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A study on co-gasification of high ash Indian coal with petcoke in a fluidized bed gasifier

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An investigation has been undertaken to study the co-gasification of high ash sub bituminous Indian coal with petcoke in a bubbling Fluidized Bed Gasifier (FBG) system. The objective of this work is to study the effect of petcoke content in coal blend feed on gasification characteristics by carrying experiments in a pilot scale 1.2 T/d FBG (I.D. 0.2m X height 4.2m) system using air and steam as gasifying agents. The gasification characteristics include cold gas efficiency, carbon conversion, calorific value and composition of synthesis gas (syngas).Reactivity study carried in High Pressure Thermo Gravimetric Analyser (HPTGA) shows that coal blend reactivity decreases with increase in petcoke content in it. Gasification results indicate that increase in petcoke content in blend leads to decrease in carbon conversion and syngas calorific value which could be attributed to low reactivity of petcoke. A very low carbon conversion and syngas calorific value for petcoke gasification indicate that it may not be viable to gasify petcoke in FBG system.

Keywords: *High ash coal, petcoke, fludized bed gasifier, syngas, cold gas efficiency, carbon conversion.*

1.0 INTRODUCTION

Gasification is a process of converting any carbonaceous fuels like coal, coke, biomass etc, to a gaseous product that has useable heating value, by employing gasifying agents such as air/O_2 and steam. Synthesis gas (syngas) generated from gasification has number of applications such as power production through integrated gasification combined cycle (IGCC) technology, hydrogen generation by water gas shift (WGS) reaction, production of liquid fuels by Fischer Tropsch process etc. There are three conventional technologies available to produce syngas from gasification; namely, entrained flow gasifier, fluidized bed gasifier (FBG) and moving bed gasifier [1-3]. Each technology has its own advantages and disadvantages. Entrained flow gasifier technology is widely used for low ash coals. Increase in coal ash decreases the gasification efficiency because of increase in slag production and thereby overall cost of the process increases [1]. It is not economical to gasify Indian coal in entrained bed gasifier as it contains high ash. Fluidized bed gasification ensures uniform mixing and is most suitable to gasify high ash coals. M/s BHEL, a manufacturer of power producing equipment, has developed a bubbling fluidized bed gasification technology that is suitable for gasification of high ash Indian coals and demonstrated it by installing 6.2 MW IGCC plant in India.

Petcoke (petroleum coke) is a solid carbonaceous residue derived from oil refinery Coker units. Petcoke has high carbon content and low ash because of which it can be considered as a potential fuel to mitigate the dependency on coal reserves. Recently co-gasification of coal with petcoke and biomass has gained considerable importance as

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coal reserves throughout the world are depleting [3]. Countries like USA, Spain, Japan, China etc. have installed gasification plants which use petcoke/biomass blended coal as feed [1,2].

Considerable research is going on to study the gasification characteristics such as carbon conversion, cold gas efficiency, calorific value of syngas and its composition for petcoke blended coal gasification. Lee et al. [3] have investigated gasification characteristics by carrying lignite blended pecoke gasification experiments in a 1 T/d entrained flow gasifier. Due to the synergetic effect, the calorific value of syngas and cold gas efficiency are higher for lignite blended petcoke gasification than petcoke gasification. Fermoso et al. [4] have investigated the effects of parameters (reactor temperature, pressure and composition of gasifying agent) on gasification characteristics by gasifying petcoke blended bituminous coal with oxygen and steam in a tubular reactor. They have reported that increase in petcoke content leads to decrease in carbon conversion. Goyal et al. [5] have modelled and simulated the fluidized bed gasifier and reported that increase in petcoke content in the feed causes lower efficiency and carbon conversion for the process. Nagpal *et al.* [6] have developed a mathematical model to simulate petcoke gasification in slagging moving bed gasifier. They have reported that compared to entrained bed gasification, moving bed gasifier gives better performance with respect to energy efficiency and oxygen consumption.

Limited studies are available in open literature on petcoke blended high ash coal gasification in FBG. No experimental work has been reported in literature related to petcoke blended Indian coal gasification in pilot scale. In this study, we have attempted to gasify petcoke blended high ash sub bituminous coal using air and steam as gasifying agents, in a pilot scale 1.2 T/d FBG plant. The objective of this work is to study the effect of petcoke in feed (coal blend) on gasification characteristics such as cold gas efficiency, carbon conversion, calorific value and composition of syngas.

