BOTTOM-BED FLUID DYNAMICS – INFLUENCE ON SOLIDS ENTRAINMENT

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Abstract – In CFB boilers, the solids concentration along the riser and the external solids circulation are important design parameters, mainly in terms of the heat balance but also influencing the risk of wear on heat transfer surfaces. This work investigates experimentally how the amount of solids entrained from the bottom region of a CFB riser is influenced by the fluidization conditions, including the presence or absence of a dense bottom bed.

The paper presents first measurements in a new cold lab-scale unit (3 m tall, 0.45 m^2 in cross section), which is a scale model of a large utility boiler. The solids inventory consists of glass spheres with a mean size of 112 µm. The operational range covers fluidization velocities between 0.1 and 1.4 m/s and riser pressure drops between 0.2 and 1.5 kPa. The vertical distribution of solids concentration is determined through pressure drop measurements between densely spaced pressure taps (15 in total) along the riser height. The external solids circulation is measured with an automatic valve system in the return leg.

The results show that the presence or absence of a dense bed govern how operational parameters influence the characteristics of the solids entrainment from the bottom region. The vertical extension of the splash zone above the dense bed depends strongly on the dense bed height. In the absence of a dense bed, a bottom region with strong solids back-mixing is established which has similarities with the splash region.

INTRODUCTION

Circulating fluidized bed (CFB) boilers is an attractive combustion technology for solid fuels as it has a number of favourable features such as high fuel flexibility, cost-effective emission control and the possibility to vary load over a wide range. The development and optimization of CFB boilers require detailed knowledge on the solids pattern in order to provide reliable design and scale up of the fluidization technology. The solids concentration along the riser (i.e. furnace) and the external solids circulation are important CFB boiler-design parameters, since they determine the heat balance but they also influence the risk of wear of heat transfer surfaces, i.e. the boiler walls and other internals such as wing walls.

The flow pattern of solids in CFB units has been investigated for a long time, but most of the studies are carried out in lab units with narrow risers and with a high aspect ratio (see Johansson et al., 2007). The furnace of a typical CFB boiler has a low height-to-width ratio compared with lab-scale CFB units, which are typically tall and narrow if not explicitly designed to mimic fluidized bed boilers. This results in different fluid dynamic patterns between the two types of risers. At a given height, solids in large-scale CFB furnaces exhibit a relatively flat cross-sectional solids flux profile whereas tall and narrow lab-units typically show a parabolic solids flux profiles as discussed by Johnsson et al. (1995). Zijerveld et al. (1998) also showed that the dynamics of the dense bottom bed of large size units are significantly different to the bottom region of a narrow riser, mainly since wide units exhibit less wall effects. Johnsson and Leckner (1995) concluded that as long as a dense bed is present, the bottom bed dynamics will resemble a bubbling fluidized bed (with so called exploding bubbles as observed by Svensson et al., 1996) even at high fluidization velocities under circulating conditions. The extension of the dense bottom bed in CFB boilers is typically less than 0.5 m, i.e. only occupying a small fraction of the total furnace height which is typically 10 to 40 meters in height, depending on boiler size. In addition, CFB boilers, as well as pilot and lab scale units used to mimic different in-furnace processes, often have too few pressure taps to resolve the strong gradient in pressure drop in the lower part of the furnace. Thus, there is a lack of information on how the bottom bed flow characteristics influence the flow pattern higher up in the furnace, which in turn determines the internal back-mixing of solids along the furnace walls. The internal back-mixing governs the solids which leaves the furnace and is recirculated back by means of the primary cyclone, the external solids flux, G_s, which for some designs (depending on boiler size and design) may recirculate through an external particle cooler.

