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A Survey on Circulating Fluidized Bed Combustion Boilers

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Abstract: With the growing energy demands in the power sector, Fluidized bed combustion (FBC) technology is continuously gaining importance due to its ability to burn different low grade coals and the absence of NOx production. This survey paper is intended to comprehensively give an account of domain knowledge related to CFBC boiler. The authors touch upon the design changes which are introduced in the component levels in order to ease the operation, enhance the performance and to meet the regulatory compliance. In addition, salient correlations related to hydrodynamics, heat transfer and combustion are narrated to facilitate the control and system engineers to develop mathematical models using conservation of mass, energy and momentum equations.

Keywords: Circulating Fluidized Bed boilers, hydrodynamics, heat transfer, modelling

I. INTRODUCTION

Deterioration of coal quality and pollutant gases (NOx) arising out of burning coal in conventional utility boilers lead to the development of fluidized bed combustion boilers. The main advantages of the fluidized bed combustion boilers are: reduced NOx, SOx due to relatively low combustion temperature, better efficiency and reduction in boiler size and design. It has the ability to burn low grade coal and it is less corrosive as the combustion temperature is less when compared to that of an utility boiler. In addition to all of these, the startup and shut down operation of FBC boilers are much easier.

Fluidization is the process by which the solid particles are brought to a suspended state through gas or liquid. When air or gas is passed upward through the solid particles at low velocity, they remain undisturbed. As the velocity is increased, the particles reach the state of 'Fluidization'. Basically the fluidized beds are classified into five types as described by Grace [1] namely Fixed bed combustor, Atmospheric FBC / Bubbling FBC, Turbulent FBC, Fast bed / Circulating FBC, Transport FBC. According to Raico [2], they are divided into four regions except transport FBC. When the flow rate is low, the fluid percolates through the void spaces available in between stationary solid particles [3]. This is called 'fixed bed Combustor'. Increase in velocity above the minimum fluidization velocity leads to the formation of bubbles and the solid particles behave like a boiling liquid. Such a boiler is termed as 'Bubbling Fluidized Bed combustion boilers (BFBC)'. Movement of solid particles becomes vigorous in BFBC. 'Turbulent Fluidized Bed combustion (TFBC)' lies between the bubbling and circulating beds.

Turbulent fluidization occurs after the collapse of bubbles. The mass transfer and burning rate differ for turbulent fluidization [4]. Carbon burns in a much faster rate and hence enhanced burning rate is obtained in a turbulent bed. The mass transfer rate is also higher. Some amount of solid particles which are blown out at higher velocities are circulated back to the combustor through cyclone separators. These boilers are termed as 'Circulating Fluidized Bed Combustion Boilers' [CFBC]. Basu and Fraser [5] have defined the CFBC boiler as follows: "A circulating fluidized bed boiler is a device for generating steam by burning fossil fuels or biomass in a combustion chamber operated under special hydrodynamic condition. The solid particles are transported at velocity exceeding the terminal velocity, yet there is a degree of refluxing of solids adequate to ensure uniformity of temperature in the combustion chamber".

If the velocity is further increased beyond the terminal velocity, it enters the 'transport bed' [6]. The difference between the BFBC and CFBC boilers lies with the hydrodynamics – smaller particle size, higher fluidization velocity, different particle concentration, different mixing in the beds and fuel particle circulation to the total circulation rate. The most important parameters for combustion process are combustion temperature and excess air. The bed temperature of both CFBC and BFBC are the same. As the height of the furnace is increased, the bed temperature of CFBC boiler is constant throughout the furnace and for BFBC it is different. Gas to fuel particle velocity is the same for both the boilers. But the fluidization velocity of CFBC is more when compared to the BFBC.

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According to Bo Leckner [7], if the fluidization velocity is increased the size of the bubbles formed increases. Hence the area of the cross section of combustor has to be increased. The heat transfer is higher for CFBC than BFB boilers and the heat transfer is mainly due to particle convection. The combustion efficiency in CFBC is increased due to the recirculation of solid particles. Limestone added to CFBC boiler reduces the Sox and NOx. It is comparatively less than BFBC boilers.

