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The 14th International Conference on Fluidization – From Fundamentals to Products

Refereed Proceedings

2013

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# COMPARISON OF FOUR DIFFERENT METHODS FOR MEASURING THE SOLIDS CIRCULATION RATE IN CIRCULATING FLUIDIZED BEDS

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**ABSTRACT**
In this work four different methods are proposed for the measurement of the solids circulation rate in the scaled cold flow model of a circulating fluidized bed (CFB) facility; the study is ultimately aimed to transfer the most suitable method to the corresponding oxyfuel combustion CFB pilot plant. The configuration of a screw conveyor by-passing the loop-seal provides additional possibilities for the determination of the circulation rate. Further the influence of the circulation rate on the horizontal pressure difference in the loop-seal was investigated.

Method 1 and 2 cannot be applied for the hot oxyfuel pilot plant as optical principles are used in both cases. Method 3 as well as method 4 are suitable for a transfer to the oxyfuel pilot plant as they can be performed on-line and require only simple calibration. Further the results indicated a linear correlation between the circulation rate and the horizontal pressure difference in the loop-seal for the conditions studied here.

**INTRODUCTION**
In many chemical processes gas-solids contact is an important requirement. In these processes contact between the particle and the fluid is realized in form of a circulating fluidized bed, where “the fluid phase operates in a “flow through” mode, whereas the solid phase circulates in a closed loop” (1). An important parameter to quantify heat and mass transportation and thus showing the quality of the reactor, is the circulation rate. Circulation rate measurements can be categorized into 6 groups, these being: “optical, radioactive, electrical, tracer, acoustical, heat/mass transfer and mechanical” (2). Additionally, a distinction must be made between methods which are invasive and ones which are not, furthermore some methods will require calibration, others won’t. The ideal method of measuring the circulation rate of a fluidized bed facility is non-invasive; it would also need no calibration, and would be flexible in terms of fluidization rates and temperatures (2).

Numerous experiments have been conducted in order to measure the solids circulation rate in CFB-facilities. Burkell et al.(3) measured the circulation rate by means of closing a permeable butterfly valve in the return leg, this led to an accumulation of solids. The temporal pressure difference across the valve is monitored and measured. The method was only classified appropriate for small-scale models due to higher interference in large-scale models. Burkell et al. (3) also used a method in which “the time for identifiable particles to descend through a known distance in a transparent section of a standpipe through which the solids return in moving packed bed flow" (3) was measured. Although both mentioned methods cannot be used for on-line measurement of the circulation rate, the latter method is very accurate and reliable, can however be impractical for small particles. A particularly elegant calorimetric method was also investigated by Burkell et al. (3). A cooling jacket, through which cooling water or air flows, is mounted to a heat transfer section of the facility. Both temperature difference and mass flow of the cooling medium before and after the jacket is measured; along with the temperature difference of solids before and after the heat transfer section. The circulation rate can then be estimated from a simple heat balance. Despite elaborate calibration, this on-line method proved to be dependable over a broad range of conditions.

By conducting two sets of experiments in a section of the downcomer where plug-flow was provided Bhusarapu et al. (2) as well as Roy et al. (1) used non-invasive radioactive methods to measure the solids circulation rate. The fundamental idea was to determine the solids volumetric flow by measuring the cross-sectional area, the cross-sectional averaged solids holdup along with the solids velocity. Mass flux can then be calculated with knowledge of the particle density. Initial experiments determined solids holdup by scanning the cross section of the downcomer using one radioactive source and one detector.

These experiments were conducted in various operating modes so a calibration curve could be established. Subsequently, solids velocity was determined in various operating modes by measuring the falling time of a single radioactive tracer particle between two detectors mounted on the downcomer. The requirement for the tracer particle, besides similar size and density as the particles used as inventory, is a relatively short half-life so it is harmless once it is no longer needed. After these experiments, a calibration curve for the circulation rate as a function of the fluidization rate can be created. Detailed information on these experiments can be found elsewhere (1; 2).