2.0 EXPERIMENTAL

2.1 Fluidized bed gasifier (FBG) system description

A schematic diagram of fluidized bed gasification pilot plant is shown in Figure 1. This pilot scale experimental facility consists of a FBG, two cyclones, rotary feeder, extractor,candle filter assembly and flare stack along with air compressor, steam generator and heater. The 1.2 T/d feed capacity FBG consists of three zones; the plenum section, reactor zone (I.D. 0.2m X height 1.6m) and freeboard section. Refractory bricks and insulation castable are provided inside FBG to minimize the heat loss. Thermocouples are installed radially along the axis to measure the gasifier temperature. Pressure difference across the gasifier is measured using Differential Pressure Transmitters (DPTs), which are used to monitor the quality of fluidization in the gasifier. Rotary feeder and extractor are employed to feed the material and extract ash from FBG, respectively.

2.2 Feed material preparation

High ash sub bituminous coal and petcoke are obtained respectively from North Karanpura mines, Jharkhand and Indian Oil Corporation (IOC) to carry out petcoke blended coal gasification experiments in the FBG plant. The proximate analysis, ultimate analysis and heating values of coal and petcoke are shown in Table 1. The coal and petcoke are sieved to 0.5-4 mm size. The mean diameter of coal and petcoke is 1.75 mm and 1.66 mm respectively. As per the requirement of experiment, coal and petcoke are blended manually on the ground and stored in feed system that consists of hopper, lock and receiver.

2.3 Experimental procedure

Detailed experimental procedure to gasify petocoke blended coal in a FBG plant is given subsequently. After attaining required temperature in steady state combustion mode, plant is switched over to gasification mode by admitting saturated steam into gasifier.

2.3.1 Start-up

A fixed quantity of bed material (generally ash) and lignite are thoroughly mixed before it is fed to FBG. Compressed air heated in a heater is fed to the plenum which contains conical distributor that ensures uniform distribution of air to the gasifier. Bed material gets heated up due to passage of hot air through bed. After the bed attains a temperature of 70^{o}C, required quantities of hydrogen and air are admitted to catalytic combustor. Generated hot gas in the combustor is fed to the gasifier,causes continuous increase in bed temperature. The flow of hydrogen is maintained till bed reaches a temperature of 270^{o}C. Since lignite ignition temperature is 270^{o}C, when bed attains this temperature, available lignite in the bed is auto ignited and leads to continuous increase in temperature upto 800^{o}C.

2.3.2 Combustion

When temperature of the bed reaches 800^{o}C, coal blend that is stored infeed system is admitted to the FBG with the help of transport air. Coal and petcoke undergoes combustion as bed temperature is higher than their ignition temperatures. Bed temperature increases because of the heat generated from exothermic combustion reactions. This behaviour is shown in Figure 2. Flow rates of air and feed are adjusted such that the system attains steady state with bed temperature of 950^{o}C.

2.3.3 Gasification

After system attains steady state at bed temperature of 950^{o}C in combustion stage, saturated steam (generated in steam generator) coming from heater is admitted into the gasifier in order to switch to gasification stage. The flow rates of air, feed and steam (given in Table 2) are adjusted such that reaction zone attains temperature of 1000^{o}C and subsequently system will be stabilized to attain steady state gasification. The temperature profile of petcoke blended coal gasification in FBG is shown in Figure 2. The sufficient operating velocity (>1.2m/s) is maintained in gasifier to fluidize the bed of particles in bubbling regime, by controlling the air and steam flow rates. Ash is extracted from bottom of the gasifier continuously to maintain constant bed height, through ash rotary valve and it gets cooled (through water jacket system) before it is collected in ash lock. The generated syngas is cooled in a cooler and fed to cyclone and candle filter assembly to remove fine particles present in it. The cleaned syngas is collected at regular intervals and analysed with gas chromatography technique to determine its composition. The residual syngas is flared using a flare stack which is installed after candle filter assembly.

2.4 Control Panel and Data collection

A control panel consisting of required indicators and controllers of all process parametersis installed. Important parameters like feed rate, temperatures at different heights of the gasifier, pressure drop across bed and distributor, air and steam flows rates are continuously monitored during the gasification experiment. A data acquisition system (DAS) is installed to collect uninterrupted and accurate data of process parameters from the plant. The obtained primary data is refined and used for further analysis.