There are several reasons why CFBC technology is well suited. Some of them are: fuel flexibility, ability to burn low grade coal, good emission control of SO_2, NOx, better efficiency, no need of fuel pulverization, easy startup and shut down operation and is less corrosive[8]. Instead of coal, M. Miccio, F. Miccio [9] stated that liquid fuels can also be used for the combustion in CFBC boilers. Variables like Bed height, bed temperature, fluidizing velocity, excess air ratio for burning coal, primary to secondary air ratio remain the same for liquid fuels as that of coal except the fuel feeding system. Liquid bio oil produced from biomass using fast pyrolysis process can also be used [10]. The temperature in the furnace of CFBC boilers is comparatively less with that of the conventional utility boiler which results as the outlet steam temperature in the super heater and reheater may not attain the temperature dictated by turbine inlet. Hence the solid particles and the flue gases are circulated so that the outlet temperature of the super heater and reheater can be increased. This survey paper highlights on aspects such as hydrodynamics, heat transfer and combustion related to CFBC boilers and their important design details.

II. CIRCULATING FLUIDIZED BED COMBUSTION BOILER AND VARIANTS IN COMPONENT DESIGN

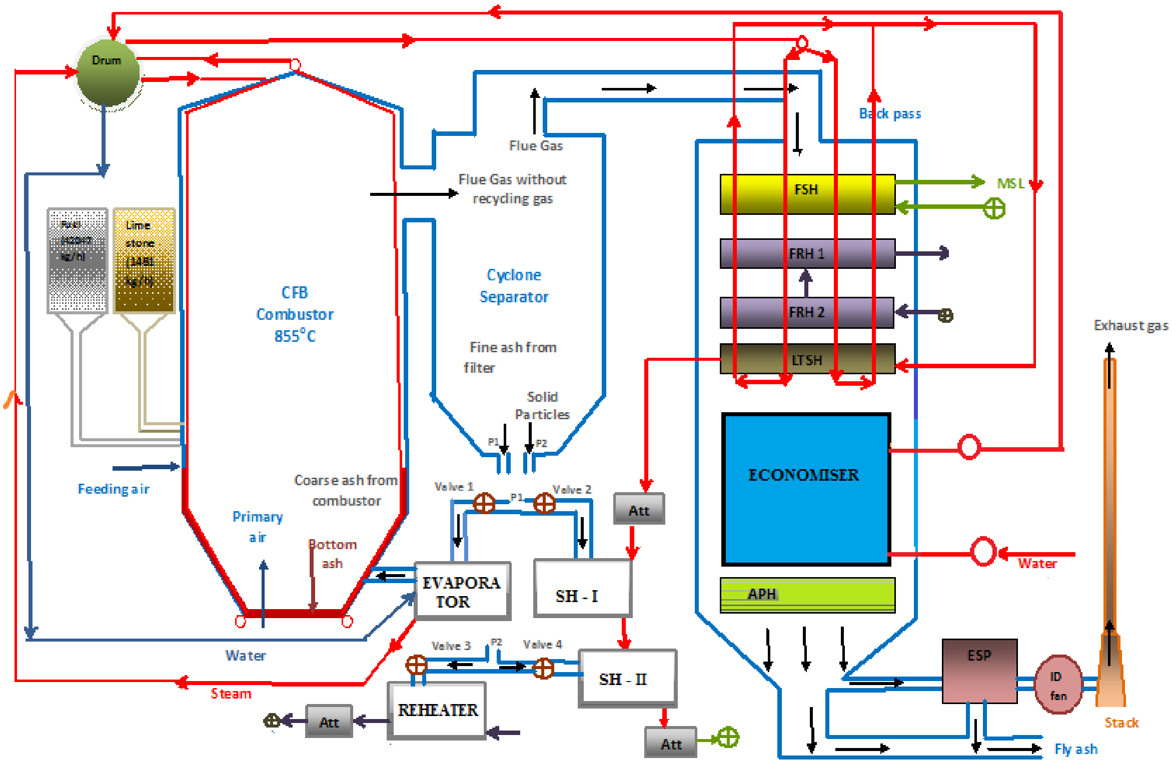

Fig.1: A typical Circulating Fluidized Bed Combustion Boiler

A typical CFBC boiler with its associated components is given in Fig.1. The boiler consists of a combustion chamber, a cyclone separator and a return leg for re-circulation of the bed particles [11]. The combustion chamber is enclosed with water-cooled tubes and a gas-tight membrane. The lower section of the combustion chamber is covered with refractory with openings for introducing fuel, limestone, secondary air, recycled ash, one or more gas or oil burners for start-up and bottom ash drains. Most of the combustion occurs in the lower section, while the heat transfer to the walls is achieved mainly by particle convection and radiation in the upper section of the combustion chamber. The cyclone

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separator can be water-cooled, steam-cooled or without cooling and is designed to separate the entrained solids from hot flue gas and return them through the return leg and possible loop seal.