In summary, G_s is an important parameter to assess as it is used to close the internal heat balance of the CFB loop. Estimates, indicate that in CFB boilers, G_s, takes values of some few kg/m^2 s and seldom exceeds 10 kg/m^2 s (Zhang et al., 1995). However, it is a challenging task to experimentally measure G_s in CFB boilers due to the elevated temperatures. So far, G_s has been estimated by indirect methods such as from heat and mass balance over the return loop (see Edvardsson et al., 2006). Cold laboratory models obviously offer a possibility to perform measurements more easily than under high temperature combustion conditions. Important works in this respect are by Xu et al. (2015), Yang et al. (2009), and Yue et al. (2005), who investigated the effect of riser solids inventory and fluidization velocity on G_s. Yet, the units applied in these works have a limited resolution in the vertical distribution of the pressure measurements, making it difficult to know the details of the bottom region flow conditions.

In all, there is a lack of studies on the interaction between the fluidization characteristics in the bottom region of a CFB furnace and G_s, in spite of that G_s is of great importance for the overall heat transfer in the CFB loop, especially for CFB designs which have an external particle cooler for transferring heat from the flue gas side to the water side. Therefore, the purpose of this work, as well as a recent work by the authors (Karlsson et al., 2017), is to evaluate how the amount of solids entrained from the riser with characteristics similar to that a CFB boiler is influenced by the fluidization conditions in the bottom region: fluidization velocity, riser pressure drop, presence/absence of a dense bed. For this, experiments were executed in a new cold CFB unit with a geometry representative for CFB boilers and with densely spaced pressure taps along the riser to resolve the steep gradient in vertical solids concentration along the riser.

EXPERIMENTAL SET UP

The cold model has a cross section of 0.45 m^2 and a height of 3 m resulting in height-to-width ratio of 4.7. The model is designed as a fluid-dynamically down-scaled model of an existing commercial CFB boiler. This paper builds on the first experiments in the unit which did not apply scaled material, partly due to safety issues (at the time it was not yet assessed that the unit was completely sealed and free from solids leakage).

The particles used in the experiment are Ballotini glass beads with a particle size distribution yielding d_{10}- d_{50}- d_{90} values of 71-112-139 µm, respectively with a solids density, ρ_{solid}, of 2600 kg/m^3. This gives a minimum fluidization velocity, u_{mf}, and a terminal particle velocity, u_t, of 0.013 m/s and 0.64 m/s, respectively, based on the average particle diameter. For each range of riser pressure drop, ΔP_{riser}, the unit was filled with a certain amount of solids and a series of runs for the given riser pressure drop range were executed without adding or removing material. This resulted in a redistribution of the solids within the circulating loop (riser and return leg) with increased velocity and thus slightly different values of the riser pressure drop. While 5 different riser pressure drop ranges were studied, only the lowest and highest are reported here, [0.15-0.28] kPa and [1.1-1.5] kPa. The maximum (primary) fluidization velocity, u_0, in these runs was 1.4 m/s, which is the maximum allowed by the air supply system. The runs reported here did not employ secondary air (although the unit is equipped with such registers).

The model has 15 pressure taps along the height of the riser, 10 of which are located along the first 0.4 m above the primary air distributor. The solid circulation flux, G_s, is measured with a pneumatically controlled butterfly valve to which a gas flow can be injected in order to make it act as a gas distributor when it is closed. A constant air flow controlled by a mass flow controller is used to fluidize the solids column formed above the valve as it is closed (a fluidization velocity of 0.02 m/s was used in the tests reported here). A pressure transducer connected to the fluidizing valve is used to monitor the accumulation rate of solids in the return leg, from which the external solids circulation can be derived.

For each case, pressure measurement were sampled at 50Hz during a minimum running period of 120 s and G_s was measured a minimum of 3 times to ensure reproducibility.

THEORY

Fig. 1 gives a schematic illustration of a CFB boiler with three characteristic zones in the vertical solids distribution in the riser/furnace, as identified by Johnsson and Leckner (1995): a dense bottom zone (bottom bed in fig. 1) with a constant solids concentration with height, a splash zone with a strong solids back-mixing to the dense zone by means of ballistic movement of clustered solids ejected by bubble eruptions from the dense bed, followed by a transport zone with a lower back-mixing, mainly occurring along the furnace walls in wall layers. In addition, there is an exit zone which determines how much of the solids that reach the top of the furnace that will leave the furnace into the primary cyclone (*cf.* Pallarès and Johnsson, 2006).

