Effects of Air Distributor Systems on Flow Behaviors in a Twin-Cyclonic Fluidized-Bed Combustor

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Abstract. *This paper presents computational and experimental studies on hydrodynamic regimes and characteristics of a conical air-sand bed in twin-cyclonic fluidized-bed combustor for three types of air entry/distributor: two propeller blades and a curve blade. Prior to cold-state tests, the computational program was used to simulate the air flow patterns inside the combustor for each type of air distributor. To attain the optimal air distributors design, the blade number was varied from 10 to 20 blades while the angles were varied from 10 to 20 degrees at specific superficial velocity of 3 m/s. From the simulation results, the three types of the swirl generators with different swirl number were selected and assembled, i.e. 11 propeller blades swirler with 14 degree, 16 propeller blades swirler with 14 degree, and 20 curve blades swirler with 20 degree for the cold-state tests. In order to obtain the major hydrodynamic characteristics (Δ_{P-u} diagrams), the experimental tests for each type of air distributor were performed by using quartz sand with the same solid density of 2650 kg/m3 at various static bed heights of 20, 30, and 40 cm and bed particle size ranges of 300–500, 500–700, and 700–1,000 µm, respectively. Four sequent hydrodynamic regimes (fixed-bed, partially fluidized-bed, fully fluidized-bed with a partial swirl motion, and swirling fluidized-bed regimes) were observed in all tests of air distributors when varying the air superficial velocity from 0 to 3 m/s. With increasing static bed height (BH) and/or bed particle size (BPS) for all types of the air distributors, the minimum velocity of partial fluidization (u_{mpf}), pressure drop at the minimum velocity of partial fluidization (Δ_{pmpf}), the minimum velocity of full fluidization (u_{mff}), pressure drop at the minimum velocity of full fluidization (Δ_{pmff}) tend to be increased. The 16 propeller blades swirler with 14 degree seems to be the best air distributor that fit to the proposed twin-cyclonic fluidized-bed combustor in this study.*

Keywords:

Conical air-sand bed, Hydrodynamic regimes, Swirl number

1. Introduction

Hydrodynamic characteristics of a gas–solid bed are one of the major parameters for optimal design and operation of a fluidized-bed combustion system (furnace or combustor), as well as for proper selection of auxiliary equipment. A large number of research studies have addressed hydrodynamic regimes and characteristics of columnar (cylindrical or prismatic) bubbling fluidized beds using a single bed material [1,2]. As shown in these studies, one of the major hydrodynamic characteristics of a fluidized bed, the minimum fluidization velocity (u_{mf}) is essentially the function of the bed density, particle size and voidage, while the corresponding pressure drop across the bed (Δ_{pmf}) is mainly dependent on weight and crosssectional area of the bed.

During the recent two decades, a large number of studies have been performed on tapered and conical fluidized-bed systems widely used in various chemical and biochemical applications [3,4]. Unlike columnar reactors with similar heat input, a conical FBC employs a lesser amount of the inert bed material, which may result in saving auxiliary fuel during the combustor start up [5–8].
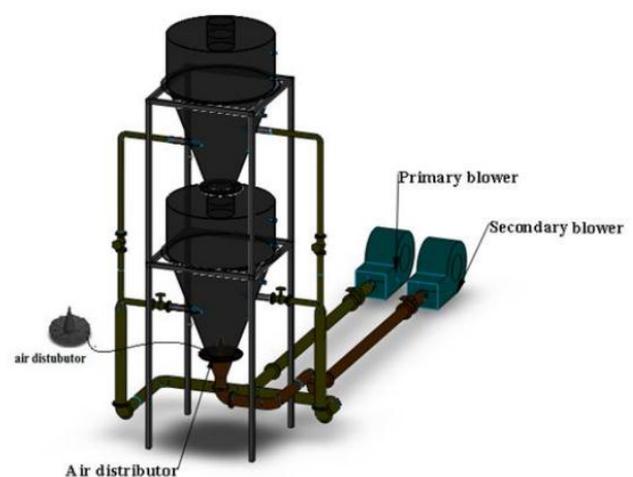

Fig. 1: Schematic diagram of the experimental set up with the twin-cyclonic FBC.

