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Particle Circulation Rate in High-Temperature CFB: Measurement and Temperature Influence

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Introduction

The circulating fluidized bed (CFB), as one major type of chemical reactors and gas–solid contactors, has been widely applied to various industries. Compared with other types of fluidized beds, a distinctive characteristic of CFB is its circulation of a kind of solid particles, which may be catalyst, reactant, solid fuel, sorbent, heat carrier particles, and so on, between the riser and downcomer of the bed. Therefore, to determine how many particles are circulated, which is known as the particle circulation rate G_s, is one of the most basic points for designing, operating, and controlling a CFB. In response to this, the measurement and prediction of G_s has been one of the indispensable issues since the studies on CFB and its relative technologies were started early in the 1960s.[1] However, the measurements so far carried out are mostly in cold test rigs, causing the available equations for G_s to be completely based on such cold-model data. The practical applications with CFBs, such as fluid catalytic cracking (FCC) plants and CFB boilers, have few runs at room temperatures. Thus, for quite a long time we asked ourselves how the particle circulation rates G_s measured in room-temperature test rigs are representative of those occurring in actual hot and high-temperature facilities.

Although no direct measurement of G_s was made at actual running high temperatures, several indirect determination methods were proposed. A well-documented method is the use of a coolant pulse sent to the downward-moving particles inside the downcomer.[2,3] The coolant creates a locally low temperature and tracing this low temperature downstream the pulse input position determines then the speed of particles downward movement. With further the voidage of the particles in the downcomer, which is assumed to be equal to the minimum fluidization voidage, one can determine the particle circulation rate G_s. Another noteworthy proposal for measurement of G_s is by the pressure drop across the cyclone for the riser.[4] It was suggested that such a pressure drop is subject exclusively to the particle flux through the cyclone. However, the method requires a direct measure of G_s to build a calibration diagram in advance.

Why has no investigator measured the particle circulation rate G_s in high-temperature CFBs so far? The major reason should be the difficulty and tediousness of the measurement. The most accurate measurement method for G_s is the use of a switch (or dividing) valve, such as the inverse Y-type valve, mounted on the downcomer of a CFB. The valve makes it possible to collect the circulated particles into a standpipe in a time interval preset in a timer and in turn to weigh the collected particles to determine the particle circulation rate with high accuracy. Concerning beds running at room temperatures, it is surely easy and simple to conduct the measurement. This, however, is not so easy in the beds under temperatures, say, >873 K, because the commercially available switch valves are rarely resistant to such high temperatures. Besides, it is also dangerous and hard to handle the particles at >873 K collected in the standpipe.

Without accurately measured G_s values at actual running temperatures of up to 1173 K, for example, for decades we have been completely ignorant of how temperature affects G_s in CFBs. Therefore, this communication will deliver first a reliable measurement of the particle circulation rate G_s of a CFB running at temperatures of up to a few hundreds of degrees Celsius and then clarify how temperature influences G_s. Furthermore, how accurately the correlations quoted in Table 1 predict G_s will also be evaluated based on a comparison of our measured data with their estimated values.

Experimental and Results

The measure of G_s at temperatures of up to 1073 K (but 1173 K is also possible) was implemented with a newly designed

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Table 1. Correlations for G_s Referred to in the Article

Authors	Equations
Bi and Fan[5] *	$\frac{U_g}{\sqrt{gd_p}} = 21.6 \times Ar^{0.105}\left(\frac{G_s}{\rho_f U_g}\right)^{0.542}$
Shi and Reh[6]	$G_s \frac{2500}{\rho_p} = 26.4(Fr_p^*)^{1.4}$ $Fr_p^* = \frac{U_g - u_t}{\sqrt{gd_{16}}}\frac{\rho_g}{\rho_p - \rho_g} \times \left[4\left(1 - \frac{V_2}{V_1}\right)\right]^{1/4}\left(6.5\frac{Z_{mf}}{H_t}\right)^{1/2}$

