CAPACITANCE PROBES FOR THE INVESTIGATION OF THE FLUID DYNAMICS OF TURBULENT FLUIDIZED BEDS

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Abstract – An investigation of the turbulent fluidized bed regime was carried out using Group B particles according to Geldart's classification. The experimental plant was a CFB pilot-scale cold model (diameter: 0.4 m, height: 15.6 m). As bed material quartz sand (Sauter Mean Diameter: 188 µm, Geldart B) was used. For the determination of the fluid dynamic behavior in the fluidized bed riser probe measurements were carried out at heights between 1.5 m and 8.34 m above the air distributor. A detailed validation of capacitance probe measurements in a fluidized bed system has been done by comparison with suction probe and pressure drop measurements. The gas velocity was varied in a range between 2 and 4 m/s. Results show a good agreement of solids concentrations measured by capacitance probe and pressure measurements. A typical core-annulus flow structure was observed. The results of the local solids circulation rate determined by capacitance probe were found to be different from suction probe measurements.

INTRODUCTION

To maximize yields and performance of fluidized bed reactors detailed knowledge of the fluid mechanics is essential. According to the process requirements different states of fluidization are favorable. For processes, such as Fluid Catalytic Cracking (FCC), Methanol to Olefins (MTO), or Chemical Looping Combustion (CLC), the turbulent fluidized bed regime is used because of different advantages compared to other regimes. These are high solid hold-ups (25-35% by volume), a limited axial mixing of gas and the avoidance of gas bypassing because of the breakup of bubbles (Bi et al., 2000). The properties of a fluidized bed are defined by its fluid dynamic behavior which bases on particle properties, fluid properties and reactor design. In carbon capturing combustion technologies like CLC the turbulent fluidized bed is operated with oxygen carriers (OC). Mostly, these are metal oxides which can be classified as particles of group B according to Geldart. The occurrence of bubbles starts at or only slightly above minimum fluidization velocity for these particles (Geldart, 1973). Whereas for bubbling fluidization a bed surface can still be observed, at turbulent fluidization a clear surface is not visible anymore because of particle entrainment from the bed. Turbulent fluidized beds are mostly divided into a dense phase at the bottom and a dilute phase above. Only a quite small amount of particles can be found in the diluted phase. The dense phase contains the main amount of the bed material. In both phases the motions of the particles are turbulent. Solid clusters and small voids of irregular shapes can be observed. (Bi et al., 2000) As Kruse and Werther (1995) describe clusters mainly move downward at the riser wall whereas a dilute upflowing stream can be observed in the horizontal middle of the riser in the upper zone.

To determine the flow structure in fluidized beds different measurement techniques are used in literature. One of these is the capacitance probe. Using the working principle of a capacitor, capacitance probes allow measurements of the local solids concentration, velocity of distinctive flow events (e.g. clusters, bubbles) and solid circulation rate. The solids concentration can be calculated directly from the signal of a capacitance probe because it is in direct relation to the measured local dielectric constant. Determination of the velocity of clusters/bubbles is done by cross-correlation of two signals. Thus, a two-channel capacitance probe is necessary (Werther, 1999). As described by Hage and Werther (1997) this kind of probe has the advantage compared to other measurement techniques that it can be used at elevated temperatures up to 1000°C.

Another measuring method in fluidized beds is the suction probe. By sucking solids out of the fluidized bed during a certain time and area the local solid circulation rate can be estimated from the mass of solids. Up- and down-flow of particles must be measured separately (Rhodes et al., 1988). It is proven that the integral of the local flux over the bed's cross section area measured by this method is similar to external solid circulation rate measurements (Kruse and Werther, 1995). The suction probe is a simple designable measurements technique and can also be used under high temperature conditions (Werdermann, 1992).

In this work the flow behavior of Geldart B particles in a turbulent up to a fast fluidized bed was investigated. The solids concentration was measured by a capacitance probe and compared with results from pressure drop measurements. Furthermore, the velocity of solids (clusters) and the solids circulation rate in the fluidized bed were determined. To validate the results taken with the capacitance probe measurements with a suction probe were carried out.

