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Hydrodynamic and combustion behavior of low grade coals in the riser of a circulating fluidized bed combustor

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Abstract

This study is conducted for understanding the fluidization behavior in a CFB combustor for low ranked coals. A lab-scale cold CFB test rig was built at the NFCIET Multan for understanding the fluidization behaviour. Influence of fluidizing air on the fluidization behavior was observed. It was found that voidage along the riser height is affected by riser geometry. The combustion behavior of low grade coals from Thar coal was also explored in a CFB Combustor. The influence of the fluidizing air on the combustion performance was examined and their effect on emissions was established. The temperature in the riser of the CFB rose quickly to around 900°C. This rise in temperature has caused an increase in the amount of exhaust gasses which has their influence on the suspension density. From this study, a firsthand experience of combustion behavior of low grade Pakistani coals was documented.

Keywords: circulating fluidized bed (CFB); combustion; fluidization; low grade coal; temperature profile.

Introduction

Fluid-catalytic cracking (FCC) are industrial processes that are continuously improving over the past two decades in the circulating fluidized bed (CFB) combustors. In a riser reactor, for producing lighter hydrocarbon products rapidly and also for converting residuum stocks or high molecular weight gas oils, in most refineries FCC units are used [1,2]. It is estimated that biomass has production on annual basis ranged to 2740 Quads and by comparing with the other renewable energy, biomass has widespread distribution geographically in the world [3,4]. Hydrodynamics plays a vital role in evaluating CFB performance. Some important areas of performance have limited information and this limited knowledge hinder the operation and/or design of industrial CFB reactors [5,6]. Flow instabilities, internal structure, their velocity propagation and frequency characteristics and flow behavior can be understood in better way by presenting high-speed camera measurements in different forms [7,8]. A number of researches on CFB hydrodynamics have been done by understanding the influence of fluidizing on the hydrodynamics in a CFB. Ziqu et al. (2018) [9] reported that coal preheating combustion technique has proved to be an effective method to burn semi-coke and anthracite. Mun et al. (2016)[10] has done the co-firing of biomass in a 500 MWe coal fired power plant which resulted in high plant efficiency. Liu et al. (2019) [11] have documented the load response rate of a CFB boiler and it was found the relative load change rates exceed 2.0%/min. Cong et al. (2019)[12] have studied the interaction between tobacco stalk and coal during co-combustion. Engin et al.(2018) [13] have reported that the most challenging problem in CFB combustion is SO_2 emissions. Zhou et al. (2018) [14] have investigated about production yields, pollutant gas emission, and the quality of high-grade raw materials such as tar and coal gas.

Thar, is an asset of having around 175 billion tones of coal is the biggest coalfield of Pakistan and Thar coal ranges from lignite-B to sub-bituminous-A having low sulfur and high moisture content. However, due to some mining constraints there is still no bulk supply of Thar is available. The use of lignite as energy sources and low-ranked coals increased recently. In order to convert lignite into gaseous fuels studies are being carried out [15,16]. Biological gasification processes of coal and lignite is cost effective and more efficient than the other conventional thermal processes because they are important for energy requirements in future [17].

Wang et al. (2017) [18] investigated experimental and computational fluid dynamics (CFD) analysis of low grade coal combustion. Margarita et al. (2018) [19] experimentally found that the major gas emissions from the industrial combustion of coal. Byambajav, et al. (2018) [20] studied hydrolysis of lignin and low rank coal in a drop-tube fixed bed reactor. Wang et al (2016) [21] studied the thermal decomposition behavior of bituminous coal, rice husk, pine sawdustand their blend using the thermal analysis techniques.

As the fluidization velocity of the bubbling fluidized bed (BFB) increases, the foaming

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activity turns out to be extremely violent, bubbles combine and turn out to be substantial lastly grow to shape a center space in the thick area of the vessel. In the meantime the cloud and emulsion consolidation and withdraw to the dividers of the vessel. In this state we have a quick fluidized contactor (FF). Between the BFB and FF administrations we have a hard to depict turbulent bed (TB). At considerably higher speeds the divider area diminishes, breaks down, as the vessel enters the pneumatic passing on administrations (PC). This is being outlined in Figure 1. The main reason of this work is to assess the combustion behavior of low quality coals from Thar. The information about the Chamalung mountain range coals from Baluchistan are listed in Table 1 while Table 2 shows proximate and ultimate analysis of examination low grade coals from Pakistan.

