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

Refereed Proceedings

2013

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ABSTRACT

This paper defines a back-mixing coefficient as a measure for characterizing the solids flow in CFB boiler furnaces; $c_{BM} = (u - u_t)/u_{eff}$ where u_{eff} is the effective solids velocity. A comprehensive mathematical model is used to quantify and discuss the solids back-mixing processes in a large (~330 MW_{th}) CFB boiler furnace burning petcoke and bark. The model was previously validated against experimental data (mainly pressure drop, in-situ solids flux, heat balance and gas concentration fields) in different large scale CFB boilers.

Three main solids back-mixing processes are identified: 1) A dense bottom region back-mixing (c_{BM}= 45) due to the low effective solids velocities originating from the dynamics of the bottom region flow, 2) Splash zone back mixing (c_{BM}= 1 to 45) from clustered solids projected up from the bottom region, 3) Transport zone back-mixing (c_{BM}= 1) at furnace walls resulting in solids size segregation with respect to height in furnace. It is found that 80% of the furnace bed mass is present below the first 4 meters of the furnace which is 37 meters in height.

INTRODUCTION

Knowledge of the gas and solids mixing in Circulating Fluidized Bed (CFB) boiler furnaces is important for modeling of combustion and heat transfer. The solids mixing determines the solids hold-up, mixing and distribution of the fuel particles in the furnace. Thus, understanding of the solids mixing process is a key for establishment of mathematical models for design and scale up of CFB boilers. So far, modeling of CFB boilers rely to a large extent on correlations and semi-empirical expressions. Modeling from first principles (Computational Fluid Dynamics) is limited if resolving an entire boiler with all different solids and their size distribution, especially if considering comprehensive modeling, including fluid dynamics, combustion and heat transfer (1). Thus, comprehensive modeling is mainly limited to semi empirical modeling. The aim of this paper is to contribute to the understanding of the boiler solids flow mixing as basis for modeling. The paper is based on results and experiences, including experimental results obtained in large scale boilers (e.g. (2)-(5)).

CFB FURNACE CHARACTERISTICS

The furnace of a CFB boiler has typically the following characteristics (6):

- Aspect ratio of the furnace (H_0/D_{eq}) of the order of or less than 10;
- Aspect ratio of the settled bed (the bed formed if the solids are not fluidized) of less than 1, i.e., $H_{b,settled}/D_{eq} < 1$;
- Solids belonging to Group B in the Geldart classification; and
- Externally recirculated solids net flux typically less than 10 kg/m^2s.

In this paper we use the concept of solids back-mixing to discuss and explain the flow and solids mixing behavior in a CFB furnace. With solids back-mixing we refer to the process which makes the solids remain for a certain time in the furnace in spite of the fact that the superficial velocity exceeds the terminal (free fall) velocity of the individual particles. In fluidized bed systems, the back mixing is a result from different types of clustering phenomena, resulting in that the clustered solids will have an effective terminal velocity (of the "cluster") which often by far exceeds the terminal velocity of the single particles forming the cluster. Thus, the effective solids velocity, u_{eff}, is low.

Figure 1 shows the solids size distribution in a CFB boiler as well as for bubbling fluidized bed boiler (BFB) under typical operating conditions, in both cases taken as in-bed samples near the primary gas distributor. Obviously, in the case of the BFB, the superficial velocity in the bed is lower than the terminal (free fall) velocity of almost all bed solids. Only some fines resulting from the fuel conversion (fly ash) and fragmentation and attrition will leave the furnace and needs to be captured in post furnace treatment (fly-ash filters). On the contrary, for a CFB, Figure 1 shows that the superficial velocity exceeds that of the terminal velocity of the major part of the bed solids.