According to the newly design of this combustor, the appropriate type of the swirlers for the twin-cyclonic fluidized-bed combustor with cone shape bed was the main objective in this study. To characterize the different air distributor systems, the computer programming was firstly used in the simulation. The major hydrodynamic characteristics were also investigated for the wide ranges of bed heights (20, 30, and 40 cm) and bed particle sizes (300–500, 500–700, and 700–1,000 μm).
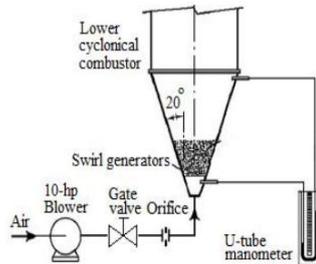

Fig. 2: Experimental facilities for the cold-state experiments

2. Materials and Methods

2.1 Simulations

The computational program (Solid work) was used to simulated for designing an optimal blade number (varies from 10 to 20 blades) and blade angle (varies from 10 to 20 degrees) of two major blade types, propeller blades and curve blades, air distributor.

In the simulations, the fluidizing air at specific superficial velocity of 3 m/s was injected at the combustor bottom via the air distributor to generate the swirling flow.

By considering of the flow pattern from graphical velocity profiles, the optimal blade number and blade angle were selected for each air distribution system.

2.2 Axial flow swirler

The swirl number is usually defined as the fluxes of angular and linear momentum and it is used for characterizing the intensity of swirl in enclosed and fully separated flows [9].

The swirl number, Sg, can be calculated from the following equation (1)

$$S_g = \frac{r_0 \pi r_e}{A_T} \left[\frac{\text{tangential flow}}{\text{total flow}} \right]^2 \qquad (1)$$

The where r_e is the radius of the swirler exit, r_o is the inner diameter of the swirler, and A_t is the total area of tangential inlet. Taking into account the above parameters of the three swirlers, the swirl number (reflecting the swirl intensity of the air flow at the air distributor exit) was estimated for each assembly.

2.3 Experimental

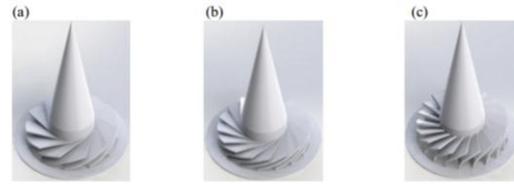### 2.3.1 Experimental Set-up

Fig. 3: Schematic diagram of the annular-spiral air distributors used in the twin-cyclonic fluidized bed combustor (a) 11 propeller blades swirler with 14 degrees (b) 16 propeller blades swirler with 14 degrees, and (c) 20 curve blades swirler with 20 degrees

Fig. 1 shows the schematic diagram of an experimental set-up with the twin-cyclonic FBC that assembled with two cyclonical combustors connected by the circular pipe along a centerline. Each combustor consisted of 2 main parts (i) a conical section of 1 m height with a 40° cone angle with the internal diameter of 0.25 m at lower base and the internal diameter of 1 m at the top layer and (ii) the cylindrical section of 0.5 m height with 1 m inner diameter.

Besides the combustor, the experimental setup included a 10-hp blower that used for supplying the fluidizing air through the proposed three types air distributors at the bottom part of the lower cyclonical combustor.

Fig. 2 depicts the detailed information of the experimental facilities used in this cold-states study. The rate of airflow through the bed (Qa) was controlled by a gate valve downstream from the blower. The relationship between Qa (quantified by integrating the velocity profile across the air pipe) and the valve opening was determined prior to experiments. A multifunction flow meter model: Testo-512 (Testo AG, Germany) with the L-type Pilot tube was used to measure air velocity across the air pipe in specific calibration tests.