Materials and Methods

Cold CFB schematic diagram is shown in Figure 2. It consists of a distributor of stainless steel, an air supply device, stainless steel primary and secondary cyclones, a fast column of Plexiglas and a solid feeding system. Zheng et al. (2000) [22] have assumed that the amount of solid at an axial position and pressure gradient at that position are directly related to each other according to axial particle distribution. The apparatus used for the experiment consisted of a dust collector coal feeder, circulating fluidized bed (CFB) type experimental combustor, control panel and blower. The CFB hot test rig is shown in Figure 3. The test rig CFBC is a vertical tubular furnace with height of riser about 3 m. From the bottom, the fluidizing air is supplied and as a result cyclone separated the circulating particles from air and through the loop seal downstream of the furnace, the particles returned to tubular furnace. The feed rate adjusted by the screw feeder.

Thermocouples recorded the temperatures at different locations in the CFB rig. Supply air flow rate, furnace pressure, were also noted. The gas analyzer recorded the concentrations of CO, CO_2 and O_2 in the produced gas.

In CFBC about 200 g of the circulating sand were loaded and by supplying primary air, a fluidized bed was formed and in-furnace temperature increased. Temperature change of the loop seal recorded by observing the fluidized bed. Before the CFB, in order to attained pre-set temperatures about 3-4 hr consumed. Thermo gravimetric analysis (TGA) of the devolatization behavior of coals used for selecting the pre-set result [20]. Constant feeding of coal was started with gas composition and in-furnace temperature in order to attain CFBC temperature to the specified temperatures. After stabilizing the temperatures, the fluidized air flow rate was changed and the exhaust port was monitored for emissions. The exhaust gases were monitored for a specific ignition condition and it was done three times for repeatability and accuracy. While measuring outflows, a period inside of 5-10 minutes was taken to permit the CFBC to settle. It is critical to have smooth flow of coal through the feeder as it can significantly influence the amount of stoichiometric air necessity for perfect burning conditions [23], [24], [25]. The pre-set temperatures from the CFB were acquired before feeding was done. Consistent feeding of coal was done at a particular gas flow rate and in-heater temperature conditions after the CFBC temperature achieved the predefined temperatures. The desired flow rate of the fluidizing air was kept constant during a particular experiment.

Results and discussion

The riser flow on the basis of experimental observation characterized by: (i) volume fraction profile of nonlinear axial solids, (ii) a tendency of solids to form and (iii) downward motion of riser along the walls and upward solids movement in the center of the riser (Core/Annulus, or C/A stream). Another hydrodynamic mode recommended by [26] for speaking to stream of gas of fluidized Group A powders in the thick stage. The particles shape groups expanded the development of a heterogeneous void structure having bunches of particles and interstitial holes.

The fluidization images from the experiments shown in Figure 4 and Figure 5, suggest that continuous formation and disintegration of clusters is characterized from riser flow and also that clusters have different sizes, solids volume fractions, velocities and shapes. Towards the wall, the size and number of clusters increased and near corners is maximum, in the acceleration and dilute region. Wall clusters generally move downwards while Core clusters may move downwards or upwards. Particularly close to the focal point of the cross-area, the quantity of bunches is conversely related with rise and close to the divider, the extent of group diminished with expanding rise [27].

Also, slip velocity increased with reduced in drag and permit clusters to grow in size and to collect particles. Solids may slip either to the inside or to the outside in the core region of a riser exit due to high density dependent on acceleration due to gravity ‘g’ and magnitude of inertia. Figure 6 shows the various forces acting on the particle.

