Performance of Enugu Sub-Bituminous Coal in Fluidized Bed Combustor

Abdulkarim Nasir, *Member, IAENG*, Shuaibu N. Mohammed, and Abubakar Mohammed

Abstract—**Producing electricity through the combustion of coal is one of the oldest and cheapest ways of generating electricity. The importance of fluidized bed combustion in utilizing the energy of especially low-grade coals for power generation is widely accepted. Nigeria with billions of tonnes of untapped coal and ironically with gross insufficient electrical energy supply can take advantage of fluidized bed combustion technology for energy production. The aim of this research is to investigate the applicability of this technology to Nigerian low-grade coals (Enugu sub-bituminous coal). To achieve this, a pilot fluidized bed combustor of 3m tall and 155mm diameter was fabricated with all the necessary equipment. The experiment was carried out using Enugu sub-bituminous coal of sizes 850µm. The effect of coal batch sizes was investigated by feeding the coal over-bed in batches of015, 0.25, 0.35, 0.45 kg/batch. The bed and free-board temperatures were measured using accurate digital thermocouples across the diameter of the bed. An orifice meter was constructed and installed to monitor the pressure drop and consequently the fluidizing velocity. This makes the determination of the minimum fluidization velocity possible. The minimum fluidization velocity was obtained to be 1.64 and 1.91m/s for a coal batch feed of 150 and 450g respectively.**

Key words: Fluidized bed, Electricity, combustion, coal, energy

I. INTRODUCTION

Long periods of availability of cheap liquid and gaseous fuels have favourably influenced industrial and technological development worldwide. At the same time, it has also resulted in an almost complete interruption of research and development of new technologies for coal and other solid fuels combustion [1]. Coal has been increasingly neglected for energy production, especially in thermal energy production for industry. In many countries, coal was also suppressed for use in electric power production by large boiler units.Only countries with extensive coal reserves, traditionally oriented to coal as an energy source continued to rely on coal, at least in large utility electric power systems. A similar orientation was also characteristic of some undeveloped countries rich in coal, which could not afford the use of oil even when it was relatively cheap[1].It is estimated that 41% of global electricity generation depends on coal. Its utilization is even higher in countries like South Africa and PR China where it is averaging 93% and 79% respectively [2].Fossil fuel combustion is a major energy source in the world. The combustion has been a strong driving force behind the industrial revolution since the 18th century. Lately, the rapid growing use of fossil fuels has been causing severe environmental impact due to pollutant emissions. Acid rain is caused by the emission of nitrogen and sulphur oxides ($N0_x$, $S0_x$) which converts to nitric and sulphuric acid in the atmosphere. Particle emissions, especially fine particle, have been found to be a health risk [3], in addition to carbon dioxide concentration in the atmosphere. This is expected to increase the greenhouse effect and hence the average temperature of the earth.

Combustion of solid fuel for heat and energy is as old as recorded history. While energy needs are greater and the uses more varied, combustion remains the single leading source of energy production. The energy produced by combustion is no longer used as a direct source for most people. It is used to generate steam for personal and commercial uses such as the generation of electricity.

Coal is used as an energy source in large-scale utility production in many parts of the world. Maximizing the amount of heat extracted from the coal burned is critical for affordable energy production and lessening the impact of this combustion on the environment. It is widely acknowledge that coal, as one of the main energy sources, plays an important role throughout the world. The utilization of low-grade coal in energy is necessary due to increasing cost and decreasing reserves of high-grade fuels. Less work has been reported on combustion of Nigerian coals [4], but since fluidized bed presents a typical problem of non-linearity in operational condition, it becomes difficult to assume existing operational parameters for Nigerian coals. Such non-linearity of coal combustion manifest in heat and mass transfer since these depends on fluid flow conditions.

Fluidized Bed Combustion (FBC) seems to be the most promising technique for use of low-grade solid fuels and to reduce the quantity of atmospheric pollutant such as $S0_2$ and $N0_x$ released during the combustion.

The term fluidized bed describes a finely granulated layer of solid material (referred to as “the mass”) that is loosened by fluid flowing through to such an extent that the particles of solid material are free to move to a certain degree. It is called “fluidized” because the solid material takes on properties similar to those of a fluid. The status of any particle-fluid system is limited by two bench marks: the so called minimum fluidization velocity and the entrainment velocity. When a system is operating between these two benchmarks it is known as a bubbling fluidized bed or bubbling AFBC. When a fluidized bed combustion system is designed to operate above the entrainment velocity it is known as a circulating fluidized bed.