2.5 Experimental conditions

Petcoke blended coal gasification experiments are carried in FBG plant by changing the petcoke percentage (10%, 20%, 30%, and 40%) in the feed (coal blend). Same feed particle size(0.5-4 mm)is used for all experiments. The detailed experimental conditions are shown in Table 2. The minimum fluidization velocity and bubbling regimes are calculated (by taking into consideration of bulk density, particle density and mean diameter of particles) for all experiments, using standard procedure available in the literature. Bubbling velocity regimes changes accordingly with feed particle density and mean diameter of feed particles. Based on these values, the sufficient operating velocity of fluid in the gasifier is maintained so that bubbling fluidization occurs in the gasifier. The temperature inside the gasifier is controlled by manipulating the feed, air and steam flow rates.

TABLE 1		
PROXIMATE & ULTIMATE ANALYSIS OF FEED		
Source	**Coal**	**Petcoke**
Proximate analysis (dry basis, wt%)		
Moisture	4.9	0.7
Volatile matter	29.7	9.5
Ash	34.4	0.8
Fixed carbon	31.0	89.0
Low heating value (LHV) (kcal/kg)	4237	8692
Ultimate analysis (wt%)		
C	75.1	93.5
H	5.9	3.5
S	2.0	1.0
N	1.5	0.6
O[a]	15.5	1.4

[a] By difference

3.0 RESULTS & DISCUSSION

The composition of syngas generated depends on a number of gasification parameters like temperature, pressure, feed rates and hydrodynamics etc. The major reactions that occur during the gasification of any carbonaceous material (such as coal, petcoke and biomass) [2, 4, 5] are shown subsequently. The gasification reactions are crucial as calorific value and composition of syngas depends on reaction rates of these equations and conversions that take place during these reactions.

Combustion reaction:

$$C + O_2 \longrightarrow CO_2\ ; \Delta H^0_{298} = -394 kJ.mol^{-1} \quad ....(1)$$

Buodourd reaction:

$$C + CO_2 \longleftrightarrow 2CO; \Delta H^0_{298} = +172 kJ.mol^{-1} \quad ....(2)$$

Water gas reaction:

$$C + H_2O \longleftrightarrow CO + H_2; \Delta H^0_{298} = +131 kJ.mol^{-1} \quad ....(3)$$

Methanation reaction:

$$C + 2H_2 \longleftrightarrow CH_4; \Delta H^0_{298} = -75 kJ.mol^{-1} \quad ....(4)$$

The heat required for endothermic gasification reactions is provided by exothermic combustion reactions. The carbon conversion (X) and cold gas efficiency (η) for gasification process are defined by Eq. (5) and Eq. (6) respectively. Carbon conversion depends also on residence time (τ , average time spent by particle in the gasifier) of particles which is defined by eq. (7). Low τ implies that particles are not participating in the reactions for sufficient time, which shall leads to low X .

$$Carbon\ Coversion\ (X) = \frac{F_{carbon,syngas}}{F_{carbon,in}} \quad ....(5)$$

$$Cold\ gas\ efficiency\ (\eta) = \frac{F_G H_G}{F_S H_S} \quad ....(6)$$

$$\mathrm{Re}\ sidence\ time(\tau e = \frac{Gasifier\ Bed\ weight}{Feed\ flow\ rate} \quad ....(7)$$

Here, $F_{carbon,syngas}$ is flow rate of carbon (kg/h) in syngas, $F_{carbon,in}$ flow rate oSf carbon (kg/h) entering into the gasifier, H_G is the flow rate of syngas (kg/h), H_G is the lower heating value (LHV) of syngas (kcal/kg), F_S is the flow rate of feed (kg/h) and H_S is the lower calorific value of feed (kcal/kg) to the gasifier.

3.1 Gasifier temperature

Gasifier bed temperature has major impact on gasifier performance as reaction rates and conversions depend mainly on it [3],[8].