Froude number represented the ratio between gravity and solids inertia given by

$$Fr_R = \frac{\bar{u}_{st}^2}{g\,R}$$

By referring Figure 6, demonstrates that amidst a curve leave a molecule which see that outspread segment of the speeding up because of gravity (g cos45° or g/), i.e. = g/.equivalent to an outspread increasing speed (Around F_{rR} = 1, proposed that spiral slip is limited. To within the riser exit (`inward' development) yield greater development at littler Froude number and yield greater development of solids to the outside of the riser exit ('outward' development) at bigger estimations of Fr_R. Around a Froude number Fr_R = $1/\sqrt{2}$ in a riser exit, outward/inward movement of solids is minimum according to radial acceleration balance suggested. Fr_R gives much above $1/\sqrt{2}$, for higher or 5 m/s average exit velocity. So movement of the particle occurred at outside of the riser exit. In circulating fluidized beds, determination of voidage distribution axially is an important factor, within the riser it relates to solid hold up and also measure of pressure drop along the CFB. In order to determine riser column voidage profile axially is by measuring the profile of axial differential pressure. In a CFB riser, the axial profile for particle distribution consisting of following sections: developed bottom-dense transition, the acceleration, exit sections and top-dilute. Usually, bottom-dense (lower dense) section termed from the combination of developed bottom-dense sections and the acceleration. For obtaining hydrodynamic behavior of sand and hydrodynamic properties such as voidage pressure drop, fluidizing behavior, experimental observations were performed. Along the riser section for measuring pressure drops at different primary air flow rates, manometers are used. At greater air flow rates, pressure is expected to be high as the dense gas-solids phase is deform easily without appreciable resistance and well aerated. Figure 7 shows the pressure drop variation for various particle sizes.

The flow velocities were much higher than the minimum fluidization velocities. However, the experimental setup was able to give visual observations for onset of fluidization. The pressure drop at various heights in the riser section is shown in Figure 8.In circulating fluidized beds, to study the axial voidage distribution is an important factor because pressure drop is determine along the CFB and within the riser is closely related to the mean solid time residence. In terms of solids distribution, The CFB consisting of following zones as discussed earlier i.e.: at the top, a dilute zone and a dense zone at the bottom of the riser. Figure 9 shows the voidage distribution. By earlier researchers, proposed a typical S-shaped distribution. By many others, this distribution was not observed. By making comparison between these papers, it observed that that the S-shaped distribution depends highly on superficial velocity, solids size distribution and solids circulating rate. It was observed that with the height above the distributor the voidage increased. However at lower section of the riser, this increase is more pronounced. The axial voidage, however, tends to remain constant in the upper zone. Pressure drops per unit height of the bed is high than the upper section due to the lower section of the fast bed is denser. In our study, the axial void age distribution not purely S–shaped but almost close to this shape.

In Figure 10, temperature stabilization at various locations in the CFBC is shown. The steady temperatures at fixed coal federate of 1.6 kg/hr and primary air flow rate of 31 m^3/hr were recorded. It is of great satisfaction that the low grade coal showed stable behavior in the fluidized bed which is a positive sign of controlling the combustor temperatures. In the CFBC at constant primary air flow rate and at different coal feed rate temperature profile is shown in Figure 11. The coal showed good combustion behavior with the temperature in the riser exceeding 900°C [28, 29]. This is encouraging that such temperatures are needs in large coal fired power plants for production of superheated steam. Hence the Thar Coal shows a promising option for building large coal fired power plants in Pakistan. The emissions behavior showed low values low CO under for various experimental conditions during the experiment which shows good combustion behavior. Also the methane production was in the range of 0.1-0.6 % which implies that the rig was operating in combustion mode and temperatures was stabilized for sustainable combustion.

Table 1: Information about Baluchistan coals

Name of Coal Field	Area of Coal Field Sq. Km	Seam thickness in meters			Estimated coal reserves (million ton)
		Max	Min	Avg.	
Duki	100	1.0	0.3	0.5	13
Chamalung	120	1.0	0.3	0.5	N.A

[Farid A. Malik, Abid Aziz (2015) Use of coal in the energy mix of Pakistan, 32nd Annual International Pittsburgh Coal Conference (IPCC 2015)]

Table 2: Duki coal Proximate and Ultimate Analysis

Duki Coal Proximate Analysis			
Moisture	Volatile matter	Fixed Carbon	Ash
11.79	33.06	31.42	24.18

Duki Coal Ultimate Analysis						
%Carbon	%Hydrogen	%Nitrogen	%Sulphur	%Ash	%Oxygen	GCV
50.00	5.53	1.40	7.16	24.18	11.73	9743 Btu/lb