*This equation was originally proposed to predict the so-called saturation capacity G_s^* to feature the regime transition between the so-called turbulent and fast fluidizations. However, it can be used to predict G_s when the gas–solid flow inside the riser has coexisting bottom dense and top dilute flow sections and further the flow state of the top dilute section varies only slightly with increases in the overall pressure drop across the riser.[7,8]

heat-resistant switch valve. Figure 1 shows a sketch of the structure of the valve, which consists mainly of a switch blade, a shaft, and a hanger that closes the blade and a part of the shaft into a chamber. A standpipe connecting to the hanger received the particles switched from the downcomer. Turning the switch blade through a handle on the shaft from the solid-line position to the dotted-line location illustrated in Figure 1 implemented the switch of the particle flow. As one may see from Figure 1, the use of a shaft, which is water-cooled and located in one side of the downcomer, ensured the valve's resistance to temperatures of up to 1173 K. Although water-cooling makes the part of the shaft inside the hanger resistant to such high temperatures, locating the shaft into one side of the hanger allows further the switch blade to stay away from the downcomer's high-temperature particle stream during the time without G_s measurement. The latter causes the switch blade to be usually off contact with hot particles because every measure of G_s lasts only tens of seconds or 1 to 2 min. In addition, a water-cooling pipe coil can be inserted into the bottom section of the standpipe to cool the high-temperature particles switched into the pipe. This would facilitate the handling for the hot particles held in the standpipe.

The actual measurement of G_s was conducted in a CFB facility shown in Figure 2, where the part denoted as "G_s measure" refers to the above-mentioned heat-resistant switch valve and its accompanying standpipe mounted into the downcomer [inner diameter (ID) = 52.7 mm] of the bed. This CFB facility was originally a dual fluidized bed gasification plant that had a restructured siphon shown in Figure 2 as the bubbling fluidized bed between the riser and downcomer.[9] This new type of siphon, called the reactor siphon,[10] not only controls the particle flow from the downcomer to riser but also serves as a chemical reactor. For example, when char combustion generating the entailed endothermic heat for fuel gasification occurs in the riser, the fuel gasification can be arranged into the BFB.[9] The riser of this CFB had an ID of 52.7 mm and a height of 6.4 m. The BFB was a rectangular two-dimensional bed (height: 1.98 m) having a 700-mm long expanded section above its base as the freeboard (see "side view of BFB" inside the upper dotted-line box). The cross-sectional areas of the base and freeboard were 370 × 80 and 370 × 160 mm^2, respectively.

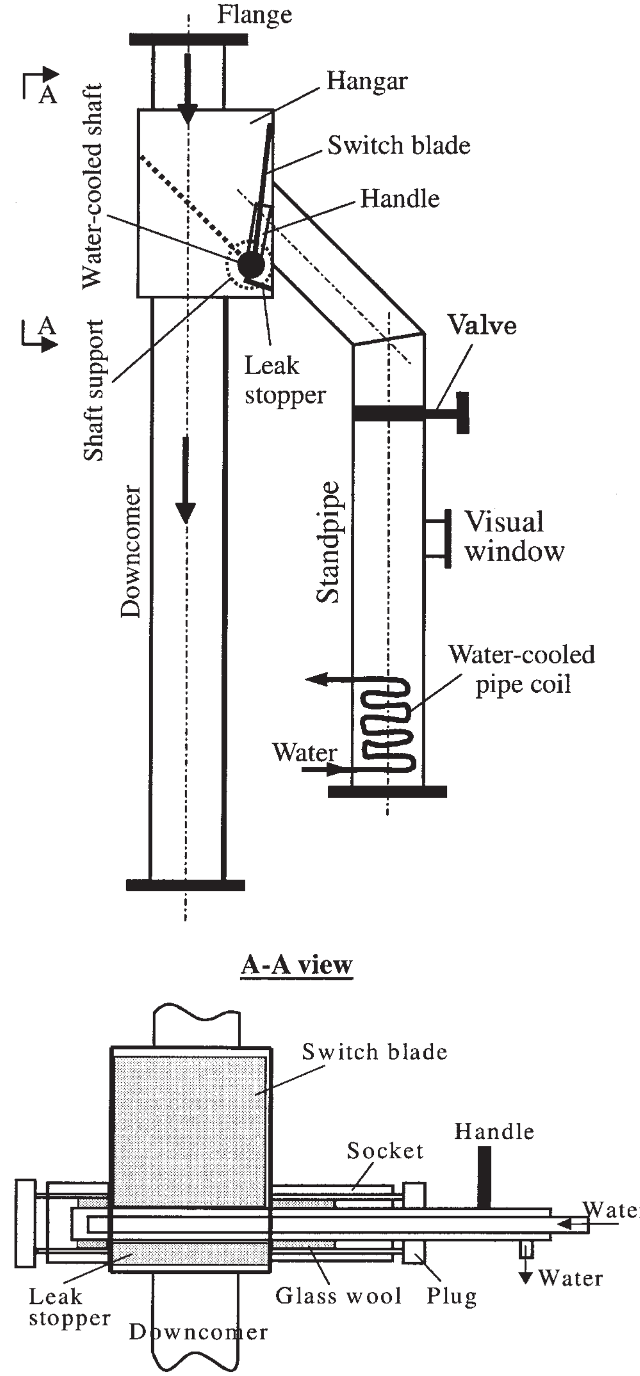

Figure 1. Designed heat-resistant particle switch valve for the use in high-temperature beds.