CIRCULATING FLUIDIZED BED SETUP

The experiments were carried out in the circulating fluidized bed plant shown in Fig. 1. Air compressed by an air blower enters the fluidized bed riser through a porous air distributor plate. Via pressure drop measurements over a measuring orifice the superficial gas velocity was determined. The riser has a diameter of 0.4 m and a total height of 15.6 m. Entrained bed material leaves the riser over an abrupt exit into the primary cyclone and is separated from the air. Via a syphon the entrained bed material is recirculated into the riser. A separate section of the downcomer pipe is mounted on weighing sensors. By closing a valve temporally this allows a measurement of the solid circulation rate. The air leaves the plant over a secondary cyclone, a bag filter and an induced draft fan.

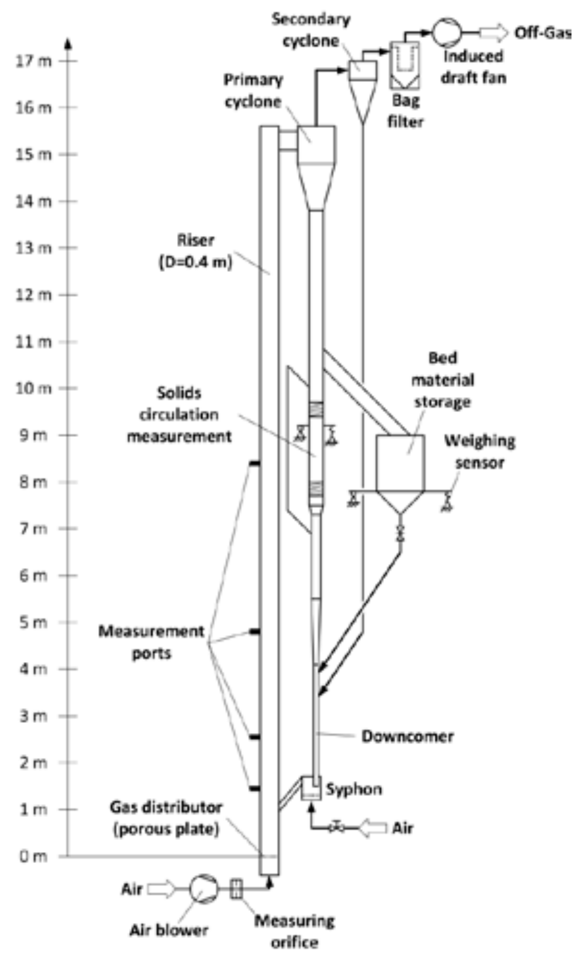

Fig. 1. Flow sheet of the circulating fluidized bed setup.

Four measuring ports installed in the riser at the heights 1.5 m, 2.6 m, 4.84 m and 8.43 m above the distributor plate were used for probe measurements. The probes were placed at nine different radial positions (r/R=-1;-0.75;-0.5;-0.25;0;0.25;0.5;0.75;1). The plant was operated at ambient conditions. The bed inventory was adjusted to 88 kg, giving a static bed height of 0.5 m.

Related to different oxygen carriers used in literature quartz sand was chosen as reference bed material. With a mean particle size ($d_{50,3}$) of 196 µm and a solid density of 2599 kg/m³ the quartz sand belongs to group B according to Geldart's classification (Geldart, 1973). The particle size distribution is shown in Fig. 2 and was measured with a Camsizer XT (Retsch Technology GmbH) according to ISO 13322-2. This device photographs the projection area of the particles with two cameras. In this work, all measured particle diameters are calculated as the area equal diameter of a circle to the projection area of a particle. The solid density was measured via a Helium MultiVolume Pycnometer 1305 (Micrometrics).

Table. 1. Properties of the bed material (quartz sand).