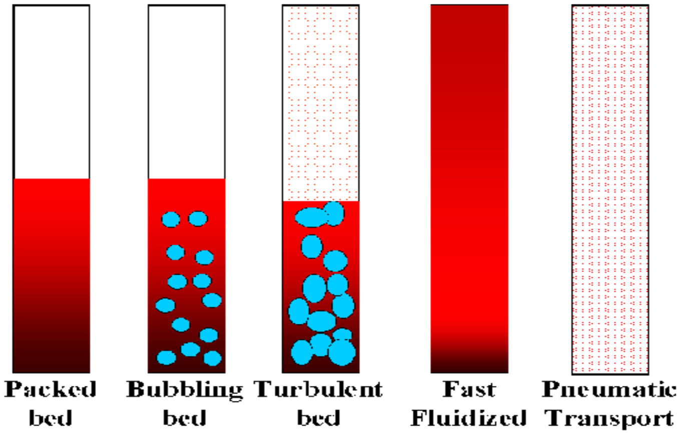

Fig 1: Fluidization regimes in vertical riser
D. Kunii, Octave Levenspiel (2013) Fluidization Engineering, 2nd Edition, Butterworth-Heinemann,

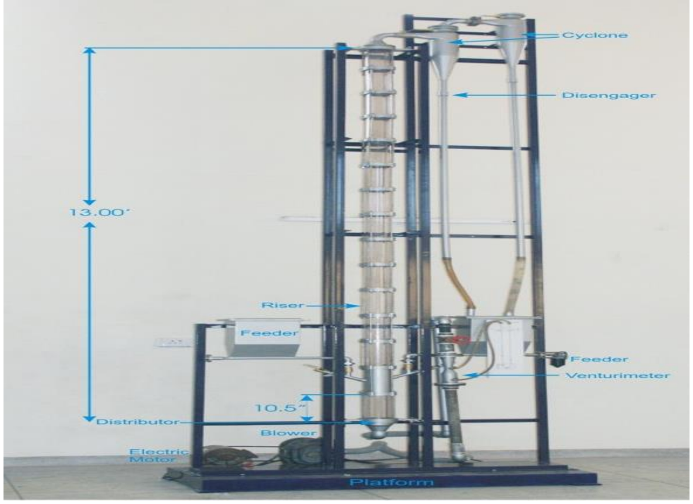

Figure 2. Cold CFB test rig at NFC-IET, Multan

Fig 3: Photograph of hot CFB test rig at NFC-IET, Multan

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Fig 4: Fluidization behavior of sand particles of various sizes at low primary air flow

Fig 5: Fluidization behavior for sand particles at high primary air flow

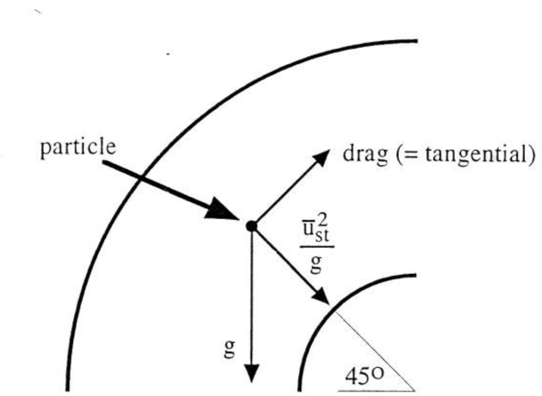

Fig 6: Motion of particle in exit bend

[Meer E. H., Thorpe R. B., Davidson J. F., (2000) Flow patterns in the square cross-section riser of circulating fluidized bed and the effect of riser exit design. Chemical Engineering Science 55: 4079-4099]

