	(mm)	(mm^3)
1 (40 cm)	13	72	0.019	530	17.8
2 (50 cm)	13	89	0.019	650	21.9
3 (60 cm)	13	99	0.019	720	24.5
4 (125 cm)	13	138	0.019	1000	34.1

2.3 Measurement of solid holdup

In the present work, a solid concentration of bed material was captured by a thief probe, which was designed to investigate the solid concentration in the gas-solid flow of the CFBC system by Chen and others (2008). The device was a drawer-style with seven connected grids and sliding case. The sampling points (S) and schematic diagram of the thief probe are shown in Figure 1a and b, respectively. As can be seen in Figure 1a, the axial solid distributions were measured along the horizontal axis at levels of Z = 40, 50, 60, and 125 cm above the air distributor systems. Due to diameter variations at different heights of the conical section of the combustor, the dimensions of solid holdup measuring probes at each sampling point were variable, as shown in (Table 1). The grid lengths were determined by dividing the combustor diameter into seven equal lengths, and the center of each grid was located at r/R = 0, ±0.33, ±0.67, and ±1 (where r is the distance from the center of the combustor and R is the radius at the top of the conical section).

Ignoring the quantities of air in every grid, the local solid hold-up (ε_i, ratio between solid concentration and solid density; ρ_i/ρ_s) in the measuring point can be calculated by the following correlation:

$$\varepsilon_i = \frac{m_i}{\rho_s V_i} \qquad (1)$$

where m_i represents the mass of silica sand in a grid i (kg) and V_i is the volume of the grid i of the thief probe (m^3). ϱ_s is the bulk solid density of silica sand for each size of particle diameter (kg/m^3).

The instrument was calibrated with a fiber optic reflection probe that could measure the solid concentration at the front wall of the reactor as by Chen and others (2008), and the maximum discrepancy between the measured solid holdup by the thief probe and the fiber optic reflection probe was found to be in the range of ±10%.

3. Results and discussion

3.1 Distribution of solid holdup

For the investigation of the solid concentration at Z = 125 cm, only a small amount of bed material was found, therefore, the solid holdup at that point was negligible. Figure 2 shows the radial profiles of the solid holdup for different levels (Z): 40, 50, and 60 cm, above the air distributor system in the twin-cyclone combustor operated at the primary air velocity $2u_{mf}$ without secondary and tertiary air injection for sand particle size diameters of (a) 600–710 μm and (b) 1,000–1,700 μm.

With this type of swirl generator, the primary air passed through the base of the bed material and the particles were forced to travel in the tangential and axial directions. While, the axial flow provided the fluidizing of the bed material, the tangential caused the swirling motion. The magnitudes of these velocity components represented the complex bed behavior (Kaewklum and Kuprianov, 2010). As seen in Figure 2, the radial profiles exhibited symmetric distributions with respect to the combustor axis. For a wide range of particle sizes, the solid holdup was high at the center of the center of the combustor and gradually decreased to almost zero at the combustor walls. This can be explained by the swirling flow of the primary air accelerated a centripetal force of the sand particles which radially moved inwards to the center of the combustor.

Due to the geometry of the conical bed (the cross-sectional area increased with an increase in the combustor height), the primary air velocity decreased at the upper section and led to the lower solid carrying capacity. Consequently, a lean solid hold up was found at the higher level. A similar trend of radial solid hold up profiles were obtained when the bed material was switched from d_p = 600–710 μm to the bigger particle size of d_p = 1,000–1,700 μm.

