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Influence of Indian lignite on gas solid hydrodynamics of a 210 MW CFB riser

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Abstract. The circulating fluidized bed combustion (CFBC) technology is better alternative to be adopted for generating power than PC fired boiler technology due to several advantages in which mainly fuel flexibility, environmentally friendly and low cost compared to combination of PC fired boiler with FGD for similar environmental performance. Unlike PC fired boilers, CFB boilers are suitable for low grade fuels like lignite. The huge availability of lignite in India reduces the import cost of bituminous coal which is regularly supplied as a fuel for PC fired boilers from other countries. The objective of the present paper is that the study of gas solid behaviour in 210 MW CFB riser by using mathematical equations. In this study, the key parameters of hydrodynamics (suspension density, local voidage, pressure drop) which are affecting the design and performance of CFB boiler are studied at different height levels of riser. Three Indian lignite samples (Tamilnadu, Gujarat and Rajasthan) which are successfully used in commercial operations of CFB boiler in India are assumed for this study with two mean particle diameters. This work is also determined and compared the heat transfer coefficients of boiler elements (water wall, wing wall and furnace superheater) placed in the riser.

1. Introduction
Circulating fluidized bed technology uses the principle that the crushed coal along with lime stone is introduced into the lower furnace where it is kept suspended and burnt partially upward flow of primary air. The secondary air is injected at the bottom of upper furnace where complete combustion takes place [1].Understanding of gas solid behaviour is an important section for design and evaluation of performance of CFB boilers. The solid particles and gas in the riser influence many parameters like principal dimensions of furnace, pressure drop along the furnace height, heat transfer coefficients, rate of solids circulation, bed density and surface area of boiler elements [1]. CFBC furnace is divided into lower dense zone and upper dilute zone based on the solid particles present. Dense zone is considered from distributor to secondary air ports. The dilute zone placed in between secondary air ports to riser exit. Hydrodynamics is required for this zone to identify changes of physical and chemical behaviour. The dilute can be divided into two vertical sections like annular and core regions. The more solid particles accumulate together and the gas velocity becomes low in the annular region which is connected to wall. The gas velocity is high and dispersion of solids takes place in core region [2].

There are many studies available in open literature for axial voidage and bed density which are decreased from bottom to top of the bed [3-9]. Kunii and Levenspiel [4-5] developed correlations for estimating suspension density and axial voidage at any section in the riser. Adanez et al. [3] developed equations for decay factor using particle diameter, equivalent diameter of riser, riser velocities. Allan S Issangaya et al. [10], Afsin Gungor et al. [11] and Todd S Pugsley et al. [12] discussed about radial voidage in their studies at different operating conditions. The local voidage is a function of mean bed voidage at respective section and solids concentration at the wall is almost 2.3 times the mean bed solid concentration [2]. The thickness of boundary layer decreases along with height and varies in decimetres for commercial CFB risers [13]. The suitable correlation of local voidage at all radial locations in the riser is proposed by Allan [10].

Heat transfer coefficient is a function of bed temperature and suspension density. There are many correlations available for commercial CFB boilers to predict heat transfer coefficient of water wall in open literature [2, 14 -19] at different bed temperatures (550^0C- 940^0C) and densities (2-80 kg/m^3). Dutta and Basu [14] studied about heat transfer coefficient of wing wall for 20 MW and 170MW CFB boiler and developed a correlation of heat transfer coefficient for wing wall. The primary super heater is placed at the middle of the furnace. Basu [1] compared the heat transfer coefficients of primary superheater with water wall based on bed temperature. The heat transfer coefficient of superheater is slightly higher than water wall when bed temperature varies from 830 to 860^0C and slightly reduced when bed temperature crosses 880^0C.

Even though many researchers explained the gas solid behaviour experimentally and mathematically in the furnace, a detailed mathematical model for low grade fuels like Indian lignite is not available properly till date. The present work focuses the mathematical study of hydrodynamic parameters in the riser of 210MW CFB boiler using three types of Indian lignite which are popularly used in commercial operations. General and suitable correlations which are available in open literature and used for commercial operations are assumed for this work. This study is concentrated 0.8mm and 0.9mm of mean particle diameters.

Table 1. Ultimate analysis of lignite samples.