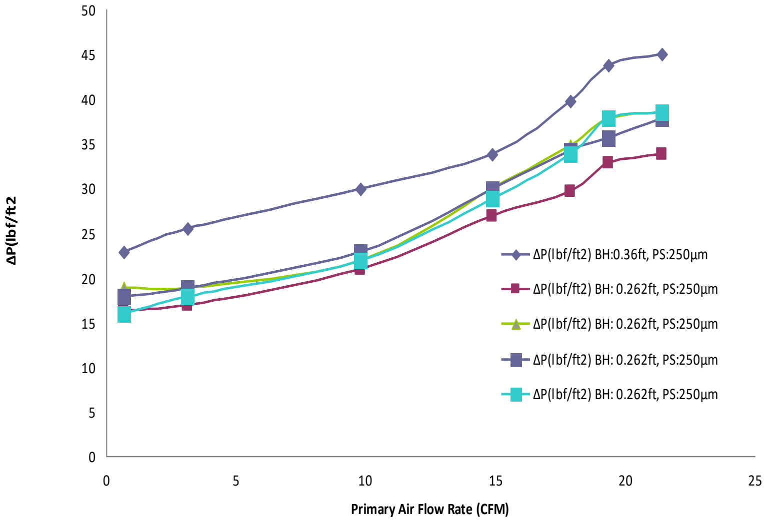

Fig 7: Pressure drop variation with primary air flow for various particle sizes

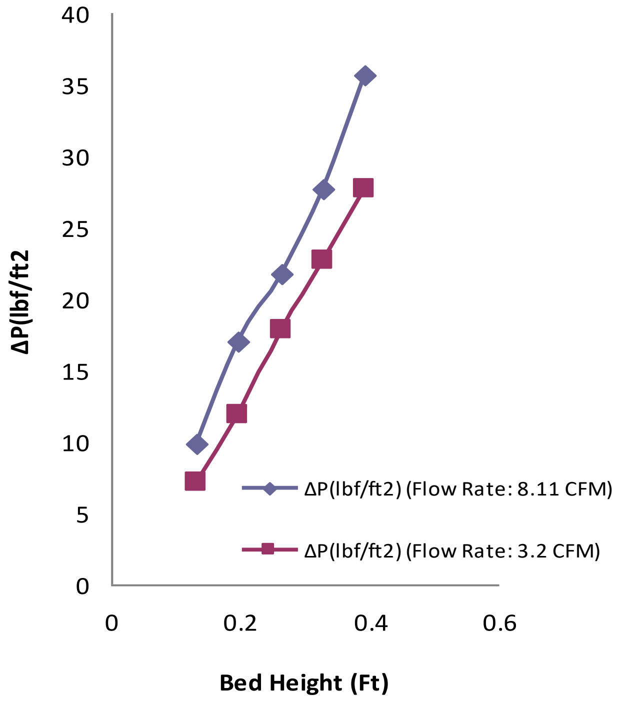

Fig 8: Pressure drop variations along riser height

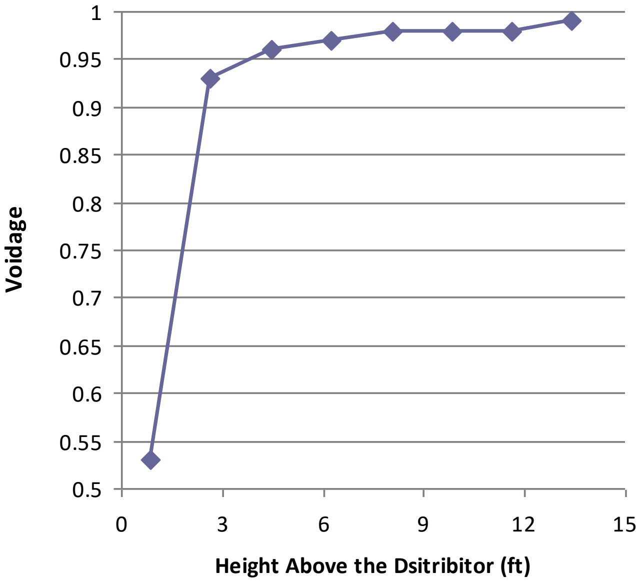

Fig 9: Voidage distribution along riser section

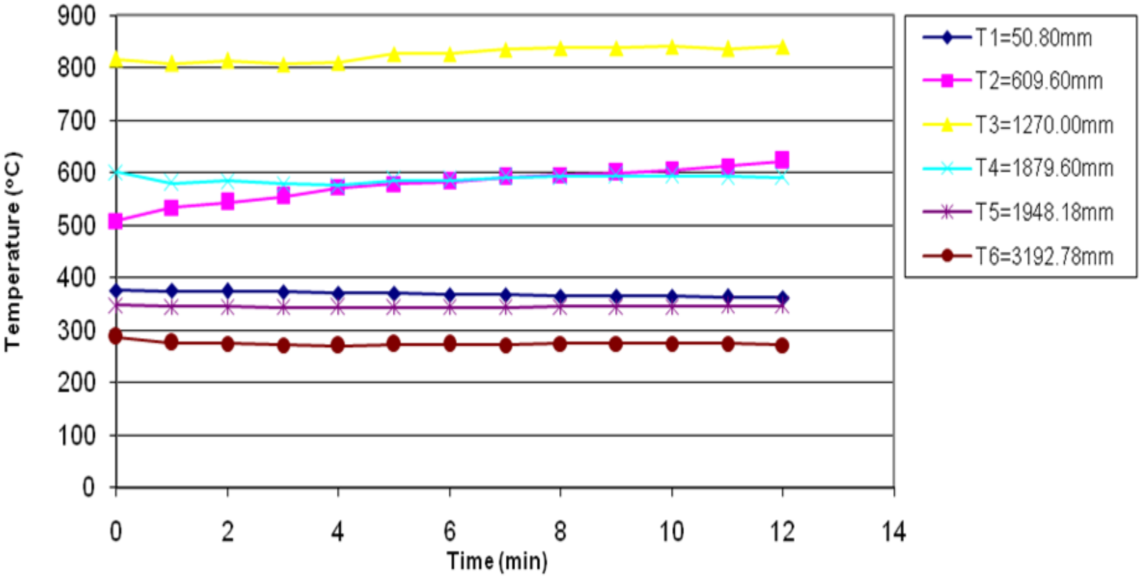

Fig 10: Temperatures at various locations in the CFB

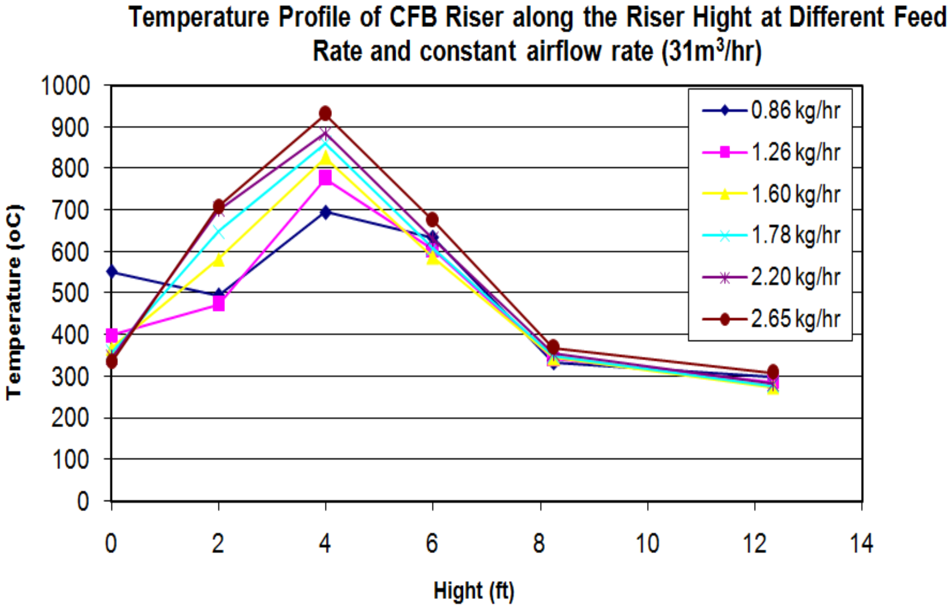

Fig 11: Temperature profile in the CFBC at various coal feed rates

4. Conclusions

In a CFB, it is important to understand the axial particle along the riser height. Pressure drop measurement along the CFB riser helped to determine the voidage in the CFB riser. It was found that the CFB riser has a dilute zone at the top of the riser and a dense zone at the bottom of the riser. In the hot CFB combustor, the combustion behavior of low grade coals was evaluated and their emission behavior was understood. Thar coal is promising option for power generation sector in Pakistan.

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