TABLE 2						
EXPERIMENTAL CONDITIONS						
Parameters	**Petcoke percentages in feed**					
	0%	**10%**	**20%**	**30%**	**40%**	**100%**
Feed temperature (°C)	25	25	25	25	25	25
Feed rate (kg/h)	27.4	27.4	29.2	29.1	25.8	29.0
Air flow rate (kg/h)	59	60	59	61	61	54
Steam flow rate (kg/h)	4.4	5.2	6.3	5.2	5.1	7.0
Min fluidization velocity (m/s)	1.2	1.2	1.2	1.1	1.1	1.0
Bubbling regime (m/s)	1.7-5.2	1.7-5.2	1.7-5.1	1.7-5.0	1.6-4.9	1.4-4.5
Operating velocity (m/s)	1.9	1.85	1.85	1.85	1.85	1.9
Residence time (min)	55	64	51	55	54	45
Gasifier temperature (°C)	1000	1000	1000	1000	1000	1020
Operating pressure (kg/cm^2)	1.25	1.25	1.25	1.25	1.25	1.25

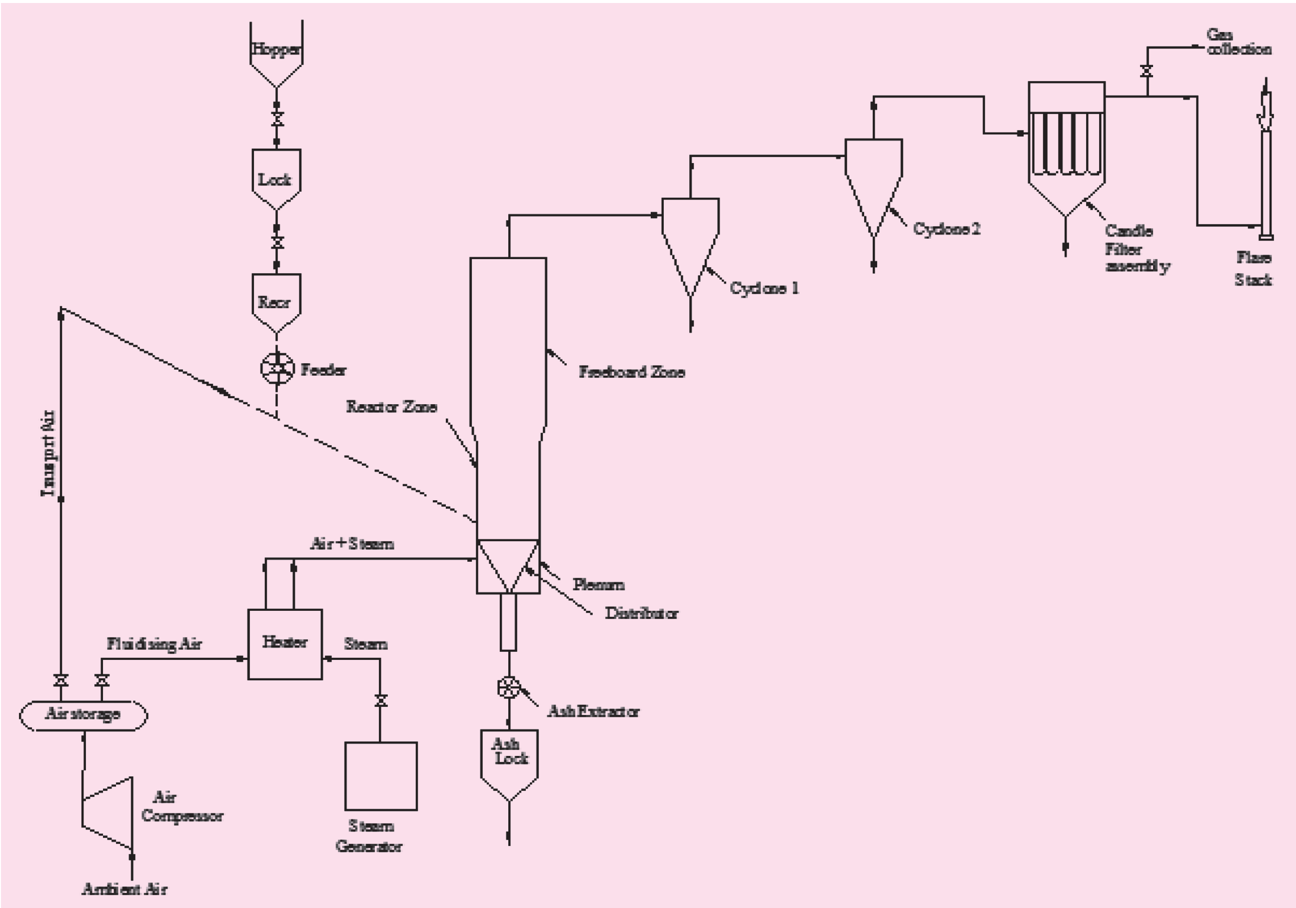

FIG. 1 PROCESS FLOW DIAGRAM OF FBG PLANT

The gasifier is operated at temperature below 1050° C in order to avoid clinker formation and loss of fluidity of the bed in FBG [2]. Figure 2 shows the typical profile of gasifier temperature of the FBG plant for petcoke blended coal gasification. The temperature in the reaction zone is higher than bottom because the feed enters into gasifier in this zone and gasification reactions occurs in this zone. The freeboard temperature is lower as it contains fine particles and syn gas generated in reaction zone.

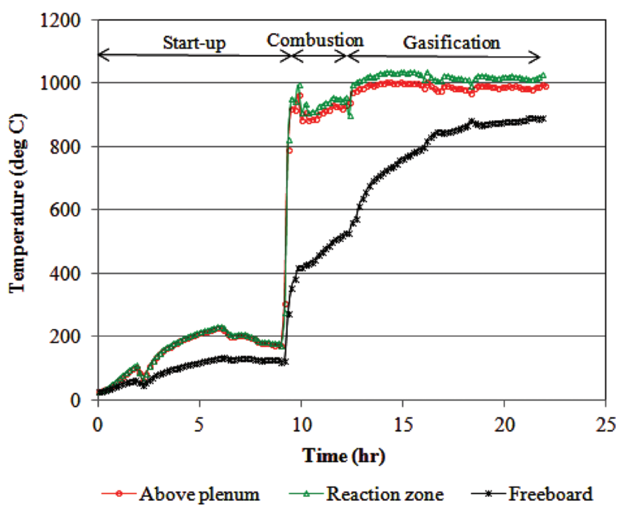

FIG. 2 TEMPERATURE PROFILEDURING EXPERIMENT IN FBG

3.2 Reactivity of petcoke blended coal

Using High Pressure Thermo Gravimetric Analyser (HPTGA) reactivity of petcoke blended coal char is studied, by employing CO_2 as gasifying agent. Figure 3 shows the variation of carbon conversion with time for coal and petcoke at 10 atm pressure and 1000°C temperature. The variation of reaction rate with carbon conversion for petcoke and coal is shown in Figure 4. The low reactivity of petcoke could be attributed to non porous nature of petcoke relative to coal. This is confirmed by images of surfaces of coal and petcoke samples (Figure 5) taken with scanning electron microscope (SEM). As petcoke percentage in coal blend increases, reactivity of the blend decreases due to the low reactivity of petcoke compared to coal. The results of reactivity study indicate that reaction rate increases rapidly, attains maximum, subsequently it decreases (Figure 4). Liu et al. [7] have attributed this variation to the evolution of the char particle structure such as surface area. At low carbon conversion, the surface area increases due to enlargement of pores in the particle and then decreases as pore interactions and pore wall collapsing becomes significant. The evolution of pore structure (e.g. surface area and pore volume) during the reaction is linked to the initial structure of char.