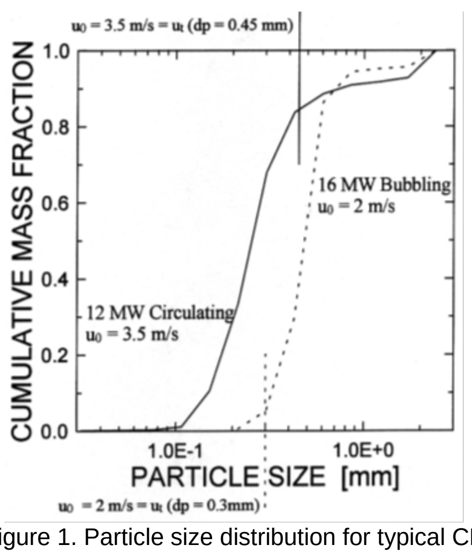

Figure 1. Particle size distribution for typical CFB and BFB boiler conditions. Unpublished data taken from the Chalmers 12 MWth CFB boiler and the Chalmers 16 MWth BFB boiler.

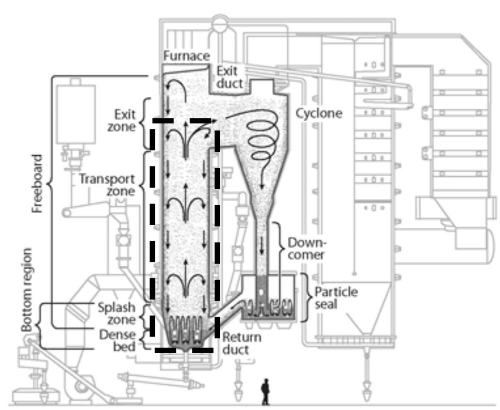

Figure 2. Gas and solids flow zone division in a commercial-scale CFB boiler. Boiler sketch courtesy of Metso Power Oy. The rectangle indicates the zones in focus in this paper.

Thus, if the single particle terminal velocity $u_t$was determining the solids flow, most of the solids would be entrained and flow up through and out of the furnace. Indeed, a substantial amount of the solids is entrained and recirculated but, as mentioned above, a large fraction, in fact the major part, of the solids is back-mixed within the furnace forming three distinct regions in the furnace, each with a substantial, but different, back-mixing of the solids.

The dashed rectangle in Figure 2 shows key regions in a CFB in focus of this work, with respect to fluid dynamics and solids back mixing with the three main back-mixing zones indicated. Thus, the in-furnace flow can be divided into three main zones; a dense region above the primary air distributor which typically is present in the form of a dense bed, a splash zone above the dense region and a transport zone (7). In addition, there is an exit zone in the top of the furnace where the backflow effect, determines the share of the upflowing solids in the core region will leave the furnace and thus be externally recirculated. The remaining share of solids will be internally recirculated through the downflowing wall layers. The solids flow in the exit zone differs between different boiler designs with the solids flow dependent on the furnace design such as if this is equipped with internal superheater elements. Thus, the gas and solids flow in the furnace-exit region is difficult to generalize, although for typical CFB boiler conditions, the flow behavior seems mostly to depend on if there are internals in the near furnace exit or not (see (6) and references therein).

The Dense Region

The dense region holds a substantial amount of the mass in the furnace. Yet, its extension is only some half a meter or so above the primary air distributor. Provided a sufficiently high solids inventory, a *dense bed* is established in the bottom part of the furnace. The dense bed can be maintained also when the superficial velocity exceeds the terminal velocity of a major part of (or all of) the bed solids (*cf.* Figure 1). This is mainly because the primary gas passes through the dense bed in a heterogeneous way, partially in the form of large bubbles, which, at high velocities, create a shortcut of gas between the gas distributor and the region above the dense bed (2). Experiments show that the pressure drop within the bed corresponds to bubble/void densities, $\delta=(\varepsilon-\varepsilon_{mf})/(1-\varepsilon_{mf})$, less than 0.5, i.e. the solids phase can be seen as the continuous phase in which bubbles and voids are immersed (ε = voidage). Thus, a dense bottom bed with such linear pressure drop has only been observed under the condition that $\delta<0.5$ (7, 8). In summary, the dense bed is present if there is a region for which the following holds:

$$\frac{\Delta p}{\Delta h} = const \qquad (1)$$

and,

$$\delta = \frac{\epsilon-\epsilon_{mf}}{1-\epsilon_{mf}} < 0.5 \qquad (2)$$

Where ε is the average voidage in the bed (ε = 1-*c*; *c* = solids concentration). More work should be carried out to understand the significance of the conditions at which $\delta\geq0.5$.

