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Original Research Paper

Experimental and theoretical study on hydrodynamic characteristics of tapered fluidized beds

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ABSTRACT

A novel fluidized bed ash cooler was developed for circulating fluidized bed boilers based on a proposed modified tapered fluidized bed. A cold model was built to study the hydrodynamic characteristics of the modified tapered fluidized bed, and its critical superficial gas velocity u_{mf} and critical velocity for full fluidization u_{mff} were particularly studied. The effects of taper angle α, static bed height H, air inlet section width δ and particle size d_p on the u_{mf} and u_{mff} were experimentally investigated. Furthermore, a theoretical model and an empirical correlation have been proposed to predict the u_{mf} and u_{mff}, respectively. The predicting capabilities of the model and correlation have been experimentally discussed. And the predicting capability of the model has also been compared with that of an existing representative model. It is found that both the u_{mf} and u_{mff} increase with the increase of taper angle α, static bed height H and particle size d_p, but decrease with the increase of air inlet section width δ, respectively. Additionally, the predicted values of u_{mf} and u_{mff} compare well with the experimental data, and the model has a better capability than the existing representative model in predicting the u_{mf} of the modified bed.

1. Introduction

The circulating fluidized bed (CFB) boiler technology has become one of the approved clean coal combustion technologies that commercially applied. As a key auxiliary device for CFB boilers, bottom ash cooler (BAC) is used to treat the high temperature bottom ash discharged from the furnace of CFB boiler to reclaim heat, and to have the ash easily handled and transported. Without its good operational reliability, the reliability, safety, and stable operation of the boiler cannot be guaranteed [1–3]. There are many kinds of BACs equipped for large-scale CFB boilers with the continuous development and improvement of CFB boiler, such as water-cooled ash cooling screw [3], rolling-cylinder ash cooler [3–5], high-strength steel belt ash cooler [6] and fluidized bed ash cooler (FBAC) [7–14]. And fluidized bed ash cooler (FBAC) has been proven to be more attractive than other kinds of BACs, because of its unique technical features such as a higher heat-transfer coefficient, a greater output capacity, a function of returning partial of fine particles of the bottom ash back into the furnace by fluidizing air from the FBAC, and a better thermal economy of reclaiming heat in the bottom ash [7,8]. And the majority of FBACs are the rectangular bubbling fluidized-bed type [9–12]. In China, unfortunately, the application and further development of those FBACs are restricted by some disadvantages such as poor flow ability of the bottom ash, defluidization, agglomeration, etc. As the coal resources are in short supply, the China government has strongly supported using CFB boilers to combust the low-calorie fuel such as coal gangue and stone coal, whose ash content are even greater than 70% and practical discharged bottom ash has a wide range of size distribution and contains coarse particles that are too large to be satisfactorily fluidized in FBACs [8,13–14]. All in all, the poor performance of those FBACs is attributed to the defluidization of coarse particles and all the consequences arising therefrom. It is noteworthy that there is another kind of FBAC, which is called gas-tank spouted bed ash cooler, could handle practical bottom ash under the use of a rather high superficial gas velocity. But its large air consumption, which finally returns to the furnace, has a great impact on the combustion condition of the furnace, and a restriction to its output capacity [9,14]. Therefore, it is necessary to develop a novel FBAC that can overcome the problems encountered by the existing FBACs and meet the needs of large-scale CFB boilers.

Tapered fluidized bed (TFB) has been proven to be an appropriate alternative to bubbling fluidized bed when dealing with particles with a wide particle size distribution. Because of the increase in cross-sectional area along the bed height of tapered fluidized bed, the gas velocity decreases with the bed height. Therefore, a relatively high gas velocity is obtained at the bottom of the bed which could ensure the fluidization of the coarser particles better [15–18]. Based on the basic operating principles and technical

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Nomenclature

BAC	bottom ash cooler
CFB	circulating fluidized bed
FBAC	fluidized bed ash cooler
TFB	tapered fluidized bed
A	constant in Ergun's equation, $A = 150\frac{(1-\varepsilon_0)^2}{\varepsilon_0^3}\frac{\mu_g}{(\phi_s d_p)^2}$
Ar	Archimedes number, $Ar = \frac{g d_p^3 \rho_g(\rho_s-\rho_g)}{\mu_g^2}$
B	constant in Ergun's equation $B = 1.75\frac{(1-\varepsilon_0)}{\varepsilon_0^3}\frac{\rho_g}{\phi_s d_p}$
d_p	particle size (m)
F	drag force exerted on the particles in the bed by the fluidizing gas (N)
F_c	drag force exerted on the particles in the central region of the bed by the fluidizing gas (N)
G	effective weight of the particles in the bed (N)
G_c	effective weight of the particles in the central region of the bed (N)
g	gravity (m/s)
H	static bed height (m)
h	height (m)
L	height of the top surface of the inclined base from the gas distributor (m)
ΔP_b	bed pressure drop (Pa)
Re_{mff}	Reynolds number at u_{mff}, $\mathrm{Re}_{mff} = \frac{d_p u_{mff}\rho_g}{\mu_g}$
s	cross-sectional area of the bed (m^2)
s_c	cross-sectional area of the central region of the bed (m^2)
u_g	gas velocity (m/s)
u_{g0}	superficial gas velocity at the air inlet section (m/s)
u_{mf}	critical superficial gas velocity (m/s)
u_{mff}	critical velocity for full fluidization (m/s)
W	width of the bed column, W = 0.2 m