Fig. 3 shows the proposed three types of swirl generator with the different swirl numbers, 11 propeller blades swirler with 14 degree (swirl number of 0.1), 16 propeller blades swirler with 14 degree (swirl number of 1.6), and 20 curve blades swirler with 20 degree (swirl number of 2.7).

For each swirl generator, it consists of 2 major parts (i) blade for adjusting the swirling flow entry to the bed and (ii) the swirl stabilizer to sustain the swirl motion, especially at the combustor bottom. The design details can be seen in Ref. [6].

2.3.2 Experimental Planning

After receiving the optimal blade number and blade angle from the simulation results, the experimental study were conducted to characterize the hydrodynamic behaviors for each type of air distributor.
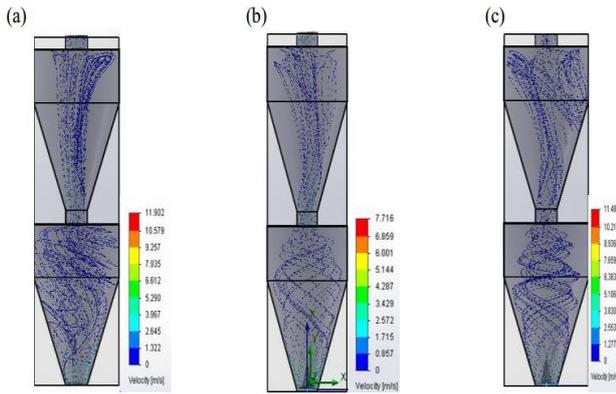
Fig. 4: Behavior of air flow in the twin-cyclonic fluidized-bed combustor at specific superficial velocity of 3 m/s using three type of axial flow air distributors (a) 11 propeller blades swirler with 14 degrees (b) 16 propeller blades swirler with 14 degrees, and (c) 20 curve blades swirler with 20 degrees.

Fig. 5: Effects of bed particle size on the Δp-u diagram of the twin-cyclonic fluidized-bed combustor at static bed height of 30 cm for various type of air distributor (a) 11 propeller blades swirler with 14 degrees (b) 16 propeller blades swirler with 14 degrees, and (c) 20 curve blades swirler with 20 degrees.
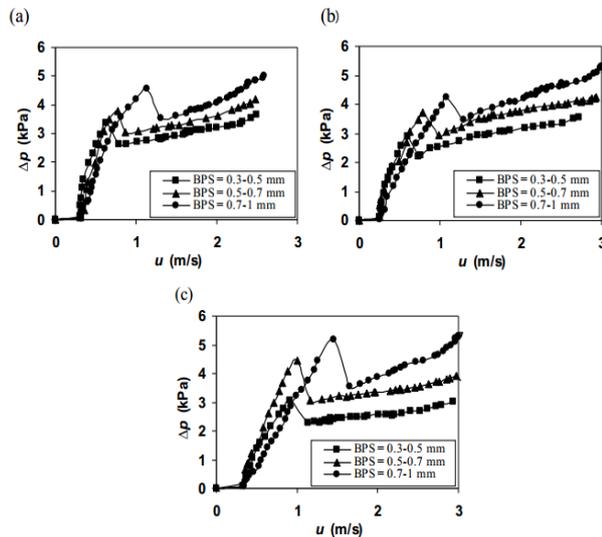
Quartz sand of solid density 2650 kg/m^3 was used as the bed material at various static bed heights (BH) of 20, 30, and 40 cm. The bed particle size was variable: 300–500, 500–700, and 700–1,000 μm. Prior to trials, quartz sand was placed in the conical section forming a loosely packed bed.

To measure the total pressure drop across the bed and air distributor (Δ_p) for variable superficial air velocity (u), one of the two static pressure probes that connected to the U-tube manometer was arranged in the air duct below the air distributor, while another one was fixed at the top of the conical section of the combustor.