Lignite Ultimate Analysis	Neyveli Lignite[20]	Surat lignite [21]	Giral lignite [22]
Carbon (%)	27.5	30	30.09
Hydrogen (%)	2.2	2.5	2.24
Sulphur (%)	0.7	1.2	6
Oxygen (%)	10.4	11	6.27
Nitrogen (%)	0.2	0.3	0.4
Moisture (%)	50.5	45	40
Ash (%)	8.5	10	15
HHV (kJ/kg)	10665.49	11882.7	12843
LHV (kJ/kg)	8864.79	10156.2	11304.3

2. Selection of Indian lignite

The power sector in India is looking for more CFBC boilers which are best suited for low grade coals like Indian lignite compared to conventional (PC fired) technology. The Indian lignite coals are high moisture content and have sulphur content varies in between 0.3 and 6% [23]. Hence these coals are suitable for clean power generation in CFBC boilers. The lignite in India is predominantly available with total quantity of 44138MT in Tamilnadu, Rajasthan and Gujarat [24]. Three lignite samples which are successfully used for power generation are taken for this study. The ultimate analysis and

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particle distribution of these samples are given in table 1 and 2. The limestone assumed for this study is taken from commercial operations of CFB power plants in India [22] and shown in table 3.

Table 2. Particle size distribution assumed for lignite samples in this work [25], [20]

Particle size	100%	80%	50%	d50
mm	<15	<10	<1	0.8-1

Table 3. Limestone assumed for this work

Limestone analysis [22]	
$CaCO_3$ (%)	96.8
$MgCO_3$ (%)	1.2
Moisture (%)	0.28
Inert (%)	1.72

3. The hydrodynamic model

The riser consists of lower and upper section. The upper furnace is divided into annular and core regions. The secondary air is injected above the refractory. The solids in the gases are recirculated at lower furnace through loop seal and return leg. The three boiler elements are placed in the riser. Generally water wall is placed in the upper furnace. Basu and Nag [2] said that the height of the water is equal to the upper furnace. The wing wall is used for taking evaporative load in the study. The wing wall is connected to ceiling of furnace and side walls. The superheater is located in the bottom of the upper furnace. The riser configuration with heat exchangers is shown in figure 1.

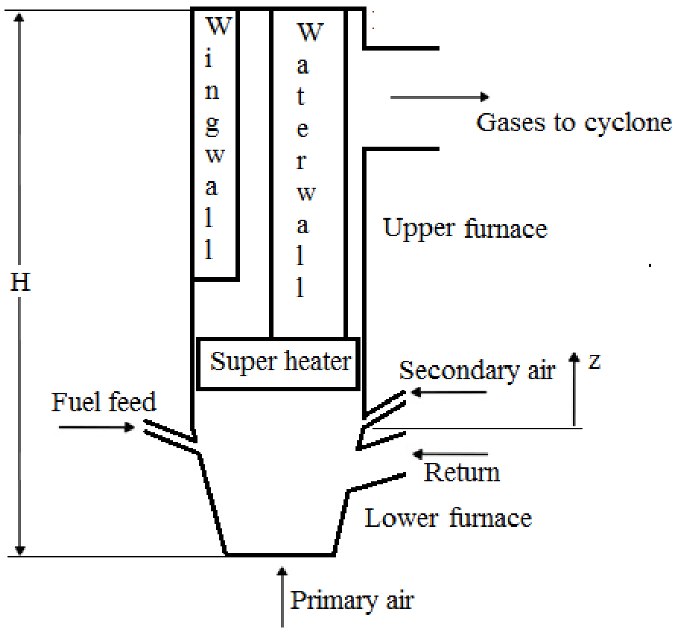

Figure 1. CFB Riser configuration with boiler elements

The following assumptions are taken in case of operating parameters for this model.

- The bed temperature is assumed as 850^0C to reduce NOx emissions, erosion problems, losses of combustion and thermal stresses on water tubes [1].
- Ca/S ratio is taken as 2 at which the sulphur capture efficiency reaches 90% and high lime stone reactivity takes place [1].
- Fluidization velocity is assumed as 6 m/s above which the amount of carry over unburnt carbon particles, stack gas losses and erosion problems may increase [1].
- Minimum solids circulation rate is assumed through the riser.
- The primary air ratio and combustion efficiency are assumed as 40% and 99% for combustion calculations.

The various correlations which are used for predicting hydrodynamic model are taken from open literature and given below.