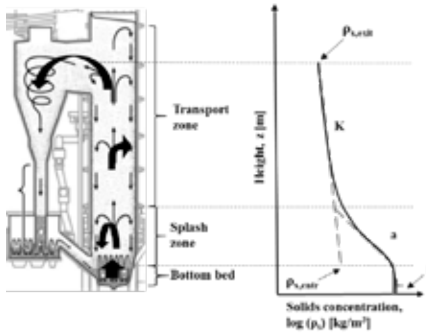

Fig. 1. Schematic illustration of a CFB boiler with the different fluid-dynamical zones, evaluated parameters and typical solids concentration dependence with height.

The criterion for determining the dense bed height, H_b, applied in this work is the height from the primary air distributor over which the vertical pressure drop is linear as described by Johnsson et al. (1991). In this work the straight line was defined as a linear fit to the pressure measurements, applying the condition that the straight line was fit to at least three of the lowest pressure measurements, using the least square method with a value of R^2 of less than 0.975. Thus, this criterion can obviously not assess the existence of a dense bed with a height below that of the location of the third lowest pressure tap. Therefore, under these conditions, the solids concentration in the height interval between the two lowest pressure taps (located at 0 and 0.016 m) is measured and compared to the solids concentration that corresponds to a bubble fraction, δ_b, of 0.5 which, assuming the dense phase (in between bubbles is maintained at minimum fluidization conditions) corresponds to a solids concentration of 760 kg/m^3. If the measured solids concentration exceeds this value, the conditions are defined as a dense bed (the dense phase is the continuous phase, i.e. δ_b, <0.5 in which bubbles are immersed whereas δ_b, >0.5 corresponds to a continuous gas phase holding a dispersed solids phase). From evaluation of all runs fulfilling the first criterion (linear pressure drop over at least the three lowest pressure taps) it was, as expected, observed that also the second criterion was fulfilled. Thus, if both of the two above-described criteria are fulfilled, the run is considered to have a dense bed in the bottom region. If only the second criteria (δ_b, <0.5) is fulfilled the conditions are considered to correspond to a "dense zone". If neither of the two criteria are fulfilled, the bottom region flow is considered to be without any dense zone.

Above the dense bed zone a splash zone is formed, in which back-mixing is dominated by ballistic movement of particle clusters and coarser particles, yielding a strong exponential decrease in solids concentration with height above the dense bed. The decay constant was described by Johnsson and Leckner (1995) as $a = 4\,u_t/u_0$. Pemberton and Davidson (1986) discussed that the mechanism for particle ejection from the bed surface to the freeboard alters depending on the bubble eruption at the bed surface. As the bed hydrodynamics affects the bubble pattern it will thereby affect the ejection of solid particles from the bed. Almendros-Ibáñez et al. (2009) studied these different bubble patterns and showed that the bubble velocity and the type of bubble eruption gave different particle ejection velocities. Garcia-Gutierrez et al. (2014) measured the ballistic motion due to bubble eruption and showed that the solids ejection velocity correlates to the bubble velocity and therefore also the dense bed height.

The transport zone is described as a core flow of dilute solids flowing upwards and a wall layer with backmixing of solids mainly by means of downward flowing wall layers at the riser walls (Davidson 2000, Johansson et al., 2007). The solids back-mixing yields an exponential solids concentration decay with height described by the decay constant (K). With this, the vertical profile of solids concentration along the freeboard of large-scale CFB boilers has to be described by means of an equation containing two terms, each representing the two backmixing mechanisms discussed above (see Johnsson and Leckner 1995);

$$\rho_s(h) = \left(\rho_{s,H_b} - \rho_{s,entr}\right)e^{-a(h-H_b)} + \rho_{s,entr}e^{-K(h-H_b)} \qquad h \geq H_b \qquad (1)$$

