Hydrodynamics of Circulating Fluidized Bed Combustor: A Review

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Abstract

Study of hydrodynamics plays an important role in defining the operation of circulating fluidized bed (CFB).It leads to understanding of gas-solid flow in the riser of CFB under variety of conditions. Hydrodynamic flow structure in the CFB is very complex and should be investigated first. With the improvement in the studies of hydrodynamics and fluidization regimes, a clear picture of flow structure in CFB can be approximated. Flow in the riser of CFB is generally characterized by two regions i.e. bottom and at the top of the column. Several methods like optical probes, X-ray defraction, visual observations have been used by many researchers to study the hydrodynamics of CFB.Hoewever,due to its complexity more and more research papers are presented in this field. This paper also reviews different flow regimes involved in a CFB.

Key words: hydrodynamics, probe, flow régimes, fast fluidization.

Introduction

The CFB technology is used around the world to generate electric power by utilizing various low grade fuels, including coal with reduced pollutants in an environment friendly manner.

Circulating fluidized bed (CFB) combustors are used in a number of processes, especially combustion and catalytic reactions such as fluidized catalytic cracking. The CFB combustor is outstanding in its fuel flexibility, low emission of pollutant, high combustion efficiency and adoptability to load change (Basu & Nag 1996).

CFB combustor are also characterized by the approximate isothermal nature and high rate of heat transfer between the fluidized medium and the heat transfer surfaces with the better knowledge of heat transfer mechanism design and operation can be improved, and the energy evolved during the combustion process can be used with higher combustion efficiency (Afsin Gungor 2008)

Hydrodynamics Behavior of CFB

Study of hydrodynamic plays a vital role in defining the operation of a CFB. It leads to understanding of several aspects of gas-solid suspension behavior in the CFB of different sizes and shapes, operated under a variety of conditions. However, due to lack of information in some areas, makes the understanding of CFB difficult and hinders in designing and operation of CFB (Mastelone et al 1999).

The hydrodynamic flow structure in the riser column is very complex and should be investigated for the better understanding of

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bed-to-wall heat transfer characteristics (Gupta and Reddy 2005)

The macroscopic hydrodynamic behavior of a CFB was firstly studied by Yerushalmi and Cankurt et al (1978, 1979). Yerushalmi et al (1978) have systematically studied the effects like solid mass flux and gas velocity on pressure drop, slip velocity and bed expansion in CFB.

Youchau and Kwauk et al (1980) have defined certain empirical correlations to predict voidage profiles for fast fluidization. The predicted profiles were found to have an inflection point which can be taken as the separation between the dense phase and dilute phase. Yerushalmi and Avidan et al (1982) studied the bed expansion in CFB systems in terms of their similarity to the particulate fluidization. The two phase theory was found not to be valid in high velocity regimes.

The pressure gradient at an axial position in the riser of CFB is proportional to the amount of solids at that position (Yerushalmi and Cankurt 1979, Youchau and Kwauk 1980, Wienstien and co-worker 1983). This has been confirmed by a number of investigators (Arena 1985, Cen 1986, Feaugir 1986).

It is really difficult to predict the flow in the riser. A fully developed flow section in which existence of three sections was visualized by Monceaux et al (1985). The flow consists of three different sections: an acceleration section at the bottom of the column, a section of constant pressure gradient which is the characteristics of a fully developed flow and a disengagement section where the pressure is greater and is less than that in the fully developed flow region. It was also found that at high circulation rate the fully developed region may disappear in some cases.

Based on experimental results obtained from a 152 cm. diameter column operating in different fluidization regimes, Yerushalmi et al (1986) has presented of a fluidization map, which depicts the slip velocity versus the solid volumetric concentration at the bottom of the bed. A unique relation between the slip velocity and the solids volume concentration over the bubbling and the turbulent regimes was obtained. In the fast fluidization regime, however, this relation also depends on the solid rates.

Monazzam et al (2005) made a series of experiments on circulating fluidized bed 0.3m internal diameter cold models to evaluate the operating flow regimes and their transitions. Parameters studied include varying riser gas velocities ranging from dense phase flow regimes through fast fluidization (S-shape riser flow).

Emad et al (2006) also tried to study the hydrodynamics of CFB. The authors used powder (Geldart C) to a CFB of coarse particles (Geldart A) and the solid circulation rate was investigated with addition of fine powders of different sizes and with different hold-ups to the bed. The study was preformed in a CFB of 2m in height and 0.052m in diameter, using FCC catalyst particles of 66 micron as coarse particles and cohesive aluminum hydroxide powders of 0.5-15 micron to the fine powders. The effects of hold up, fine powder size and gas velocity on SCR were investigated. It was found that SCR strongly depended on hold up of fine powders of 0.05-10 micron in size and decreased with the hold up of fine powders under constant gas velocity.

Leckner and Golriz et al (1999) examined the dense zone and found that it could be explained by pressure of bubble. They reported the height of the dense zone was about 1.0m from the distribution in a 12 MW thermal CFB boiler.