Minimum fluidization velocity, Grace J R [26]

$$\mathrm{Re}_{mf} = \frac{U_{mf} d_p \rho_g}{\mu} = \left[27.2^2 + 0.0408 Ar\right]^{0.5} - 27.2 \quad (1)$$

Particles terminal velocity, Kunii D and Levenspiel O [27]

$$U_t = \left[\frac{4\left(\rho_p - \rho_g\right) g\, d_p}{3\, \rho_g C_D}\right]^{1/2} \quad (2)$$

where $C_D = \frac{10}{\mathrm{Re}_p^{0.5}}$ for $0.4 < \mathrm{Re}_p < 500$

Transport velocity, Perales J F et al [28]

$$U_{tr} = 1.45 \times \frac{\mu}{\rho_g d_p} \times Ar^{0.484} \quad (3)$$

The minimum solids circulation rate from Yue G et al [29]

$$G_s = \frac{\rho_g^{1.627}\; U_{tr}^{2.25}}{0.164\left[d_p\left(\rho_p - \rho_g\right) g\right]^{0.627}} \quad (4)$$

Cross sectional average voidage, Bai D and Kato K [30]

$$\varepsilon_{avg} = 1 - \frac{G_s}{\rho_p (U_o - U_t)} \quad (5)$$

Density at given riser section, Kunii D and Levenspiel O [5]

$$\rho = \rho_p \left(1 - \varepsilon\right) + \rho_g \varepsilon \quad (6)$$

Axial Voidage profile equation, Kunii D and Levenspiel O [4]

$$\varepsilon = \varepsilon_e - (\varepsilon_e - \varepsilon_a)\ \exp\ [-a\,(H - H_i)],\ \text{where}\ H > H_i \quad (7)$$

There are many parameters to influence decay factor like properties of particle, operating conditions of riser. Adanez J et al [3] proposed a correlation to determine decay factor based on particle diameter

$$a\left(U_o - U_t\right)^2 = 3.5 - 1670\ \ d_p \quad (8)$$

The solids fraction at top of the bed can be determined by rate of solids circulation and superficial gas velocity. Voidage at furnace exit from Adanez J et al [3]

$$\varepsilon_e = 1 - \frac{G_s}{\rho_p U_o} \tag{9}$$

The pressure drop across the bed, Todd S Pugsley et al [12]

$$\frac{\Delta P}{\Delta L} = \rho_p (1 - \varepsilon) g \tag{10}$$

The heat transfer coefficient of boiler elements in the furnace is given by

$$h = k\left(\rho_{avg}{}^{\alpha}\right)\left(T_b{}^{\beta}\right) \tag{11}$$

The coefficients in equation (11) are taken from different studies based on commercial operations. Basu and Nag [2] for water wall, Dutta and Basu [14] for wing wall, CHENG Leming et al [31] for superheater are taken for k, α and β.

4. Results and discussions

Initially combustion and mass balance were carried out using fuel and lime stone analysis, operating parameters for 210MW CFB boiler. The hydrodynamic parameters for three samples of lignite at different mean diameter of 0.8mm and 0.9mm are discussed below.

Mean particle diameter influences bed to wall heat transfer coefficient which affects the combustor height as shown in figure 2. It was observed that larger particle diameter provided more suspension density above the refractory zone and transferred more heat to the water wall compared to smaller particle diameter. As a result, the reduction in surface area of water wall and height of upper furnace were taken place at 0.9mm of mean particle diameter particle. The height of furnace operated by Neyveli lignite occupied minimum height due to particle density and heat transfer coefficient compared to Giral and Surat lignite. Solids circulation rate developed in the furnace always related to the voidage present in the dense and fast beds. The raise in solids circulation rate takes place with reduction of mean bed voidage [3]. It was observed in this study that the rate of solids circulated to the cyclone from the riser was more in case of Neyveli lignite due to less mean bed voidage for the both the mean particle diameters.

