Review of flow regime in CFB standpipe and circulation rate measurement

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Abstract. The classification and characteristics of flow regimes in a circulating fluidized bed standpipe were briefly described. Based on the flow characteristics, several measuring methods of circulating flow rate in standpipe were introduced, including accumulation method, time-of-descent measurements, particle motion detection method, flowmeter method, and correlation method. Advantages and disadvantages of these methods were compared. It can be seen that at present, all measurement methods have some defects, which need to be further studied and improved.

1. Introduction
Circulating flow rate is one of the most important design parameters of circulating fluidized bed (CFB) boiler, which can reflect the gas-solid flow state in the furnace, and has an important influence on the mass and heat transfer characteristics, so it is necessary to measure the circulating flow rate. The measurement of circulating flow rate is mostly carried out in the standpipe. It is the basis of realizing the measurement of circulating flow rate to clarify the flow regime and flow characteristics in the standpipe. As an important part of CFB, the flow characteristics and stability of gas-solid two-phase flow in the standpipe are very important to the operation of CFB. The reverse pressure gradient flow of granular material in the CFB standpipe leads to the complexity of gas-solid two-phase flow. There are a large number of possible flow states in the standpipe, and each of them has different characteristics. This paper briefly describes the classification and characteristics of flow regimes in the CFB standpipe, and compares and analyzes the commonly used measurement methods of circulating flow rate.

2. Flow regime classification
In order to study the flow characteristics in CFB standpipe, the researchers classified the flow regimes in standpipe according to different criteria.

The first qualitatively phase regime diagram was proposed by Zenz [1]. Later, Kojabashian [2] made a quantitative analysis of the flow regime in the standpipe and proposed the flow pattern assuming a linear relationship between void fraction and gas-solid slip velocity, and he used the gas-solid slip velocity and \( \frac{u_{mf}}{\varepsilon_{mf}} \) to divide the gas-solid flow regime into fluidized solid flow and non-fluidized solid flow.

- Fluidized solid flow, \( u_{sl} > \frac{u_{mf}}{\varepsilon_{mf}}, \varepsilon > \varepsilon_{mf} \), and the particle is suspended;
• Non-fluidized solid flow, \( u_{sl} \approx u_{mf}/\varepsilon_{mf} \), and the particles move as a whole, with little relative motion. Non-fluidized solid flow is also called packed bed flow, moving bed flow or slip-stick flow.

Kojabashian divided the fluidized flow into three regions according to the direction of gas flow in the standpipe and the positive and negative of \( (\partial \varepsilon / \partial P)_{W_s, W_g} \), and further divided each region into two subgroups according to the existence of bubbles; non-fluidized flow is subdivided into the transition packed bed flow where voidage increases with slip velocity and the packed bed flow where voidage is not affected by slip velocity.

| Flow regime classification by Kojabashian. |
|--------------------------------------------|
| **Flow regimes**               | **Characterization formula**               |
| Non-fluidized solid flow         | Transition packed bed flow \( u_{sl} < u_{mf}/\varepsilon_{mf} \), \( \varepsilon \approx \varepsilon_{mf} \), \( \varepsilon = f(u_{sl}) \) |
| Packed bed flow                 | \( u_{sl} < 0 \), \( \varepsilon \approx \varepsilon_{mf} \) is constant |
| Fluidized solid flow            | Flow area I \( \varepsilon \approx \varepsilon_{p} \), \( \varepsilon \) is constant |
| The gas is flowing upwards      | \( (\partial \varepsilon / \partial P)_{W_s, W_g} < 0 \) No bubble |
| Flow area II \( \varepsilon \approx \varepsilon_{p} \), \( \varepsilon \) is constant |
| The gas is flowing downwards    | \( (\partial \varepsilon / \partial P)_{W_s, W_g} > 0 \) No bubble |
| Flow area III \( \varepsilon \approx \varepsilon_{p} \), \( \varepsilon \) is constant |
| The gas is flowing downwards    | \( (\partial \varepsilon / \partial P)_{W_s, W_g} < 0 \) No bubble |

Leung and Jones [3] proposed the flow pattern based on a more realistic relationship between slip velocity and voidage, and the flow pattern is similar to that proposed by Kojabashian. As for Kojabashian's classification of fluidized flow in the standpipe, Leung et al. [4] thought that area I was very rare in reality; the voidage of area I and III decreased along the standpipe, while the voidage of area II increased along the standpipe; therefore, area I and III were uniformly classified as Dense Phase Fluidized Solid Flow (DENFLO), and area II was classified as Lean Phase Fluidized Solid Flow (LEANFLO).

