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Research Article

Experimental Study on the Effect of Exit Geometric Configurations on Hydrodynamics in CFB

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Abstract: The exit configurations of CFB strongly influence the bulk density profile and the internal circulation of the bed material, which is called the end effect. This study analyzes the influence of three exit geometries and two narrowed exit geometries on hydrodynamics. Experiments indicate that the exit with the projected roof in CFB may be used as a separator and the projected height has a maximum. Narrowing the bed cross section near the bed exit zone is a simple and effective way to enhance the internal circulation and reduce the circulation of bed material simultaneously.

Keywords: Circulating fluidized bed, End effect, Exit geometric configuration, internal circulation

INTRODUCTION

Circulating Fluidized Bed (CFB) coal combustion technology has been widely accepted as a clean coal combustion technology for burning various fuels efficiently and recently has greatly enhanced its commercialization (Yu *et al*., 2011; Utt and Giglio, 2012).

The special features in CFB combustors, for example low gas velocity, low circulating mass flux of solids and coarse particles with wide size distributions of the bed material, etc., result in a bubbling dense bed for coarse particles in the lower and a dilute fast bed for fine circulating particles in the upper parts respectively (Baszczuk *et al*., 2012; Saastamoinen and Tourunen, 2012). Some CFB combustors without an external heat exchanger are not able to control bed temperature effectively (Chen *et al*., 2007). To improve mixing in the bed and the bed temperature control ability, the internal circulation rate should be enhanced and the external circulation rate should be reduced (Zhao, 2007; Mabrouk *et al*., 2008).

Although a great deal of operating experience in CFB has been gained in industrial practice, there is a lack of research effort in the academics focusing on hydrodynamics of gas-solid flow in CFB combustors featured with rather low ratio of the furnace height to the equivalent diameter. In such a case, the exit geometric configurations have strong influence on hydrodynamics. For the purpose for understanding the influence of the exit geometric configurations on the hydrodynamic behavior in CFB, the authors carry out a series of tests under different operating conditions and with different exit geometric configurations.

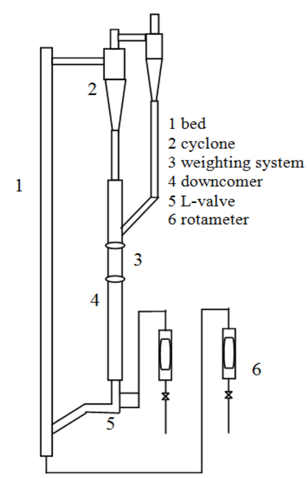

Fig. 1: Schematic diagram of experimental system

EXPERIMENTAL APPARATUS

Figure 1 shows the schematic diagram of the experimental CFB loop. The riser is 0.102 m I. D. and 5.25 m in height. The main bed is retrofitted with a 90×90 mm rectangular cross section CFB on the distribution of the internal circulating solid material. Resin is used as the solid material in the tests which is approximately 500 μm in average diameter, 1400 kg/m^3 in density and 2.7 m/s in terminal velocity.

Figure 2 shows three typical bed exit geometries. “a”, referred to as the smooth exit, has a 45°guiding baffle and an exit area of $44\times88\times10^{-6}m^2$ and is used as the comparison criterion for the other bed exit geometries. “b”, referred to as the abrupt exit, has no

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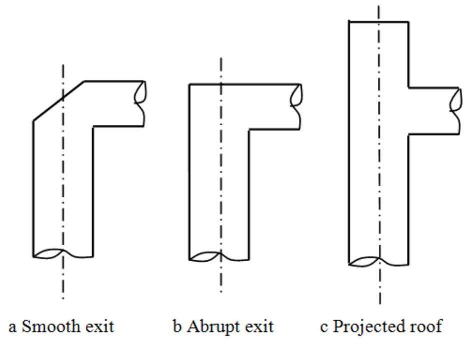

Fig. 2: Three typical exit geometries

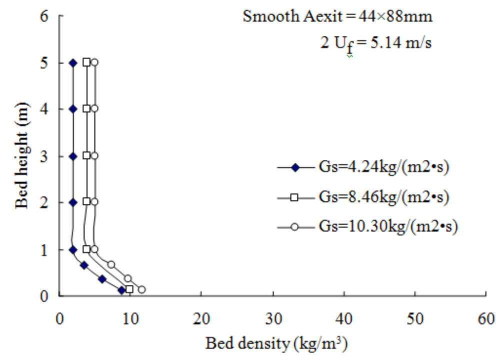

Fig. 3: Bed density profile in CFB with smooth exit

guiding baffle and no projected roof. "c" has a projected roof with height, H, which formed a cavity at the top of CFB.