The gas velocity employed in a CFB is usually in the range 4.5 to 6 m/s. Air is fed to the unit as primary air, secondary air for fuel and limestone feed, air to the loop seal and fluidizing air to the ash classifier. The bottom ash classifier is designed to remove larger bed particles and recycle small particles back to the combustion chamber for improved heat transfer. The operating bed temperature is usually in the range of 850-900 °C, but in the case of low grade fuels the bed temperature can even be below 800 °C. The temperature ranges around 850°C optimizing the sulphur capture efficiency of limestone, combustion efficiency, NOx content and agglomeration of the bed material as well.

The flue gases from the cyclones goes to the back-pass of the boiler and the bed particles are re-circulated to the combustion chamber through fluidised bed heat exchangers. There are four such fluidised bed heat exchangers namely Super heater I, super heater II, evaporator, and reheater. The combustion chamber is enclosed with water-cooled tubes and a gas-tight membrane. The lowest part of the combustion chamber is refractory-lined. The boiler has two super heaters namely final super heater (FSH) and low temperature super heater (LTSH), a bank of economisers. The super heaters, economizer and air pre-heater are located in the back-pass. The flue gas goes through the back-pass to the electrostatic precipitator and, finally, flue gases are blown to the stack. Ash is removed from the bottom of the combustion chamber by the ash-drain system. The lime feeding system is used when sulphur capture is needed.

Design changes are introduced in the component levels in order to ease the operation, to enhance the performance or meet the regulatory compliance. The following paragraphs give an account of such design modifications as appeared in the literature. Design of CFBC includes the design of riser, cyclone separator, heat exchangers etc. The CFBC boiler has external heat exchangers and has two cyclone separators [12]. Modification in the cyclone separator is made as the temperature profile is higher. The width of the cyclone inlet duct is reduced and the vortex finder is extended [13]. Fluidizing nozzle modification (T-style) leads to pressure minimization. The performance of the CFBC boiler such as combustion efficiency, stability etc is improved by slightly modifying the cyclone separator, nozzle and ash reinjection system.

Li Zhao, Xiangdong Xu [14] describes a new design model called "cell model method" and split the furnace into three regions and each region has different velocity. The regions are high velocity combustion region, low velocity heat transfer region and medium velocity suspension region. The differential velocity CFBC combustor improves the efficiency of the combustion. Circulation of bed material is by discrepancy of entrainment at differential air velocity. The velocity is in the order of 3-5m/s in the main bed and is 0.3 to 0.8 m/s in the additional bed.

A continuous stirred tank reactor model of CFBC has been proposed [15] and in this model coal, limestone, ashes which are collected in the furnace are mixed and blown into the furnace by the primary air. This method is stable and is preferred during startup, shutdown operations and during abnormal conditions. Q. H. Li, Y. G. Zhang, A. H. Meng [16] developed a novel model of CFBC called horizontal CFBC. It consists of primary, secondary combustion chambers, cyclone separator, heat recovery area, burnout chamber loop seal etc. Here the overall height of the boiler is reduced. The flow is a multi pass flow. The dilute zone comprises of upper part of primary furnace, secondary furnace and the combustion chambers whereas the dense zone is the lower part of the furnace. The solid entrained enters into the primary, secondary, third chamber, cyclone, loop seal etc and finally into the dense bed.

Sung Won Kim et.al [17] has defined CFBC based on the solids flow characteristics in a loop seal. If the solid inventory is maintained a constant and if the solid circulation increases with decrease in gas velocity, then the pressure drop across the down comer and riser increases. The flow rate of solid particles increases with the increase in aeration rate and solid inventory which results in the drop in the pressure and increase in voidage. All these are obtained with a pneumatically operated pseudo-mechanical valve for loop seal.