Leung et al. [5] modified and simplified the flow pattern classification of Kojabashian and proposed their own classification method.

| Flow regime classification by Leung et al. |
|--------------------------------------------|
| **Flow regimes**               | **Characterization formula**               |
| Non-Fluidized Regime            | Transition Packed Bed Flow \( (TRANPACFLO) \) \( 0 < u_{sl} < u_{mf}/\varepsilon_{mf} \) \( \varepsilon \approx \varepsilon_{mf} \), \( \varepsilon = f(u_{sl}) \) |
| Packed Bed Flow \( (PACFLO) \)   | \( u_{mf} \approx 0 \) \( \varepsilon \approx \varepsilon_{p} \), \( \varepsilon \) is constant |
| Fluidized Regime                | Dense Phase Fluidized Solid Flow \( (DENFLO) \) \( u_{sl} \approx u_{mf}/\varepsilon_{mf} \) \( \varepsilon \approx \varepsilon_{mf} \) \( (\partial u_{sl} / \partial \varepsilon)_{W_s} > 0 \) |
### 3. Flow regime in CFB standpipe

Depending on the amount and direction of air intake at the bottom of the standpipe, the material in the standpipe may be in a moving bed or a fluidized bed [9-10].

At present, most models in literature assume that the flow state in standpipe is moving bed [11], moving packed bed [19], minimum fluidization [20-21] or minimum fluidization/moving bed [22-23].

In fact, there may be many different flow systems in the standpipe, and it is even possible to coexist two different flow systems in the same standpipe. Therefore, the judgment of the flow state in the standpipe has always been controversial in the academic circle.

Kunii and Levenspiel [24] described a coexistence of LEANFLO in the top and PACFLO (or TRANPACFLO) in the bottom of standpipe. Leung and Wilson [25] described a coexistence of DENFLO in the top and PACFLO (or TRANPACFLO) in the bottom of standpipe. Judd and Rowe [26] described a coexistence of LEANFLO in the top and DENFLO in the bottom of standpipe.

Geldart et al. [27] observed the pressure profile of the standpipe and found that the apparent density increased from top to bottom. Wang et al. [28] found that flow in the standpipe can be divided into three regions, namely inlet, dilute and dense flow, through observation of the axial pressure profile. The inlet region is characterized by that pressure gradient is nearly zero, and the dense phase flow can be divided into fluidized (preferred) or packed.

Ji et al. [29] carried out experiments on the gas-solid two-phase flow rule in the standpipe under different working conditions in a large-scale cold mold. It was found that the flow regime is a coexistence of the upper dilute phase fluidization and the lower dense phase fluidization. When the gas volume continued to rise, the gas node would appear in the standpipe. When the gas volume decreased, the flow pattern in dense phase tended to be non-fluidized.

Li et al. [30] thought that the direction of net gas flow in the standpipe varies with the solid circulation rate according to his experimental results, and there is a critical solid circulation rate. Wei et al. [9] confirmed that the flow state in the standpipe is related to the particle mass flow rate $G_s$ through establishment of the calculation model and experimental research. There is a critical particle mass flow rate ($G_{sc}$). When the particle mass flow rate $G_s$ is lower than $G_{sc}$, the flow pattern in the standpipe is composed of dilute phase flow in the upper zone and dense phase flow in the lower zone. With the increase of $G_s$, the dilute-dense phase interface moves down; until $G_s>G_{sc}$, the dilute-dense phase interface disappears, and the flow pattern changes into a single concentrated phase transport regime, namely DENFLO.
4. Circulation rate measurement method
Circulating flow rate is one of the most important design parameters of CFB boiler. By associating gas velocity $u_r$ with circulation rate $G$, Yue et al. [31] proposed Fluidization State Specification (FSS) block diagram for the design of CFB boiler. It is necessary to measure the circulating flow rate, as it can reflect the gas-solid flow state in the furnace. At present, the main methods to measure the circulation rate include accumulation method, time-of-descent method, particle motion detection method, flowmeter method and correlation method, etc.

4.1. Accumulation method
The accumulation method is a method of measuring the accumulation rate of solid particles by stopping the flow. The principle is to close the permeation valve and form a fixed bed with a continuous accumulation of height. Solid particles accumulate in a short enough time (assuming that accumulation and consumption of solids in different parts of the system do not affect the overall behavior). Then the circulation rate can be obtained by measuring the solid accumulation rate at the butterfly valve and linking it with the pressure change.

