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Experimental study of exit effect on gas–solid flow and heat transfer inside CFB risers

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ABSTRACT

In two bench-scale cold circulating fluidized bed (CFB) risers with similar dimension but different cross section shape, the effect of different exit geometries on both gas–solid flow and heat transfer characteristics was investigated. The measured axial distribution of solid density and bed-to-probe heat transfer coefficient along the riser were found to have good correlation at certain superficial gas velocity and solid circulating flux. Abrupt exit can bring higher solid concentration and heat transfer coefficient near the exit, even in the whole riser. Due to combining effort of cavity and collision effect, solid concentration will first increase with projected height of the abrupt exit increasing. Then solid concentration will stay constant or even decrease when projected height increases over the maximum height particles can reach.

Besides exit types and operating conditions, projected height of the abrupt exit, size and shape of cross section are all important factors affecting exit effect. In this paper, exit effect becomes more significant with a circular cross section than a rectangular one.

1. Introduction

Gas–solid flow in the CFB is not only affected by fluidizing air and bed material properties, but also by the geometry and structure of the circulating system, among which the geometric configuration of the riser exit is an important factor. Exit geometry can be categorized into three types (*C*-shape, L-shape and *T*-shape, see Fig. 2). The first one is also called as smooth exit while the other two are called as abrupt exit. Because the gas solid flow directly influences the heat transfer, the exit geometry also has significant impact on the heat transfer in the riser.

Many published investigations have proved that exit effect do exist, while there is no general conclusions about to what extent the exit geometry can affect the gas–solid flow in CFB risers. Brereton and Grace [1] and Jin [2] found that exit geometry may affect gas–solid flow behavior along the whole riser, while Zheng and Zhang [3] and Bai et al. [4] concluded that an abrupt exit can only affect the flow in the upper zone near the exit. They also found the projected height of abrupt exit, h, see in Fig. 2, influences the flow behavior in this top region. On the contrary, Johnsson et al. [5] found the projected height of the abrupt exit had limited effect on gas solid flow in their cold model. Pugsley et al. [6] firstly proposed a scale effect to explain the intensity of exit effect on gas solid flow in the riser. When the ratio of riser height to riser diameter, H/d_o, was fixed, the exit effect would be restricted to the exit region when the riser diameter decreases. When the ratio is quite low, it is hard to observe pronounced exit effect especially in industrial CFB risers (4,6). Lackermeier and Werther [7] found no apparent exit effect in their industrial scale CFB boiler risers, which proved the scale effect proposed by Pugsley [6] quite well. In addition, the solid circulating flux has also great influence on the exit effect [8]. Even for the smooth exit, the material back mixing would become stronger when the solid circulating flux was extremely high [9,10].

Brereton and Senior [11] proposed the reflection coefficient, R_f, defined as the ratio of solid flow flux of downward to upward, to describe the extent of the solid back mixing caused by exit geometry. Mickal et al. [12], using the same parameter, explained how abrupt exit affects gas–solid flow in the riser. Van der Meer [13] introduced a similar parameter, the reflux ratio factor, k_m, defined as the ratio of downward solid flow flux to solid circulating flux, to study the different influence of seven exit geometries.

Kunii and Levenspiel [14] obtained theoretical solution of exit effect on the axial solid distribution in CFB risers derived from physical equations, which could be used to predict the solid concentration near the exit. Gupta and Berruti [15] proposed two parameters to analyze exit effect, that is, slip factor ψ, defined as the ratio of the actual gas velocity to the particle velocity, and reflection coefficient, defined as the mass fraction of solids that can reach the top of the riser and reflux back downward internally without leaving the riser. Harris et al. [16] investigated the influence of riser exit geometry using three different measures:

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Nomenclature

a_0, a_1, a_1	specific heat coefficient, –
C_p	specific heat of copper, J/kg °C
d_o	equivalent diameter, m
d_p	particle mean diameter, μm
d_{sphere}	copper sphere diameter, m
G_s	solid circulation flux, kg/m^2 s
h	projected height of an abrupt height, m
h_{b-p}	average heat transfer coefficient from bed to probe, W/m^2 K
H	riser height, m
L	back-mixing length, m
L^*	dimensionless length, m
T_b	bed temperature, K
T_1	initial temperature, K
T_2	ending temperature, K
U_f	superficial gas velocity, m/s
u_{mf}	minimum fluidization velocity, m/s

Greek letters

ε	solid volume concentration, –
ε_{mf}	solid volume concentration at minimum fluidization velocity, –
ρ_{copper}	copper density, kg/m^3
ρ_o	bulk particle density, kg/m^3
ρ_s	particle density, kg/m^3
$\Delta\tau$	time interval, s

dimensionless length, R_f and solids concentration at the exit, and put forward exit Froude number Fr_R to characterize exit effect.