Although the dense bottom bed results in low effective slip velocities, without re-feeding recirculated solids from the cyclone, the bed would soon disappear.

It is a relevant question to ask if a dense bottom bed (for which δ<0.5) is always present in CFB boilers. This question is not obvious to answer since identifying the bottom bed requires several densely spaced pressure taps within the first half meter or so, immediately above the primary air distributor in the furnace. This is almost never the case in commercial boilers. Thus, when determining the solids concentration from pressure drop measurements in the lower part of the furnace, this will typically yield a lower pressure drop than that corresponding to δ<0.5. Thus, it is not possible in these cases to determine if this is due to lack of pressure taps or due to that the unit is actually operated without a dense bottom bed. In any case, below the first half a meter or so above the primary gas distributor, there is a dense region holding a substantial amount of the solids in the furnace (3).

The Splash Zone

Although the bubble-induced gas fluctuations in the dense bed quickly lose amplitude with height above the dense region, they have important implications for the characteristics of the gas-solids flow in the freeboard. Above the dense region, there is a so-called *splash* zone that consists of solids, which after ejection by the fluctuating gas-flow in the dense region, follow a ballistic movement, leading to strong solids back-mixing with a pronounced decrease in solids concentration. This, behavior was determined from pressure drop measurements in cold unit and boilers as well as from visual observations in cold units operated under conditions similar to those typical for fluidized boilers (3, 5, 7). Yet, there are no direct in-situ measurements of the splash-zone flow reported (e.g. local solids flow) due to that there is limited access in boilers for measurements in this region. In addition, the intense back-mixing in the splash zone makes it difficult to apply local measurements such as local solids flux measurements (e.g. as performed in 4), especially if considering measurements in a real boiler under combustion temperatures.

The Transport Zone

As shown in Figure 1, in CFB units the gas velocity is sufficiently high to cause a significant portion of the solids to be entrained up through the furnace and recirculated. Thus, above the splash zone, a *transport zone* is formed, with most of the back-mixing occurring at the furnace walls. Thus, the solids flow forms a core-annulus structure, i.e. with mainly up-flow in the core and continuous back-mixing at the furnace walls, thereby forming down-flowing wall layers of solids (3, 4, 7). Such continuous back-mixing represents the segregation of solids up through the transport zone with respect to solids size, i.e. the coarser the solids the higher the probability that they are separated at the furnace walls at a given level in the furnace. The taller the furnace, the greater the extension of the transport zone and, thereby, the lower will the solids flow be at top of the transport zone (i.e. if comparing two hypothetical furnaces of different height but otherwise identical).

CFB FURNACE BACK-MIXING CHARACTERISTICS

The back-mixing coefficient is defined as the ratio of the single particle slip velocity (for each size interval) to the average effective "cluster" velocity. Thus,

$$c_{BM} = (u - u_t)/u_{eff} \tag{1}$$

All velocities in Eq.1 depend on vertical location in the furnace. For a completely dispersed (single particle) flow c_{BM} equals one and for a bubbling bed it is very high (approaches infinity). The effective solids velocity for any of the above-discussed backmixing regions in the furnace is written:

$$u_{eff} = F/(A\rho_s c) \tag{2}$$

where *F* [kg/s] is the solids flow in the region studied over its cross sectional area *A* [m^2]. The single particle velocity u_t can be determined from a force balance of a single particle in free fall and, thus, becomes:

$$u_t = \sqrt{\frac{4gd_p}{3C_D}\left(\frac{\rho_s - \rho}{\rho}\right)} \tag{3}$$

where C_D is the drag of the particle, d_p is the diameter of the solids (for each size interval) and ρ is the density of solids (s) and gas.