Previous researchers have used porous butterfly valves [32-33], a purged slide valve [34] or diversion into a collecting vessel [35] to accumulate solids over times. Harris et al. [36] collected solid particles by using a slot flow meter (SFM), which was calibrated by an in situ technique, and this technique was based on the dynamic response to change of input flow. Bodelin et al. [37] installed a weighing funnel on the standpipe, allowing solids to accumulate in the funnel by shutting down mechanical valves. Kreuzeder et al. [38] measured the circulation rate by tracking the rate of solid accumulation height change per unit time in the L-shaped section of the transmission pipe under closed fluidized air condition.

Although, the technique is highly intrusive and can cause variations in standpipe operation. The system pressure and fluid flow will change as the solid particles no longer return to the standpipe, which will result in system errors. It was found that the pressure drop of the riser changed during the experiment process when using this method [40]. In addition, the accumulation method can only be used under a stable operating condition, and is not suitable for high temperature environment.

4.2. Time-of-descent measurement
The principle of time-of-descent measurement is to determine the circulation rate by measuring the falling time of an identifiable particle in the standpipe.

Patience et al. [41] measured the circulating flow rate by time-of-descent measurement, and studied the relationship between the riser pressure drop and circulating flow rate. Muir et al. [42] installed a settler in the standpipe, which was dragged down by the solid particles. The circulating flow rate was calculated by measuring the time that the settler took to move a specified distance.

Although time-of-descent measurement has no interference to the circulation system, it is greatly affected by the accuracy of the timing device and the material of the measuring section.

4.3. Particle motion detection method
In addition to the time-of-descent measurements, there are some other particle motion detection methods, such as optics, tracers, acoustics, electricity and so on.

4.3.1. Optical method. Oki et al. [43] developed a method for measuring the velocity of solid particles by using a fiber optic probe. Dong et al. [44] used an optical fiber probe to measure the radial distribution of particle velocity and the circulation rate of particles. Song et al. [45] measured the circulating flow rate at room temperature with a special high-temperature fiber optic probe. Using optical techniques, differential pressure techniques and particle extraction techniques, Medrano et al. [46] measured the circulating flow rate between the air reactor and the membrane assisted fuel reactor in a two-dimensional interconnected reactor system.
4.3.2. **Tracer method.** Kuramoto et al. [47] added fluorescent dye-coated tracers into the circulating system and detected their movement with two fiber-optic probes at different heights in the standpipe. Both Wei et al. [48] and Li et al. [49] used gas tracers, the difference is that Wei connected the bottom of the standpipe to the dense phase zone of the riser, while Li artificially isolated the standpipe from the overall system[50]. Bhusarapu et al. [51] tracked the movement of one radioactive tracer particle in the CFB standpipe operated at ambient pressure and temperature. Guio-Perez et al. [52] used ferromagnetic particles as tracers and used inductive coils to track them.

4.3.3. **Acoustic method.** The dynamic system of particles produces acoustic interference due to its own nature, which can be used to provide information of process monitoring and control. The particles also respond positively to acoustic signals applied to them.

Davies et al. [53] tried to use sound pressure wave to obtain the solid flow rate, and the results showed that this method was relatively accurate for the prediction of large particles, while the prediction of small particles was quite different from the reality. Ellis et al. [54] used acoustic emission sensors to measure the solid flow rate at room temperature. Chorpening et al. [55] used a microwave Doppler system to detect sliding or intermittent flows of particles.

4.3.4. **Electrical method.** Spenik et al. [56] used a piezoelectric pressure sensor to measure the size and density of particles to obtain the mass flow rate in the riser, which can be referred to in the measurement of the standpipe.

4.4. **Flowmeter method**

4.4.1. **Impacting flowmeter.** In many cases, flow in standpipe is non-fluidized bed flow, also known as plug flow[57]. The solid-phase velocity of the plug flow is considered uniform throughout the standpipe. The bulk density of solids changes little with solid phase velocity, and the average velocity of solids in the standpipe is approximately equal to the local velocity[58]. The gas-solid mixture in the standpipe can be regarded as a quasi-fluid[59]. The impacting flowmeter is more effective for particles in the state of free fall or non-pneumatic transport. The principle of impacting flowmeter method is to calculate the circulating flow rate by measuring the force of falling particles on the target.

Judd and Bernhardt [60] placed a cylinder perpendicular to the flow direction in the dense phase of the standpipe and obtained the particle flow rate by measuring the drag force on the cylinder. Wu et al. [61] installed a double-ended wire mesh baffle with a rotating shaft on the top of the standpipe.