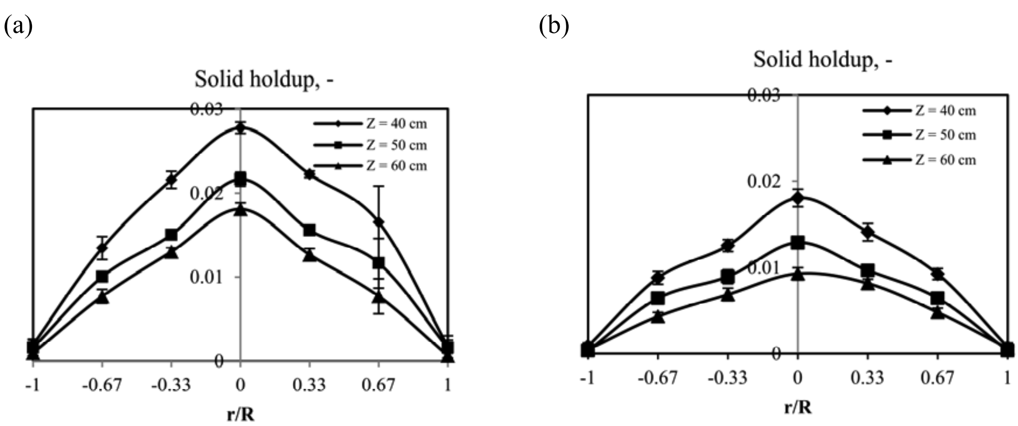

Figure 2. Radial profiles of solid hold up for different levels of the twin-cyclone combustor operated at the primary air velocity $2u_{mf}$ for sand particle size diameter of (a) 600–710 μm and (b) 1,000–1,700 μm.

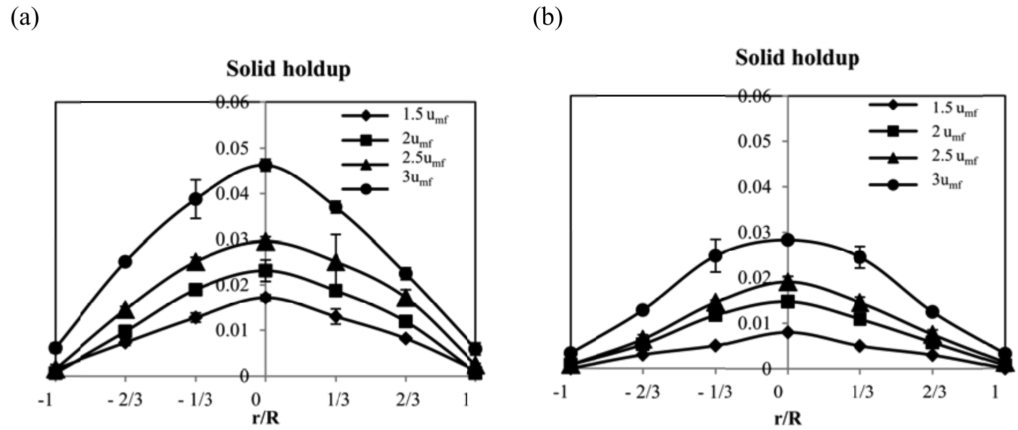

Figure 3. Effects of primary air on solid holdup at the combustor levels of (a) 40 cm and (b) 60 cm for particle size diameter of 710–1000 μm.

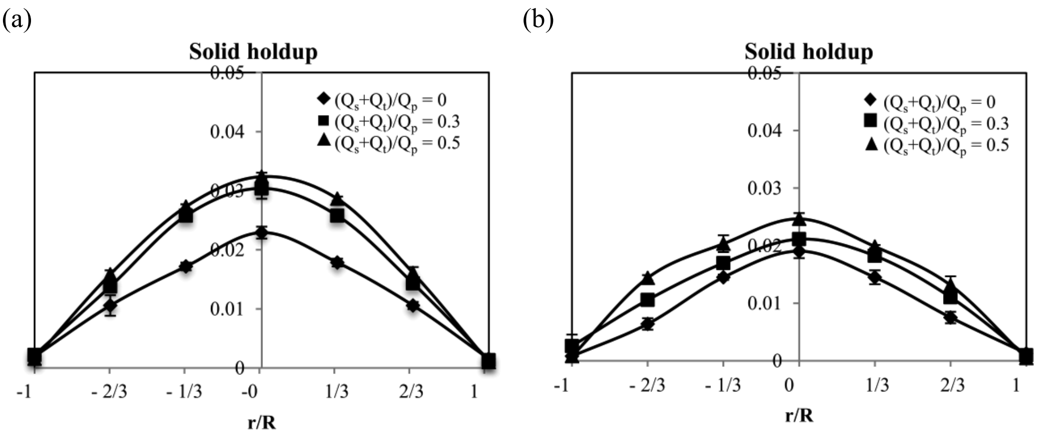

Figure 4. Effects of secondary and tertiary air injections on solid holdup at the combustor levels of (a) 40 cm and (b) 60 cm for the primary air velocity $2u_{mf}$ and particle size diameter of 710–1000 μm.