3. Results and Discussions

3.1 Simulations

Fig. 4 shows the velocity profiles for three selected types of annular spiral air distributors in the twin-cyclonic combustor simulated at specific superficial velocity of 3 m/s.

In all selected simulation results, it was observed that the swirling flow was initiated at the combustor bottom, up raised through the connecting pipe and eventually reduced the degree of swirling at the top of combustor.

From the flow behavior, at the generator exit, the air flow started to rotate around the reactor's axis and kept this swirl motion to the upper region. As seen in Fig. 4 (b) and (c), due to the higher swirl number of the 16 propeller blades swirler with 14 degrees ($S_g = 1.6$) and 20 curve blades swirler with 20 degrees ($S_g = 2.7$), its can sustain the swirl motion to the higher level comparing with 11 propeller blades swirler with 14 degrees ($S_g = 0.1$).

According to the simulation results which ensuring the swirling flow of the conical bed of the twin-cyclonic fluidized-bed combustor, the three types of air distributors were selected and assembled for the cold-state experiments.

3.2 Flow regimes of an air–sand bed

Fig.5 depicts the effects of bed particle size on the $\Delta_{p\text{-}u}$ diagram of the twin-cyclonic fluidized-bed combustor at static bed height of 30 cm for various types of air distributors. The behavior of the tested air-sand beds exhibited four sequent hydrodynamic regimes, namely, the fixed-bed, partially fluidized-bed, fully fluidized-bed with a partial swirl motion, and swirling fluidized-bed regimes.

At the fixed bed, the bed behavior began from loosely packed bed that has frictional contact between particles in an assembly. When increasing u within the fixed-bed regime at relatively low superficial velocities, Δ_p was found to be increased until the maximum value, Δ_{pmax}, was attained. At this critical point (u_{mpf} and $\Delta_{pmpf}/\Delta_{pmax}$), the lowest layer of a conical bed began to fluidize, therefore, the superficial velocity at this point is termed the minimum velocity of partial fluidization. For the further increasing u from the u_{mpf} to u_{mff}, the pressure drop across the bed changed from Δ_{pmpf} to Δ_{pmff}, at this superficial air velocity, the entire bed was involved in the fluidization, exhibiting a random appearance of small-size bubbles on the bed surface, which the superficial velocity at this point is termed the minimum velocity of full fluidization and the pressure drop across the bed at this point is termed the pressure drop at the minimum velocity of full fluidization. For the further increasing u, the bed entered the swirling fluidized-bed regime with selected geometrical characteristics and material properties, which this regime can be characterized by the positive gradient d(Δ_p)/du.

3.3 Hydrodynamics of air–sand beds

Table 1 shows the major hydrodynamic characteristics of a conical air-sand bed in twin cyclonic fluidized-bed combustor for three types of air entries at various static bed heights of 20, 30, and 40 cm and bed particle size ranges of 300–500, 500–700, and 700–1,000 μm.

With increasing BH and/or BPS, u_{mpf} and u_{mff} tend to increase mainly due to the increasing of the bed voidage for the case of increasing bed particle size range [10], as well as for the greater Δ_{pmpf} and Δ_{pmff} during the increasing of BH and/or BPS that can be explained by the increasing of the bed weight and mean crosssectional area of the bed.

When comparing 11 propeller blades swirler with 16 propeller blades swirler, the greater number of the blade resulted in the lower u_{mpf}, Δ_{pmpf}, u_{mff}, and Δ_{pmff} for all BH and BPS leading to the lower operational costs and also leaving a quite large range of operating air velocity that can be applied in the combustion tests (for various excess air).

However, when comparing Δ_{pmff} at BH = 30 cm between the 16 propeller blades swirler and the curve blades swirler, the curve design at the air entry of curve blades swirler caused the greater pressure drop across the air distributor than the propeller blades, which somehow effects to the total pressure drop across the air distributor and bed as can be seen in Table 1.