The major advantages of fluidized-bed combustors are uniform temperature distribution, a large solid–gas exchange area, high heat-transfer coefficients, fuel flexibility (various possible sizes and moisture contents, etc.), stable combustion at low temperatures and generally no moving

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parts [5]. It however, have some disadvantages such as additional required equipment for solid separationor gas purification, erosion of the combustor interior,agglomeration and difficultiesoperating it at partial load [6, 7]. Despite these drawbacks, FBC is arguably the best clean-coal technology due to its high combustion efficiency and reduced environmental impact [5].

TABLE I
COAL DEPOSIT IN NIGERIA

Location	Indicated Reserve (proven)	Inferred Reserve
Enugu	54	200
Ezimmo	56	60
Owukpo	57	75
Okaba	73	250
Ogboyoga	107	30
Inyi	20	320
Asaba/Ogwuasi (lignite)	250	30
Lafia Obi (cooking coal)	22	250
Others	-	1360
Total	639	2701

In Nigeria, coal can be found in areas like Enugu, Afuze, Okaba, Lafia and Ogbojoga. Lafia and Enugu coal estimate alone amount to approximately 1000million tones[8].Coal was discovered in Nigeria in 1909 and the mining activitiesbegan in 1915 at Ogbete in Enugu state, Nigeria [9]. Table I shows the coal deposition in Nigeria. The first energy resources to be exploitedfor rail transport and electricity generation in Nigeria was coal.However, coal remains the smallest contributor to the overall fuelmix and ranks low in worldwide coal production [10]. Today, the utilization of Nigerian coalis mostly for cement production for use in foundries, brick factories, bakeries and as a domestic cooking fuel. Coal is expected to play a vital role in numerousproposed power generating plantsdue to the projected increase in global energy demand to between 12 and15 GW by 2025 [11]. Recently, a Chinese consortium signed US$3.7b agreement with Nigeria for coal mining and power plant construction with the future goal of generating up to 30% of Nigerian electricity from coal [12]. The proven coal reserves in Nigeria are estimated to be about 2.5 billion tonnes and lignite constitute 250 million tonnes while the remainder are mainly sub-bituminous [9, 13]. Though Nigerian coals are mainly low rank, its caloric values are comparable with universal figures of the same rank coal. They have also been reported to have good potential for gasification and liquefaction and have fine combustion characteristics [13]. They burn with long flames, which aredesirable even though they require large combustion spaces [14].

There are limited literatures in the performance of Enugu sub bituminous in FBC. However, the effect of batch size is seldom reported. This paper presents the effect of batch sizes on the combustion characteristics of Enugu sub-bituminous coal in AFBC.

II. MATERIALS AND METHOD

A. Apparatus

Atmospheric Fluidized Bed Combustor (AFBC), compressor, laboratory test sieves, stop watch and weighing machine were employed in this study. The AFBC was assembled by connecting the inert air/gas pipe to the compressor and gas cylinder. The four thermocouples for bed, freeboard, heat exchanger inlet and outlet temperatures were then fixed and the manometers were placed on the bed and across the orifice plate. The lower part of the vertical mild steel column contained a bed of inert material. The lower end of the cylindrical column (reactor) is the distribution chamber, plenum chamber and a ceramic tile air distributor which supports the bed when de-fluidized. A Red devil 3460 compressor with 160 litre capacity and a temperature of 10^0C to 120^0C was used to supply air to the combustor through the ceramic distributor. Above the bed is a secondary airport connected 0.55m above the bed through a 12.52 mm diameter pipe to the freeboard region. The purpose of the secondary air is to create turbulence in the freeboard region and thereby enhancing the proper mixing of the combustible gases and the volatiles liberated from the bed. The secondary air supplied would ensure the complete combustion of these gases, the volatiles and any un-burnt hydrocarbons released into the freeboard zone. The heat exchanger tube was made of aluminum bronze with an outside diameter of 13.0 mm and exposed area of 0.0245 m^2. The reactor was supported by iron brackets. Four thermocouple probes were installed in the bed, freeboard, inlet and exit of the heat exchanger tubes to measure the temperatures at these points. A pressure probe was also installed in the bed to measure the pressure variation at different flow rates and velocities. An orifice plate was inserted into the 25.4 mm pipe carrying the primary air supply to the plenum chamber so as to measure the air flow rates. A mercury filled manometer was used to measure the differential pressure across the orifice. The fuel was fed into the AFBC using the above bed feeding method [1]due to its simplicity.