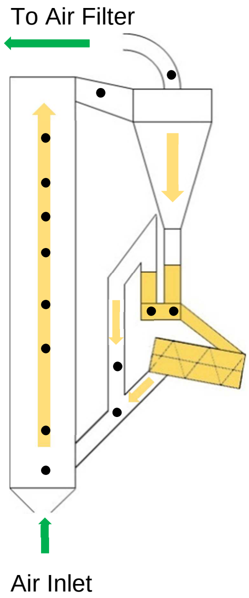


**Figure 1** – Schematic illustration of the cold flow model utilized (black dots represent the location of pressure-taps)

## EXPERIMENTAL

### Experimental Setup

The cold flow model used throughout this study is a geometrical miniaturization of the hot facility on a scale of 1:3 and is made of acrylic glass. During testing dry air is utilized to fluidize an inventory of bronze particles with a mean diameter of 54µm at atmospheric pressure; all experiments were carried out with an inventory of 2,2 kg. These values have been assumed as given, further dimensionless basic equations describing the movement of gaseous and solid material, such as Reynolds', Archimedes' and Froude's numbers, as well as the density ratio and the ratio inner

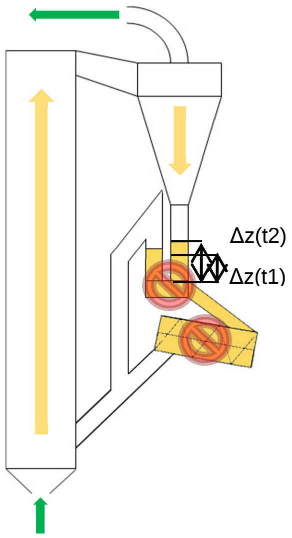


**Figure 2**- Schematic illustration of method 1

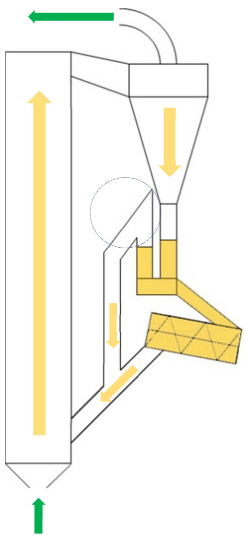

**Figure 3** - Schematic illustration of Method 2

diameter to diameter of the particles, are calculated for both facilities and the remaining parameters are chosen in a way that the ratios of non-dimensional operating figures approximated closely to 1 (4). As seen in Figure 1, the bed material is transported from a vertical 0,05m diameter, 1,68m high riser section of the facility to a cyclone where the gaseous phase is directed towards the outlet and the solids fall down into the loop-seal. Depending on the facilities settings, the solids either pass through a calibrated screw conveyor or through the loop-seal in order to return to the riser; this configuration provides additional possibilities for the determination of the circulation rate.

## Experimental Procedure

**Method 1:** During operation with activated loop-seal fluidization and deactivated screw conveyor, loop-seal fluidization is abruptly turned off. Due to this, the bed material is no longer transported via the loop-seal towards the riser; it accumulates in the downcomer instead (see Figure 2). The height of the accumulated material along with the time of accumulation is measured, together with the bulk density of the fixed bed and the cross-section, a rough approximation of the mass flux can be calculated in accordance with the following equation:

$$\dot{m} = \frac{\Delta z}{\Delta t} * \rho_B * A_{Downcomer}$$

The result of this method serves as a guide-value for the upcoming methods.

**Method 2:** The screw conveyor as well as loop-seal fluidization are turned on. Due to this the bed material is transported towards the riser via the loop-seal as well as the screw conveyor (see Figure 3). The conveyor frequency is systematically increased until all solids are transported via the screw conveyor, the transport rate of the conveyor is then equal to the solids transport rate in the riser. Mass flux can easily be determined by multiplying the spiral conveyor frequency with the gradient of the calibration curve:

$$\dot{m} = k_{Conveyor} * f_{Conveyor}$$

**Method 3:** This method depends on the idea that a specific pressure difference in the riser can be assigned to a specific circulation rate at a given inventory, due to the fact that the pressure difference in the riser is proportional to