Montast et al (1996) also found that the dense zone was characterized by a bubbling bed, and the bulk density was in the range of 700-1000 Kg/m^3 in a 125 MWe CFB boiler. These results shows that the combustion of coal, particle mixing and heat transfer in the dense zone dominate the performance of CFB boiler and a model was also formed to highlight their studies.

However, Barruti and Pugsly et al (1995) argued that dilute region is classified into these groups, predicting the axial profile of suspension density but failing in predicting the radial variations and assuming two regions. The core annulus flow structure to predict the radial variation. Those applying the fundamental equations of fluid mechanics to gas-solid flow. First two types of models which are lumped models can be easily coupled with reaction and heat transfer models to simulate CFBC reactors. A detail picture of heat transfer in CFB was also taken from their studies.

Fluidization Regimes

In recent years, although an increasing number of literature have been devoted to circulating fluidized bed (CFB), the prediction of velocities over which different fluidization regimes exists is still difficult. Understanding of flow regimes in CFB is the key to the successful design and scale up of CFB system (Monazam *et al* 2004).

Kunni et al (1997) has defined fluidization as a "phenomena through which fine solids behaves like a fluid through contact with a gas or liquid". The authors also suggested that for given particle and given superficial gas velocity, we first need to find, what contacting regime is involved in packed bed, bubbling fluidized bed and circulating fluidized bed.

The particle diameter is an important parameter in the field of fluidization and Geldart (1986) has classified solids into A, B, C, & D categories for their application in fluidized beds.

Grace (1986) has classified different types of fluidized beds on the basis of gas velocity. As the gas velocity is increased in BFB, the bubbling action becomes very violent which results in bubbles coalesce and form a core space in the dense region of the column. At the same time, the cloud and emulsion merge and retreat to walls of the vessel. In this state, we have a fast fluidized contactor (FF). Between BFB and FF regimes, he has described "Turbulent Bed (TB)". At further higher velocity, the column enters in the pneumatic conveying region (PC).

On the basis of change in velocities, fluidized beds are classified as follows:-

- Packed Bed (fixed)
- Bubbling Bed
- Turbulent Bed
- Fast Bed (Circulating Fluidized Bed)
- Transport Bed (Pneumatic or Entrained Bed)

In CFB, Basu (1991) has defined following different flow regimes:-

Location	**Regime**
Furnace (Below Secondary air level)	Turbulent or BFB
Furnace (Above Secondary air level)	Fast Fluidized Bed
Cyclone	Swirl Flow
Return leg (Standpipe)	Moving Packed Bed
Loop Seal / EHE	Bubbling Fluidized Bed
Back Pass	Pneumatic Transport

Fast Fluidization

A CFB is generally regarded as to operate in a fast fluidization regime (gas velocity> 4m/s-10m/s).

In practice however, it works in turbulent and bubbling fluidization regimes as well. (Basu et al 1991). The term "fast fluidization or fast fluidized bed" was first introduced by Yerushalmi et al. (1976). Later on the term becomes synonymous with circulating fluidized bed. It was described as a regime lying between the turbulent fluidized bed and pneumatic transport.

Basu & Fraser (1991*)* has defined CFB as "it is a regime of up flowing gas-solid suspension with a high degree of refluxing of solids which would allow a minimum level of temperature uniformity in the furnace".

A fast fluidized bed may be divided into a dense region (bottom) and a dilute (upper region) (Hartge et al 1986, 1988). The bottom region operates either in bubbling turbulent mode, depending on the superficial velocity (Brerton & Grace et al 1984). Andersons & Leckner et al (1994), however, observed that the bottom of CFB to operate in the bubbling regime, if the gas velocity increased to three times the terminal velocity of the average sized particle. The upper (dilute) zone has the solids volumetric concatenation very low, typically about 0.3% (Werdermann and Werther et al 1994). The fast fluidization is primarily affected by parameters like solids circulation rate, superficial gas velocity through the column and particle size.

Local Flow in the Riser

Flow in the riser of CFB is generally characterized by as dense region at the bottom and dilute zone at the top of the CFB. Solids move upward in the core of the riser and core annulus flow exists in the downward flow of solids.

Gasdos and Bierl *(*1978*)* found a lean core surrounded by a dense annulus when they investigated the radial variation of particle concentration in a CFB using the local solids flux probe and X-rays. After a few years, the basic core-annular distribution of particle concentration model was confirmed by Weinstein et al (1983), Dry (1990), Brereton (1993), and Horio et al (1990). These results clearly indicated the existence of a core-annulus flow structure with very significant radial concentration gradients. The boundary between core and annulus was not clearly defined. A low particle concentration in the center and high concentration in the wall region was confirmed by each of the above mentioned researcher.

Park (2003) suggested a new hydrodynamic model to represent the gas flow in the dense phase of fluidized Group A powders. The model also suggested that the particles form clusters under the influence of inter-particle forces, resulting to the formation of clusters of particles and interstitial cavities.

Brereton et al (1993) proposed a core-annulus model, in which, gas was assumed to travel rapidly upwards in the core, while the particles were either moving upwards much more slowly or moving downwards in the outer annular region. Miller et al (1992) defined the dilute core region at the center of the riser and the annulus region, in which the net solids flux was moving downward.

