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Research Article

Comparison of combustion characteristics of Petcoke and Indian sub bituminous coal in a CFB Test facility

J Jaygopal[†*], K Ganesh Palappan[†], M Rajavel[†], P S Guruchandran[†] and S Suresh[‡]

[†]Bharat Heavy Electricals Limited, Trichy, Tamilnadu, India.
[‡]National Institute of Technology, Trichy, Tamilnadu, India.

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Abstract

Fluidized Bed Combustion (FBC) is one of the best suited combustion technologies for petcoke combustion owing to its capability of handling fuels with low volatile and high sulphur content. In this study, petcoke and Indian sub bituminous coal (coal from Singareni mines, Telengana, India) are fired separately in Circulating Fluidized Bed (CFB) test facility and its combustion characteristics are studied and compared. Even though petcoke is a low reactive fuel compared to Indian coal, temperature profile shows petcoke has a stable combustion. Significant post combustion in cyclone is noticed while combusting petcoke. Around 40-60^o C rise in the cyclone temperature is noted during combustion of petcoke compared to 20-30^o C while burning sub bituminous coal. Compared to Indian sub bituminous coal petcoke has high sulphur content (4-9 %) and low ash content, therefore it requires limestone addition for in situ sulphur capture and for maintaining bed inventory. Owing to the limestone addition, petcoke firing shows a better material distribution among the splash zone. Although CFB boilers are fuel flexible, and petcoke can be fired in CFB boilers designed for Indian coals, test results show that combustion efficiency of petcoke is lower than that of Indian coal. Combustion efficiency can be improved by certain design modifications such as higher furnace height, higher cyclone efficiency and higher refractory zone. The present study explore the opportunities of using 100% petcoke in CFB boiler.

Keywords: *Petcoke combustion, Indian coal, CFB, Cyclone post combustion, Combustion efficiency*

1. Introduction

India is the 5th largest producer of oil refined products in the world (223.24 MMT- 2015) (Government of India, 2014) (Statista, 2015). It also houses the world's largest oil refinery, Jamnagar Refinery at Gujarat that process 1.24 million barrels of crude per day (Hydrocarbons Technology, 2015). Petroleum products are the largest good exported from India (18.54 % of total exports) and they contribute a major share of India's GDP (Infodrive, 2015). Petroleum coke often abbreviated as petcoke is a carbonaceous solid delivered from oil refinery coker units or other cracking processes. Petroleum production has been increasing, resulting in increased production of petcoke 4.2 MMT in 2008 to 10.06 MMT in 2015, making petcoke a cheaper alternative to Indian coal for power generation (Government of India, 2014). While, it can be used as a main fuel in a FBC boilers, it is used as a supplementary fuel blended with coal at 10-20 % before burning in a pulverized fuel (PF) boiler. Technologies also exist for gasification of petcoke to produce syngas that can be used in gas turbine for power generation. FBC boilers are more suitable for handling petcoke for its capability of handling low volatile fuel (high thermal inertia available in fluidized bed) and high sulphur content (in situ sulphur capture).

The operating experiences of CFB boilers such as Provence 250 MW CFBC, Niscol 125 MW CFBC and Texas- New Mexico 2 X 500 T/h CFB proves it is feasible to combust petroleum coke, however unburnt loss in fly ash is relatively higher (Jihui and Xiaofeng, 2007). In the present study, petcoke combustion characteristics is compared with an Indian high ash sub bituminous coal, while firing in a CFB test facility. Coal from Singareni mines, Telengana is taken as a reference for Indian coal. Both, the coal and the petcoke were fired separately in a 4 MW$_{th}$ CFBC test facility and the combustion characteristics such as temperature profile, material distribution, cyclone post combustion and combustion efficiency were studied and discussed. Studying the potential of alternative and cheaper fuels such as petcoke for CFB technology is currently required, since in many cases fuel flexibility may be a decisive factor in plant's economy and feasibility of new projects.