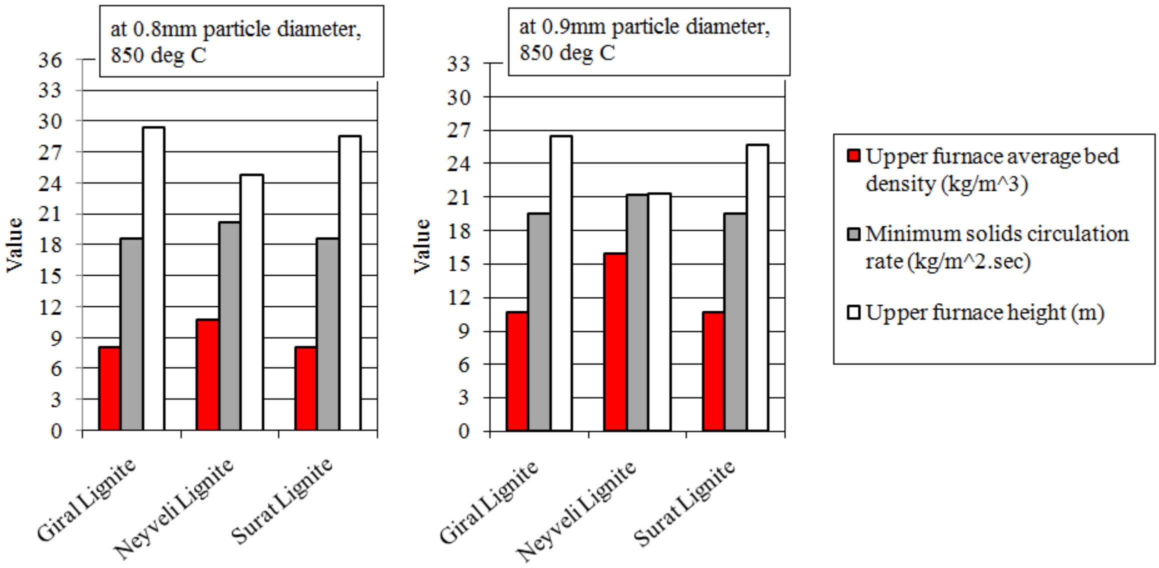

Figure 2. Average bed density, solids circulation rate and upper furnace height at two different particle diameters for three lignite samples

The figure 3 and 4 represent the pressure drop in the furnace from height of minimum fluidization to the top of the bed. Pressure drop at respective section is a function of solids fraction of bed. The average bed density of lower furnace was obtained more due to more gap between solid particles. As a result, the pressure drop per unit height was obtained more in the lower furnace (dense zone) than upper furnace (dilute zone). It was observed that the pressure drop in the risers operated by Surat and Giral lignite were obtained almost same due to negligible change in voidage and bed density. The pressure drop in the furnace operated by Neyveli lignite was more than other lignite due to high bed density.

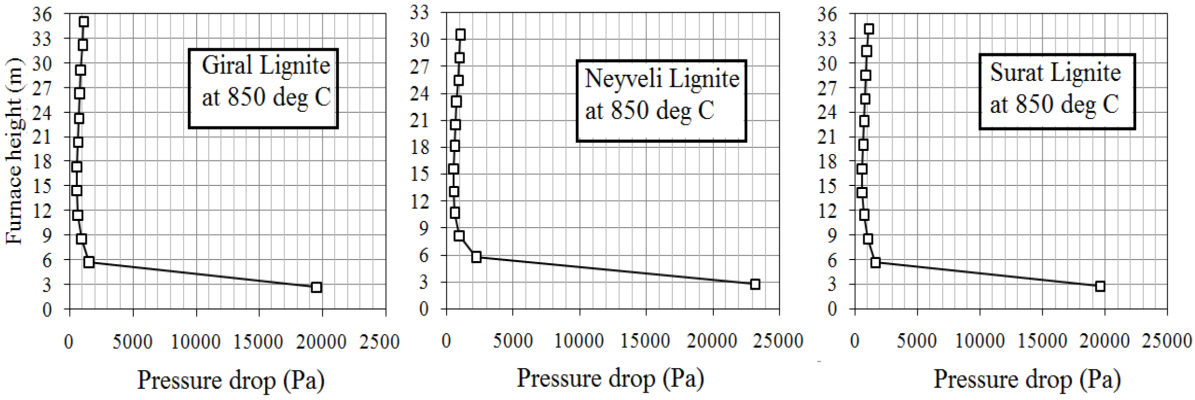

Figure 3. Pressure drop profile along the CFB riser at 0.8mm of mean particle diameter