The fluidized particles are a mixture of sand particles andcoarse fuel ash. Ash granules can be removed from the fluidized bed by “bottom” – type extraction or by entrainment with the flue gas once the ash particle have been sufficiently reduced in size by the eroding action of the fluidized sand. Solid fuel can be fed into the combustor under the fluidized bed, but “over-bed” feeding is possible and easier.

When the coal particle enters theFBC, it goes through two distinct combustion processes; volatile combustion and char combustion. For coal, volatile burn rapidly; leaving a slow-burning residual char. Char is normally present in the bed as 1 or 2% of the bed mass, although the concentrations may be higher or lower, depending on the fuel reactivity. Char particles are porous due to the loss of volatile matter, so combustion can take place either on the external surface, or on the much larger surface. For the coal particle to burn, oxygen must diffuse to the surface, react and products diffuse away from the surface. Thus both mass transfer and kinetic processes come into play and either or both can be rate limiting.

During the combustion process, the combustion heat is recovered via in-bed heat exchangers and adapted standard boiler equipment. Fly ash (and coarse ash) can be recycled for deep combustion with the help of the fuel feeding system. The air required for fluidization and combustion is fed via an air distributor which is commonly a nozzle tray whose design is classified. Freeboardis the section above the bed and its diameter is much larger than the bed diameter in some fluidized bed combustor. The reduced velocity in this region ensures that solid particles entrained in the gas flow return to the bed by gravity. Additional air for post-combustion of gaseous fuel components, known as secondary air, is often introduced into the freeboard region to ensure complete burn-out of the fuel.In theory, at the minimum velocity for fluidization, solid weight is just balanced by upward drag forces. Expansion is the bed reaction to the increase of velocity above the minimum. One of the inherent properties of fluidized bed is the high rate of heat transfer between the bed and the immersed bundles. The heat transfer steps in fluidized beds are generally seen to consist of three contributions: particle convection, gas convection and radiation.

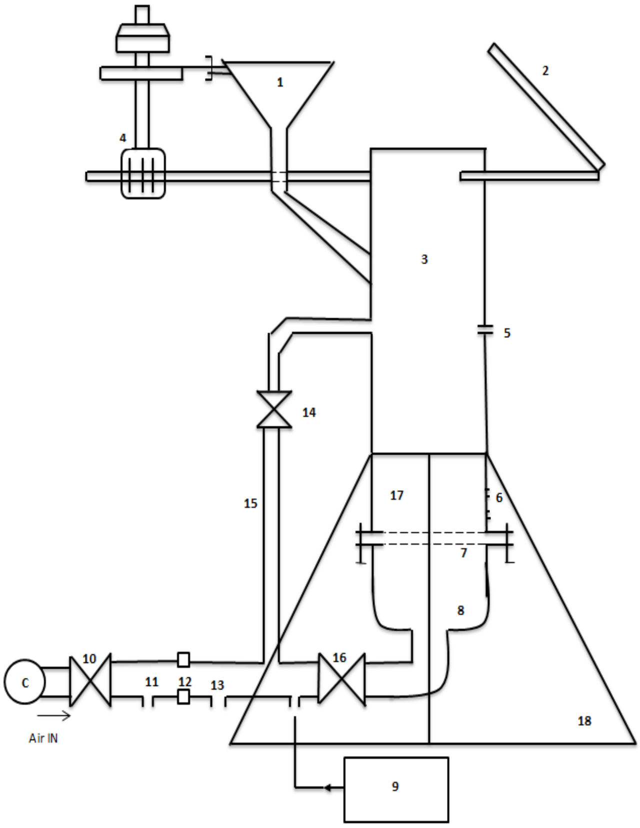

Fig.1: Fluidized Bed Combustor

TABLE II
PART DESCRIPTION OF FLUIDIZED BED BOILER

Part No.	Part Name	Part No.	Part Name
1	Vibrated feed hopper	10	3/4 inch valve
2	Reflective Stainless steel	11	Upstream stream tapping
3	Vibrating	12	Orifice
4	Reactor	13	Down Stream
5	Free board Tempt probe	14	½ inch
6	Bad temperature probe	15	Secondary
7	Distributor	16	1inch
8	Plenum Chamber	17	Bed
9	Gas Cylinder	18	Reactor Stand