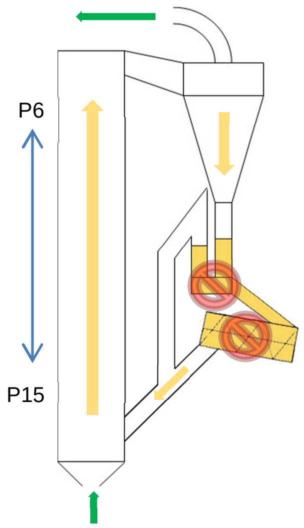


**Figure 4** - Schematic illustration of method 3 – adjustment of screw conveyor frequency

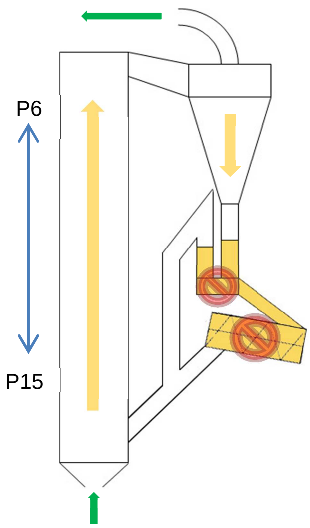


**Figure 5** - Schematic illustration of method 4 – Measurement of the pressure difference in the riser

the mass of solids therein. According to this theory there must be more mass of solids in the riser at higher circulation rates. In order to perform this method the facility must be operated with inactive screw conveyor and activated loop-seal fluidization, after which the pressure difference in the riser must be measured. After this loop-seal fluidization is deactivated and the screw conveyor's speed is increased until the same pressure difference in the riser is reached, as during operation with activated loop-seal fluidization and the screw conveyor turned off (see Figure 4). Once the desired pressure difference in the riser is reached, the mass flux can be determined in the same way as in Method 2.

**Method 4:** During operation with activated loop-seal fluidization and inactive screw conveyor, the loop-seal fluidization is abruptly deactivated. This leads to the transportation of bed material from the riser to the downcomer where it is accumulated. In the very first seconds of the emptying of the riser, the pressure difference in the riser is measured (see Figure 5). As already mentioned the measured pressure difference in the riser correlates with the mass of solids in the riser. Therefore, the temporal pressure difference must correlate with mass flux as well as with the circulation rate. The average cross-sectional mass is calculated according to:

$$\frac{d\Delta p_{Riser}}{dt} = \frac{dm_{Riser}}{dt} * \frac{g}{A_{Riser}}$$

## RESULTS

Figures 6 and 7 represent the summary of results; the graphs show nearly linear correlation of the circulation rate to the superficial velocity in the riser as well as the horizontal pressure difference in the loop-seal; with the exception of method 4. The reason for this is that the pressure build-up in the pressure hoses, connecting the pressure acquisition system with the pressure tap on the facility, is slowed down by the fact that the limited gas flow rate through the constriction at the riser wall, together with the volume of the pressure hose, result in a time-delay of the recorded pressure signal compared to the actual system pressure in the riser, further leading to an incorrect calculation of the circulation rate. The reason for this effect can be reduced to the volume of the pressure hose since the cross-sectional area and the flow remained roughly the same during all experiments.

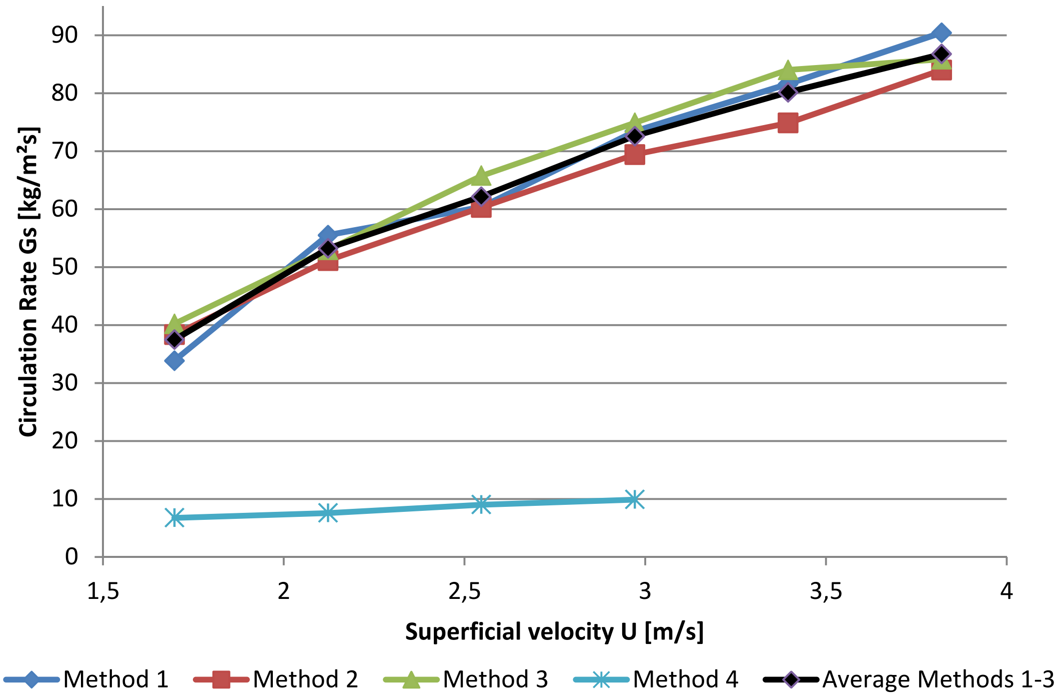


**Figure 6 –** Comparison of the results of circulation rates versus superficial velocity of the four methods and an average value of methods 1 to 3.

