



Visualization of gas-solid flow characteristics at the wall of a 60-meter-high transparent CFB riser

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ABSTRACT

Gas-solid flow characteristics at the riser wall were studied in a 60-meter-high transparent circulating fluidized bed (CFB) riser. The flowing processes of clusters were recorded by a high-speed camera. Through analyzing the pictures obtained in the 60 m riser, the coverage fraction of clusters at the riser wall f_c , the descent velocities of clusters at the riser wall U_c , the cluster-wall contact length L_c and the cluster-wall contact time τ_c were measured. Based on the experimental data, empirical formulas for estimating f_c , U_c , L_c in the 60 m riser (10 m above the distributor) were proposed. The results showed that both U_c and L_c obtained in the 60 m riser (10 m above the distributor) were larger than those obtained in risers lower than 15 m. τ_c varied between 0.07 s and 0.20 s under the experimental conditions.

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1. Introduction

Characterized by strong fuel adaptability, high combustion efficiency and low-cost emission control, circulating fluidized bed (CFB) boilers have been widely used [1–3]. To achieve a higher boiler efficiency, both the steam parameter and the capacity of CFB boiler were increased [4–6]. With the increase in boiler capacity, the furnaces of CFB boilers have become higher: the furnaces of 300 MW CFB boilers were usually 35–38 m in height [7]; the furnace of the Lagiza 460 MW supercritical CFB (SCCFB) boiler was 48 m in height [8]; the furnace of the Baima 600 MW SCCFB boiler even reached as high as 55 m [1,7,9]. As CFB boilers become massive, the gas-solid flow characteristics, especially those at the wall (f_c , U_c , L_c , τ_c) which have great influences on heat transfer, will be affected.

The ratio of the heat transfer between the wall and the clusters (or the disperse phase) is directly determined by f_c [10,11]. Both L_c and U_c decide τ_c , which is a key parameter of the convection heat transfer between the wall and the clusters [10–14]. Lints and Glicksman [15] found that f_c was a single-valued function of the cross-sectional average particle concentration ε_s and increased with the rising of ε_s . In addition, the positive influence of ε_s on f_c was also reported in the study of Liu et al. [16] and Yang and Leu [17]. However, Basu and Nag [14] suggested that f_c was mainly depended on the voidage at the wall, the voidage of

clusters and the particle concentration of disperse phase. The study on influence of polydispersity on cluster characteristics by Chew et al. [18,19] reported that f_c was mostly impacted by local position. In the research of Guenther and Breault [45], with the increase of solids circulation rate, cluster count decreased while cluster size increased towards the wall. U_c was measured by different scholars through different testing methods, and the results indicated that U_c was in a range from 0.1 m/s to 2.0 m/s [16,22–26]. The above data were usually applied to the heat transfer calculation of CFB [15,27,28]. In addition, Bi et al. [29] found that the combination of clusters would lead to the increase of U_c , while Liu et al. [16] concluded that U_c was rather insensitive to the operation parameters. Harris et al. [30] proposed a quadratic correlation to describe the relationship between U_c and the wall film thickness. Wu et al. [20] found that the particle suspension density had a positive effect on the characteristic residence length of the clusters, and proposed an empirical correlation to predict the length. In the later model of Wu et al. [27], the characteristic residence length of the clusters was considered as L_c . However, in the heat transfer calculation of a 600 MW SCCFB boiler, Cheng et al. [31] found that the calculated results were more reliable if L_c proposed by Wu et al. [27] was increased by ten times. Different methods were used to obtain τ_c [21,27,31–34]. τ_c can be calculated with the ratio of L_c to U_c [27,31], or by the relationship between L_c and the terminal velocity of the clusters at the wall [21]. Thorough analyzing the pictures taken from a video system, Wang et al. [32] found τ_c of typical clusters was about 0.1 s. High-resolution Eulerian simulation [33] and motion model of clusters [34] were also used to

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predict τ_c , the value of which was found to range from 0.02 s to 0.504 s depending on the operational parameters.

Although the gas-solid flow characteristics at the wall have been studied by many scholars, previous experiments were normally carried out in risers lower than 20 m [15–32], which were even not as high as half of the 600 MW SCCFB boiler furnace. Whether the results obtained in the low risers are applicable to the ultra-high risers still needs to be further examined. Hu et al. [7,35,36] studied the axial voidage distribution in 38 m/54 m CFB risers and found the optimal bed inventory for the saturation carrying capacity of gas. Nevertheless, studies on gas-solid flow characteristics at the wall of ultra-high riser were scarce.

To further explore the gas-solid flow characteristics at the wall of ultra-high riser, a high-speed camera was used to record the flowing processes of clusters at the wall of the transparent CFB riser with 60 m in height and 0.384 m in diameter. The hydrodynamic properties, including f_c , U_c , L_c and τ_c , have been studied.

2. Experiments

2.1. Experimental apparatus and material

As shown in Fig. 1, the experimental apparatus was mainly composed of a distributor, a 60 m riser, a cyclone, a return leg and a loop seal. The inner diameters of the transparent riser and the transparent return leg were 0.384 m and 0.060 m, respectively; the center line of the riser outlet was 59.5 m above the distributor ($h_r = 59.5$ m); and the gas was supplied by a high-pressure fluidized blower of the Baima 600 MW CFB boiler, with gauge pressure of 54 kPa. The experiments were conducted in Neijiang city of Sichuan province of China, and the relative air humidity there was about 80%, which weakened the electrostatic effect. At the same time, the hoops, which were made of steel, were used to fix the riser in every 2 m. During the experiment, the electron was conducted from the riser to the steel frame of the power plant by the hoops, so the electrostatic effect decreased further.