Loop seal operation of CFBC has four sections namely the riser, cyclone separator, loop seal section – supply chamber and recycle chamber. In the normal CFBC, the solid particles are sent to riser through cyclone separator. In P.Basu and L.Cheng [18], the solid particles which are accumulated in the cyclone separator drops into the loop seal chamber and due to the air in the chamber they are re-circulated to the riser without a pump. This is due to pressure difference between the riser and standpipe. When the riser gas velocity varies, the operating range of the loop seal aeration also changes. Loop seal air velocity increases which lead to the increase in solids flow through this loop seal. Solids flow rate decreases as standpipe size increases at constant loop seal air rate. Slit size of loop seal has no effect on solids flow rate. For given loop seal aeration rate, smaller particles will have a higher solids flow rate. Solids flow rate increases as solids inventory.

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Independent of the different operating conditions, the solid particles concentration is low in the centerline of the combustor and it is more towards the wall region. This shows the presence of core-annulus type of CFBC combustor [19]. The bottom zone height of the riser is mainly due to the pressure drop in the riser. For the same operating conditions, the pressure drop of a taller bottom zone riser is more when compared to the shorter bottom zone riser.

Addition of wing walls in two different locations namely (a) the middle of the left wall and at the top of the riser (b) the middle of the left wall and 1.3m below the roof and the effect of heat transfer due to the wing walls are well explained by Animesh Dutta and P. Basu [20]. It has been stated that the hydrodynamic conditions of water wall and wing wall are entirely different and the heat transfer coefficient of wing wall is lower than that of water wall irrespective of the position and operating condition. When the wing wall is placed at the top of the riser, the heat transfer coefficient is more than that of the wing wall placed at the mid height of the riser. The solids flow downward when the wing walls are placed on the top of the riser but the flow is upwards when it is in the middle of the riser.200MW Tonghae CFBC boiler demonstrated initially [21] had certain drawbacks such as higher SO_2 emissions, higher temperature profile etc. Modification of Cyclone separator has an advantage of reduced temperature profile and SO_2 emissions. The solid hold up in the dense phase decreases and the particle circulation ratio increases. Hence the efficiency is increased.

Though superficial velocity plays an important role in deciding the performance of the boiler, bed inventory and ash circulation rate also play an important role [22]. Ash coolers are used for circulating the ash and the design of cyclone separators should be such a way that efficiency is maintained better. Laboratory results yield the result that in the freeboard section the small coal particles are easily burnt whereas the large particles are burnt in the dense bed. Further, the particle size distribution plays an important role in determining the heat release during combustion [23], [24].

Anusorn Chinsuwan and Animesh Dutta [25] have investigated a mechanism for the heat transfer between bed to water wall using a longitudinal finned membrane. Experiments are carried out using three different test tubes namely the membrane tube, membrane tube with longitudinal fin at the crest and membrane tube with two longitudinal fins at 45˚ on both sides of the crest for the same hydrodynamic conditions. Experiments show that the heat transfer in the conventional membrane is improved by using a longitudinal finned membrane on the tube surface. The membrane tube has the highest HTC.Jun Su and Xiaoxing Zhao [26] have shown that power requirement and erosion rate is reduced by improving the efficiency of the cyclone. . Zhang P et al., [27] have stated that the heat transfer rate varies based on the heating surface arrangements made on the top of the furnace.

For a typical 300MWe CFBC boiler - with the basic components such as furnace, four cyclone separators - four double loop seal system is designed [28]. Heat transfer coefficient is reduced along the furnace height. Similarly the heat transfer coefficient is more at the corners rather than the centre of water walls. Pneumatically operated external heat exchangers are developed to control the gas- solid flow in the CFBC. The main advantage is that the heat transfer in the external heat exchangers can be adjusted by means of height of the chamber. The air flow can also change the heat transfer rate. Also an empirical relation between mass flow rate of solids and its pressure drop has been obtained [29], [30].

$$G_s = C_D \ 2\rho(1-\varepsilon_{mf}) \Delta P_O \qquad \text{(i)}$$

CFBC boiler bottom ash has more physical heat. This heat is reclaimed [31] by means of a Fluidized bed ash cooler called CFBAC. This is applied to 300MW CFBC boiler. Experimental set up shows that the CFBAC had good particle flow characteristics. Fluidizing velocity and height of separation are the two important parameters in this design. This has good cooling effect and energy conservation.