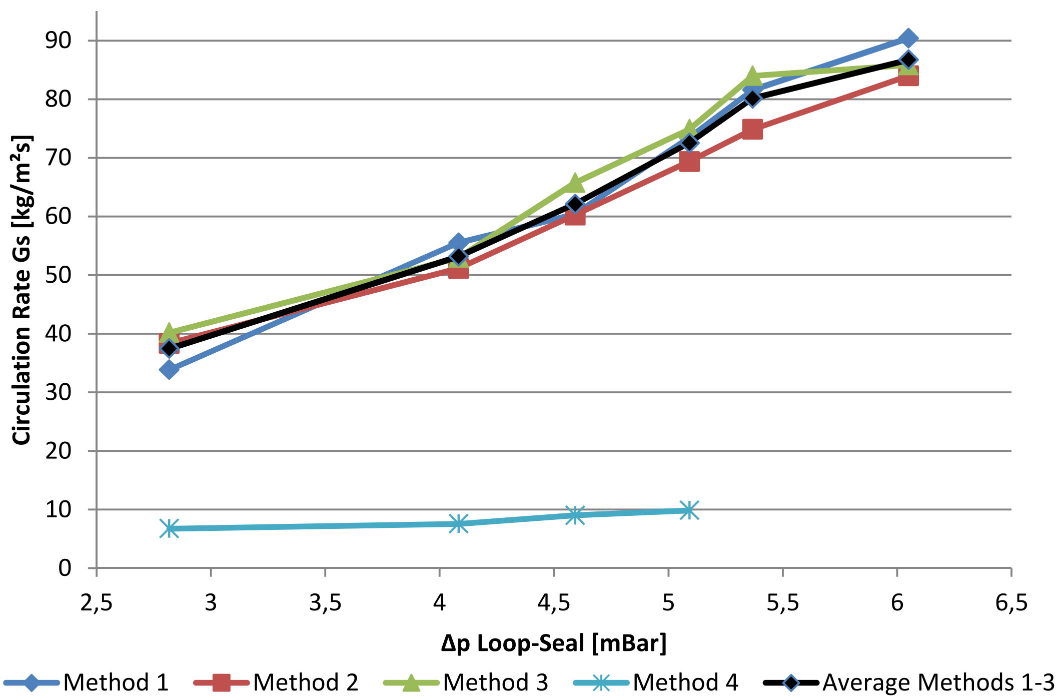


**Figure 7 –** Comparison of the results of circulation rates versus loop-seal pressure drop of the four methods and an average value of methods 1 to 3.

In Figure 8, the predicted pressure difference in the loop-seal is calculated using the linear average of results from methods 1, 2 and 3, these results are then compared with the measured pressure difference in the loop-seal. The two solid lines represent a ±10% deviation whereas the dotted line represents a perfect match of the predicted to the measured results. As it can be seen, the calculated pressure difference shows very low deviation from the measured results. This means that if the pressure difference were used to calculate the circulation rate, it would not deviate greatly from the linear average measured with methods 1, 2 and 3. However, the problem concerning the horizontal pressure difference in the loop-seal is that it is dependent on the loop-seal fluidization conditions. Further testing is required to determine the influence of the loop-seal fluidization rate on the horizontal pressure difference.