The BFB had a special "seal" to prevent the intermixing of gas between the riser and BFB.[10] This means the windbox of the BFB can have two different configurations, without and with a cut at the position beneath the seal wall (see "Windbox cut" inside the lower dotted-line box). Cutting the windbox was for making a relatively independent gas feed to the seal (F_{g2}). When there was no cut for the windbox a part of the gas supplied to the BFB (F_g) has to flow into the riser by the seal, which was found to be about 15% of the total flux F_g (being

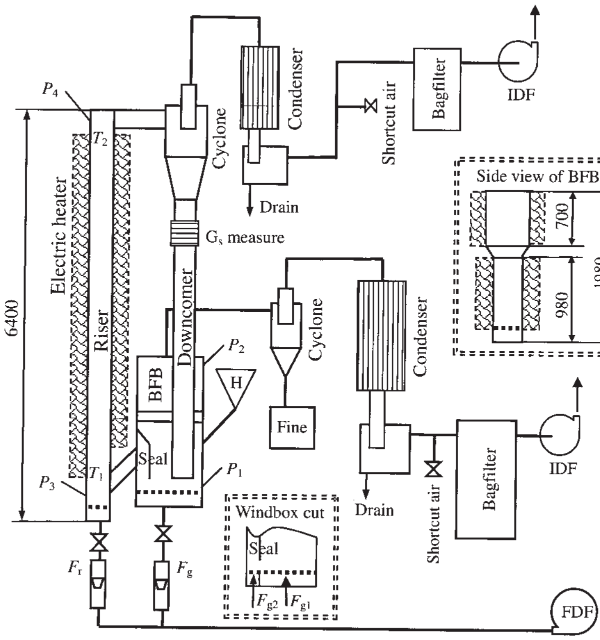

Figure 2. High-temperature experimental circulating fluidized bed.

determined with gas tracer method). Thus, the total gas flux used herein to calculate the superficial gas velocity U_g of the riser was $(F_r + 0.15F_g)$. Corresponding to this, such a total gas flux for U_g was $(F_r + F_{g2})$ in the case with a windbox cut for the BFB.

The riser and BFB were both electrically heated and temperatures of up to 1173 K were possible. Air from a common forward draft fan (FDF) was used as the fluidizing gas, whereas the silica sand characterized in Figure 3 constituted the particles tested. As indicated in Figure 2, both the riser and BFB had their independent gas condenser, bagfilter, and induction draft fan (IDF). Therefore, independent adjustment of the pressures inside the riser and BFB were allowed (through adjusting their respective shortcut air valves). According to Xu et al.,[10] the

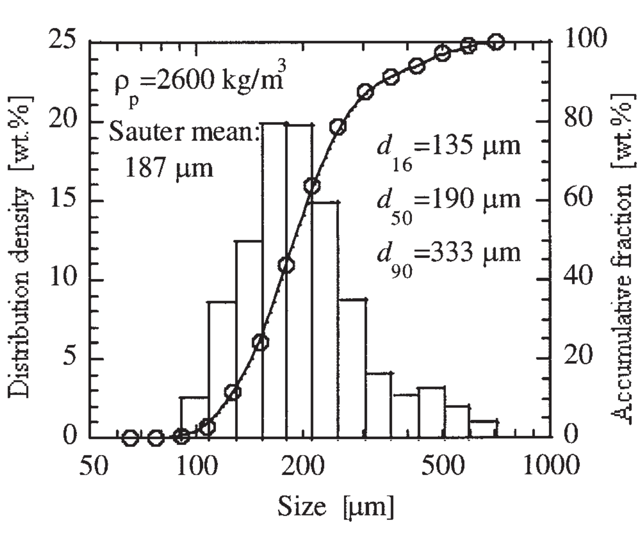

Figure 3. Major properties of the tested silica sand particles.