END EFFECT

Near the bed exit, the gas part in the upward flowing gas-solid two-phase flow turns form the vertical direction to the horizontal direction, leaves the bed, accelerates and enters the cyclone. However the stream of solid particles continues flowing upwards due to inertia. Therefore the flow separates in the bed exit area. Part of the solid particles is carried by the turning gas stream and leaves the bed exit. The remainder of the solid particles continues flowing upwards and will be affected by the bed exit geometries, which is called the end effect. The effect of the different exit geometries may be described as follows.

For the smooth exit, almost all of the solid particles are guided by the baffle, follow the turning gas stream and exited through the bed exit. Therefore this smooth exit acts like a "vacuum-cleaner" and the solid transports to the cyclone inlet level are sucked off (Liakos *et al*., 2001). Figure 3 shows the density profile along the bed height for the smooth exit, where A_{exit} is the exit area, G_s is the solid circulating mass flux. There was no increase of the bulk density near the bed exit. The internal circulation is not measured for this exit geometry.

At the abrupt exit, the solid particles separated from the gas flow collide with the roof of the abrupt exit with a particle velocity, U_s ($U_s = U_f - U_t$ approximately). The particles colliding with the roof cause a large increase of the bulk density in the top region of the CFB. Part of the particles reflecting from the roof fall down and create a descending annular solid layer near the wall, resulting in internal circulation. The abrupt exit had the limited separation ability, but its separation efficiency is low.

For the bed exit with a projected roof, a cavity is formed between the cyclone level and the projected roof. Particles coming from the separated flow enter the cavity. The kinetic energy of the particles entering the free space is converted to gravitational potential energy. As the altitude of the particles in the cavity increases, the particle velocity decreases and the bulk density increases. If the height of the projected roof is not sufficiently high, the decelerated and concentrated particle flow collide with the projected roof, causing the bulk density to further increase. However, compared with a CFB having an abrupt exit, more reflected particles are observed and circulate internally near the wall region in CFB with a projected roof. The end effect of the projected roof included the multiple effects of collision and cavity effect. Therefore, the projected roof causes a dramatic increase of the bulk density near the top in CFB.

H_{max} is defined as a maximum averaged reachable height of the separated particles:

$$H_{max} = K_1 K_2 \frac{(U_f - U_t)^2}{2g} \tag{1}$$

$(U_f\text{-}U_t)$ is approximately equal to the particle velocity in the ascending dilute core. K_1 is the coefficient considering friction between the moving particles and the surrounding gas in the cavity and K_2 is the coefficient considering the influence of the radial distribution of the gas velocity in the cross section of the bed.

When the projected height is equal to or greater than H_{max}, the energy of the separated particles is conserved as the particles decelerated and concentrated. Upon reaching H_{max}, the particle velocity is close to zero and the bulk density reaches a maximum. The individual particles agglomerate to form the clusters. The resulting clusters descend and exchange momentum with the ascending particle flow. The momentum exchange promotes a dramatic increase of the bulk density at the top of the bed. In this case, a rather high separation efficiency of the end effect causes a significant internal circulation. In Fig. 4, the curve shows that the bulk density increases and reaches a maximum at the top of the bed when the projected height is 0.45 m. The separation efficiency of the end effect and the internal circulation rate also reaches the maximum.

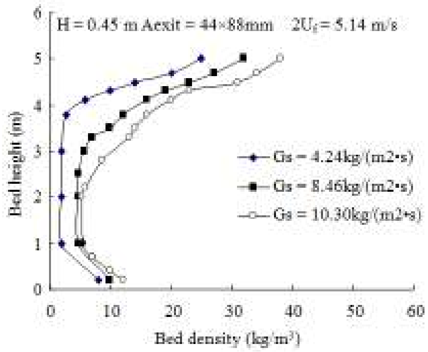

Fig. 4: Bed density profile in CFB with a projected roof

The measured data shows that the flow pattern features an ascending dilute core and a descending dense annular layer. The solid material is mainly concentrated near the surrounding wall. In a rectangular bed, the more solid material accumulates in the corners. However, the commercial CFB combustors equip with finned tubes and the expected solid material distribution would be rather uniform in the wall area.