$d_{50,3}$	SMD	ρ_s	ρ_b	u_{mf}	$c_{V,fb}$	bed height	inventory
[µm]	[µm]	[kg/m³]	[kg/m³]	[m/s]	[-]	[m]	[kg]
196	188	2599	1405	0.073	0.54	0.5	88

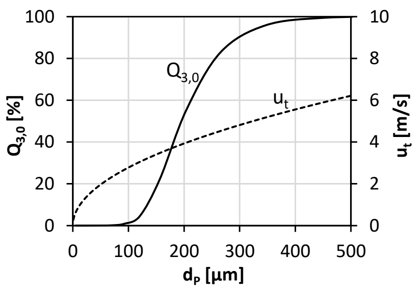

Fig. 2. Mass density distribution and terminal velocity of a single particle as functions of the particle size

The terminal velocity of a single particle which can be found in Fig. 2 is derived by a force balance of a single particle. It can be calculated by

$$u_t = \sqrt{\frac{4}{3} \cdot \frac{g \cdot d_P}{c_w(Re)} \cdot \frac{\rho_s - \rho_f}{\rho_f}} \quad (1)$$

MEASUREMENT TECHNIQUES

To measure flow structure characteristic parameters such as solid concentration, solid velocity and solid circulation rate different measurement techniques were used.

Capacitance probe

At heights of 1.5 m, 2.6 m and 4.84 m a capacitance probe (Fig. 3) was used to determine these parameters. The capacitance probe consists of two sensors/channels which were positioned horizontally one above the other in the flow of solids and gas. Radial profiles were recorded by changing the radial depth of penetration into the plant. The principal of this measurement method is based on the change of the capacity in the measuring volume when particles enter it. Resulting signals show a voltage fluctuation in direct relation to solid concentrations (Werther, 1999). Thus, it is also possible to get information about bubble and cluster/strand formation. Calculation of the solids concentrations is done over a correlation by taking the dielectric constants of the fixed bed K_{fb}, the fluid K_f and the suspension during measurement K_e into account (Wiesendorf and Werther, 2000).

$$c_V = c_{V,fb} \frac{K_e - K_f}{K_{fb} - K_f\left(1 + \frac{(K_{fb} - K_e)(K_{fb} - \beta)}{K_{fb} - K_f}\right)} \quad (2)$$

Thereby a maximum value for the solids concentration can be reached in a fixed bed with $c_{v,fb}$=0.54. According to Wiesendorf and Werther (2000) the fitting parameter β was set to 3.0.

To eliminate influences of humidity and temperature the voltage signals of air and fixed bed were measured before and after each experiment. The voltages were used to calculate the dielectric constants K_{fb} and K_f.

A schematic setup of the capacitance probe used is shown in Fig. 3. It consists of two metal pipes which have wolfram needles as core. The pipes and the needles are isolated by ceramics in between. The distance of the wolfram needles is 3.5 mm. Total diameter of the capacitance probe is 8 mm.

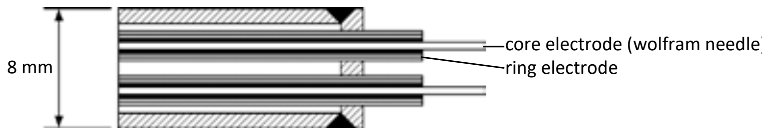

Fig. 3. Setup of the capacitance probe.

A time difference occurs between the recorded voltage signals if the probe is streamed upwards or downwards by the suspension. Using the cross correlation (Werther et al., 1996)

$$\phi_{U_1U_2}(\tau) = \lim_{T\to\infty} \frac{1}{T\sigma_{U_1}\sigma_{U_2}} \int_{-T/2}^{T/2} U_1(t)U_2(t+\tau)\,\mathrm{d}t \tag{3}$$

a determination of this difference is possible. At a sampling frequency of 10,000 Hz correlations at signal time intervals of 51.2 ms in steps of 25.6 ms over the whole length of the recorded signal (60 s) have been calculated. The results were used to determine the velocity of solid material. The determined velocity is limited to a maximum value of 35 m/s.

Taking the solid concentrations and the solid velocities of each time interval into account, the temporal solid circulation rates were determined and time-averaged.

Suction probe

For the validation of the results created by the capacitance probe a suction probe was used. The working principal of this probe is to suck a sample of the suspension flow out of the fluidized bed. Solid material is separated from gas in a cyclone whereby local solid sampling is possible. Fig. 4 shows a flow sheet of the used suction probe system. The whole suction probe itself has an outer diameter of 10 mm; the suction pipe has a round orifice with an inner diameter of 4 mm which is positioned for a suction of vertical suspension flows (upwards or downwards). Inside the probe the sucked suspension flow is accelerated by using additional air to avoid blockage due to solid accumulation and guarantee dilute pneumatic conveying. Solid material is collected in a sampling vessel after separation from the gas in the cyclone. A pump is used to induce an under pressure and realize suction. The volume flow is controlled by rotameters.