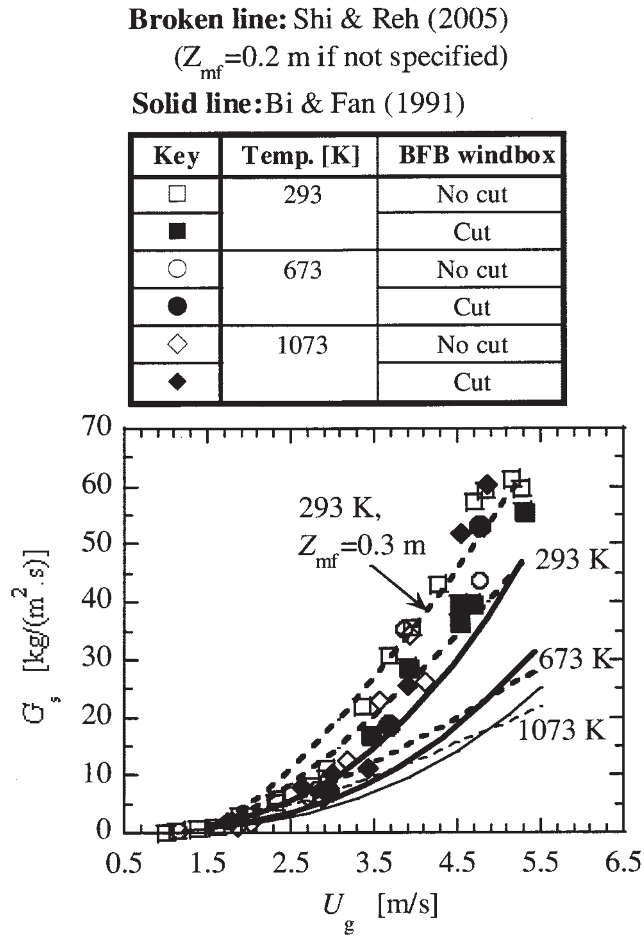

Figure 4. Solid circulation rate vs. superficial gas velocity measured at varied bed temperatures and a comparison of the measured values with predictions from the literature correlations listed in Table 1.

The property parameters used in the calculations are summarized in Table 2.

pressure difference between the BFB and riser greatly affect the particle circulation rate in the bed. Thus, in this work all the data reported herein were obtained at pressures of about −500 Pa in the top of the riser (P_4) and about −1800 and 6000 Pa in the top (P_2) and bottom (P_1) of the BFB. The equality of the indicated pressures P_1 and P_2 in all the tests also ensured the particle amount remaining in the CFB for a similar amount. All tests proceeded with similar temperatures in the BFB and rise, such that the axial temperature profile inside the riser was almost uniform. Thus, herein (in Figure 4) the average of the temperatures measured in the riser bottom (T_1) and top (T_2) was adopted to typify the temperature of the riser. Measurement of G_s was conducted for three temperatures: the room temperature (293 K) and about 673 and 1073 K. It was done with varied airflow F_r to the riser but under fixed F_g, if no windbox cut, or F_{g1} and F_{g2}, when with a windbox cut, to the BFB. Our early results[10] confirmed that, as long as the airflow to the BFB, which is a siphon as well, is considerably high, this flow rate should not greatly influence G_s. All the airflows were monitored and controlled with rotameters.

Table 2. Property Parameters of Air and Particles Used in Calculating G_s from Literature Correlations

Temp. (K)	ρ_f (km/m^3)	μ_f (kg/(m.s)	Particle Properties	Ar	u_t* (m/s)
293	1.251	1.76E-5		662.5	1.34
673	0.508	3.34E-5	In Fig. 3	74.7	1.15
1073	0.319	4.47E-5		26.2	0.95

*The listed u_t was estimated from the single particle force balance equation and drag coefficient reported in Xu and Li.[11]

Figure 4 shows the obtained experimental G_s values at three temperatures, where the gas velocity U_g refers to the values at the mentioned operating temperatures. Furthermore, the open and solid markers are for the cases without and with a windbox cut, respectively. It is obvious that at a given superficial gas velocity U_g both the tested cases led to a similar particle circulation rate G_s, showing in fact that the measurement itself had high reliability and accuracy. Furthermore, one can see that the data from different operating temperatures shared only a slight difference, demonstrating for the first time that the CFB's operating temperature does not greatly affect the bed's particle circulation rate.