Thus, one exponential decay cannot describe the backmixing above the bottom bed region. The term $\rho_{s,Hb}$ is the solids concentration in the dense bed, in this work determined experimentally from pressure drop measurements in the height interval 0-0.016 m. The concentration of the dispersed solids at the bottom region, $\rho_{s,entr}$, is the amount of solids entrained from the bottom region into the splash zone, that is not back-mixed but instead enters the transport zone. It is characterized by a solids concentration corresponding to the value of the dispersed solids concentration extrapolated to the dense bed surface (or, in absence of a dense bed, at the bottom of the riser); see Fig. 1 and Karlsson et al. (2016) for a detailed description. The solids concentration at the outlet to the cyclone, at the top of the riser, $\rho_{s,exit}$, is obtained by extrapolating the exponential decay in solids concentration in Fig. 1, as obtained from the pressure drop described. With this, the upwards flux at the top of the riser can be described as:

$$G_{s,top} = \rho_{s,exit}(u_0 - u_t) \tag{2}$$

The difference between the external solid circulation, G_s, and the solids core up-flow at the top of the riser indicates the so-called solids backflow effect, i.e. solids which after reaching the top of the riser are internally recirculated through the wall layers (see Johnsson et al., (1999) for detailed study on this).

RESULTS AND DISCUSSION

The results on the external solids recirculation are presented with respect to the conditions in the bottom region of the riser. Thus, in the following result plots, “dense bed” conditions are indicated by filled symbols, “dense zone” conditions with half-filled symbols and conditions without any dense zone with open symbols – applying the above mentioned criteria to distinguish between these three bottom region conditions. Since the external solids circulation, G_s is a result of the overall backmixing phenomena up through the riser, the G_s results are related to the bottom bed, splash zone and transport zone conditions, as obtained from the pressure drop measurements.

While all cases with a high riser pressure drop have a dense bed, as seen in Fig. 2 (filled symbols), the lower riser pressure drop range contains runs belonging to all of the three categories: dense bed (filled symbols), dense zone (half-filled symbols) and no dense zone (open symbols), with the dense bed lost when the excess gas velocity reach around 0.8 m/s. The dense bed height decreases with fluidization velocity when the inventory is kept constant, as reported by Svensson et al. (1996).

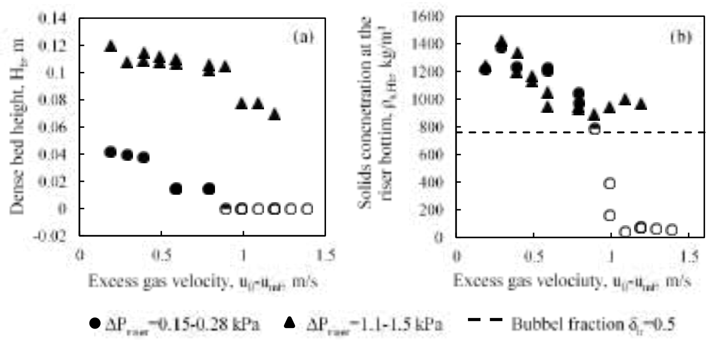

Fig. 2. a) The height of the dense bed (filled symbols) and dense zone (half-filled symbols) with increase in fluidization velocity (open symbols = no dense zone present) for two different ranges of riser pressure drop and b) corresponding values of solids concentration.

Fig. 3 shows the experimental values of the decay constant for the solids concentration in the splash zone together with the correlation from Johnsson and Leckner (1995). As can be seen, the splash-zone back-mixing decreases with an increase in velocity and increase with riser pressure drop and thereby by dense bed height (as seen by comparing with Fig. 2). The latter is explained by the fact that less solids inventory (lower riser pressure drop) yields a lower dense bed and thus smaller bubbles which produce less vigorous bubble eruptions, yielding lower velocities of the clusters thrown up into the freeboard. The bed height dependency in solids back-mixing in the splash zone has not been identified in previous work reported in literature. Thus, this dependency was not identified by Johnsson and Leckner (1995), i.e. the dashed curve in Fig. 3 since they only present data for one furnace pressure drop, of around 7 kPa. Instead they varied the average bed solids size (three different particle size distributions) and the fluidization velocity ($0.6 \cdot u_t$ to $2.2 \cdot u_t$). Since the present work also differ to the one by Johnsson and Leckner by the fact that their correlation is developed by means of full scale boiler measurements (elevated temperature) and the data in the present work is from cold nonscaled conditions more work is required to determine how the bottom bed conditions and furnace pressure drop influence the splash zone decay.