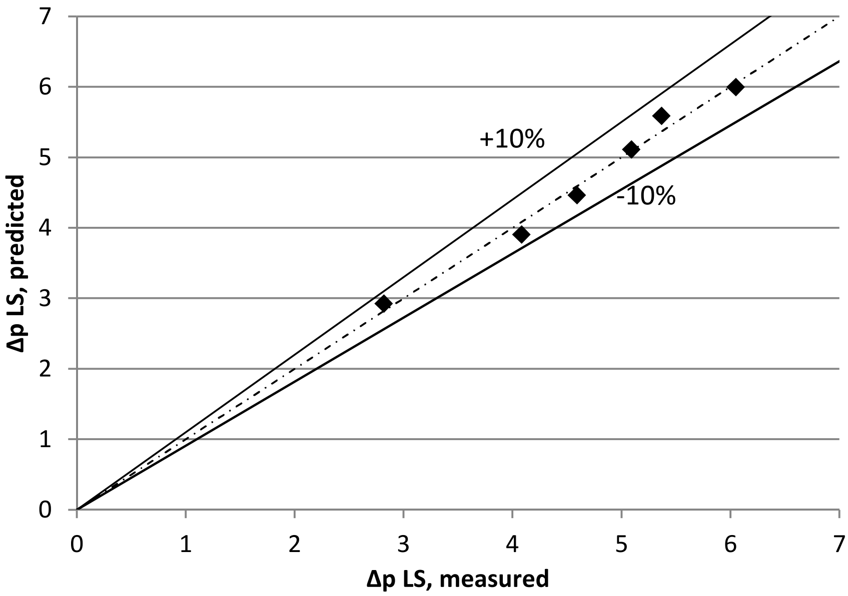


**Figure 8 –** Relation between predicted and measured pressure difference in the loop-seal

## CONCLUSION

Generally, low deviation from the linear average can be observed when correlating the circulation rate and the pressure difference in the loop-seal, since there is a relation between the pressure difference and the friction forces of the particles as they move through the loop-seal (5).

Though one might expect a quadratic correlation of the pressure difference in the loop-seal or the superficial velocity from the circulation rate due to the equation:

$$\Delta p = \lambda * \frac{U_S^2}{2} * \frac{A_{Wall}}{A_{Cross.\ Sec.}} * \rho_B$$

(6)

Testing shows that a linear relationship is accurate enough for the estimation of the circulation rate for the chosen operating parameters. More testing must be conducted in order to prove whether this correlation is linear or rather quadratic. Further the pressure difference of the loop-seal can be used as an accurate on-line method for circulation rate determination if a calibration is performed using a reliable measuring technique beforehand.

As shown in Figures 6 and 7, all methods excluding method 4 show similar results, yet some methods are more suitable for application or transfer to the hot pilot plant than others. The two optical methods: method 1 and method 2 are among the least practical measuring techniques, they are most prone to error and can only be used on-line if they are calibrated with the pressure difference in the loop-seal. In addition these two methods cannot be transferred to the hot facility without modification of the existing facility, as the downcomer and loop-seal are not transparent. Transfer of method 3 to the hot facility can be recommended not only because it is the least time consuming of the four methods, it solely requires calibration of the screw conveyor. There is also potential for on-line measurement of the circulation rate with method 3 if the screw conveyor frequency is continuously adjusted to keep the pressure difference in the riser constant. Small screw conveyors can be recommended in order to achieve high frequencies so the screw conveyor's irregular behavior does not show peaks in the riser's differential pressure.

Method 4 has been chosen for transfer to the 100kW oxyfuel pilot plant for its convenience, as the method can be operated in an on-line fashion and it requires simple calibration. Pressure sensors mounted directly to the riser walls, eliminate the unwanted effect observed in the cold flow model experiments and circulation rate measurements from the oxyfuel pilot plant have shown satisfactory results.

## NOTATION

| | |
|---|---|
| $A_{Cross.\ Sec.}$ | Cross-sectional area |
| $A_{Downcomer}$ | Cross-sectional area of downcomer |
| $A_{Riser}$ | Cross-sectional area of the riser |
| $A_{Wall}$ | Wall area |
| $f_{Conveyor}$ | Frequency screw conveyor |
| $g$ | Gravitational acceleration |
| $G_S$ | Circulation rate |
| $k_{Conveyor}$ | Gradient of screw conveyor calibration curve |
| $\dot{m}$ | Mass flux |
| $\dot{m}_{Riser}$ | Mass flux riser |
| $U$ | Superficial velocity |
| $U_S$ | Solids velocity |
| $\dot{V}$ | Volume flow of primary fluidization gas |
| $\Delta p_{Riser}$ | Pressure difference in riser |
| $\Delta p_{LS}$ | Pressure differnce loop-seal |
| $\Delta t$ | Difference in time |
| $\Delta z$ | Difference in height |
| $\lambda$ | Friction coefficient |
| $\rho_B$ | Bulk density of fixed bed |

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