Figure 4 also plots the G_s values at three temperatures estimated from the literature correlations summarized in Table 1. These correlations were developed based on experimental measurements at room temperatures.[5,6] The flow system calculated was the same as that used in our experiment, which was an air–sand flow inside a riser with an ID of 52.7 mm (D_t) and a height of 6.4 m (H_t). Table 2 summarizes the major property parameters, which are ρ_f, μ_f, Ar, and u_t, involved in the estimation under different temperatures. Figure 3 details the size distribution of the silica sand particles used, providing the necessarily required characteristic data about particles. The particle bed height Z_{mf} in the minimum fluidization state inside the riser, which is required by the equation proposed by Shi and Reh,[6] was determined roughly from the total pressure drop across the riser, say ($P_3 - P_4$), denoted in Figure 2. Because the experimentally detected ($P_3 - P_4$) varied from 2500 to 4500 Pa, Z_{mf} was set to be 0.2 and 0.3 m (for the case at 293 K) to indicate the lower and higher edges of such a pressure range, respectively. Figure 4 shows first that the cited correlations both produced an obvious and also similar influence of operating temperature on G_s (see $Z_{mf} = 0.2$ m for the equation of Shi and Reh[6]). At a given gas velocity U_g, increasing the operation temperature likely decreases G_s and the decreasing degree against a given temperature increase is higher when the temperature is lower.

Thus, the quoted correlations are unable to correctly predict the influence of temperature on G_s so that they cannot be used for high-temperature conditions. Nevertheless, from Figure 4 we can see that the estimated G_s value at 293 K, which is indicative of room temperature, is somehow representative of the attained experimental data. The correlation of Shi and Reh[6] with the higher Z_{mf} (=0.3 m) predicted well the data at higher U_g values (>3.5 m/s), whereas this correlation with the lower Z_{mf} (=0.2 m) and the equation proposed by Bi and Fan[5] both generated a more accurate prediction at the other lower U_g value. Thus, on the whole neither can fit all the experimental data, although the accuracy appears to be slightly better for the correlation of Shi and Reh. Nonetheless, the equation proposed by Bi and Fan is very simple to use.

Essentially, the operating temperature of a CFB exclusively influences the properties of gas to vary its ability to transport particles. Thus, the inability of the correlations listed in Table 1 for predicting the temperature influence indicates that the physical characteristics of gas, such as density and viscosity, are not properly correlated in their equations. Consequently, further investigation is needed concerning this aspect.

Conclusion

In summary, we can conclude that for CFBs the operating temperature in all likelihood scarcely affects the particle circulation rate G_s. This makes the experimental data and empirical predictions from the correlations for G_s acquired at room temperatures directly applicable to high-temperature conditions. The correlation itself, however, cannot be extended to the other higher temperatures. Through this work it was demonstrated as well that the correlations of Shi and Reh[6] and Bi and Fan[5] both reasonably predicted the variation tendency of G_s with U_g at 293 K, although neither completely reproduced all of our measurements. Thus, both, if used at about 293 K, should be recommended to compute the possible range of G_s, but the correlation from Shi and Reh is superior in that it is capable of considering the influences of a few parameters other than U_g, such as the secondary airflow rate and particle inventory in the whole bed (shown with Z_{mf}). Probably because of this, the correlation of Shi and Reh exhibited a slightly higher accuracy than that of the correlation proposed by Bi and Fan.

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Notation

- Ar = Archimedes number
- d_p = Sauter mean particle diameter, m
- d_i = particle diameter at accumulative fraction i% (i = 16, 50, 90), m
- D_t = inner diameter of riser, m
- F_i = airflow i (=r, g, $g1$, $g2$) illustrated in Figure 2, m^3 h^{-1}
- g = gravitational acceleration, m s^{-2}
- G_s = particle circulation rate, kg m^{-2} s^{-1}
- G_s^* = saturation carrying capacity, kg m^{-2} s^{-1}
- H_t = total height of riser, m
- P_i = pressure at position i (=1, . . . , 4) marked in Figure 2, Pa
- T_i = temperature at position i (=1, 2) marked in Figure 2, K
- u_t = terminal velocity based on d_p, m s^{-1}
- U_g = superficial gas velocity in riser, m s^{-1}
- V_1 = primary airflow rate, m^3 h^{-1}
- V_2 = secondary airflow rate, m^3 h^{-1}
- Z_{mf} = particle bed height equivalent to minimum fluidization state in riser, m

Greek letters

- μ_f = gas viscosity, kg m^{-1} s^{-1}

ρ_f = gas density, kg m^{-3}
ρ_p = particle density, kg m^{-3}

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