In the absence of a dense bed, a bottom region with strong solids back-mixing is still established which has similarities to the splash region established in the presence of dense bed (e.g. an exponential decay of solids concentration with height). This is the reason why data points for the cases with no dense bottom zone is included in Fig. 3.

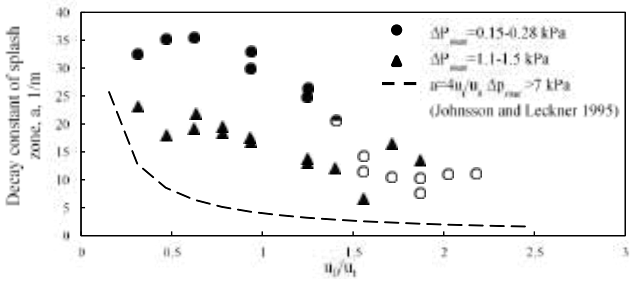

Fig. 3. Decay constant of the solids concentration in the splash zone, a, describing the back mixing of particles back into the dense bed. Filled symbols: dense bed, half-filled symbols: dense bottom zone, empty symbols: no dense bottom zone.

The concentration of the dispersed solids at the bottom region ($\rho_{s,entr}$ in Fig. 1) increases with fluidization velocity but is not affected by the riser pressure drop as can be seen in Fig. 4. However, the dispersed solids at the bottom region shows a saturation behaviour at a sufficiently high velocity, when the dense bed can no longer be maintained. Fig. 4 includes a comparison with previous data by Karlsson et al. (2016) obtained in a pseudo-2-dimensional cold model, revealing similar patterns of the dispersed solids at the bottom region: as long as there is a dense bed, there is a “buffer” of solids that can be entrained by increasing the gas velocity, but an saturation is reached related to a loss of the dense bed (open circles for present data and open squares for the previous study).

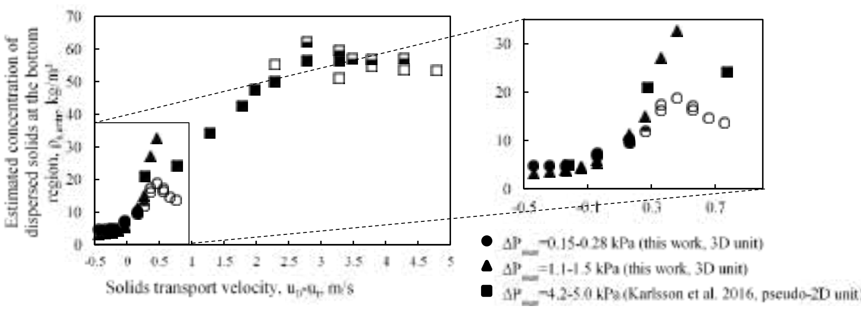

Fig. 4. The concentration of dispersed solids at the bottom region (as defined by Karlsson et al., 2016). Filled symbols: dense bed, half-filled symbols: dense bottom zone, empty symbols: no dense bottom zone.

Fig. 5 gives the experimental values of the decay constant *K* in the transport zone as obtained in this work. As can be seen, there is a decrease of the decay constant with fluidization velocity but no clear dependency on the amount of solids in the riser (ΔP_{riser}), including if there is a dense bed present or not.

The solids concentration at the top of the riser, $\rho_{s,exit}$, increases with gas velocity, as seen in Fig. 6a. The solids entrainment from bottom region together with the decay constant for the solids concentration in the transport zone affects the top concentration.