The studies of Yang et al (1990) showed that the radial profiles of local particle velocity were flat in the center region and steep in the region near the wall. This kind of profile is similar to that of particle concentration in the core-annulus model. Yang et al (1992) also noticed that the slip velocity flattened in the central region and was greater in the region near the wall. This was also confirmed by Miller et al. (1992), however, the authors did not indicate any relationship between slip velocity and solids concentration.

The experimental results of Shuyan et al (2005), suggested that riser flow is characterized by continuous formation and disintegration of clusters. In the dilute region, the number and size of clusters increase towards the wall and were found maximum near corners. Core clusters moved upwards or downwards, however, wall clusters generally moved downwards. The number of clusters decreased with increasing elevation, especially near the center of the cross-section.

Solids Flux Distribution

A number of researchers have studied solids flux in CFB and different probes have been developed by various authors to measure the solids flux in the riser of CFB.

Van Breugal et al (1970) studied the flow conditions in the riser of a CFB by using an isokinetic probe. It was reported that solids mass flux was insensitive to pressure and effect of suction velocity was insignificant.

Monceaux et al (1986) using a non-isokinetic sampling probe, observed "similar profiles" behavior of solids flux" in the CFB. It was reported that at a given gas velocity, radial profiles of reduced mass flux was insensitive to imposed solids flux.

Experimental work of Rhodes et al (1992a) confirmed the results of Monceaux et al (1986) by conducting experiments in two risers of 0.152 m and 0.305 m internal diameter. It was found that at higher gas velocities, the profiles became less parabolic in shape, and the thickness of the annulus region decreased. In the larger riser, the profiles flattened, and the relative thickness of the annulus was less than those observed in smaller riser.

The study of gas-solid flow near the wall of CFB is important in understanding the hydrodynamic behavior of a CFB. Gasdos and Bierl et al (1978) and Dry et al (1987), described the solids distribution in the dilute entrained section of the top of the riser as a dilute core surrounded by a denser annular layer of solids. Other experimental findings of Weinstein et al (1986), Bader et al (1988) and Horio et al (1988) confirmed the lean core, dense annulus bed structure in a circulating fluidized bed riser. They concluded that the actual suspension density near the wall of a CFB was found about 1.4 to 2.8 times denser than mean suspension density.

Bolton and Davidson et al (1988) and Rhodes et al (1988) reported that the layer of particles near the bed wall moved downward, and then flow rate of solids layer increased exponentially with distance from the top of the riser. The voidage of this layer was experimentally estimated to be in the range of 0.7 and 0.8. Schaub et al (1989) by using the measurement of a large scale CFB reported that the bed structure adjacent to the wall behave distinctly from that of lean core.

The study of Bader et al (1988) showed that there existed a strong radial suspension density gradient, with a maximum at the wall and a minimum at the center. Solids flux measured across the cross-section of the riser were, parabolic radially. Bodelin et al (1994) named these profiles as "dilute" and "denser" profiles.

Wang et al (1995) studied the effect of temperature on solids mass flux, in a 0.161 m internal diameter CFB riser. The temperature was varied from 20-550^{o}C, superficial gas velocity was changed from 2.5 to 5 m/s, and imposed solids flux was varied from 2 to 60 Kg/m^{2}s. It was observed that solids flux exhibited symmetry in the region of the riser where $r/R < 0.8$, while it exhibited a degree of asymmetry near the riser wall. They also confirmed the presence of quasi-similar profiles in the riser of a CFB at a higher temperature, and concluded that the effect of temperature on mean suspension density and solids flux was mainly due to the change in viscosity of fluidizing gas.

Diego et al (1995) used type B of Geldart classification solids and measured radial solids flux profiles at different axial positions using non-isokinetic probes. They reported that radial flux profiles showed a core-annulus flow structure with upward solids flux in the core in a dilute suspension and downward flux in the annulus in a dense suspension. The upward and downward solids fluxes decreased with the height in the dilute region.

Wong et al (1992) developed a predictive model based on the core-annulus flow structure to evaluate the axial voidage profile and internal flow structure along the riser of a CFB. Through comparisons with experimental data, the proposed model was shown to be able to qualitatively and quantitatively predict the effect of operating variables such as superficial gas velocity and solids mass flux on the axial voidage profile.

Various researchers including Wilde et al 2005; Xu et al 2003; Davidson 2000, Contractor et al 2000; Mandal et al 1995 have reported that the pressure gradient at an axial position is proportional to the amount of solids at that position. For this to be valid particle velocity must be constant and the friction between solids and the riser wall is neglected.

Conclusion

Some fundamentals of fluidization, hydrodynamic behavior in CFB's have been critically reviewed. The major findings are summarized as follows:

1. The understanding of the process of hydrodynamics in circulating fluidized bed is still a difficult task. However a suitable approximation is possible.
2. Solids mass flux is higher near the riser wall than in the core region of the riser.
3. Understanding of flow regimes is important in the studies of hydrodynamics.
4. The CFB is considered to operate in the fast fluidization regime.

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