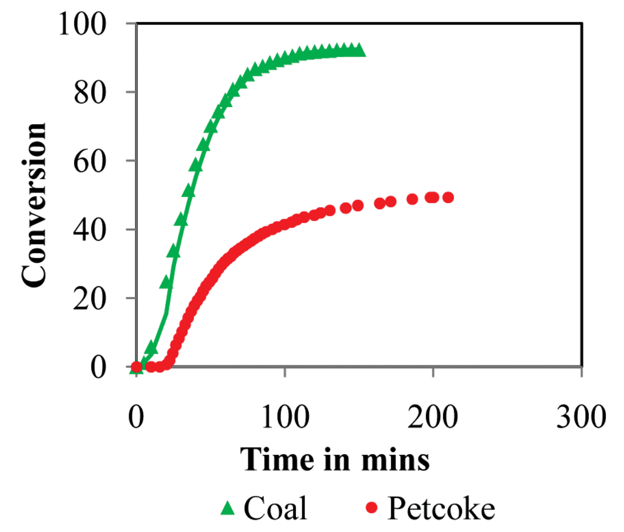

FIG. 3 VARIATION OF CONVERSION WITH TIME

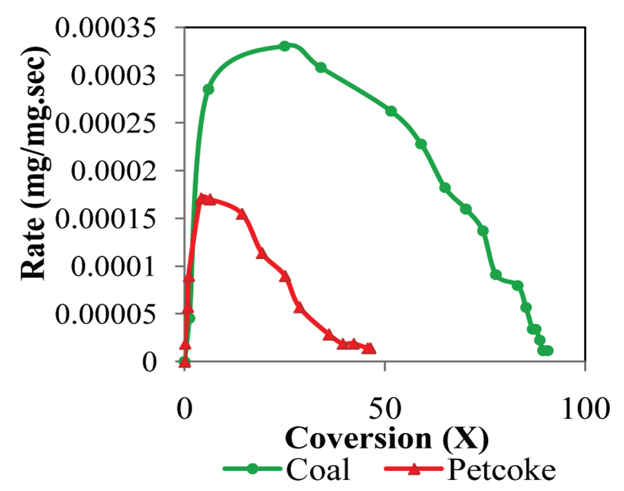

FIG. 4 VIEW OF A CST BOILER FOR STEAM GENERATION

3.3 Carbon conversion

Carbon conversion is one of the gasification characteristics that determine the performance of the gasifier. Carbon conversion depends on many factors such as operating temperature, pressure, hydrodynamics of bed, residence time etc. The variation of carbon conversion with petcoke percentage in coal blend is shown in Figure 5. The reduction in carbon conversion with increase in petcoke percentage in feed could be attributed to low reactivity (shown in Figure 3) of petcoke [3]. The gasifying agents air and steam are unable to penetrate into the petcoke surface as petcoke is non porous relative to coal (Figure 6), causing low carbon conversions. The carbon conversion for petcoke gasification in FBG operated at 1020^{o}C is just 25%, which could be attributed to low residence time (45 min) of particles apart from low reactivity of petcoke. On the other hand higher carbon conversions (~90%) reported in entrained flow bed gasifiers due to higher operating temperatures (1400-1600^{o}C) and use of oxygen instead of air as gasifying agent [2, 3, 4].The carbon conversion could be improved by recycling particles (increases residence time) collected in cyclone to gasifier through loop seal mechanism.

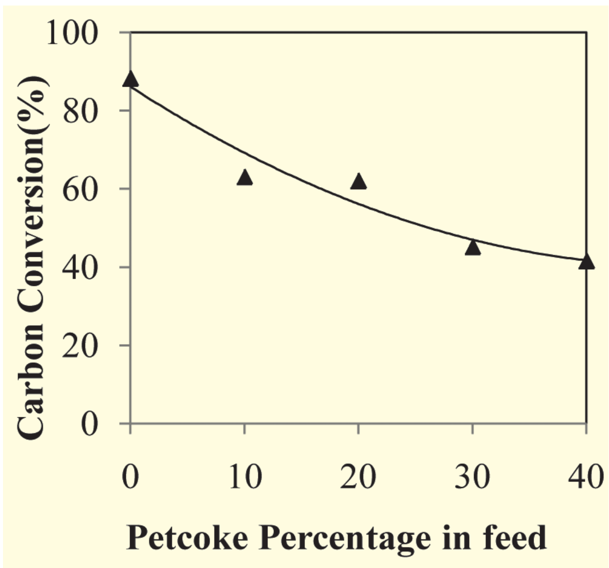

FIG. 5 VARIATION OF CARBON CONVERSION WITH PETCOKE CONTENT IN FEED

3.4 Syngas composition

Composition of syngas is a very important parameter of gasification as it determines the quality or calorific value of syngas. Figure 7 shows the variation of syngas composition with petcoke percentage in coal blend. The concentrations of CO and H_2 decrease with increase in petcoke content in coal blend which can be attributed to low carbon conversion. The concentrations of CO, H_2 and CH_4 observed during the experimentation are in the ranges of 12-15%, 11-14%, and 0.5-0.7% respectively.