*Corresponding author: **J Jaygopal**

2. Lab analysis

Analysis such as proximate, gross calorific value, ultimate, bulk density and the chemical composition of ash were conducted for petcoke and Indian coal samples. Results are presented in Tables 1 to 5. It can be seen from the results petcoke is a high carbonaceous high calorific value fuel. The quantity of fuel requirement is less for petcoke fired boiler compared to Indian coal fired boiler of the same capacity. Compared to Indian coal, petcoke has high sulphur and low ash content. Therefore, petcoke requires sorbent limestone for sulphur capture in a CFB boiler, which also serves for maintaining inert bed inventory in furnace. The in situ sulphur capture using lime stone in CFB boilers are represented by the reactions 1 & 2:

Sulphur capture by limestone

$$CaCO_3 \rightarrow CaO + CO_2 \quad (1)$$

$$CaO + SO_2 + ½\, O_2 \rightarrow CaSO_4 \quad (2)$$

Low volatile content of petcoke results in a lower reactivity and lower fragmentation of fuel in the furnace. Bulk density results as shown in Table 4 indicates petcoke is a heavier fuel than Indian coal.

Thermo-gravimetric burn out study of petcoke and Indian coal were performed in a TA instruments make Differential Scanning Calorimeter-Model Q600 SDT. Heating rate of the experiment was 10^0 C/min from room temperature to 1000^0 C. Reaction medium was air at flow rate of 100mL/min. It can be seen from Figure 1 that ignition temperature of Indian coal is 300^0 C while that of petcoke is 390^0 C.

Table 1 Proximate analysis of petcoke & sub bituminous Indian Coal (Air dried basis)

S. No	Parameter	Unit	Petcoke	Indian coal
1	Moisture	%wt.	1.11	2.99
2	Volatile Matter	%wt.	13.42	25.07
3	Ash	%wt.	1.79	32.84
4	Fixed Carbon	%wt.	83.68	39. 10

Table 2 Gross Calorific value of petcoke & sub bituminous Indian coal (Air dried basis)

S. No	Parameter	Unit	Petcoke	Indian Coal
1	Gross calorific Value	Kcal/ Kg	7981	4586

Table 3 Ultimate analysis of petcoke & sub bituminous Indian coal (Air dried basis)

S. No	Parameter	Unit	Petcoke	Indian Coal
1	Carbon	%wt.	85.32	55.68
2	Hydrogen	%wt.	3.09	2.62
3	Sulphur	%wt.	7.16	0.72
4	Nitrogen	%wt.	1.25	1.28
5	Moisture	%wt.	1.11	2.99
6	Ash	%wt.	1.79	32.84
7	Oxygen (Balance)	%wt.	0.28	3.87

Table 4 Bulk density of petcoke & sub bituminous Indian coal feed material

S. No	Parameter	Unit	Petcoke	Indian Coal
1	Bulk density	gm/ cc	0.8582	0.7065

Table 5 Chemical composition of petcoke ash and sub bituminous Indian coal ash

Constituents	Formula	Unit	Petcoke	Indian coal
Silica	SiO_2	%wt.	48.5	62.2
Aluminium Oxide	Al_2O_3	%wt.	15.6	23.9
Iron Oxide	Fe_2O_3	%wt.	6.9	5.8
Titanium Oxide	TiO_2	%wt.	1.10	1.40
Calcium Oxide	CaO	%wt.	3.3	3.4
Magnesium Oxide	MgO	%wt.	1.9	1.1
Vanadium Penta Oxide	V_2O_5	%wt.	13.8	-
Nickel Oxide	NiO	%wt.	3.7	-
Sodium Oxide	Na_2O	%wt.	2.30	0.40
Potassium Oxide	K_2O	%wt.	1.3	0.6
Sulphate	SO_3	%wt.	1.3	0.6
Others	-	%wt.	0.3	0.6