B. Materials

The materials used in this study are Enugu sub bituminous coal and limestone. Sand particle of diameter 850 µm wasused as bed material. Propane gas and air was used to fluidize the bed and also raise the bed temperature to 750°C – 900°C.The sub bituminous coal is dull black and generally contains 20–30% moisture. The heat content ranges from 16-24 million Btu/ton and is used for generating electricity and space heating. Sub bituminous coal is the highest coal in rank after lignite and it is softer than bituminous.The properties of the Enugu sub bituminous coal and limestone used are shown in Table III.

TABLE III
PROPERTIES OF ENUGU SUB-BITUMINOUS COAL AND LIMESTONE CHEMICAL COMPOSITION

Enugu Sub-bituminous Properties (%)		Limestone Chemical Composition
Moisture	7.0	CaO
Ash (%dry)	3.0	Mg
Volatile matter	40.3	SO_2
Calorific value (MJ/kg)	37.5	Al_2O_3
Carbon	75	Fe_2O_3
Hydrogen	6.0	SiO_3
Sulphur	3.0	LOI
Oxygen	13	Equi $CaCO_3$
		Equi $MgCO_3$

C. Sample Preparation

The sample was prepared by fermenting a coal lumps from the Enugu Sub-bituminousinto small sizes using a crusher. A sieve size of average particles diameters of 0.85 mm was used.Visual examinations were used to remove any unusual size of particles. Inert bed material was prepared for the 0.85mm size for experimentation. The density of the coal particles was measured using mass-volume ratio by pouring a known mass of the coal particles into a container of known volume.

D. Experimental Procedure

The combustor column was charged with inert bed material of sand particles with an average diameter of 0.85 mm and a limestone of mass 1.6kg.The air compressor valve was gradually opened to allow air passed through the ceramic tile air distributor. The air velocity was gradually increased and the corresponding pressure drop across the bed was recorded until a point where further increase in the fluidizing velocity had no effect on the pressure drop across the bed (pressure drop stabilizes). At this point the bed was fully fluidized. The minimum fluidizing velocity was recorded and the bed was left to continue fluidizing for 10 minutes to ensure proper mixing. The behaviour of the bed was observed through a stainless steel plate reflector. Butane gas was then introduced and burnt in the bed to raise the temperature of the bed to 750°C – 950°C. 0.85 mmcoal particle diameter was charged into the combustor in batches of 0.15, 0.25, 0.35 and 0.45kg per batch. The gas supply was cut off as soon as combustion can be sustained by coal alone. The combustion product was collected for analysis. The temperatures across the bed were measured carefully by adjusting the position of the thermocouple probe inserted in the temperature port in the bed. The vibrator was calibrated to continuously feeding coals into the combustor. The following parameters were measured, recorded and analysed; bed temperature, freeboard temperature, inlet and outlet water temperatures from the heat exchanger, pressure drop across bed, pressure drop across the orifice, fluidizing velocity, coal burn out time, ambient temperature, mass flow rate through the heat exchanger, inlet and outlet gas(air) temperatures.

E. Results and Discussion

Fluidization Velocity and Pressure

As the combustion air passes through the bed, its behaviour was observed through a stainless steel reflector situated at the top of the column. At incipient fluidization, a thick cloud of dust was observed. As soon as the velocity of the compressed air was increased, the bed became fully fluidized. Figure 2 shows that as the superficial velocity increases from 0.5 m/s to 2 m/s, the orifice pressure drop increases from about 260 N/m^2 to 4000 N/m^2. The increase in the superficial velocity was also accompanied by a corresponding increase in the volumetric flow rate (Figure 2).Figure 3 shows that the use of batch system of weight 150 to 450 g with particle diameter of 0.85 mmfed into the fluidize bed increases the minimum fluidization velocity of the bed from 1.64 to 1.91m/s respectively.The pressure at which the bed attained stable fluidization was lower than the theoretical value. However, the compressor nozzle pressure at which the bed became fluidized was far higher than the bed pressure. This was due to the fact that there was pressure drop along the pipe and within the plenum chamber. From theory, theoretical pressure drop is always greater than the measured and the theoretical value is indicative of the degree of gas misdistribution.Figure 4 shows that as the superficial velocity increases, the bed pressure drop also increases. This increase continues until the fluidization was attained. At fluidization further increase in superficial velocity have no consequence on the bed pressure drop. There was an increase in bed pressure drop as the batch weight increases.