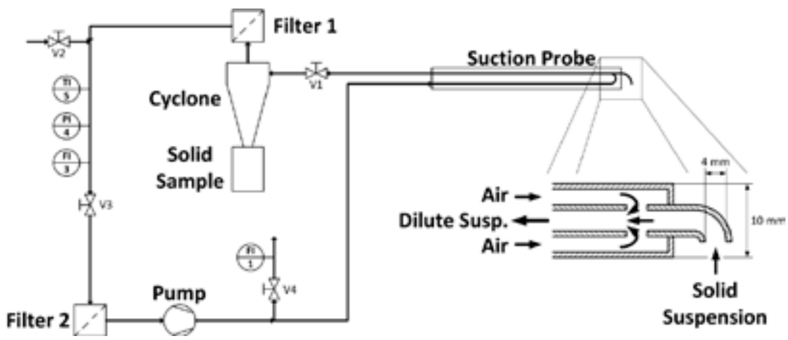

Fig. 4. Flow sheet of the suction probe system for solid sampling.

Because the local solid velocity is unknown and shows strong fluctuations an isokinetic sampling is not realizable. But as proved by several authors in literature (Rhodes et al., 1988; Rhodes and Laussmann, 1992; Kruse and Werther, 1995) in diluted flows isokinetic suction of the suspension is not necessary and the influence of the suction velocity on the results is neglectable. The influence of the suction velocity on the mass of particles sucked into the probe was investigated. The results have been independent of the suction velocity in a wide range. Finally a suction velocity of 18 m/s had been chosen.

With the sucked solid mass and the time

of suction the local solids circulation rate was calculated. Radial solids circulation rate profiles were measured at plant heights of 2.6 m, 4.84 m and 8.43 m from gas distributor. Besides the particle size distribution was measured using a Camsizer XT (Retsch Technology GmbH).

Pressure drop measurements

During probe measurements, the pressure drop over the height of the riser was measured using 27 pressure difference sensors (type: 140PC, Honeywell International Inc.). Pressure drops can be used to determine a radial averaged solids concentration by

$$\frac{\mathrm{d}p}{\mathrm{d}h} = \left(\rho_s - \rho_f\right) \cdot c_V \cdot g + \frac{1}{A_t} \cdot \frac{\mathrm{d}(\dot{m}_s \cdot u_s)}{\mathrm{d}h} \tag{4}$$

The last term of this equation $\frac{1}{A_t} \cdot \frac{\mathrm{d}(\dot{m}_s \cdot u_s)}{\mathrm{d}h}$ describes the acceleration of bed material in the dense phase of the fluidized bed. To calculate the solids concentration in the plant this term was assumed to be neglectable.

RESULTS AND DISCUSSION

Solids concentration

For the validation of the capacitance probe as a measurement method for solids concentrations the results were compared with solids concentrations calculated from the pressure drop. Results are shown in Table 2. To realize a comparison of both measurement techniques the local solids concentrations of the capacitance probe were averaged over the cross-sectional area of the riser. Concentrations measured by the probe are in a good agreement to the results of the pressure drop measurements. Capacitance probe measurements tend to underestimation of the solids concentration especially at higher superficial gas velocities. The results show a strong dependence of the superficial gas velocity and the measuring height. As expected the solids concentration decreases with increasing height and decreasing superficial gas velocity.

Table. 2. Comparison of the cross-sectional area averaged solids concentration measured with the capacitance probe and the solids concentration determined by pressure drop measurements at different heights and superficial velocities.

h [m]	u_l [m/s]	c_V by capacitance probe [-]	c_V by pressure drop [-]
1.5	2	0.007	0.007
	3	0.015	0.014
	4	0.023	0.025
2.6	2	0.003	0.003
	3	0.006	0.007
	4	0.011	0.014
4.84	2	0.002	0.003
	3	0.004	0.006
	4	0.008	0.011

Compared to pressure drop measurements a capacitance probe allows the determination of local concentrations. Thus, radial profiles can be measured. As Fig. 5 (a) shows higher concentrations occur at the riser wall (r/R=-1;1) while in the riser center a diluted phase is present. This behavior is well known and described in literature (Wiesendorf and Werther, 2000). Besides, it was observed that the profiles measured are non-symmetric. The profiles show a constant non-symmetric fluid dynamic behavior independent of the superficial gas velocity.