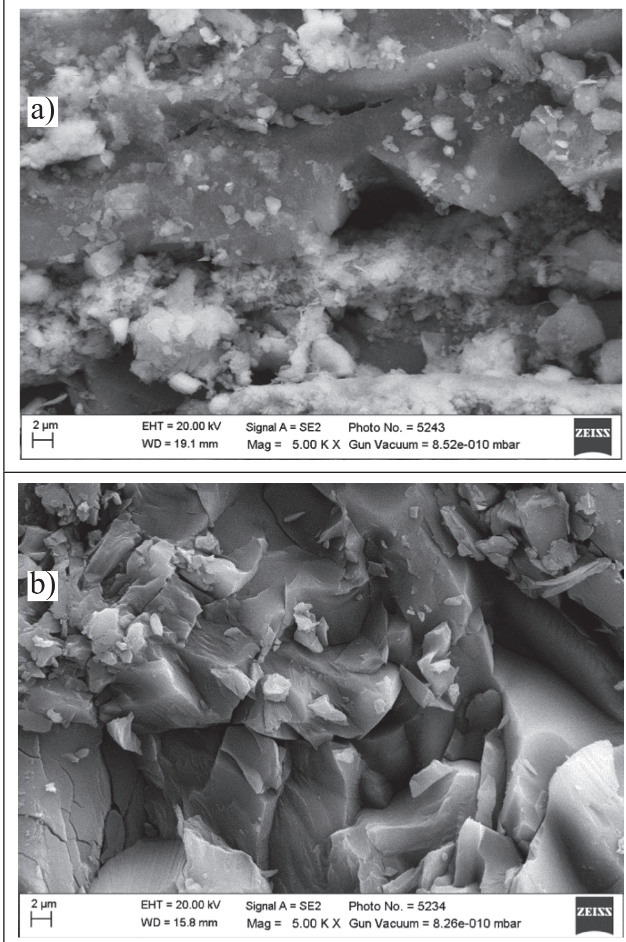

FIG. 6 FIG. 6SEM IMAGE INDICATING:
a) PRESENCE OF PORES ON COAL SURFACE
b) ABSENCE OF PORES ON PETCOKE SURFACE

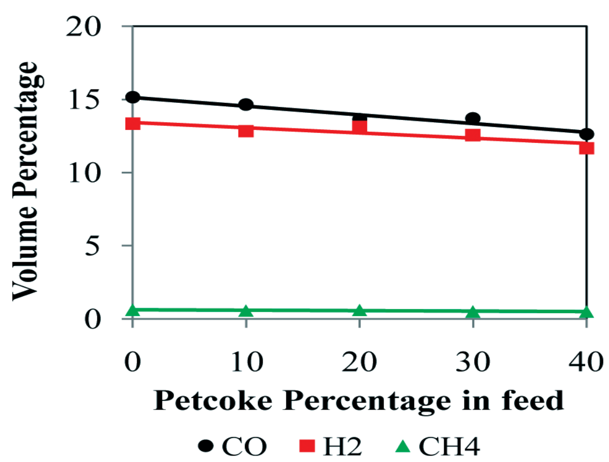

FIG. 7 VARIATION OF SYNGAS COMPOSITION WITH PETCOKE CONTENT IN COAL BLEND

3.5 Syngas LHV and cold gas efficiency

Syngas LHV depends mainly on concentrations of CO and H_2 as of CH_4 is concentration too low. The syngas composition is driven by gasification reaction rates and conversions. The cold gas efficiency and syngas low heating value (LHV) decrease with increase in petcoke content in coal blend as shown in Figure 8.