A static bed height of 30 cm with the particle size range of 500–700 μm seems to be appropriate, ensuring stable swirling of the bed as well as a sufficient amount of the bed material, but high enough to sustain ignition and combustion of biomass fuels in the cone-shaped twin-cyclonic fluidized-bed combustor with the selected cone angle. An increase in the static bed height will apparently lead to a greater amount of the bed material and also a higher pressure drop across the bed (i.e., substantially higher operating costs); however, too low a bed height may cause deterioration of fuel–air mixing in the combustor bottom part. Too small particle size range might lead to the bubbling fluidized bed; however, too big particle size range also might lead to the spout fluidized bed or cannot fluidized.

Table 1 Summary of the minimum velocity of partial fluidization (umpf), pressure drop at the minimum velocity of partial fluidization (Δpmpf), the minimum velocity of full fluidization (umff), pressure drop at the minimum velocity of full fluidization (Δpmff) for various bed height (BH) and bed particle size (BPS)

BH (cm)	BPS (μm)	11 propeller blades swirler with 14 degree				16 propeller blades swirler with 14 degree				20 curve blades swirler with 20 degree			
		Δp_{mpf} (kPa)	u_{mpf} (m/s)	Δp_{mff} (kPa)	u_{mff} (m/s)	Δp_{mpf} (kPa)	u_{mpf} (m/s)	Δp_{mff} (kPa)	u_{mff} (m/s)	Δp_{mpf} (kPa)	u_{mpf} (m/s)	Δp_{mff} (kPa)	u_{mff} (m/s)
20	300-500	2.05	0.58	1.53	0.64	1.96	0.40	1.32	0.54	1.92	0.69	1.77	0.79
	500-700	2.77	0.68	2.31	0.77	2.44	0.53	1.75	0.69	3.27	0.74	1.98	0.96
	700-1000	3.59	0.93	2.69	1.10	3.16	0.76	2.23	1.17	4.13	1.20	2.48	1.51
30	300-500	3.36	0.63	2.61	0.79	2.91	0.60	2.19	0.73	3.06	0.91	2.30	1.14
	500-700	3.80	0.78	3.03	0.87	3.72	0.78	2.93	0.99	4.45	1.00	3.08	1.16
	700-1000	4.56	1.14	3.54	1.31	4.24	1.08	3.48	1.29	5.19	1.45	3.56	1.65
40	300-500	4.62	0.80	3.48	1.13	4.47	0.69	3.39	1.04	4.29	1.12	3.52	1.29
	500-700	5.46	0.95	4.22	1.23	5.14	0.92	3.87	1.19	5.21	1.26	4.06	1.37
	700-1000	-	-	-	-	-	-	-	-	-	-	-	-

The 16 propeller blades swirler with 14 degrees seems to be the best air distributor that fit to the proposed twin-cyclonic fluidized-bed combustor in this study. With this design, the major hydrodynamic characterized by u_{mpf}, Δ_{pmpf}, u_{mff}, and Δ_{pmff} from the cold-state experiments, the 16 propeller blades swirler with 14 degrees can be further employed in the combustion experiments.

4. Conclusions

As revealed by the experimental data, all types of the air distributor were successfully designed (by computer programming), assembled, and tested in the proposed twin cyclonic fluidized-bed combustor. The specific conclusions from this research study are as follows:

(1) Four sequent hydrodynamic regimes (fixed bed, partially fluidized-bed, fully fluidized bed with a partial swirl motion, and swirling fluidized-bed regimes) are observed in the conical fluidized bed when varying the air superficial velocity from 0 to 3 m/s.

(2) By considering of bed stability, amount of the bed material, operational costs and operating air velocity, a static bed height of 30 cm with the particle size range of 500–700 μm seems to be appropriate for firing biomass fuels.

(3) The 16 propeller blades swirler with 14 degree seems to be the best air distributor that fit to the proposed twin-cyclonic fluidized-bed combustor in this study.

5. Acknowledgement

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Biography

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