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Some Cold Model Studies on Design and Developmental Aspects of a Cyclone Type Entrained Flow Gasification System using Blended Low Grade Coal with Dolochar Wastes

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***Abstract*— The overuse of conventional fuels in various industrial and power sectors is leading to problem of energy crisis in the present scenario. Imposition of emission norms by government regulating bodies to reduce environmental pollution is getting increased attention to search for a cleaner burning fuel. Producer gas or syngas is expected to play an important role in meeting the existing gap between the energy supply and energy demand. Dolochar, a solid waste generated in sponge iron plant invariably contains 15-30% unburned carbon. Conventionally, a sponge iron unit generates about 0.25 tons of dolochar as solid wastes for the production of 1 tonne of sponge iron. The commercial recovery of carbon values from these wastes through advanced gasification process may provide added advantage to the economy and efficient utilization of resources as well as environmental pollution control. A cyclone type entrained flow gasification system may be considered as a suitable option to gasify these high ash content wastes by blending it with low grade coal. In order to develop a suitable prototype gasifier to handle these high ash content feedstock, four cold model reactors with different geometries were designed and fabricated by adopting cyclonic principle and the characteristics of each reactor with respect to ash separation efficiency and total pressure drop were evaluated. Based on the cold model studies, a prototype entrained flow gasifier having a barrel internal diameter 0.325 m and L/D ratio 6.5 with a furnace volume of 0.13 m^3 was designed and the performance of the prototype reactor with respect to Equivalence Ratio (ER), adiabatic flame temperature, steam to fuel ratio on gas composition, cold gas efficiency, turndown ratio and conversion rates etc were theoretically discussed to create more understanding of this system.**

***Index Terms*— Blended Coal & Dolochar Gasification, Entrained flow, Cyclone type, Cold model studies, Ash separation, pressure drop, Theoretical performance evaluation.**

I. INTRODUCTION

Due to non-availability of high grade coal, the Indian steel industries adopt poor quality (F-grade) coal for production of sponge iron which is used as a raw material for steel production. In the process of sponge iron production, a huge quantity of solid wastes known as dolochar is generated and the disposal of these wastes is a major concern. The industry operating one DRI (direct reduced iron) kiln of 100 TPD capacities could produce ~40 TPD dolochar containing 15-30 % of FC and ~1680 GCV kcal/ kg with very low volatile matter [1]. Also a large quantity of coal fines are generated in the coal crushing dehusking system which can be mixed with char fines or dolochar to be used as a fuel in any system. This means a large proportion of carbon values are going to be wasted unless its commercial value is recovered by some suitable physical, chemical or thermo-chemical route. The dolochar does not have any utility till now and is simply dumped in the plant premises occupying valuable space. Gasification is a potential route for thermo chemical breakdown of carbon-containing constituents of dolochar to yield a gaseous fuel (termed producer or syngas). The high ash content dolochar blended with F-grade coal as a feedstock material for entrained flow gasification system require through understanding of the characteristics of the flow field under isothermal conditions, separation of ash particles from the product gas, pressure drop inside the gasifier reactor. Breault [2] has reviewed the hydrodynamics and kinetics of various types of gasification technologies with a variety of fuels under different conditions from air blown to oxygen blown and atmospheric pressure to several atmospheres. Compared to other gasification technologies, entrained flow gasification technology has the advantages of high gasification intensity, high reaction rates, high carbon conversion, product gas free of oils and tars, and can be easily practiced on a larger scale [3-8]. Under atmospheric pressure and medium temperature from 1150 ^{O}C to 1450 ^{O}C, the gasification characteristics of pulverized coal in an electric heating drop tube furnace influenced by residence time and reactor temperature has been reported in literature [9-12]. The main important variables affecting gasification based process designs are gasifying agent, gasifier operating pressure and fuel characteristics [13-14]. Design and operational aspects of cyclone type gasifiers has been studied by some investigators to promote separation of particles from the product gas [15-18]. The use of cyclone as particle separator for pollution control have been considered as a cost effective means and can operate at high temperature and pressure [19-20]. The magnitude of centrifugal force in an induced vortex within the particle laden fluid flow affects the separation of particles in a cyclone separator [21]. The descending and ascending of particles through the outer and inner spirals (cores) with centrifugal forces surpassing the gravity at the conical section contribute to particle separation [22-23]. Syred et al. [18] conceptualized the insertion of vortex collector and central

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collector pockets in an inverted cyclone gasifier in order to promote the separation of ash particles from the product gas. The influence of particle size, input velocity and vortex finder height affecting pressure drop and collection efficiency on a cyclone has been studied by some investigators [24-28].