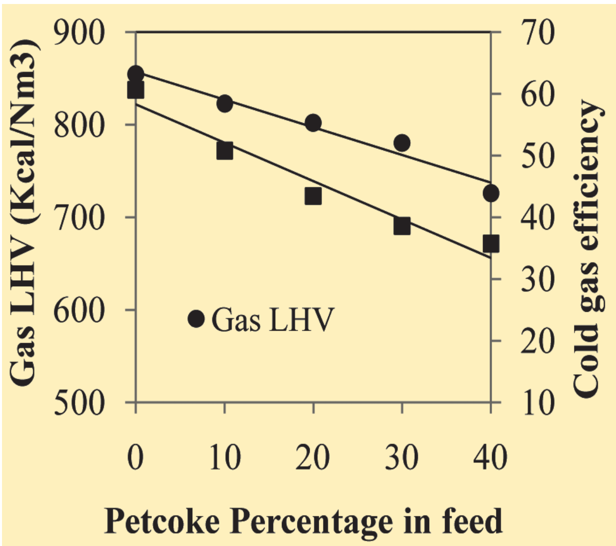

FIG. 8 EFFECT OF PETCOKE CONTENT IN FEED ON SYNGAS LHV & COLD GAS EFFICIENY

Due to reduction in carbon conversion, there is reduction in the concentrations of CO and H_2 and which lead to low LHV and cold gas efficiency. It is observed that the cold gas efficiency for 40% petcoke in coal blend is just 36% and which clearly shows that particles collected in cyclone have to be recycled to improve the carbon conversion. Lee et al. [3] reported a syngas calorific value of 1500-1800 kcal/Nm^3 and cold gas efficiency of 35-55% when petcoke is gasified in oxygen blown entrained flow gasifier operated at 1400-1600^{o}C, where as the calorific value of syngas obtained by gasifying petcoke in FBG system is mere 601 Kcal/Nm^3.

3.6 Comparison of coal gasification with petcoke gasification in FBG

Table 3 shows the comparison of gasification characteristics for petcoke gasification and coal gasification carried out in a bubbling FBG system.

The carbon conversion for petcoke gasification is mere 25% as sufficient residence time could not be maintained (Table 2) due to design and operational constraints. The residence time for petcoke should be maintained sufficiently high to increase the carbon conversion (Figure 3) because of its low reactivity.

The syngas generated from petcoke gasification has very low carbon conversion and low LHV which shows that petcoke gasification is may not be economically viable in FBG without recycling of fines, as more than 90% cold gas efficiencies are reported for petcoke gasification in entrained bed gasifier.

TABLE 3

COMPARISON OF COAL GASIFICATION WITH PETCOKE GASIFICATION

Contents	Coal gasification	Petcoke gasification
Gasification characteristics		
Carbon conversion	88	25
Cold gas efficiency	61	16
Syngas LHV (kcal/Nm^3)	854	601

3.7 Measures to improve the calorific value of syngas

The results obtained from the petcoke blended high ash Indian coal gasification in a pilot scale 1.2 T/d FBG plant are not up to the expectation. The low carbon conversion and low syngas calorific value shows that it may not be viable option to gasify petcoke in FBG plant. To improve the calorific value of syngas from petcoke gasification following measures are to be explored.

- Increasing O_2 percentage in air or replacing air with O_2 as gasifying agent: Calorific value of syngas increases by increasing oxygen in air as more CO_2 is produced which favours high CO and H_2 concentrations.

- Recycling of fines collected in cyclone to gasifier: Residence time of feed particles increases by recycling fines which leads to increase in carbon conversion and accordingly calorific value of syngas should increase.
- Decreasing feed particle size in feed: Carbon conversion and calorific value of syngas increases by reducing the size of the feed particles as surface area available for gasification reactions increases.

4.0 CONCLUSIONS

Fluidized bed gasification technology is most suitable for gasifying high ash Indian coals. The abundant availability of petcoke and its high carbon contentis prompting the world to study co-gasification of coal with petcoke. In this investigation, co-gasification of high ash sub bituminous Indian coal and petcoke are studied by carrying experiments in a 1.2 T/d pilot scale FBG (I.D. 0.2mX height 4.2m) plant, using air and steam as gasifying agents. The conclusions of this study are as follows:

- The results indicated that increase in petcoke content in coal blend leads to decrease in carbon conversion which could be attributed to the low reactivity of petcoke.
- The volume percentages of CO, H_2, and CH_4 in syngas are in the ranges of 12-15%, 11-14%, and 0.5-0.7% respectively. It has been observed that the concentrations of CO and H_2 in the generated syngas decreases with increase in petcoke content in coal blend.
- The results showed that syngas calorific value and cold gas efficiency are also decrases with increase in the feed petcoke content. The calorific value of syngas and carbon conversion for coal gasification are 854 kcal/Nm^3 and 88% respectively, where as for petcoke gasification the values are 601 kcal/Nm^3 and 25%.
- The results of this investigation indicate that gasifying petcoke in FBG is may not be viable optionas the carbon conversion and calorific values are very low compared to entrained bed gasifier. To improve the calorific value of syn gas measures such as increasing oxygen concentration in air, recycling of fines into gasifier and use of smaller particle size feed etc, have to be explored.

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