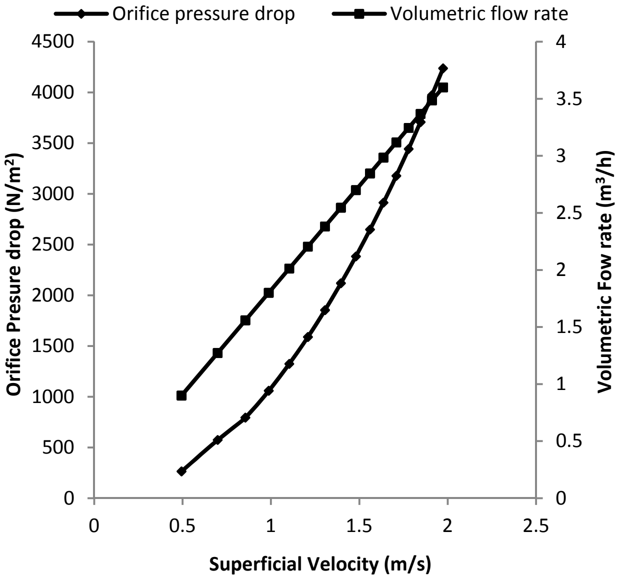

Fig 2: Pressure Drop across the Orifice and the Volumetric Flow rate

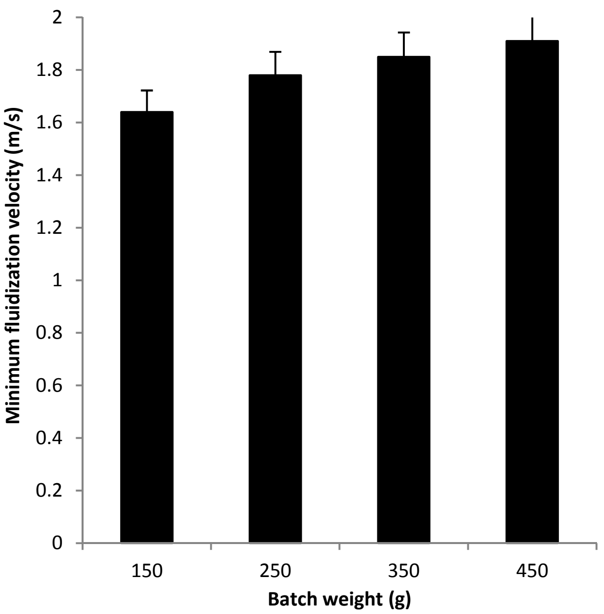

Fig 3:Minimum Fluidization Velocity for Different Batches

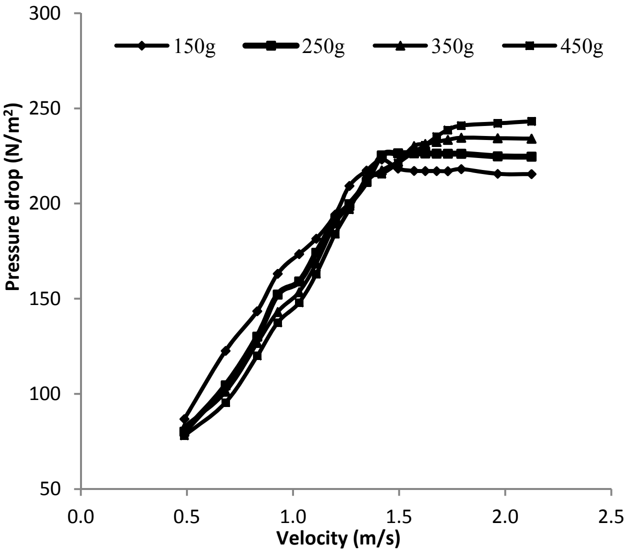

Fig 4: Pressure Drop Across Bed Against Superficial Velocity

Freeboard and Bed Temperature

The bed was heated to 850^{o}C before coal feeding began. Bed temperature reduced to 810^{o}C as soon as coal was added as some heat was used in heating. This is so because the coal is being heated hot to its ignition temperature. Thereafter there was continuous rise in bed temperature as the combustion process continued. It was however observed that once the temperature of the bed was above 800^{o}C combustion is sustained by coal and nearly complete. This was as a result of good mixing of inner particles promoted by bubbling action of the bed which allowed particles to receive radiant energy from the flame and corrective heating which helped to maintain bed temperature. The bed temperature rose to the 850^{o}C and fluctuates between the ranges of 840^{o}C – 950^{o}C within 2mins of coal feeding.