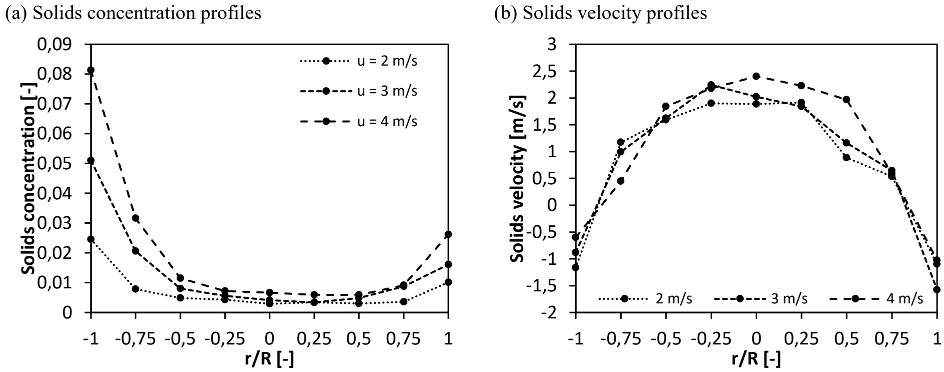

Fig. 5. Radial solids (a) concentration and (b) velocity profiles at a height of 1.5 m from air distributor.

Solids velocity

The cross correlation is determined by distinctive events, i.e. signal structures with steep gradient and high amplitude, which belong to sudden changes in solids concentrations. It is assumed that the velocity of these changes equals the velocity of the solid material because distinctive flow events result in significant changes in solids concentrations.

Particles at the riser wall (r/R=-1;1) have time averaged a downward directed movement as Fig. 5 (b) shows. In contrast, in the riser center (r/R=0) the solid material rises. A parabolic profile can be observed. In the bottom zone of the riser no significant influence of the superficial gas velocity on the solids velocity can be observed. It can be assumed that particles rise faster in the center by increasing the superficial gas velocity. Fluctuations in the velocities measured are caused by cross-correlations.

By consideration of the distribution of determined solid velocities it can be noticed that only upwards directed velocities were measured in the riser center whereas at the riser wall in addition to down-flow also up-flow occurs. This phenomenon was also observed visually at a glass segment of the fluidized bed riser.

Connecting these results with the radial profiles of the solids concentration two main flow characteristics become obvious: in the riser center a diluted phase rises while at the riser wall a down-flow of a dense phase appears. This behavior is reported in literature as the core-annulus flow (e.g. Kruse and Werther, 1995).

Solids circulation rate

The solids circulation rate determined with the capacitance probe results from the measured solids concentration and the solids velocity. In contrast to this, with the suction probe the solids circulation rate was measured directly by sucking a defined mass of particles in a certain time over a certain area. Fig. 6 shows generally lower values for the solids circulation rate determined by capacitance probe than measured by suction probe.

Suction probe measurements show a clear radial core-annulus profile. With increasing height the local solids circulation rate decreases. This was observed over the whole range of superficial gas velocities investigated. The results shown in Fig.7 (b) are the sum of the local solids circulation rates for up and down flowing particles which were measured separately. As proven by Kruse and Werther (1995) the cross-sectional area averaged solids circulation rates determined by suction probe fit to solids circulation rates measured externally in the downcomer. Furthermore, it was also observed by suction probe that down- and up-flow occurs at the riser wall whereas only up-flow was found in the center as also described by the analysis of the solids velocity measured by capacitance probe.

Because the solids concentration measurements of the capacitance probe were verified using pressure drop measurements the difference in the local solid circulation rate compared to suction probe measurements must follow from the results of the solids velocity. As described before the so called “solids velocity” is a velocity of the interface between dense and diluted regions in the flow. The real velocity of single particles can be higher so that the here used “solids velocity” influences the results of the solids circulation rate.