Industrial CFBC's are operated at low operating pressures. Evaporation of water is more in CFBC's operating at low operating pressure. To avoid over heating of flue gas at furnace exit, the evaporator tubes are submerged. But the submerged tubes get affected by erosion. In order to alleviate the erosion to the submerged tubes, Evaporating Loop Seal (ELS) has been developed [32]. ELS work at lower fluidization velocity and hence erosion is alleviated.

Internal recirculation-CFBC boilers are developed by Babcock and Wilcox and it has two stage impact solids separator namely the primary and the secondary stage. The secondary stage is multi stage dust collector. The main advantages as described by M.Maryamchik [33], Belin.F [34] are high solid collection efficiency, controlled furnace temperature, high separator reliability etc. Feeding limestone leads to high sulphur retention. Fuel ash which is a combination of fly ash and bottom ash contains unburnt carbon particles and lime particles. Loffler et al., [35]; Hou et. al., [36] proved that by injecting NH_3 at the entrance of the cyclone separator and circulating ashes significantly reduces the N_2O emission which is an important pollutant in CFBC boilers.

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670t/h Solid – fuel combustion CFBC model with enriched oxygen described by J.Krzywanski et.al [37] has two different conditions. Combustion in a gas mixture based on $O_2 - N_2$ and the other one without N_2 that is O_2-CO_2. The temperature in the bottom dense zone increases and hence enhanced heat transfer takes place in the oxygen enriched zone. CO_2 is more in the oxygen enriched CO_2 based gas mixture. Increase in CO_2 and decrease in CO leads to better efficiency. NOx is reduced in both the environments. This is one of the designs of CFBC boiler which yields better Heat Transfer Coefficient, better efficiency, lower emissions etc.

According to J.F. Li.et.al [38], the combustion of 300MWe CFBC boilers in China are unstable. Moreover slagging outside the furnace is more and cyclone separators are overheated. CFBC boilers with once through steam cycle has better efficiency when compared to the existing boilers as the CO_2 content is reduced [39]. While using this, the evaporation and economizer duties are reduced and the superheat duty is increased. Evaporation duty is reduced when the lower furnace refractory lining is thickened and when the evaporator wing walls are removed. 10% of tubes looping of platen super heaters are added to increase the superheat duty. Oxy-fuel combustion is oxygen fired CFBC which has major reduction in CO_2. This is one of the Carbon capture and storage (CCS) technology. This has been described by Arto Hotta [40].

Different operational conditions such as excess air, bed operational velocity and particle diameter on bed temperature and the overall CO, NOx and SO_2 emissions from the combustor are investigated [41] and are validated using 50 kW CFBC combustor and an industrial-scale 160 MW CFBC combustor which uses different types of coal. The effects of bed operational velocity and coal particle diameter on mean bed temperature and emissions of CO, NOx and SO_2 results have been investigated for three particle diameters (540, 651 and 852 μm) and for six bed operational velocity values (of about 4.15, 4.50, 5.00, 5.50, 6.00 and 6.50 ms^{-1}). Bed operational velocity has a more significant effect on CO emission than to bed temperature. Increasing excess air decreases SO_2 and NOx emissions. However, NOx emission increases with the operational bed velocity while SO_2 emission decreases.

The next important area of CFBC is controller design. Though all the fluidization types look similar, there exists some difference between them. PID controllers, fuzzy logic controllers are applied to CFBC by many authors. The main control loops in a CFBC boiler [42] are: Steam pressure (boiler load) control, Flue gas O_2 content control, Combustion air distribution control, Drum level control, Superheated steam temperature control, Combustion chamber pressure control, Bed pressure control, SO_2 control.

III.HYDRODYNAMIC BEHAVIOR AND HEAT TRANSFER OF CFBC

All paragraphs must be indented. All paragraphs must be justified, i.e. both left-justified and right-justified.

The study of hydrodynamic behaviour leads to the understanding of gas- solid flow in the furnace under different operating modes. Hydrodynamics of solids are explained based on porosity or voidage of bed material, average gas velocity, mass flow rate of solid particles etc. Several authors have described the hydrodynamics of CFBC boilers in many ways. The hydrodynamics mainly depend on bed pressure drop; solid particles concentration, fluidization velocity and circulation rate of solid particles.