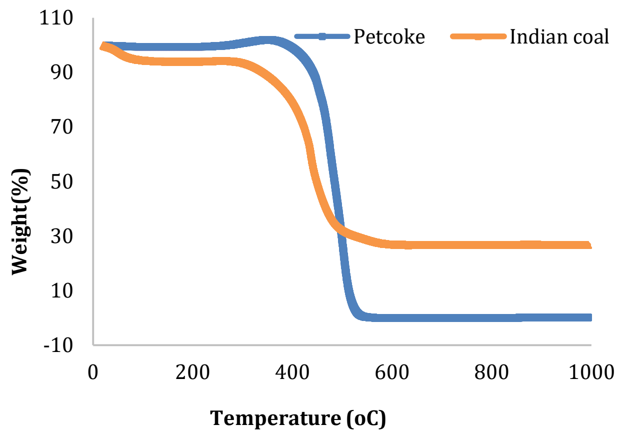

Fig. 1 Thermo-gravimetric analysis of Petcoke and Indian coal

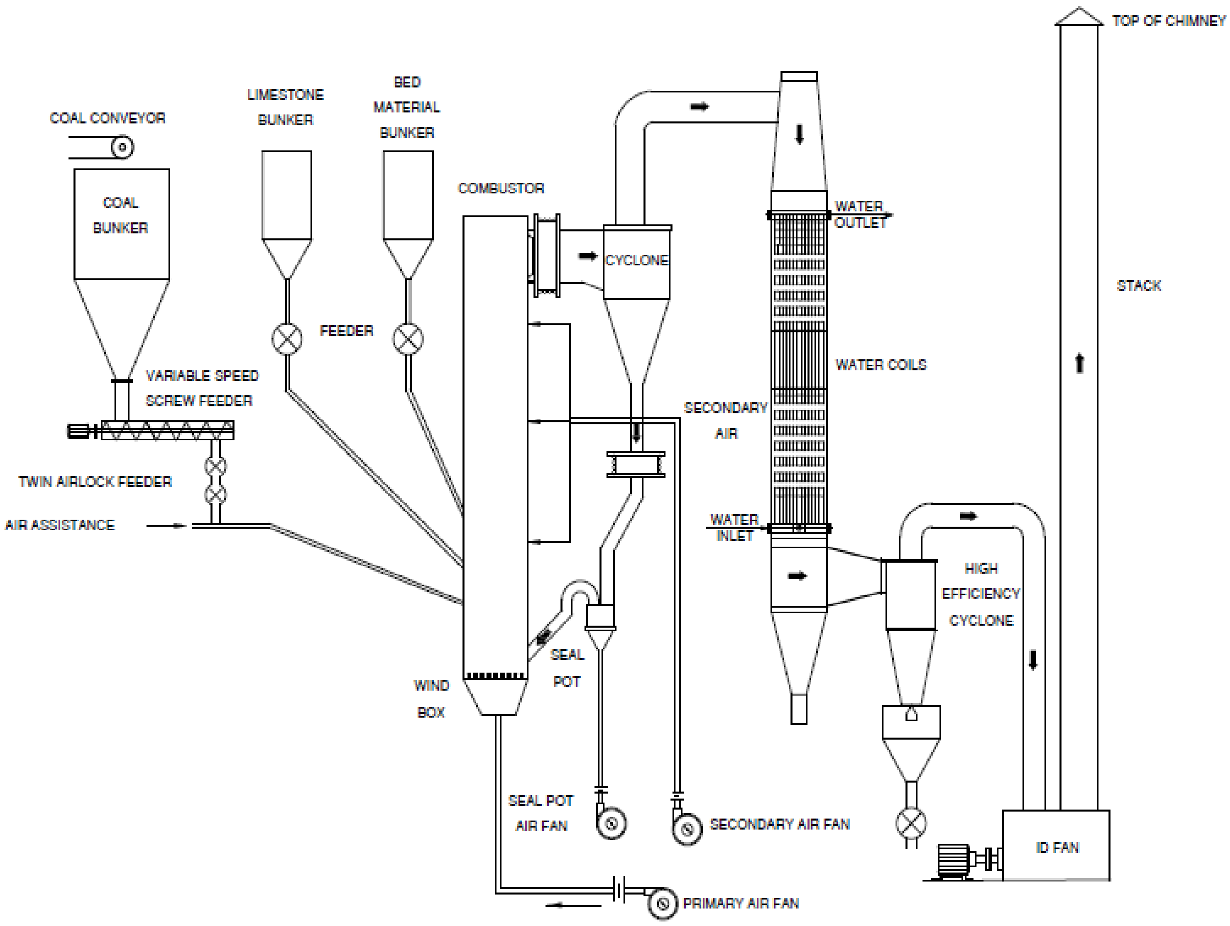

Fig. 2: Schematic diagram of CFB Test facility

3. Experimental setup

3.1 Experimental Facility

The schematic diagram of 4 MW_{th} CFB facility is illustrated in Figure 2. Combustor is of rectangular cross section of area 1 m^2 and of aspect ratio 2.3. The lower part of the combustor is lined with refractory to maintain the bed temperature and to reduce erosion. The fuel, stored in the bunker, is admitted to the combustor through a variable speed screw feeder. A high pressure centrifugal fan provides primary air (40-50 % of total air) through a bubble cap nozzle type air distributor, located at the bottom of the combustor. A positive displacement blower delivers about 50-60% of the combustion air through secondary air nozzles. A cyclone captures coarser particles and a loop seal returns the collected ash into the furnace. The flue gas exiting the cyclone is cooled in a convection back pass before leaving to the stack through an induced draft (ID) fan. A dedicated blower supplies air for fluidizing the recirculating material in loop seal.