For low G_s, internal circulation created by the end effect causes the transition of the flow pattern from dilute transport to fast bed and extends the residence time of the solid material in the bed. These experimental results are consistent with the other results mentioned above.

It is clear that a well designed bed exit has the function of a preliminary separator which may improve the performance improvement, for example increasing the bed temperature control ability, extending the bed material residence time (Harris *et al*., 2003), reducing the roof erosion by the suspended solid layer near the top of the bed and reducing the external circulation rate, consequently reducing the energy consumption and the erosion rate in the back pass of CFB boilers.

NARROWED BED CROSS SECTION EFFCT

Figure 5 shows the special designed bed exit structures featured with narrowed cross section and a projected roof. In Model 1 a nose is installed with a full bed width just under the bed exit level. The width of the installed nose in Model 2 is equal to the width of the bed exit duct. In the experiments the extending depth of the nose, B, is 20, 40 and 60 mm respectively.

Figure 6 and 7 show the effect of the extending depth on the bulk density profile in the bed separately for Model 1 and Model 2. The experimental results indicate the same trend that the bulk density in the upper part of the bed increases from 20 mm to 40 mm. However when the extending depth reaches 60 mm, the increment of the bulk density in the upper part of the bed disappears. Figure 8 schematically shows the gas-solid flow pattern in the upper part of the bed. If the extending depth is equal to or greater than 60 mm, the

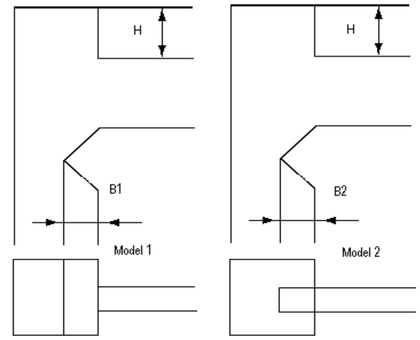

Fig. 5: Narrowed bed exit structures

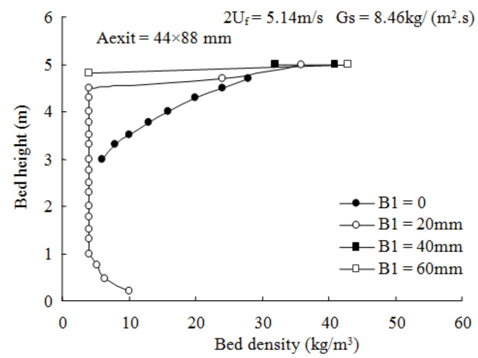

Fig. 6: Influence of B on bulk density profile (Model 1)

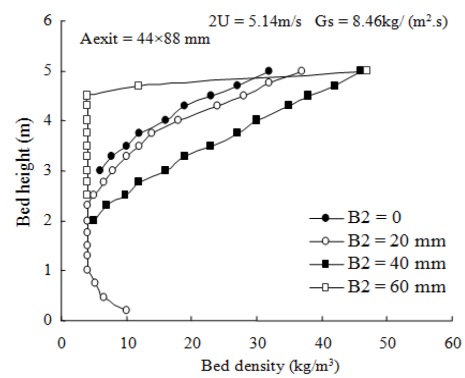

Fig. 7: Influence of B on bulk density profile (Model 2)

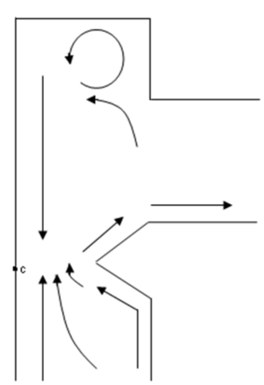

Fig. 8: Internal flow mechanism in CFB with narrowed bed cross section

gas stream is guided to the front wall of the bed and the gas stream blows over the descending solid layer near the front wall. The solid particles are re-entrained into the cavity. Thus a recycling zone of the solid particles is formed in the cavity (Lackermeier and Werther, 2002). Under the point C showed in Fig. 8 the descending solid layer disappears for the reason of strong stripping ability of the gas stream.

CONCLUSION

- The exit configurations of CFB strongly influence the bulk density profile and the internal circulation of the bed material, which is called the end effect.
- The exit with the projected roof in CFB may be used as a separator and the projected height has a maximum.
- Narrowing the bed cross section near the bed exit zone is a simple and effective way to enhance the internal circulation and reduce the circulation of bed material simultaneously.

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