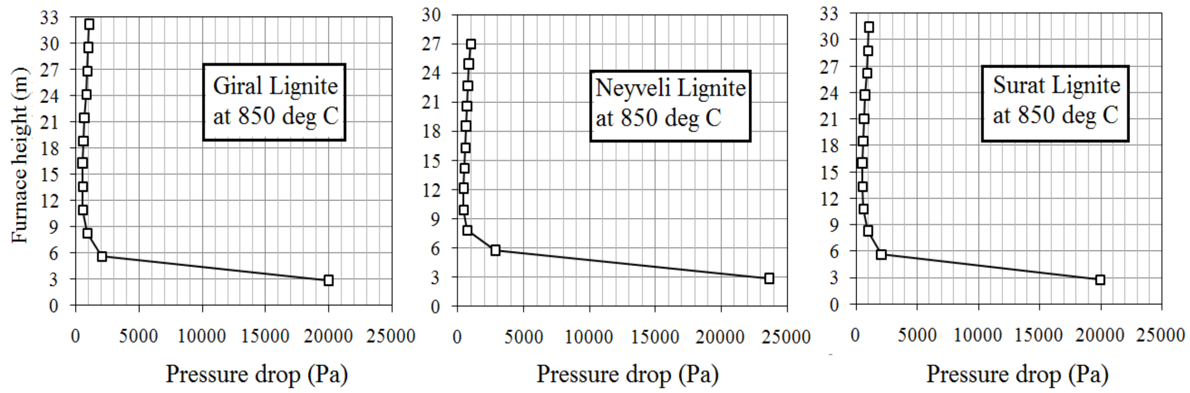

Figure 4. Pressure drop profile along the CFB riser at 0.9mm of mean particle diameter

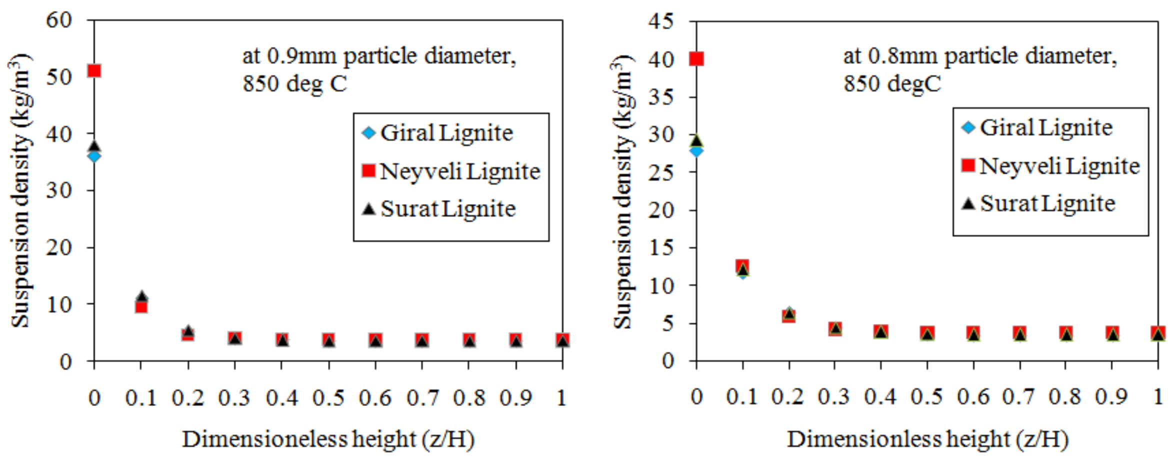

Figure 5. Suspension density profile from the top of the lower furnace to top of the upper furnace

The figure 5 explains suspension density at ten sections of upper furnace at 6 m/s of superficial gas velocity. Generally bed is denser just below the upper section of riser. When secondary air is introduced, the solid particles dispersion is taken place and voidage is increased. Due to this, bed density is suddenly dropped at the beginning of upper furnace. The density of bed at respective section was determined by the equation (6). It was understood that solid particle decaying is more in furnace operated by larger mean particle diameter. As a result, the density drop was higher for larger particles compared to smaller particles at the bottom sections of upper furnace as shown in figure 5. Small changes were observed in voidage and densities from third section of upper furnace to riser exit. The reason is that the particles were already dispersed totally.

When the larger particle diameter is considered, the solids falling velocity near the wall is decreased. As a result, more particles were accumulated and reduction in voidage near the wall was taken place. In case of three samples of lignite, the local voidage near the wall was more in the furnace operated by Neyveli lignite due to more bed density as shown in figure 6.