3.2 Effect of primary air on solid holdup

Figure 3 shows the effects of the primary air velocity on the radial distribution of the solid holdup in the combustor at levels of (a) 40 cm and (b) 60 cm above the air distributor system. The radial solid hold up was significantly affected by the primary air velocity. By increasing the primary air velocity, the radial profiles gradually moved upward, particularly at the center of the combustor. The stronger swirling flow produced a strong circular motion and higher kinetic energy to carry greater amounts of sand particles. Comparing the solid concentrations for the fixed primary air at different combustor levels (see Figure. 3a and b), the radial profile was more uniform at the higher level due to a smaller effect of the swirling flow. The dense bed was found at the central region for r/R = 0–1/3, where the diluted solid holdup occurred near the combustor walls for r/R = 2/3–1.

3.3 Effect of secondary and tertiary air injections on solid holdup

Figure. 4 shows the effect of the secondary air flow rate (Q_s) and the tertiary air flow rate (Q_t) injections on the radial distribution of the solid holdup in the combustor at levels of (a) 40 cm and (b) 60 cm above the air distributor system. For the fixed combustor level, the solid holdup increased with the tangential injections of the secondary and tertiary air compared with the non-secondary and tertiary air injections. The increase in the solid holdup for the increasing secondary and tertiary air injections was found to be due to the effects of two different parameters: the increased total air flow and the stronger swirling of the mixing flow. By increasing the secondary and tertiary air at the fixed primary air velocity, the total air volume in the combustor increased and led to the higher velocity of the mixing air flow in the tangential component. More particles were blown to the higher combustor level, which could be noticed by the small difference between the values of the solid concentration at Z = 40 cm and 60 cm.

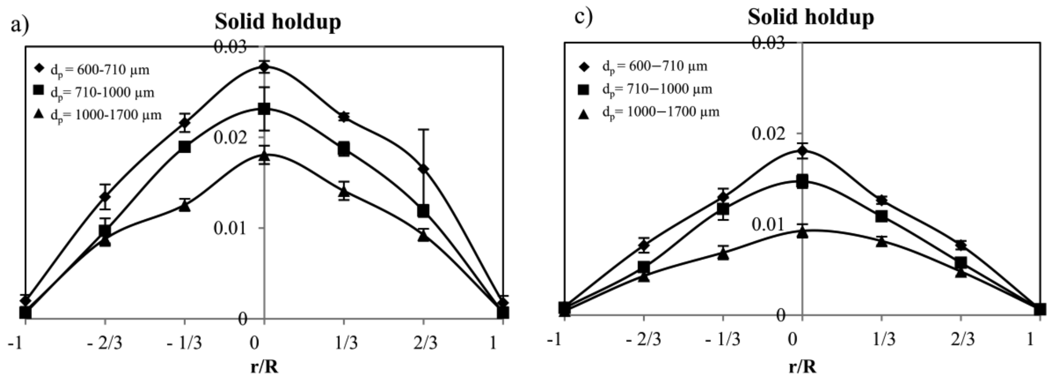

Figure 5. Effects of particle size of bed material on solid holdup at the combustor levels of (a) 40 cm and (b) 60 cm for the primary air velocity $2u_{mf}$.

3.4 Effect of sand particle size on solid holdup

Fig. 5 shows the effects of the particle size of the bed material on the solid holdup at the combustor levels of (a) 40 cm and (b) 60 cm for the primary air velocity $2u_{mf}$. From the Geldart's gas-fluidized bed classification, the particles in these experimental tests can be categorized into two groups: Group B for the fine particles of 600−710 μm and 710–1000 μm and Group D for the larger particles of 1000–1700 μm. The radial profile of the solid holdup was slightly affected by the bed particle size. The solid holdup increased with the decreasing bed particle size. During the supply of the swirling flow to the fine particles, interparticle forces (when the particles interact with each other) became more negative (i.e., tensile) compared with the large particle; however, due to their light weight, the impact of gravitational forces on the particles was weak and caused the denser solid holdup for the fine particles.

4. Conclusions

The present work studied the effects of operating conditions and bed particle size on the distribution of solid holdup along the radial and axial directions in a twin–cyclone combustor with a swirling fluidized bed. The experimental results showed that the radial profiles exhibited symmetric distributions with respect to the combustor axis. For a wide range of operating conditions and particle sizes, the solid holdup was high at the center of the combustor and gradually decreased to almost zero at the combustor walls. By increasing the primary air velocity, the solid holdup increased in all the sampling levels, particularly at the center of the combustor. The increase in the solid holdup could be achieved by increasing the secondary and tertiary air injections due to two different parameters: the increased total air flow and the stronger swirling of the mixing flow. The solid holdup increased with a decrease in the bed particle size.

Acknowledgements

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