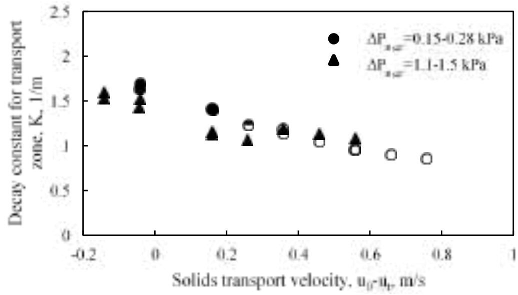

Fig. 5. The solids concentration decay constant in the transport zone, K, describing the back-mixing of material to wall layer. Filled symbols: dense bed, half-filled symbols: dense bottom zone, empty symbols: no dense bottom zone.

As can be seen from the open symbols in Fig. 6a, when the dense bed is lost the solids entrainment from the bottom region start to level off with increase in velocity. The reason that there is still an increase $\rho_{s,exit}$ with velocity, when the bottom bed can no longer be maintained, is explained by the fact that the decay constant along the transport zone decreases with increased velocity. Thus, even if the entrainment from the bottom saturates when the bottom bed can no longer be maintained, the transport zone decay still decrease with increased velocity resulting in that more bed material is able to reach the top of the riser without backmixing to the wall layers. This is in agreement with the previous work by Karlsson et al. (2016) who also showed that in absence of a dense bed an increase in pressure drops – reduced transport zone decay - promoted the solids entrainment from the bottom region.

Fig. 6b shows the increase in G_s with increase in fluidization velocity, as obtained from the measurements with the valve in the cyclone dipleg. It should be noted that the value of the terminal velocity (u_t) is based on the averaged bed particle size, i.e. the finer solids start to circulate at gas velocities below what corresponds to u_t. As can be seen, the values are low in comparison to the above mentioned estimates of G_s in CFB boilers (typically from a few kg/m^{2}s to some 10 kg/m^{2}s). This should be a result of that the unit used here is a scale model of a CFB boiler, yet not operated according to scaling laws.

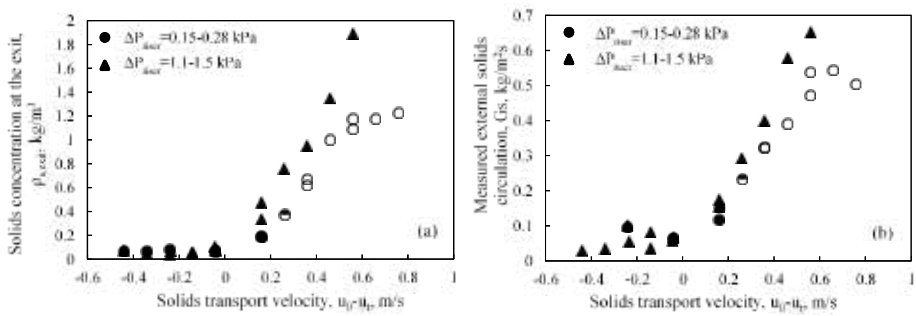

Fig. 6. a) Solids concentration at the riser exit as a function of solids transport velocity for different pressure drop. b) External solids circulation as a function of solids transport velocity for two different pressure drop ranges. Filled symbols: dense bed, half-filled symbols: dense bottom zone, empty symbols: no dense bottom zone.

The above results together with findings from previous work by the authors of this work (Karlsson et al., 2016) should provide an explanation to the experimental trends on how G_s depends on the in-furnace flow conditions, which to some extent seem contradictory (see Karlsson et al., 2016 and references therein). As an example Yang et al. (2009) evaluated the effect of solids inventory on the solids concentration at the riser top for different riser pressure drops. They did not observe an increase in the solids concentration at the riser top with an increase of riser pressure drop, only increase in solids concentration in the bottom region. A plausible explanation to this is that a dense bed was established after adding enough solids, saturating the solids entrainment into the transport zone and thus yielding constant solids concentration values in the upper riser locations when increasing the solids inventory. Yue et al. (2005) on the other hand described the exit solids concentration to increase with the total solids inventory in riser, which indicates that a dense bed may have been lacking. Still, as mentioned above, it is not clear from these works which type of bottom region conditions were present in the work of these authors: a dense bottom bed, a dense zone or a no dene zone.