Considering the controversy in experimental findings and the limitation of the existing theoretical explanations, the scale effect may be one of the potential explanations for the different observations, while it still needs more experiment results to be proved.

Reddy and Nag [17] found that there was a corresponding increase in heat transfer coefficient near the abrupt exit resulting from the significant increase of particle concentration. Because the heat transfer has direct relation with the local gas solid density, the axial heat transfer coefficient distribution along the riser height can also reflect the impact of exit geometry on gas–solid flow. So by considering the exit effect on both gas solid and heat transfer, more reasonable explanation on the exit effect may be found.

In this paper, based on previous studies, scale effect mentioned above is further discussed with comparative study in two bench scale CFB apparatuses with similar riser height but different shapes of cross section. Exit geometry effect on vertical distribution of particle concentration and bed-to-probe heat transfer coefficient were studied with three different types of exit.

2. Experimental

Fig. 1 shows the schematic diagram of two bench scale CFB apparatuses, referred as A and B. The CFB apparatuses both consist of riser, cyclones, standpipe and loopseal. In apparatus A, as shown in Fig. 1(A), the riser is of 4.5 m in height with a rectangle-section of 0.316 × 0.08 m^2. In apparatus B, as shown in Fig. 1(B), the riser is of 4.3 m in height with a square-section of 0.1 × 0.1 m.

As shown in Fig. 2, *L*-shape exit and *T*-shape exit were equipped in riser A. The *T*-shape exit in riser A has variable projected height of 0.1 m, 0.35 m and 0.6 m. *C*-shape exit, *L*-shape exit and *T*-shape exit were equipped in riser B. The *T*-shape exit in riser B has only one fixed project height of 0.15 m.

In the two experimental apparatuses, measurement techniques for pressure drop, fluidizing air flow rate and solid circulation flux are exactly the same. Pressure ports, which also performed alternatively as heat transfer measuring ports, were arranged along the circulating loop and the pressure profile was measured on line through pressure sensors. The axial profile of solid volume fraction (1-ε) and voidage ε could be calculated from the pressure profile (Eq. (1)). Fluidizing air and aeration air in loopseal were supplied by rooster fans and measured on-site by float flow meter.

$$\varepsilon = 1 - \frac{\Delta p}{\rho_s g \Delta h} \tag{1}$$

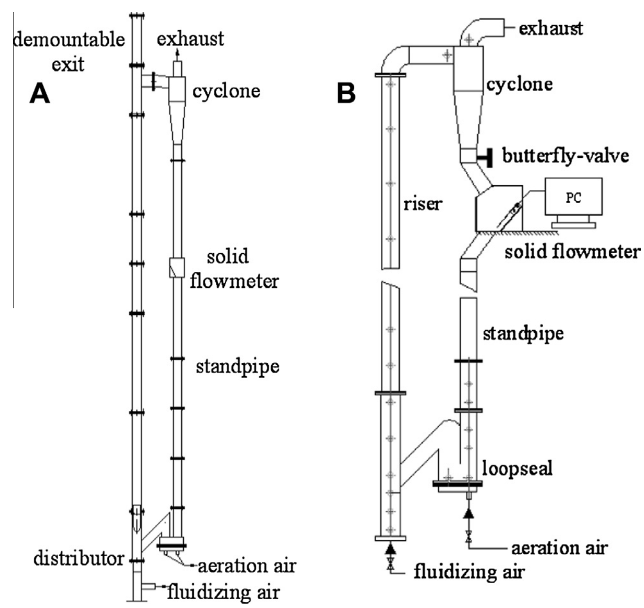

Fig. 1. Schematic diagram of experimental apparatus.

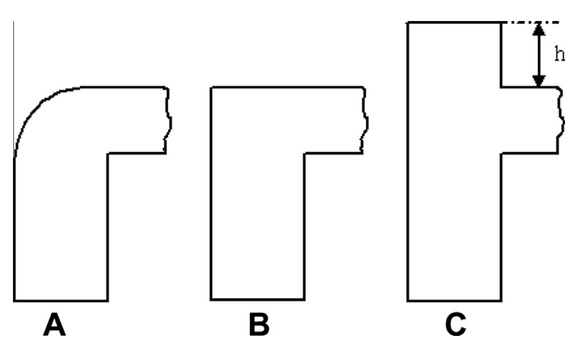

Fig. 2. Exit geometry applied.

Two methods were used to measure the solid circulating flux, *Gs*. One was based on the time accounting for the recirculation solids to accumulate to a certain height in the standpipe after a sudden close of a butterfly valve installed in the standpipe. The other method used a self-designed online solid circulating rate