It is indicated from literature that the geometrical features of the cyclone type gasifier reactor has to be adequately modified and designed to maximize ash separation from the product gas with minimal pressure drop for high ash content feedstock material. Further, sufficient swirl flow and high temperature are required to be generated inside the gasifier reactor to achieve high intensity gasification and high conversion rate of the feedstock. In this context, four model reactors with different geometries were designed and fabricated in the laboratory for cold model studies. The characterization studies of blended coal and dolchar in a fixed weight ratio, comparative evaluation of the models for ash separation and pressure drop influenced by entrained air inlet velocity, dimension of the reactors with the insertion of vortex finder etc. were discussed. Based on the cold model studies, the performance of a prototype reactor for gasifying high ash content blended coal and dolochar with different dolcohar fractions with respect to Equivalence Ratio (ER), adiabatic flame temperature, steam to fuel ratio on gas composition, cold gas efficiency, turndown ratio and conversion rates etc were theoretically discussed to create more understanding of this system.

II. MATERIALS AND METHODS

A. *Characterization studies*

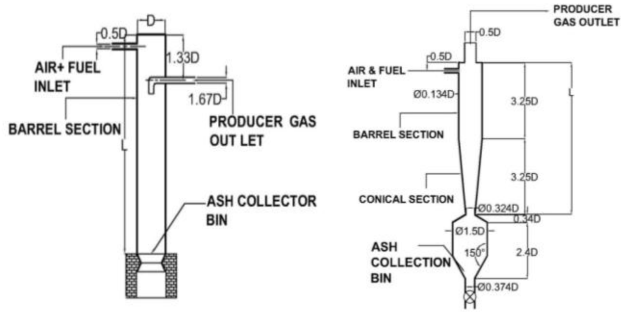
The non-coking coal (F-grade) and dolochar samples for the investigation were collected from M/s Arati Steel Pvt. Ltd., Odisha. Initially the coal and dolochar were pulverized in a ball mill and were sieved through BS Mesh (106 μm) to obtain desired particle size. The moisture content of the samples were determined by using Moisture analyser (Make: Denver Instrument, Germany, Model: IR60, Accuracy: 0.01%). The calorific value of the samples were measured with digital bomb calorimeter (Make: Parr, Model: 6100 Isoperibol calorimeter, precision classification: 0.2% class). The proximate and ultimate analysis was carried out by LECO TGA and LECO CHN Analyser respectively and is presented in Table-1. The blended coal and dolochar mixture in the fixed weight ratio of 80:20 were burnt in a muffle furnace and the ash generated was taken for its characterization studies. These ash samples were subsequently used for cold model studies. The particle density of the ash was determined using standard specific gravity bottle and was found to be 2745 kg/m^3. The particle size distribution (PSD) of the ash samples was carried out using Malvern Particle Size Analyzer (MASTERSIZER 2000) and the median particle size, d_{50} of the sample was found to be 25 μm.

Table-1: Proximate, Ultimate analysis and Gross Calorific value of Coal, Dolochar and blended mixture on air dried basis

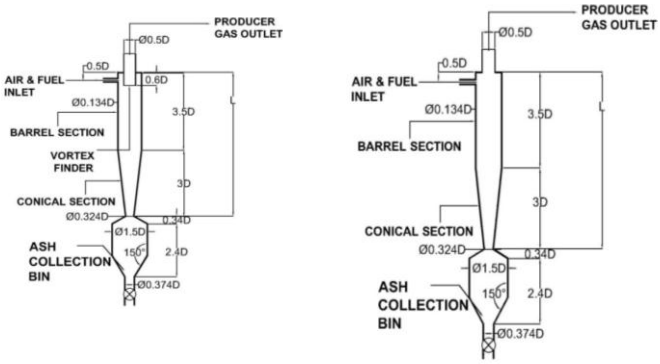
Proximate analysis	**F-grade coal**	**Dolochar**	**$*R_{80/20}$**
Moisture (%)	4.08	3.26	4.16
Volatiles (%)	23.87	4.04	18.38
Ash (%)	39.94	66.92	46.66
Fixed Carbon (%)	32.11	25.78	30.8
Gross calorific value (MJ/kg)	14.112	6.93	13.61
Ultimate analysis			
Carbon (%)	42.78	21.3	37.15
Hydrogen (%)	2.812	0.665	2.233
Nitrogen (%)	1.62	2.02	2.017
Sulphur (%)	0.41	0.02	0.37
Oxygen	8.368	5.436	7.38