The bed pressure drop varies for circular and non circular bed [43] and packed bed [44] with fluidization height. During combustion process, due to collisions with inert bed particles, abration of char particles takes place and small particles of char separate from the main particles. This process is called attrition, and it depends on the coal type [45]. An understanding of solids suspension density both in axial and radial directions gives a better flow pattern which has an impact on heat transfer [46]. The correlations for these attributes namely the bed pressure drop, solid particles suspension density, circulation rate of solid particles, fluidization velocity and their impact on heat transfer are given in table 1 and 2 respectively.

Yue et al., [24]; Li et al., [16] state that there exists a post combustion of solids and gaseous particles in the cyclone separator and is sensitive to coal type, and it is severe when a low volatile anthracite coal is burnt. The particle size distribution, primary to secondary air ratio and fluidizing air flow rate plays a major role in the post combustion. Jun Su, Xiaoxing Zhao et.al. [26] have grouped the CFBC boiler based on the bed material. The effective material is the fine particles and ineffective material is the large material. The ineffective material remains in the bed while the fine particles are entrained out of the bed.

The heat transfer plays an important role in CFBC design. There exist three mechanisms for heat transfer. They are (i) fluid-to-particle heat transfer (ii) particle-to-fluid heat transfer and (iii) bed to wall heat transfer. Heat transfer between the medium and surface plays an important role in determining the efficiency of the combustion system. As far as the

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heat transfer is concerned, much heat is involved in the case of fixed bed and hence large temperature gradients are involved. The temperature gradient remains constant or it is maintained at constant by controlling continuous feed and circulation of solid particles. Gas to particle heat transfer coefficient can be calculated [47] using the Nusselt's relation,

$$N_u = 1.6 \times 10^{-12} (R_e / \varepsilon)^{1.3} P_r^{0.33} \qquad \text{(ii)}$$

where R_e, P_r are defined in the table. The heat transfer between the fluid and particles are given in two forms [48] (i) for gas-solid and (ii) for liquid-solid fluidization. For
Gas- solid system,

$$h D_p / k = 0.015 (D_p G / \mu)^{1.6} (C_p \mu/k)^{0.67} \qquad \text{(iii)}$$

For Liquid- solid system,

$$h D_p / k = 0.016 (D_p G / \mu)^{1.3} (C_p \mu/k)^{0.67} \qquad \text{(iv)}$$

Heat transfer from a fluidized bed to wall consists of three components namely Particle convection, Particle radiation and Gas convection. Here the particle convection and radiation are given the prime importance whereas the gas convection is generally disregarded as the density of gas is less than that of the solids [49]. Andersson and Leckner [50] explained that the overall heat transfer co-efficient is mainly due to convective heat transfer co-efficient and radiative heat transfer co-efficient of suspended particles. Thermal conductivity is also neglected when considering heat transfer in CFBC combustion systems [51]. Werdmann and Werther [52] have extracted the following correlation for the convective heat transfer coefficient

$$h_c = 7.46 \times 10^{-4} \left(\frac{k_g}{d_p}\right) \rho_s^{0.562} \left(\frac{D_b \rho_g u_g}{\mu_g}\right)^{0.757} \qquad \text{(v)}$$

The above correlation must be added to the radiative coefficient to obtain the overall heat transfer coefficient. By neglecting the heat radiation and convection in the dilute phase, a simpler empirical correlation for the overall heat transfer coefficient to the water wall of a CFBC presented [53] is given by

$$h = 5\rho_s^{0.391} T_b^{0.408} \qquad \text{(vi)}$$

The overall heat transfer coefficient from bed to wall at the bottom dense zone is given [8] as

$$h = 40(\rho_b)^{1/2} \qquad \text{(vii)}$$

where ρ_b is given by $\rho_b = \rho(1-\varepsilon) + C\,\varepsilon$

Heat transfer from bed material to wall tube is given by

$$Q_{bw} = hA_w(T_b - T_w) \qquad \text{(viii)}$$

Several authors have described the structure of the riser as core and the annulus. The temperature of the core is greater than that the annulus and hence heat transfer between the thick wall and the annulus is less than the heat transfer between the thin walled annulus and the core [12]. The heat produced is more in the dense bed than the dilute bed. Radial or tangential injection of secondary air into CFBC riser also causes a change in the heat transfer coefficient. Yong Jun Cho [54] expressed that when the secondary air is injected in radial manner, convectional heat transfer coefficient increases while the overall coefficient decreases. With the tangential injection, the convective heat transfer coefficient increases and the particle convective heat transfer coefficient decreases.