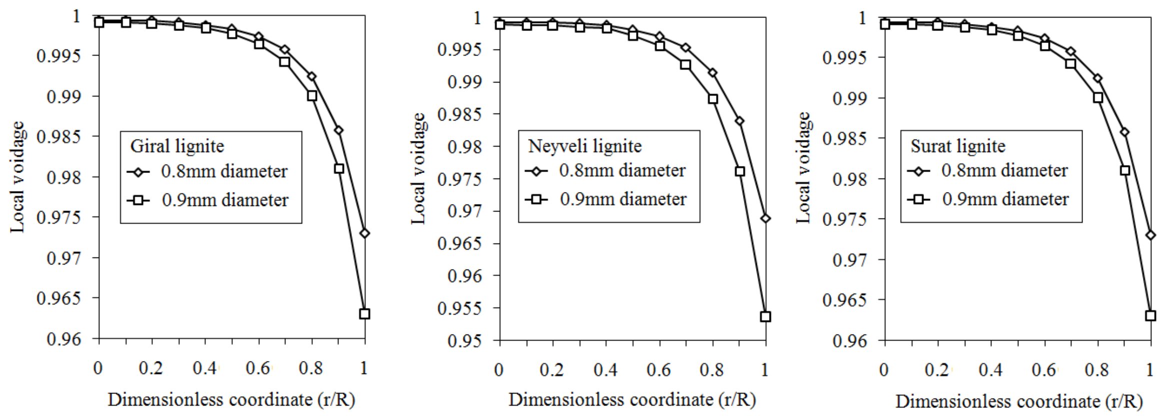

Figure 6. Local voidage profile for three Indian lignite at mean bed voidage of upper furnace

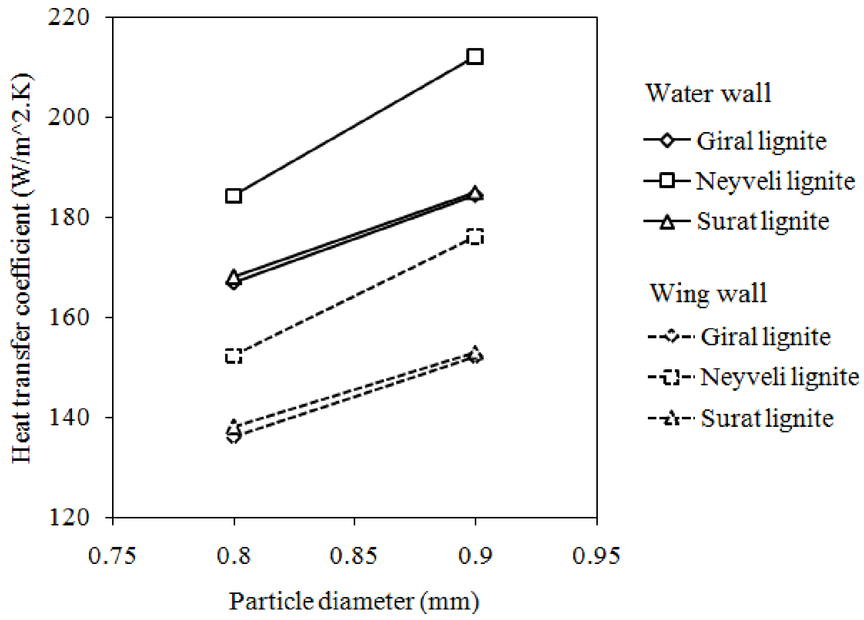

Figure 7. Projected water wall heat transfer coefficient at constant bed temperature of 850°C at different particle diameter

The heat transfer coefficient of boiler elements in the furnace is affected mainly by suspension density and bed temperature. The amount of heat is transferred to furnace heating elements by solid particles which are falling down (clusters) and gas which is flowing up. The figure 7 shows relationship between mean particle diameter and heat transfer coefficient for three samples of Indian lignite. Heat transfer coefficient of water wall was high for Neyveli lignite due to high particle and bed density. More heat was transferred at 0.9mm of mean particle diameter due to less mean bed voidage. In case of Giral and Surat lignite, it was observed that the heat transfer coefficients were not changed much due to negligible change of bed density and solids circulation rate. The wing wall heat transfer coefficients were reached almost 30% of the water wall heat transfer coefficients in this study by assuming a suitable correlation from Dutta and Basu [14]. The heat transfer coefficients of superheater were almost equal to the water wall heat transfer coefficients.