The bed temperature was observed to be higher than that in the free board; this should be due to the fact that part of the hot gases that were burnt in the bed accumulated in it. The introduction of secondary air assisted in the complete combustion within the freeboard region. As coal was added to hot bed and the secondary air inlet was cut off, there was considerable pyrolytic decomposition of the coal. But as the secondary air was re-introduced, the smoke reduced, volatile matter from the hot bed raised and got burnt in the secondary air region.

Visual observation of the combustion behaviour at the start of the experiment showed that when air flow was too little, not much of the combustible gas was burnt. When it was too much its cooling and diluting effect inhibited combustion. Thus, combustion in the freeboard was only possible over a moderately wide range of secondary air flow.

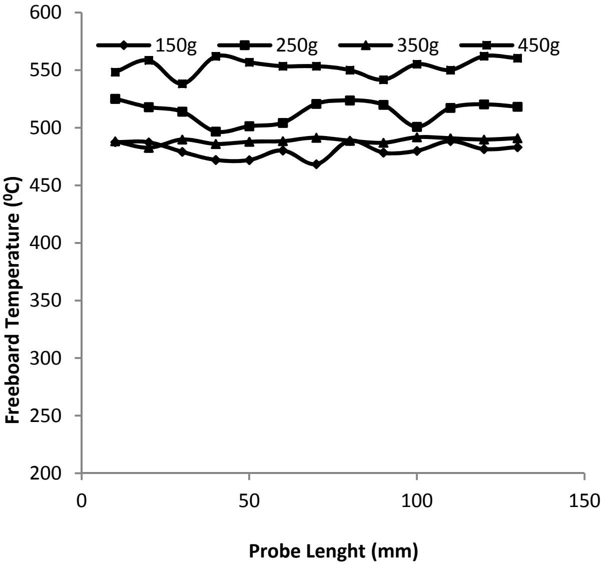

Fig 5: Bed Temperatures across probe length

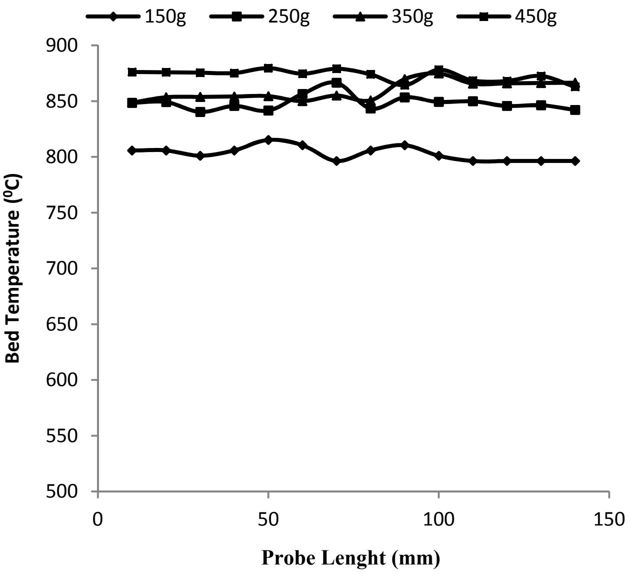

Fig 6: Bed Temperatures across probe length

III. CONCLUSION

The performance and applicability of Nigerian Enugu Sub-bituminous coal in Fluidized Bed Combustor has been presented. The effect of batch feeding of coal into the FBC and the temperature profile during the combustion of the sub-bituminous coal was discussed. The maximum bed temperature of 879^{o}C was obtained for a batch feed of 450g and the minimum bed temperature of 796^{o}C was obtained for 150g batch feed.The attainment of 879^{o}C bed temperature in a short time of 2 minutes confirms the high convective heat transfer coefficient of FBC technology. This is made up of gas and particle convection and it is as a result of intensive gas-particle mixing.

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