B. *$*R_{a/b}$: Weight ratio of Coal and dolochar, a: coal, b: Dolochar*

In order to ascertain the pressure drop and ash separation efficiency, four model reactors were constructed in the laboratory and the schematic diagram of the four models is shown in Fig.1. All the reactors are of returned flow type cyclones having tangential feed inlet with a fixed L/D ratio of 6.5. Reactor-1 is a simple cylindrical barrel shaped where as Reactor-2 a standard cyclone having equal barrel and conical sections. Reactor-3 consists of smaller barrel section compared to conical section. Reactor-4 is a replica of Reactor-3 but with the provision of a vortex finder at the top. All the four reactors were provided with ash collection bin at the bottom section.



Reactor-1 Reactor-2



Reactor-3 Reactor-4

Fig. 1: Cold model reactors for the studies

III. EXPERIMENTAL

A. *Evaluation of pressure drop*

The pressure drop is an important variable to evaluate the performance of the cyclone type entrained flow gasification system with high ash content feedstock material. The total pressure drop over the cyclone consists of expansion loss at the inlet, contraction loss at the entrance of the outlet tube, the swirling loss due to the friction between the gas flow and the cyclone wall and a dissipation loss of the gas dynamic energy in the outlet. The total pressure drop (ΔP) for the reactors were evaluated by conducting cold model studies.

The lay out diagram of the experimental set-up for the cold model studies is indicated in Fig.2.

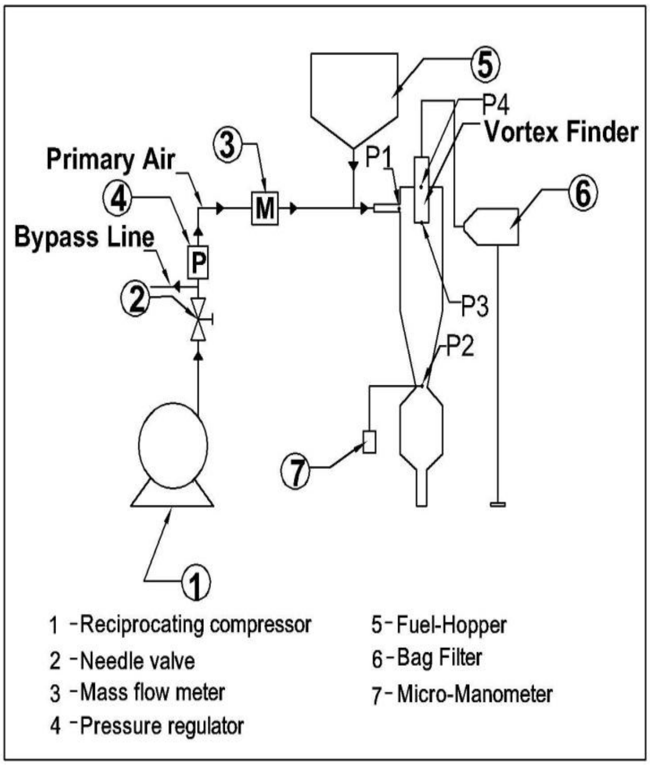


Fig. 2: Experimental set-up for the cold model studies

The reactors were made out of perspex material of 5 mm thickness. Each reactor was provided with a fuel feeding hopper of 2 kg capacity and was installed on the air inlet pipe near the reactor. A reciprocating compressor was used to supply compressed air to the reactors and the air flow rate was controlled by means of a needle valve and a pressure regulator. A mass flow meter was mounted on the primary air flow line to record the mass flow rate of air supplied to the reactor. A micro-manometer (Model: HD350 & Make: Extech instruments, Germany) was used to measure the differential pressure across the reactor sections with mean velocity of flow by the following probe equation:

$$U = K\sqrt{\frac{2(\rho_w - \rho_{air})gh}{\rho_{air}}} \tag{1}$$

Where, U is the mean velocity of the flow (m/s), K is the probe factor, h is the pressure differential measured by the manometer (m of water), ρ_{air} is the density of air (kg/m^3) and ρ_w is the density of water (kg/m^3). The pressure loss due to expansion at the cyclone inlet (ΔP_1) can be expressed as:

$$\Delta P_1 = \left(1 - k_i \frac{b}{R + b - \tilde{c}b - r_c}\right)^2 \frac{\rho_g v_i^{\,2}}{2} \tag{2}$$

where k_i is the correction co-efficient, b is the cyclone inlet width, c is the width of the inlet cutting into the cyclone body, R is the radius of cyclone barrel, $\tilde{c} = c/b$, r_c is the radius of core flow, ρ_g is the gas density, v_i is the inlet velocity in m/s. Similarly, the pressure loss due to contraction (ΔP_2) at the gas outlet can be determined by using the following equation:

$$\Delta P_2 = 4.5\,\frac{\left(1 - 3\tilde{d}_r^{\,2}\right)}{K_A^{\,2}}\,\frac{\rho_g v_i^{\,2}}{2}$$

where, $\tilde{d}_r = r_e/R$, r_e is the radius of the cyclone outlet, $K_A = D^2/d^2$ is the inlet air ratio, D is the diameter of cyclone barrel and d is the cyclone outlet. The swirling loss due to friction (ΔP_3) between the gas flow and the cyclone wall can be calculated by the following equation:

$$\Delta P_3 = \frac{f_0 F_s \rho_g \left(V_{\theta w} V_{\theta e}\right)^{1.5}}{2\,X\,(0.9\,Q_i)}$$

where f_o is the friction co-efficient, F_s is the area of contact surface, $V_{\theta w}$ is the tangential velocity at radius R, $V_{\theta e}$ is the gas tangential velocity at r_e and Q_i is the inlet gas flow rate. The gas tangential velocity at the outlet tube and gas axial velocity in the annular region at the outlet wall is of significant importance in determining the pressure loss due to dynamic dissipation (ΔP_4). The dynamic pressure loss (ΔP_4) at the outlet tube may be computed by using the following equation:

$$\Delta P_4 = \frac{\rho_g}{2}\left(\bar{V}_\theta^{\,2} + V_{ze}^{\,2}\right)$$

where $\bar{V}_\theta$ is the mean tangential velocity in cylone outlet and V_{ze} is the axial velocity in outlet annular region. The pressure drop in the vortex finder affects significantly from operational and economical standpoints. The vortex finder which otherwise acts as the gas outlet duct needs to be dimensioned properly to prevent a short circuit between the gas inlet and outlet with adequate residence time for efficient particulate separation. In order to evaluate the pressure drop as a function of vortex finder height, experiments were conducted by varying the length of vortex finder i.e. at 0.5D, 0.6D, 0.7D and 0.8D using Reactor-4 and the pressure drop data obtained at different air inlet velocities were recorded for analysis. The experimental pressure drop data obtained from the cold model studies were compared with the computed pressure drop using Eqns. 2 to 5

B. *Ash separation efficiency*

In case of reverse flow cyclones with tangential inlet, due to centrifugal force the solid particles are thrown to the wall where they lose energy and fall moving under the action of gravity at the bottom of the device. The inflowing fluid rotates within the main body of the chamber and is constrained to follow a spiral flow path. Any particles suspended within the fluid are subjected to an enhanced radial acceleration. The larger particles migrate outwards to the cone wall where they travel downwards spiral to the base of the chamber and exit at the underflow. The smaller particles migrate more slowly and therefore their distribution across the flow changes littlie. Those in the centre are captured in the upward flow and spiral upward and out through the vortex finder. The reminder is discharged with the coarse fraction at the underflow. The separation efficiency is very much affected by the particle size, particle density, fluid viscosity and constructive parameters of the cyclone. The separation efficiency for the four reactors was computed by using the empirical model of Koch and Licht [24] which can be written as:

$$\eta_i = 1 - exp\left\{-2\left[\frac{G\tau_i\,Q}{D^3}\,(n+1)\right]^{0.5/n+1} (3)\right\}$$

where, G is the cyclone configuration factor, τ_i is the relaxation time (seconds), Q is the volumetric gas flow rate (m^3/sec.), D is the cyclone body diameter and n is the cyclone vortex exponent.