Wu et al. [62] developed a kind of flowmeter which worked by measuring the torque of a hinged plate when falling solids impacted the plate. Similarly, Hu et al. [63] designed an impacting flowmeter to measure the impact force of solid particles by means of bending moment and strain, and realized online measurement.

4.4.2. **Turbine flowmeter.** Compared with impacting flowmeter, turbine flowmeter is favored by many researchers because of its high sensitivity and less interference to particle flow.

Liu et al. [64] placed an impeller flowmeter in the dense phase section of the standpipe. The special impeller would rotate under the push of materials, and the volume flow rate of particles through the standpipe could be obtained by measuring the rotating speed of the impeller. Ludlow et al. [65] installed a rotating spiral blade made of glass fiber in the standpipe, determined the average velocity of solid flow by recording the solid accumulation rate under the condition of stopping the solid circulation, and measured the rate of pressure drop change to determine the solid cycle rate.

4.5. **Correlation method**

It is difficult to measure the flow state of the standpipe directly, so some researchers have shifted the direction to such easily measurable parameters as pressure, and obtained the circulating flow rate through correlation method.
Based on the related literature and experimental data of a cold dual fluidized bed, Lim et al. [66] established an correlation relationship by using four dimensionless numbers $Fr, Re, u_0/u_t, \rho_s/\rho_g$ as the key parameters to estimate the solid circulation rate under high solid-gas density ratio. The correlation was verified by the literature data of a dual fluidized bed steam gasifier at high temperature, and the results show that the maximum deviation of the estimate is 25%.

In a circulating fluidized bed, control of the solid circulation rate can be achieved by changing the opening of the mechanical valve at the bottom of the standpipe. Grieco and Marmo [67] modified the predictive equation proposed by Jones and Davidson [68] and Cheng [69] and established the relationship between the pressure drop of the mechanical valve and the flow of solids through the control valve at room temperature.

Monazam and Shadle [70] adopted a transient method: stopping the solid phase flow into the standpipe when the standpipe was in the state of full dense transportation, then analyzing the derivative of the transient pressure drop of the standpipe with respect to time, and correlating the solid circulation rate with the axial pressure distribution and the solid holdup of the riser.

4.6. Others
In addition, Burkell et al. 366] also studied the modified orifice meter and calorimetric method, and conducted comparative analysis with the permeable valve accumulation method, time-of-descent measurement and impacting meter mentioned above. The results showed that the pressure drop obtained by the modified orifice meter was too small to be recorded under low circulation rate, and it was also difficult to measure under high circulation rate because of the great fluctuation of pressure drop. The problem of calorimetric method was that the pipe had radial temperature gradient and the heat loss in the test section could not be accurately determined, so the accuracy was low, and the measurement would cause additional heat loss. These two methods have many defects and are difficult to be widely used.

4.7. Summary
In general, the accumulation method is simple to operate, but it has a great disturbance to the system, and the changing conditions cannot be measured. Time-of-descent measurement has no interference to the flow in the tube, but it requires more experimental equipment and measuring equipment, and cannot be measured online. Optics, tracers, acoustics, electricity and other methods for particle motion detection use relatively advanced technologies, the specific accuracy of which remains to be studied. The flowmeter method has the characteristics of online measurement and low interference to flow. However, the friction resistance brought by the rotating elements in the turbine flowmeter may influence the experiment and the impacting flowmeter has a slightly insufficient measuring capacity under high circulation rate and high temperature. And it is inevitable that the correlation method has errors.

Therefore, the measurement method and technology of circulating flow rate still need to be further studied and improved.

5. Conclusion
The flow pattern in CFB standpipe is generally divided into fluidized flow and non-fluidized flow. Fluidized flow can be divided into dense phase fluidized solids flow and lean phase fluidized solids flow, or bubbling fluidized flow and non-bubbling fluidized flow. Non-fluidized flow can be divided into transition packed bed flow and packed bed flow.

The gas-solid two-phase flow in the standpipe presents a variety of flow state superposition, and it is generally assumed to be moving bed flow in the simulation.

An ideal measurement technology of circulating flow rate in standpipe should have the characteristics of online measurement, no interference to the steady flow in standpipe, large range and applicable to high temperature operation. The main methods to measure the circulation rate include accumulation method, time-of-descent measurement, particle motion detection method, flowmeter
method and correlation method, etc. However, all of these measurement methods have some defects at present. Therefore, the measurement methods and techniques need to be further studied and improved.

Acknowledgments
This study was supported by the National Key R&D Program of China (No. 2018YFF0216000).

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