3.2 Field Test of petcoke and Indian sub bituminous coal

Petcoke and Indian coal were fired separately in CFB test facility. Limestone was added along with petcoke for in- situ sulphur capture. Particle size distribution of the feeds are shown in Figure 3. Mean particle size of petcoke, limestone and Indian coal are 417 µm, 143 µm and 400 µm respectively. It can be seen that over 55 % of the limestone is in the range of 150-1000 µm, 20 % is below 150 µm so that they ensure good fluidization properties and has sufficient amount of fines for sulphur capture and heat transfer. The furnace was initially heated up and then maintained up to 850^0 C by charcoal during start up.

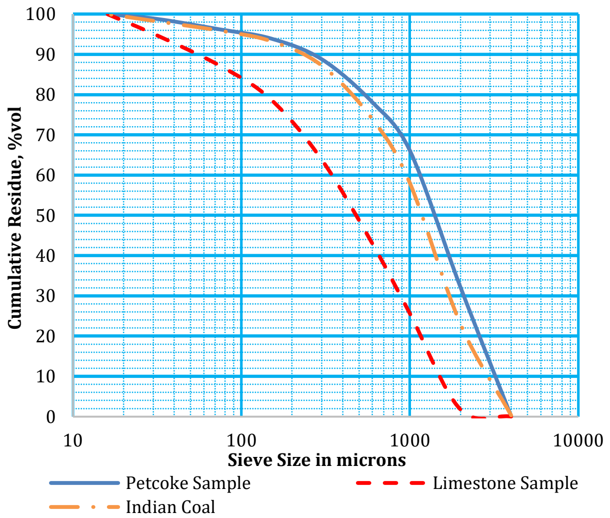

Fig. 3: Particle size distribution of CFB test facility feed material

After bed temperature become stable and giving sufficient time for complete charcoal combustion, fuel is feed into furnace using screw feeder. After achieving the steady state predetermined key test parameters like fluidizing velocity, excess air and bed height was maintained for eight hours as shown in Table 6.

Table 6: Test conditions at CFB facility

Sl no	Parameters	Unit	Range
1	Combustor bottom velocity	m/sec	2.5-3
2	Overall velocity	m/sec	5-5.5
3	Combustion bottom temp	^{0}C	800-950
4	Primary: Secondary air ratio	ratio	40:60
5	Ca/S Molar ratio (petcoke)	ratio	2.5-3
6	Wind box pressure	mm WC	630 -690

Measurements like pressure, temperature were taken using calibrated instruments installed along the height of furnace, furnace exit, and cyclone and seal pot.

4. Results and discussions

4.1 Temperature profile

Temperature measurements were taken along the height of combustor and the temperature profile plotted for Indian coal and petcoke is shown in Figure 4.

As fuel enters into the furnace, it mixes with the bed and it absorbs heat from the bed for drying and heating the fuel. A slight dip in bed temperature is noticed for petcoke as well as for Indian coal at this zone (0.02 H). As sub stoichiometric condition is maintained below the secondary air elevation and majority of the combustion take place above secondary air elevation, the major difference in temperature profile between Indian coal and petcoke is observed above the secondary air elevation. Volatile matter burns in a diffusion flame at boundary between oxygen and unburnt volatiles. In case of isolated fuel particle, a diffusion flame will develop around the particle, whose position will depend upon the rate of oxygen diffusion to the flame and upon the rate of volatile release (Basu, 2006). Indian coal has 10-20 % more volatile content than petcoke, thus its combustion rate is faster and it can be seen as a small hump in the figure (at 0.14 H). For example, it would take 50-120 sec for a devolatilized char of size less than 0.2 mm to burn out (Keairns, *et al*, 1984), while for a coal particle of 0.1 mm size the estimated time for de-volatilization and combustion is 22 and 32 seconds respectively (Brereton, 1997). The rapid increase of temperature observed in Indian coal is therefore not witnessed in petcoke.