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IV. CONCLUSION

Description on a typical circulating fluidized bed combustion boiler and narration on the design changes which are introduced in the component levels in order to ease the operation, enhance the performance and to meet the regulatory compliance are given. In addition, salient correlations related to hydrodynamics, heat transfer and combustion are provided. Mathematical modeling and simulation has been an effective tool in analyzing and optimizing the performance and diagnosing the faults. It is believed that this paper will be of use for control and system engineers to model CFBC boiler to analyze the plant performance during normal and abnormal situations and assess the efficacy of different control schemes to meet the performance criteria desired by the plant owners and operators.

APPENDIX - NOMENCLATURE

A_w - Surface area of tube wall surface
C - Gas concentration
C_D - Orifice discharge coefficient
D_b - Bed diameter
D_p - Diameter of the particle
G - Superficial velocity
Gs - Mass flow rate of solids
h - Net heat transfer coefficient
k - Thermal conductivity of fluid
k_g - Thermal conductivity of the gas
T_b - Bed temperature
T_w - Wall temperature
u_g - Velocity of gas
ΔP_O - Pressure drop in the orifice
ε_{mf} - Voidage at minimum fluidization
μ - Fluid viscosity
ρ_s - Suspension density of the bed
ρ_g - Density of the gas
μ_g - Viscosity of gas
ρ_b - Local bed density
ε - Voidage

TABLE I

HYDRODYNAMICS IN CFBC

S.No	Symbol		Parameter	Formulae	Ref.
1	ω_a	 K_a U_c ρ_b m_c d_c	mass flow rate of char consumed by attrition attrition constant char velocity average bed density char mass carbon particle diameter	$\omega_a = k_a\left(U_c - \frac{G_s}{\rho_b}\right)\frac{m_c}{d_c}$	55
		U_c ρ_c ϵ	char velocity char density voidage	$U_c = \frac{G_s}{(1-\epsilon)\rho_c}$	
		G_s U U_{mf}	Circulation rate of particles fluidization velocity Minimum fluidization	$G_s = 785(U - U_{mf})\exp(-6630 d_c)$ where	56
		ρ_b M A_b H	average density of the bed the total mass of the bed cross-sectional area of the bed bed height	$\rho_b = \frac{M}{A_b H}$	

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		A_r C μ d_p	Archimedes number Gas concentration Viscosity Mean particle diameter	$U_{mf} = \mu\,[(33.7^2 + 0.0651A_r)^{0.8} - 33.7] / C\,d_p$	63
2	ω_b	C_g A_c	burning rate of char particles oxygen concentration in the free stream surface area of a char particle	$\omega_b = \frac{C_g}{1/h_m + 1/k_c} A_c$	5
		K_c E A' R	char reaction rate coefficient Activation energy coefficient vary with the characteristics of coal and its chemical composition universal gas constant	$k_c = A'\exp\left(\frac{-E}{RT_s}\right)$	66
		d_c d_g	carbon particle diameter molecular diffusivity of oxygen	$h_m = \frac{12Sh\varphi D_g}{d_c RT_m}$	
		T_b T_s T_m	bed temperature particle temperature mean temperature	$Tm = \frac{Tb + Ts}{2}$	
		S_h ϵ Re Sc U_s μ_g	Sherwood number Voidage Reynolds number Schmidt number Slip velocity Viscosity of gas	$Sh = 2\varepsilon + 0.69\left(\frac{Re}{\varepsilon}\right)^{0.5} Sc^{0.33}$ $Re = \frac{u_s d_c \rho_g}{\mu_g}$ $Sc = \frac{\mu_g}{\rho_g D_g}$ $Us = \frac{u}{\epsilon} - \frac{Gs}{(1-\epsilon)\rho c}$	57
		D_g T_b ς P	diffusivity coefficient Bed temperature particle porosity Pressure	$D_g = 8.677 \times 10^{-8} \frac{T_b^{1.75}}{P} \varsigma^2$ where	60
	ΔP	L_f ε_f ρ_s ρ_f g	Bed Pressure drop Bed height Voidage density of solid particles density of fluidizing medium acceleration due to gravity	$\Delta p = L_f\left(1-\varepsilon_f\right)\left(\rho_s - \rho_f\right)g$ where	5