In the experiment process, particles were carried to the upper riser by the gas, and then flowed into the cyclone to be separated. After that, almost all the particles returned to the riser through the return leg and the loop seal in turn, and then participated in the next loop. The ultra-fine particles carried by the gas were collected by a bag-type dust remover connected to the cyclone.

The experimental material was Quartz sand with a particle density of 2660 kg/m³, a bulk density (ρ_b) of 1382 kg/m³ and a Sauter mean diameter of 200 μ m, the physical parameters of which were basically identical with those of the circulating ash in actual CFB boilers. In this

paper, the static bed height H_s is used to represent the total solid inventory I_v , and the conversion relation is shown as follows:

$$I_v = \frac{\pi}{4} D_r^2 H_s \rho_b \quad (1)$$

The main variables in the experiment were the superficial gas velocity U_g and the static bed height H_s . U_g was controlled to be in a range from 1.08 m/s to 5.23 m/s, and H_s ranged from 285 mm to 795 mm.

2.2. Measurement

There were 47 pressure taps along the riser's axial direction. The pressure taps P1, P2, P3 were located at the positions of the wind chamber, $h_r = 0.05$ m and $h_r = 1$ m respectively. From $h_r = 1$ m to $h_r = 31$ m, the pressure taps were installed at intervals of 2 m, while from $h_r = 31$ m to $h_r = 60$ m, the interval was 1 m.

The gas-solid flow state at the wall of the 60 m transparent riser was recorded by a JVC type high-speed camera, the shooting frequency of which was 500 Hz. The shooting positions were $h_r = 1$ m, 3 m, 10 m, 17 m, 25 m, 32 m, 46 m, 54 m, respectively.

U_g was measured online by a hot wire anemometer and a flute-form flowmeter at the air supply duct.

2.3. Experimental data processing

2.3.1. Cross-sectional average particle concentration ε_s

ε_s was derived by the pressure drop, as follows:

$$\Delta p / \Delta h_r = \rho_p g \varepsilon_s \quad (2)$$

$\Delta p / \Delta h_r$ was the average pressure gradient of the whole experiment process, which started when the experimental became stable and ended when the air supply was stopped. Due to the high separation performance of the cyclone, almost all the particles were separated and the particles collected by the bag-type dust remover were usually <2% of the initial total solid inventory after the experiment. As a result, $\Delta p / \Delta h_r$ maintained at a relatively stable value throughout the experiment. To make the differences in ε_s in the upper riser under varied operational conditions clearer, both the axial ε (voidage, i.e. $1 - \varepsilon_s$) profile and the axial $\Delta p / \Delta h_r$ profile were proposed in this paper.

2.3.2. Coverage fraction of clusters at the riser wall f_c

There were four successive steps to get f_c , as follows.

(I) The outline of the clusters was sketched and the clusters were shaded by drawing software, as shown in Fig. 2(b).

(II) The shaded clusters were cut out as Fig. 2(c) shows.

(III) As Fig. 2(c) was the projection of the actual shape, it was divided into 6 parts whose actual areas were equal according to the relationship between the eye distance and object distance, as shown in Fig. 2(d). The coverage fraction of clusters of each part was obtained by drawing software, the average of which was the actual instantaneous coverage fraction of clusters. Some typical pictures were shown in Fig. 2(e) to 2(s).

(IV) The total shooting time at each position was about 2 min and the time interval of selecting the images was 4 to 5 s. 25 pictures were selected at each position. The average of the actual instantaneous coverage fraction of clusters in the 25 pictures was considered as the actual time-averaged coverage fraction of clusters f_c . The analysis of f_c mainly focused on the area of $h_r > 10$ m.

2.3.3. Descent velocity of clusters at the riser wall U_c

There were three successive steps to get U_c , as follows.

(I) The video was converted into pictures at equal time interval τ_e , and the pictures were numbered as Pc_i in chronological order.

(II) The characteristic position of a cluster in different pictures (Pc_s and Pc_e) was found respectively, and d (the vertical displacement of

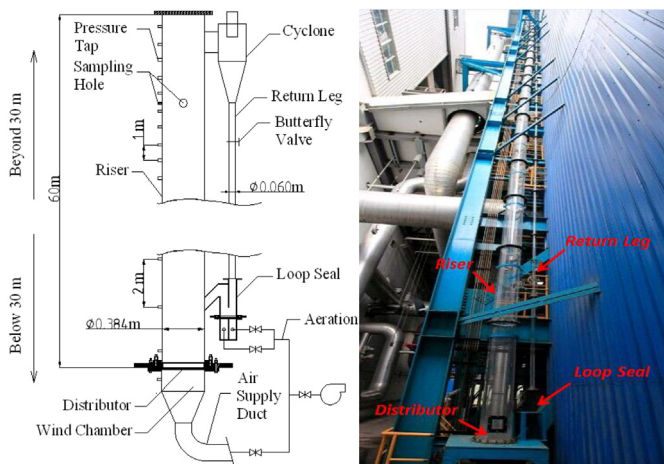


Fig. 1. The 60-metre-high transparent CFB cold experimental apparatus.

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