Petcoke is majorly char (90- 85%), comprising of carbon, ash, nitrogen and sulphur. On reaching above 750^0 C char oxidizes to gaseous products CO, CO_2, SO_2, NO and NO_2. Since burn out time of char of petcoke is more than that of lateral dispersion it is spread all around the cross section and the small unburnt particles will be entrained. Thus the number of feeding point required for petcoke is less than that of Indian coal. Due to high reactivity, Indian coal combusts even on higher elevation, while petcoke majority of combustion take place at dense and splash zone. Volatile content also aids in primary fragmentation, increasing the distribution of lower size fuel particles in the lean zone of furnace.

Therefore, as height increases temperature decreases too sharply for petcoke when compared to Indian coal resulting in a lower furnace outlet temperature for petcoke. For the combustor of same dimensions, the combustion loss of petcoke will be more than that of Indian coal as petcoke need more residence time. Therefore, to increase the residence time and maintenance of temperature, a taller furnace with a higher refractory zone may be required for complete combustion of petcoke.

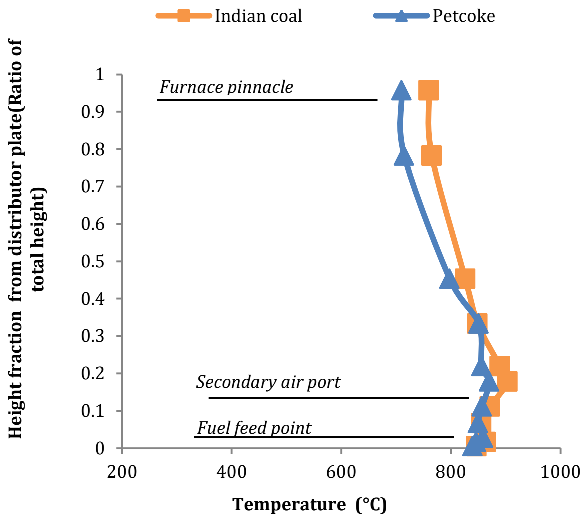

Fig. 4: Comparison of Temperature profile of Indian coal and Petcoke

4.2 Material Distribution

The bed quality is influenced greatly by boiler feed distribution and ash formation (Yang, *et al*, 2004). Pressure drop of combustor was maintained and the total pressure drop at each zone, naming dense zone, splash zone and lean zone were estimated. Zone from distributor plate to 0.05H is considered as dense zone, 0.05 H to 0.17 H is considered as splash zone, 0.17 H to the furnace outlet is considered as lean zone, where H is the total height of the furnace. Pressure drop at each zone is divided by the total pressure drop along the furnace, to obtain the distribution of material at each zone.

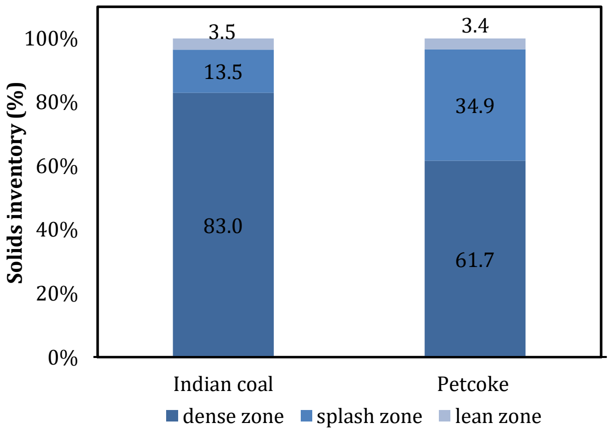

Fig. 5: Comparison of Bed Material distribution of Indian coal and Petcoke (with lime) among dense zone, splash zone and lean zone

Figure 5 compares the distribution of solids inventory in dense zone, splash zone and lean zone between petcoke and Indian coal. It can be noticed that lean zone of Indian coal and petcoke has almost the same distribution, Indian coal has 3.5 % of the total inventory in the furnace, petcoke has 3.4% of the total inventory. It can also be seen that splash zone of petcoke fired boiler has relatively better distribution of material. In spite of low fragmentation ratio and low content of petcoke, the improvement in distribution in splash zone and lean zone, takes place due to limestone addition which contributes the fines.