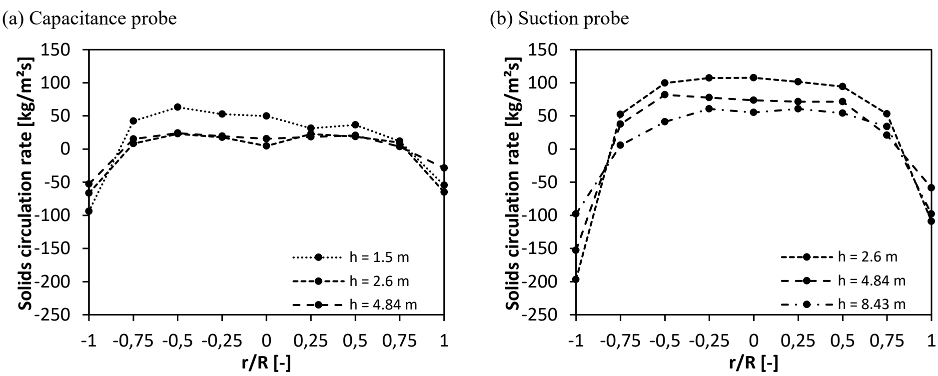

Fig. 6. Radial solids circulation rate profiles at a superficial velocity of 3 m/s at different heights measured (a) by capacitance probe and (b) by suction probe.

To investigate the fluidized bed on segregation effects the particle size distributions of the samples taken by suction probe were measured. Radial segregation effects were not found. With increasing height an axial decrease of the mean particle size was observed as shown by Fig. 7. Bigger particles tend to stay in the bottom zone because of their higher terminal velocity. With increasing superficial gas velocity the mean diameter also increases in the upper region of the riser which was also shown by Kruse and Werther (1995).

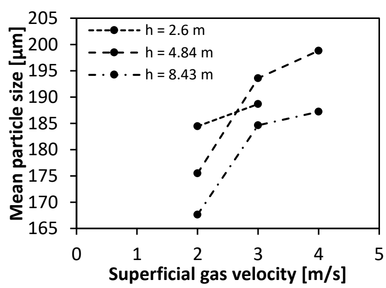

Fig. 7. Influence of superficial velocity and height from distributor on mean particle size.

CONCLUSIONS

Solids concentration measurements with the capacitance probe in a turbulent fluidized bed of group B particles have shown that they are in a good agreement to the measurements via pressure drop. The solids concentration averaged over the cross-section showed a strong influence of superficial gas velocity and measuring height. With increasing superficial gas velocity the solids concentration increases. In contrast to this, measuring height and solids concentration show an opposed behavior.

Using cross-correlation the velocity of distinctive flow events was determined and assumed to be equal to the solids velocity. Whereas in the riser center only an up-flow of particles was found, at the riser wall down- and up-flow occurred. Connecting the results of the solids concentration and the solids velocity it can be seen that the flow in the freeboard above a turbulent fluidized bed is dominated by a core-annulus flow.

The capacitance probe gives only a limited hint on the solids circulation rate. Values for the solids circulation rate taken by suction probe seem to be more precise.

No radial classification was detected. An axial decrease in mean particle size was found with increasing height from the air distributor.

NOTATION

A_t	cross-sectional area of the plant
c_V	solids concentration
$c_{V,fb}$	solids concentration of fixed bed
$c_w(Re)$	drag coefficient
d_P	particle size, µm
$d_{50,3}$	mean diameter, µm
g	length, m
h	height, m
K_e	dielectric constant of suspension
K_f	dielectric constant of fluid
K_{fb}	dielectric constant of fixed bed
$\dot{m}_s$	solid mass flow, kg/s
p	pressure, Pa
$Q_{3,0}$	mass density distribution, %
SMD	sauter mean diameter, µm
t	time, s
T	integration time for cross-correlation, s
U	voltage, V
u_l	superficial velocity, m/s
u_s	solid velocity, m/s
u_t	terminal velocity, m/s
β	fitting parameter
ρ_b	bulk density, kg/m³
ρ_s	solid density, kg/m³
ρ_f	fluid density, kg/m³
σ_U	standard deviation of signal U, V
τ	signal time delay, s
$\phi_{U_1U_2}$	cross-correlation function

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