5. Conclusions

- A mathematical model of gas solid behaviour for 210 MW CFB riser was developed using three types of Indian lignite. Key parameters of hydrodynamics like suspension density, local voidage, heat transfer coefficients and minimum solids circulation rate were investigated at superficial gas velocity of 6 m/s and two different mean diameters of particle.
- It is understood that the suspension density and particle size are two main parameters which affect the heat transfer in the furnace and principal dimensions of the furnace.
- It is observed in the determination of gas solid behaviour that the grate heat release rate was appeared in the preferable limits (3-3.4MW/m^2) where erosion problems and power required to drive FD fan are kept minimum.
- It is observed that the average bed density, the hear transfer coefficient and bed cross sectional area of the furnace are more for same particle size in case of Neyveli lignite compared to other. The height of the furnace operated by Neyveli lignite is obtained low due to less surface area of water wall compared to other lignite.

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7. Nomenclature

Ar	Archimedes number (-)
a	Decay coefficient (-)
Ca/S	Calcium to sulfur molar ratio
C_D	Drag coefficient (-)
d_p,d_{50}	Mean particle diameter (m)
D	Furnace cross section equivalent diameter (m)
G_s	Solid circulation rate (kg/m^2 sec)
g	Gravitational constant (9.81 m/s^2)
H	Bed height (m)
H_i	Height of riser at respective section (m)
h	Heat transfer coefficient (W/m^2K)
Re_{mf}	Reynolds number at minimum fluidization (-)
Re_p	Particle Reynolds number (-)
T_b	Average bed temperature (^{o}C or K)
U_o	Superficial gas velocity (m/s)
U_{mf}	Minimum fluidization velocity (m/s)
U_t	Terminal velocity (m/s)
U_{tr}	Transport velocity (m/s)
z	Height of point from secondary air level (m)
ΔP	Pressure drop in the bed (Pa)
ΔL	Unit height in the bed (m)

Greek letters

ρ_{avg}	Average bed density (kg/m^3)
ρ_p	Density of solid particle (kg/m^3)
ρ_g	Density of gas (kg/m^3)
ε	Bed voidage (-)
ε_a	Voidage at secondary air injection (-)
ε_{avg}	Average bed voidage (-)
ε_e	Voidage at the exit of furnace (-)
μ	Viscosity of gas (N.S/m^2)

8. References

[1] Basu P 2015 *Circulating Fluidized Bed Boilers-Design, Operation and Maintenance* (Switzerland: Springer)

[2] Basu P and Nag P K 1996 Heat transfer to walls of a circulating fluidized bed furnace *Chemical Engineering Science* **51(1)** 1-26

[3] Adanaz J, Gayan P, Garcia-Labiano F, L F de Diego 1994 Axial voidage profiles in fast fluidized beds *Powder Technology* **81** 259-268

[4] Kunii D and Levenspiel O 1991 Flow modeling of fast fluidized beds *Circulating Fluidized Bed Technology III* Basu P, Hasatani M & Horio M (Eds) (Oxford: Pergamon Press) p.91-98

[5] Kunii D and Levenspiel O 2005 *Fluidization Engineering 2nd edition* (New Delhi: Elsevier)

[6] Davidson J F 2000 Circulating fluidized bed hydrodynamics *Powder Technology* **113** 249-260

[7] Maximilian J Hodapp, Jhon J Ramirez-Behainne, Milton Mori, Leonardo Goldstein Jr July2012 Numerical studies of the gas- solid hydrodynamics at high temperature in the riser of a bench scale circulating fluidized bed *Int. J. Chemical Engineering* (Cairo: Hindwai)

[8] Siddhartha shrestha, Brahim Si Ali, Badrul Mohamed Jan, Mooktzeng Lim, Khalid El Sheikh 2016 Hydrodynamic properties of a cold model of dual fluidized bed gasifier: A modeling and experimental investigation *Chemical Engineering Research and Design* **109** 791-805

[9] Basu P 2006 *Combustion and Gasification in Fluidized Beds* (Florida: CRC-Taylor &Francis Group)

[10] Allan S Issangya, John R Grace, Dingrong Bai, Jingxu Zhu 2001 Radial voidage variation in CFB risers *Canadian J. Chemical Engineering* **79** 279-286