A better distribution of particles at lean zone results in better heat transfer at higher elevations (Gao, *et al*, 2005), as heat transfer coefficient is proportional to the square root of suspension density (Glicksman, 1988). Increased amount of particles increases the particle convention and cluster radiation (Basu, 1990) (Dutta and Basu, 2004). Thus, the size distribution and amount of limestone added plays an important role in heat transfer coefficients of petcoke fired CFBC.

4.3 Cyclone post combustion

Cyclone post combustion is the effect in which fuel gets combusted in the cyclone and results in an increase of temperature at cyclone (Yue, *et al*, 2006). High velocity and high residence time in the cyclone (Grief and Muschelknautz, 1994) promotes char combustion in the cyclone. This will lead to an increase of the temperature of solids and flue gas in the cyclone and loop seal region. Excessive temperature rises and constricted area may lead to issues like sintering in the loop seal. Increased flue gas temperature also affects the heat balance in heat transfer surfaces like super heater and re-heater. It also increases the CO concentration at exit of cyclone. Post combustion in a CFB boiler is strongly influenced by fuel properties especially the volatile content (Yue, *et al*, 2006).

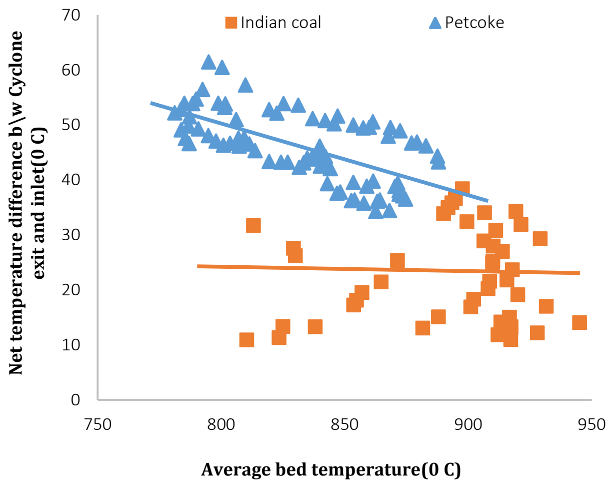

Fig. 6 Cyclone post combustion for Petcoke and Indian coal

Cyclone post combustion characteristics of both petcoke and Indian coal were compared by measuring the net increase in cyclone temperature. Maintaining parameters mentioned above in Table 6 and fluid flow rates in heat transfer coils, bed temperature was increased by increasing the fuel flow rate, thus increasing the furnace outlet temperature.

Temperature difference between the inlet and exit of cyclone was measured and its variation on varying the furnace temperature was studied. Figure 5 shows the variation of the net cyclone temperature rise against change of furnace temperature. It can be seen from Figure 6; post combustion is in the range of 40-60^0 C for petcoke while 20-30^0 C for Indian coal.

This difference is due to low reactivity and the low ash content of petcoke. Since petcoke is a low reactive fuel, the combustion fraction in the furnace is lesser than that of high reactive fuels. It results in higher amount of unburnt carbon being elutriated and captured by cyclone. The cyclone provides high residence time and high velocity aiding the combustion in cyclone. Secondly, for combustion of char, the oxygen from free stream must overcome the following resistances: (a) diffusion resistance of inert particle around the char particle, (b) diffusion resistance through ash layer, and (c) the diffusion resistance through the gas film layer around char particle (Basu, 1999). While the high ash Indian coal offers the diffusion resistance mentioned in (a) and (b), petcoke will expose themselves to the external environment with very less resistance due to its low ash content.

The post combustion can be mitigated by increasing the combustor temperature. Raising the combustor temperature increases the combustion fraction inside the combustor reducing the amount of elutriated carbon from the furnace. It can be seen from the figure that on increasing the furnace temperature the post combustion effect is significantly reduced in case of petcoke. However, the furnace temperature cannot be increased above a limit as the optimal temperature range for sorbent reactivity is 800- 850 ^{0}C (Leckner and Amad, 1987) (Schaub, *et al*, 1989). The bed temperature rise does not affect Indian coal as the amount of the elutriated carbon is not significant enough to cause variation.

Even though the furnace outlet temperature of petcoke is less than that of Indian coal, the cyclone post combustion increases temperature of the flue gas exiting the cyclone. Back pass coils must be designed considering this fact.