MODELING

The model developed by the authors (6, 9) is applied to determine the solids distribution throughout the CFB loop for a large CFB boiler of around 330 MW_{th} burning petcoke and bark. The furnace has a cross section of approximately 100 m^2 and is 37 m tall. The model was previously verified against measurements in several large scale boilers including the Chalmers 12 MW CFB boiler and the 330 MW_{th} CFB boiler modeled in this work from which the authors have access to exact data of the geometry and measurement results (9). The model provides a three dimensional description of the furnace flow, accounting for particle size distributions of the solids fractions. Thus, the local solids concentration and solids flows can be determined from which the back mixing coefficient and residence times in the different zones in the furnace can be obtained, including the core and the wall layers of the transport zone. In addition, the model also considers combustion, attrition and mass balance of combustibles and bed ash. Thus, the total residence time of the bed solids can be determined, both for the furnace as a whole and for the different zones; bed and splash zone as well as for the wall and core regions of the transport zone. The modeling is solved by discretizing the furnace into 100 000 cells (with the cyclone, return leg and particle cooler implemented with respect to pressure balance in zero dimension). Figure 3 shows the furnace geometry of this work, as implemented in the model.

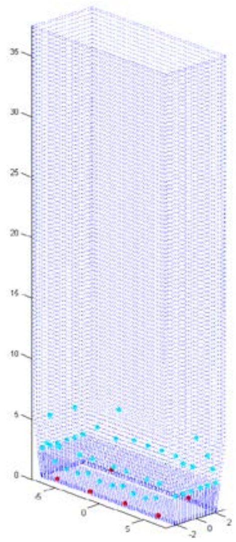

Figure 3. The 330 MW_{th} CFB furnace geometry as implemented in the modeling.

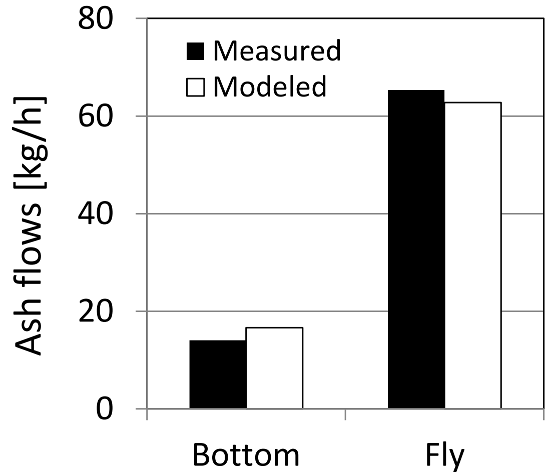

Figure 4. Bottom and fly ash flows in the Chalmers 12 MW_{th} CFB boiler – measured and modeled.

Figure 4 exemplifies previous validation work for the model by a comparison of bottom and fly ash flows from experiments with corresponding modeled data for the Chalmers 12 MWth CFB boiler (9). A good agreement is obtained.

RESULTS

Figure 5 gives the back-mixing coefficient, c_{BM}, along the centerline of the furnace as obtained from the modeling. As can be seen, there is a strong back-mixing in the bottom bed and in the splash zone, i.e. the back mixing ratio is high (the effective slip velocity is low). After a strong decay, at a height of about 4 m above the primary gas distributor c_{BM} takes a value of 1, and this height can be taken as the start of the transport zone over which back mixing mainly occurs at the furnace walls (core solids are trapped into the downflow of solids in the wall-layers). Table 1 lists the residence times and the back-mixing ratio for the in-furnace solids, for the three furnace zones.

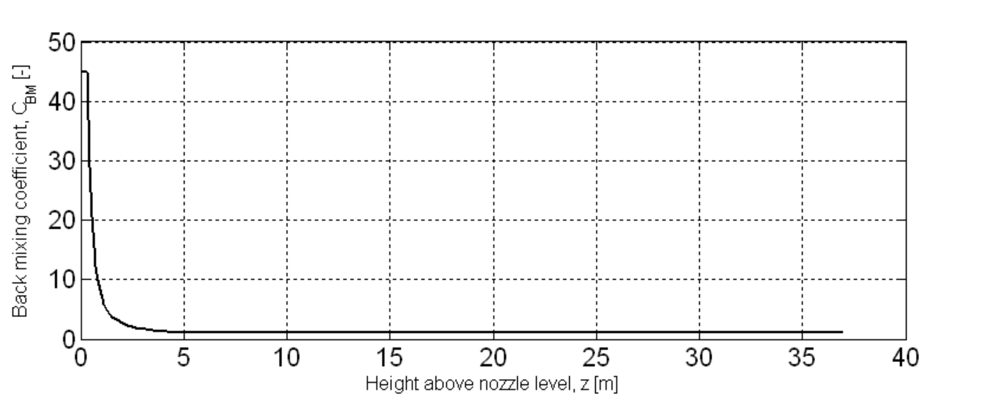

Figure 5. The back mixing coefficient along the centerline of the furnace for the 330 MW_{th} CFB investigated in this work.