TABLE II

HEAT TRANSFER IN CFBC

Sl.No	Symbol		Parameter	Formulae	Ref.
1	h_c	ρ_s ρ_g T_b D_b d_p u_g μ_g k_g	Convective heat transfer coefficient suspension density of the bed, density of the gas, temperature, bed diameter, diameter of particle, velocity of gas, viscosity of gas thermal conductivity of the gas.	$h_c = 7.46 \times 10^{-4}\left(\frac{k_g}{d_p}\right)\rho_s^{0.562}\left(\frac{D_b \rho_g u_g}{\mu_g}\right)^{0.757}$	52
	h		Overall heat transfer coefficient	$h = 5\rho_s^{0.391} T_b^{0.408}$	53

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TABLE III IMPACT OF PROCESS / PHYSICAL PARAMETERS

Sl.No.	Parameters	Authors/ Year	Impact Of Parameters
1.	velocity	G.Visser and M.Valk , 1993	Porosity and heat transfer co-efficient is defined as a function of fluidizing velocity. In low velocities, the particle convective component of heat transfer is very low or negligible.
		Afsin Gungor, 2009	Operating velocity affects the efficiency of the system. Heat transfer, Rhe-area ratio also affects the efficiency of the system.
2.	particle size	B.A.Andersson , 1998	Size of the Particle affects the heat transfer co-efficient.
		Yong Jun Cho et.al. , 1996	The heat transfer co-efficient is high for smaller particles and low for larger particles.
3.	Circulation rate of solids	Yong Jun Cho et.al. , 1996	As the circulation rate of solids increases the heat transfer co-efficient increases.
		Werner.A, 2001	The circulation rate of solid particles is a function of inventory and not the superficial velocity.
4.	Height of the furnace	Q.Wang et.al, 1999	As height of the furnace is increased the concentration of solid particles is less both in the core and the annulus region.
		Leckner et.al, 2003	The heat transfer coefficient of wall to bed increases. As the height increases the HTC decreases.
		L.Huilin et.al, 2000	As the height of riser increases, the heat transfer due to radiation decreases. Here the heat transfer due to convection is kept a constant with low circulation rate and wide particle distribution. SO2 retention is also included.
		Zhang H. et. al, 2005	Peripheral heat transfer is not uniform throughout the riser and heat distribution varies with the height.
5.	Bed Pressure	A.V.S.S.K.S.Gupta and P.K.Nag, 2002	When the pressure is low, the force which drags the solid particles is less and hence the bed voidage is also less. When the bed voidage is decreases the inventory increases. Increase in pressure leads increased bed voidage in the bottom dense region and decreased voidage in dilute region. Heat transfer coefficient increases with increase in pressure, superficial velocity and bed temperature.
		P.Basu, Nyoman.S.Winaya , 2002	With increase in pressure, the thermal conductivity of gas particles increases which leads to further increase in heat transfer co-efficient.
6.	Particle size distribution	Saastamoinen et.al, 2003	Particle size distribution affects heat transfer and flow dynamics in boiler.
7.	Particle concentration	Wennan Zhang, 1995	The particle concentration is more near the wall
		Q.Wang et.al, 1999	The particle concentration is more in annulus region and it is less in the core region.
8.	Solid mass inventory	L.Huilin et.al, 2000	Temperature of the gas is a function of solid mass inventory.
9.	Bed Temperature	P.Basu, Nyoman.S.Winaya, 2002	Increase in bed temperature increases heat transfer coefficient.
10.	CO_2 concentration at high temperature	P.Basu, Nyoman.S.Winaya, 2002	Volumetric concentration of CO_2 increases the partial pressure of CO_2. This leads to an increase in gas emissivity and radiative flux. Hence the HTC increases as well as the emission increases.
11.	Addition of limestone		When limestone is added, the heat transfer coefficient (both convection and radiation) increases as the CO_2 concentration is increased. Otherwise the O_2 concentration is increased.
12.	Particle suspension density	Jim in Kim, Guiyoung Han, Changkeun Yi, 2002	The axial dispersion coefficient increases with increase in suspension density and gas velocity

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