4.4 Combustion efficiency

The overall combustion efficiency is estimated using Equation 3 by measuring the carbon loss in bottom ash and fly ash. The ratio of heat energy associated with the carbon lost in the fly ash and bottom ash, to the heat energy in feed coal is a measure of combustion efficiency of the system:

Combustion efficiency

$$= \left(1 - \frac{(carbon\ lost \times Carbon\ HHV)}{(Heat\ energy\ in\ coal)}\right) \times 100 \qquad (3)$$

It can be seen from Figure 7 that while the combustion efficiency of Indian coal is around 98-99 %, the combustion efficiency of petcoke is lower 90-95 %. This is due to the low reactivity of petcoke.

It can also be seen petcoke' s combustion efficiency is very sensitive to furnace temperature when compared to Indian coal. But temperature cannot be increased after a limit as it affects the limestone reactivity. An increase of temperature also results in increase of emissions and probable ash deposition. Thus the operational temperature must be decided based on consensus between emission factor and combustion efficiency. Petcoke requires a higher residence time and hence the furnace height may be increased suitably. Lafanechere, Basu and Jestin (1995), studies on effect of fuel properties on combustion design also confirms the requirement of higher furnace for low volatile and high carbon fuels. Combustion tests of petcoke conducted in bench scale test rig at Jianghan University,China reports high unburnt carbon (Tie*, et al*, 2002). However, the unburnt loss can be reduced to a considerable level with suitable furnace and cyclone design.

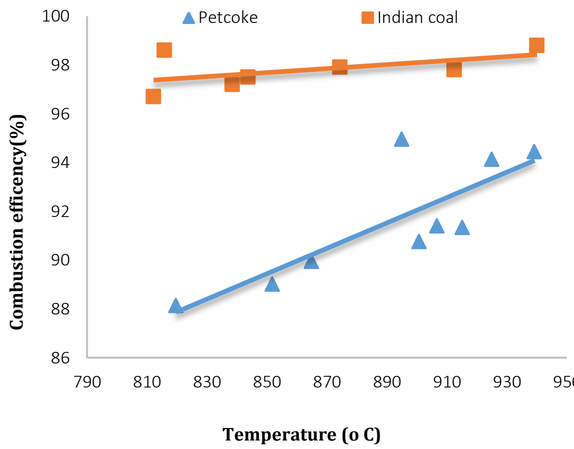

Fig. 7 Combustion efficiency for Petcoke and Indian coal

Conclusions

Petcoke was successfully combusted in CFB test facility and its combustion characteristics was compared to Indian coal combustion characteristics. Even though the petcoke combustion efficiency is less compared to high ash Indian coal, further improvements can be achieved by certain design modifications. The main glimpses of the studies conducted are presented below:

1) While petcoke combustion takes place mainly at the bottom of the furnace, combustion of Indian coal takes place at higher elevations also. For the same bed temperature, furnace outlet temperature of petcoke is lower than that of Indian coals. To improve the furnace outlet temperature and combustion; petcoke fired boiler requires a higher refractory zone.

2) In the experiment petcoke had a higher distribution of material at the splash zone, compared to Indian coal, this was due to limestone added. Heat transfer coefficients of petcoke fired boiler is highly dependent on the amount and size distribution of limestone added.
3) Cyclone post combustion is noticed in petcoke while it is minimal for Indian coal. Cyclone post combustion can cause variation in flue gas temperature can affect the performance of super heater and re heater. Heat exchanger coils at back pass of petcoke must be designed considering the cyclone outlet temperature. It will also increase the CO concentration at exit of cyclone. Cyclone post combustion effect can by mitigated by increasing the furnace temperature, which also reduces the amount of elutriated unburnt carbon from furnace.
4) Subjected to same conditions and boiler dimensions, combustion efficiency of petcoke is lower to that of Indian coal. To improve the combustion characteristics of low reactive petcoke, high residence time is required which can be attained by a higher furnace with higher refractory zone. Higher furnace height will also reduce the cyclone post combustion.
5) Combustion efficiency of petcoke is very sensitive to combustion temperature, but combustion temperature cannot be increased beyond certain limit as it increases the gaseous emissions and affects the limestone reactivity. Thus the operational temperature must be optimized based on emission control and combustion efficiency

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