[11] Afsin Gungor and Nurdil Eskin 2007 Hydrodynamic modelling of a circulating fluidized bed *Powder Technology* **172** 1-13

[12] Todd S Pugsley and Franco Berutti 1996 A predictive hydrodynamic model for circulating fluidized bed risers *Powder Technology* **89** 57-69

[13] Johansson A, Johansson F, Leckner B 2007 Solids back-mixing in CFB boilers *Chemical Engineering Science* **62** 561–573

[14] Dutta A and Basu P 2002 Overall heat transfer to water walls and wing walls of commercial circulating fluidized bed boilers *J. Energy Institute* **75(504)** 85-90

[15] Dutta A and Basu P 2003 An improved cluster-renewal model for estimation of heat transfer coefficients on the water-walls of commercial circulating fluidized bed boilers *Proc. 17th Int. Conf. Fluidized Bed Combustion* (New York: ASME) FBC2003-042

[16] Andersson B A and Leckner B 1992 Experimental methods of estimating heat transfer in circulating fluidized bed boilers *Int. J. Heat Mass Transfer* **35** 3353-3362

[17] Golriz M R and Sunden B 1994 An experimental investigation of thermal characteristics in a 12MWth CFB boiler *Expt. Heat Transfer* **7** 217-233

[18] Andersson B A 1996 Effects of bed particle size on heat transfer in circulating fluidized bed boilers *Powder Technology* **87** 239-248

[19] Baskakov A, Breitholtz K, Leckner B 2001 Complex heat transfer in furnaces with a circulating fluidized bed *Heat Transfer Research* **32 (7 & 8)** 343-348

[20] Balasubramanian S, Sudhindra K, Surendra Bhat An insight into advanced technology in circulating fluidised bed combustion steam generators *TATA Consulting Engineers Ltd Bangalore* http://www.tce.co.in/cfbc%20sg_tce_paper.pdf

[21] Wate S R 2013 *Environmental Impact Assessment for proposed Installation of Surat lignite Power project (SLPP) Station III, 2x300MW Lignite based Thermal Power Project at NaniNaroli* (Nagpur: National Environmental Engineering Research Institute) p.2.33

[22] https://www.scribd.com/presentation/19666291/CFB-Presn-NTPC11-07-06 (Last visit 31/01/2018)

[23] Lakshminarasimhan M, Ravikumar B, Lawrence A, Muthukrishnan M 2013 High sulfur lignite fired large CFB boilers-design and operating experience *Proc. 10th Int. Conf. circulating*

Fluidized Beds and Fluidization Technology Knowlton T M, PSRI (Eds.) (ECI Symposium Series)

[24] Coal controller's organization 2016 *Provisional Coal Statistics (2015-2016)* (Kolkata: Ministry of coal Government of India) p 21

[25] https://www.scribd.com/document/355900321/EXPERIENCE-ON-OPERATION-AND-MAINTENANCE-OF-CFBC-BOILER-AT-KLTPS-KUTCHH-GUJARAT-pdf (Last visit 31/01/2018)

[26] Grace J R 1982 Fluidized -bed hydrodynamics *Handbook of Multiphase Systems* Hestroni G (Ed) (Washington: Hemisphere) p.8.5-8.64

[27] Kunii D and Levenspiel O 1990 Entrainment of solids from fluidized beds II operation of fast fluidized bed *Powder Technology* **61**193-206

[28] Perales J F, Coll T, Llop M F, Puigjaner L, Arnaldos J ,Casal J 1991 On the transition from bubbling to fast fluidization regimes *Circulating Fluidized Bed Technology III* Basu P, Hasatani M & Horio M (Eds) (Oxford: Pergamon Press) p.73–78

[29] Guangxi Yue, Junfu Lu, Hai Zhang, Hairui Yang, Jiansheng Zhang, Qing Liu, Zheng Li 2005 Design theory of circulating fluidized bed boilers *Proc. 18th Int. Conf. Fluidized Bed Combustion* (New York: ASME) FBC2005-78134

[30] Bai D and Kato K 1999 Quantitative estimation of solids holds up at dense and dilute regions of circulative fluidized beds *Powder Technology* **101** 183-190

[31] Leming Cheng, Qinhui Wang, Zhenglun SI, Zhongyang LUO, Minjiang NI, CEN Kefa 2007 Heat transfer in a large-scale circulating fluidized bed boiler *Front. Energy Power Eng. China* **1(4)** 477-482