Table 1.Mass distribution, residence times, gas velocities, solids concentration and back mixing coefficient for the 330 MW_{th} CFB investigated in this work.

		Dense region	Splash zone	Core region	Wall layer	Return leg	Furnace	Unit
Mass	kg	21 393	22 207	8 946	3 415	53 200	55 961	109 161
Mass fraction furnace	-	0.382	0.397	0.160	0.061	-		
Mass fraction unit	-	0.196	0.203	0.082	0.031	0.487	0.513	
One-pass residence time	s	18.0		2.4	1.7	158.7	164.7	
Gas velocity	m/s	4.3	4.12-3.23	3.38-5.08	0	-		
Effective particle velocity	m/s	0.0403	0.04-0.99	3.12-3.42	1.18-8.73	-		
Solids concentration	kg/m3	1101	1101-25.3	25.3-1.12	4.97-50.54	-		
c_{BM}	-	45	45-1	1	-	-		

Table 2.Total residence times [s] for the bed solids (ash and fuel; petcoke and bark) for the 330 MW_{th} CFB investigated in this work.

<table>
<tr><td colspan="4">CFB loop
33 576 (9.3 h)</td></tr>
<tr><td colspan="3">Furnace
17 102 (4.7 h)</td><td>Return leg
16 474 (4.6 h)</td></tr>
<tr><td>Dense+splash
13 926 (3.9 h)</td><td>Core
1 887</td><td>Wall layers
1 288</td><td></td></tr>
</table>

As seen from Table 1 there is more than 100 tons of solids in the CFB loop of which around 50% is present in the furnace for the operating conditions applied in this work. The remaining part is in the return leg, which includes an external particle cooler in which most of this material is present. As for the furnace it can be seen that about 80% of the solids in the furnace is present in the dense region and the splash zone, i.e. below around 4 meters height. Thus, from a “thermal inertia” point of view these two regions are highly important for maintaining the in-furnace heat balance and temperature distribution up through the furnace.

The residence times given in Table 1 correspond to the average one-pass time for the regions given. The longest time is spent in the return leg due to the low velocities in the external particle cooler with its large mass. As a consequence of the high values of c_{BM} in the dense region and splash zone, the residence time of the solids is longest in these regions compared to the transport zone, in spite of their limited vertical extension. The residence time in the wall layers and in the core region are relatively short, due to the fact that most of the backmixing from core to wall layers takes place in the bottom transport zone, i.e. solids are likely to leave the core region after only a few meters of upflow and thus have a short wall layer path to flow before reaching the dense bed again.

Table 2 lists the total residence times in the regions of the CFB loop burning petcoke and bark, considering the mass balances, progress of combustion (including fragmentation) and ash attrition. As can be seen the average residence time is around 9 hours in the unit. If burning pure biomass in a bed of inert solids such as silica sand, a much longer residence time should be expected (higher fraction of inert solids and less bed ash).

CONCLUSIONS

A back-mixing coefficient, c_{BM}, is defined as a measure for characterizing the solids flow in CFB boiler furnaces. A comprehensive model, which was previously validated, is used to determine c_{BM} together with residence times of the bed solids for a 330 MW_{th} CFB boiler. The importance of the dense region and the splash zone is shown; they constitute around 80% of the furnace bed mass and yield significant backmixing with c_{BM} values up to 45. Thus, these regions have a profound impact of the thermal performance of the CFB boiler. Consequently, in CFB boiler modeling it is important to emphasize in modeling these zones, although a physically sound description is a challenge considering the strong backmixing and highly intermittent gas solids flow in both these regions.

ACKNOWLEDGEMENT

This work is financed by the Chalmers Energy Initiative. Data provided by Metso Power Oy is greatly appreciated.

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