Fig. 7 shows the comparison between the measured value of the external solids circulation and the estimated value of the solids flux at the top of the riser (see Eq. 2). Therefore the difference between the measured and calculated G_s from Eq. 2, should give an estimation of the solids backflow effect. Fig 7. Shows that the estimated backflow increases with an increase in solids flux, which is expected. Yet, to estimate G_s from pressure drop measurements (Eq. 2) is associated with significant uncertainty which can be seen from that for the lower values of solids flux in Fig. 2, the measured solids flux is greater than the corresponding one estimated from Eq. 2. This is explained by the fact that the solids in the upper core have, on an average, a smaller particle size than the mean diameter of the solids used in Eq. 2, i.e. the terminal velocity is overestimated and the solids flux, from pressure drop measurements, is therefore underestimated. In addition, there are of course an uncertainty in the estimated value of the solids concentration at exit as obtained from the pressure drop, this uncertainty is likely to increase the lower exit solids concentration (and solids flux).

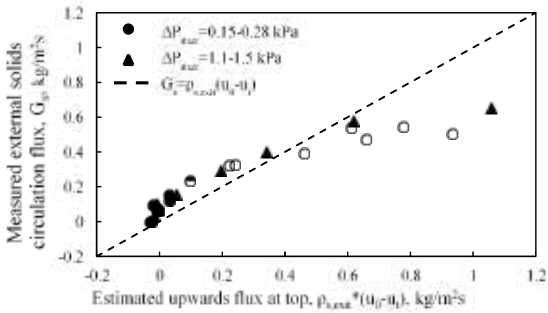

Fig. 7. External solids circulation as a function of the estimated upwards solids flux at the top of riser. Filled symbols: dense bed, half-filled symbols: dense bottom zone, empty symbols: no dense bottom zone.

CONCLUSIONS

First measurements in a new scale model of a utility CFB boiler is presented with the aim to increase the understanding on how the amount of solids entrained from the bottom region of a CFB riser is influenced by the fluidization conditions and the bottom bed conditions.

It is shown that above a certain value of the riser pressure drop a dense bed could be maintained for all the fluidization velocities investigated, in contrast to the runs at a lower riser pressure drop, for which the dense bed could not be maintained for fluidization velocities exceeding 0.8 m/s. It is found that the splash-zone decay constant decrease with increased riser pressure drop and also with increase in fluidization velocity. An increase in riser pressure drop yields an increase in the dense bottom bed height and from this the decrease in splash-zone decay constant can be explained by; that an increase in bed height gives larger and faster bubbles, yielding more vigorous ejection of solid clusters.

The concentration of the dispersed solids at the bottom region is saturated when the dense bed is lost, i.e. remains constant with a further increases in fluidization velocity.

The transport-zone decay constant, representing the back-mixing to the wall layers in the transport zone is affected by the gas velocity but not by the riser pressure drop or the presence/absence of a dense bed in the bottom region.

The external solids circulation is found to increase with fluidization velocity, until the dense bed can no longer be maintained, similar to the exit concentration. The difference between upwards core flux in top and measured solids circulation flux, i.e the solids backflow at the riser exit, increases with gas velocity, but is found to be independent of the bottom bed conditions.

ACKNOWLEDGMENT

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NOTATION

a	decay constant in splash zone, m^{-1}
d_p	particle diameter, m
G_s	measured external solid circulation flux, kg/m^2s
$G_{s,top}$	estimated upwards solid flux at top, kg/m^2s
H_b	dense bed height, m
K	decay constant in transport zone, m^{-1}
u_0	fluidization velocity, m/s
u_{mf}	minimum fluidization velocity, m/s
u_t	terminal velocity, m/s
δ_b	bubble fraction
ΔP_{riser}	pressure drop across the riser, kPa
$\rho_{s,Hb}$	concentration of solids between height 0-1.6cm, kg/m^3
$\rho_{s,entr}$	concentration of the dispersed solids at the bottom region, kg/m^3
$\rho_{s,exit}$	solids concentration at the exit of riser, kg/m^3
ρ_{solid}	solids density, kg/m^3

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