Greek letters

α	taper angle (°)
δ	width of the air inlet section (m)
ε_0	bed voidage (–)
μ_g	gas viscosity (Ns/m^2)
ρ_g	gas density (kg/m^3)
ρ_s	particle density (kg/m^3)
ϕ_s	sphericity of the particles (–)

features of TFB, which has a better adaptability to practical widely distributed particles than bubbling fluidized bed, a novel FBAC called Bi-spouted-bed fluidized bed ash cooler has been proposed by Chongqing University, and has obtained an invention patent in China [19]. In order to further enhance the adaptability to practical widely distributed bottom ash, chambers of the patented ash cooler are constructed based on a novel proposed modified tapered fluidized bed. Compare with TFB, an air inlet section is located below the inclined base of the modified tapered fluidized bed so as to guarantee better fluidization of coarser particles, which is attributed to the fact that gas velocity is always maintained at a high value throughout the air inlet section. Moreover, to enhance the heat transfer between the particle bed and heat transfer tubes on the premise of guaranteeing a good flow ability of the bottom ash, a relatively larger tapered angle is selected to allow more heat transfer surfaces could be submerged within the particle bed.

Numerous investigations on hydrodynamic characteristics have been carried out for gas–solid and liquid–solid TFBs. However, most previous works focus on TFBs with a relatively small taper angle and no air inlet section, where the taper angle is no more than 60° [15–18,20–29]. To the best of our knowledge, investigation on hydrodynamics of a tapered fluidized bed characterized of a large taper angle that is larger than 60° and an air inlet section has rarely been reported in literatures. Therefore, in order to provide available guidelines for the design, operation and structure optimization of Bi-spouted-bed fluidized bed ash cooler and valuable reference for the investigation of hydrodynamics in TFBs, experimental and theoretical studies on certain important hydrodynamic characteristics of the proposed modified gas–solid tapered fluidized beds are carried out in this work. In our previous work on this project we have investigated the lateral mixing of particles in the bed [30].

In the present work, experimental investigation on hydrodynamic characteristics of the proposed tapered fluidized bed has been conducted. The effects of taper angle α, static bed height H, air inlet section width δ and particle size d_p on the critical velocities of regime transition, i.e. critical superficial gas velocity u_{mf} and critical velocity for full fluidization u_{mff}, have been experimentally investigated. Furthermore, a theoretical model and an empirical correlation have been proposed to predict the critical superficial gas velocity u_{mf} and the critical velocity for full fluidization u_{mff}, respectively. The predicting capabilities of the model and correlation have been experimentally discussed. And the predicting capability of the proposed model was also compared with that of a representative model proposed by Jing et al. [25].

2. Experiments

A schematic diagram of the experimental apparatus is shown in Fig. 1. It consists of a gas supply system, a test rig body, a dedusting system, etc. The test rig body consists of a rectangular column with a cross section of 300 mm × 200 mm and a height of 800 mm, an inclined base and an air inlet section located at the bottom of the column. The front side and back side of the column are made of transparent Plexiglas. Therefore, the movement of particles in the column could be easily observed. To investigate the effects of taper angle α and air inlet section width δ on the critical superficial gas velocity u_{mf} and critical velocity for full fluidization u_{mff}, three different taper angles, α = 90°, 70° and 50°, and three air inlet section widths, δ = 60 mm, 52 mm and 44 mm, are employed in this study.

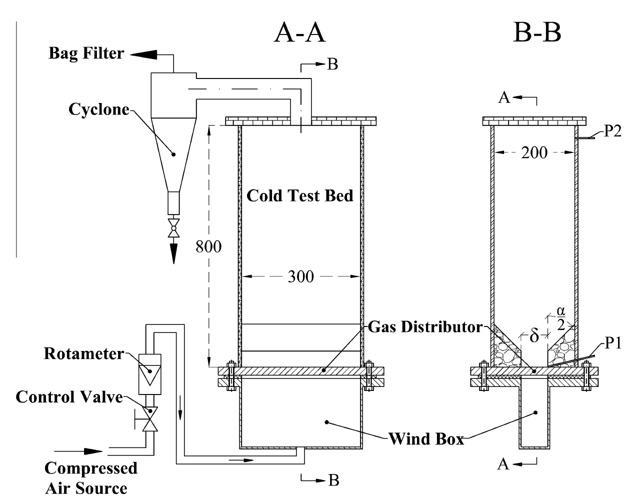

Fig. 1. Schematic diagram of experimental apparatus.