Using the experimental set up as shown in Fig. 2, experiments were conducted to separate the particles from turbulent gas flow via centrifugal force induced by a swirling flow inside the reactors. Ash used for the study was obtained by burning coal blended with dolochar in the fixed ratio of 80:20 in a laboratory furnace. A bag filter having 150 mm diameter, 3 m long and 25 μm mesh size was placed at the gas outlet of the reactor to collect the ash particles possibly entrapped with the outgoing gas. 500 grams of ash was weighed accurately in an electronic type balance and was loaded to the fuel hopper. By varying the air inlet velocity, the amount of ash collected in the ash collection bin and bag filter were noted down. The experiment was repeated for all the reactors at air inlet velocity in the range of 18-30 m/s. The separation efficiencies for the four reactors were determined by using the following empirical formula:

$$\eta_{sep} = \left[\frac{(W_1 - W_2) - (W_4 - W_3)}{(W_1 - W_2)} \right] x100 \tag{6}$$

Where, W_1 is the initial weight of ash at storage bin, W_2 the residual weight of material in the storage bin, W_3 the initial weight of outlet bag filter and W_4 the final weight of outlet bag filter. In order to reduce uncertainty associated with weight measurements, experiments were repeated thrice at a specific air inlet velocity and the average values of initial and final weights were used to determine the ash separation efficiency.

IV. RESULTS AND DISCUSSION

A. *Pressure drop across the reactors*

Pressure drop across the cyclone affects the separation or collection efficiency. By increasing the inlet air velocity, the energy requirement to entrain the fuel material also increases. Thus, it is quite important to measure the pressure drop associated with each inlet velocity so as to have energy audit for economic operation of the gasification system. The pressure drops for the four reactors in velocity range of 18-30 m/s recorded during cold model studies were plotted and presented in Fig. 3. It is observed from the Fig.3 that the experimental data fitted very well to the computed pressure drop data obtained by employing Chen & Shi model [25]. As expected, the pressure drop through the four reactors increased as inlet air velocity increased. Reactor-4 with the insertion of a vortex finder incurred higher pressure drops as compared to Reactor-2 & 3, but incurred lesser pressure drop as compared to Reactor-1 in the studied range of velocities. Further, it is indicated that the pressure drop significantly increases beyond an air inlet velocity of 23 m/s. Thus, it is quite essential to operate the gasifier reactors by controlling the flow rate of entrained feed stock materials at lower velocity ranges i.e. 18-23 m/s in order to reduce the operating costs.

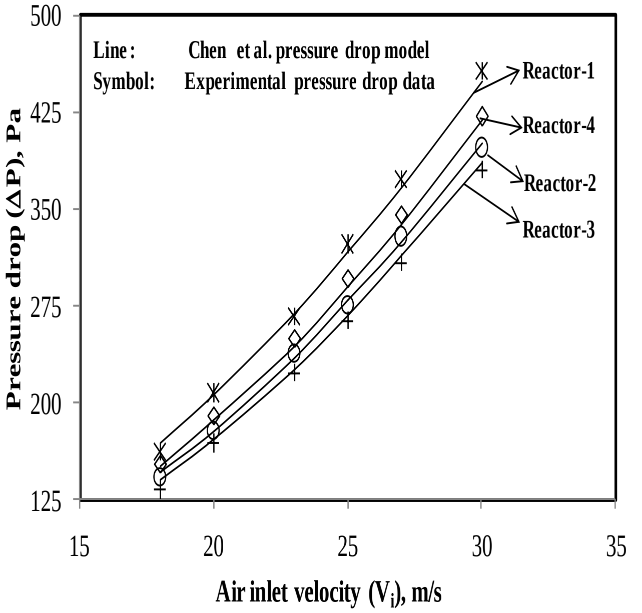


Fig. 3: Effect of air inlet velocity on pressure drop for the four model reactors

The pressure drop data obtained at different air inlet velocities by varying the vortex finder lengths in Reactor-4 is plotted in Fig.4.

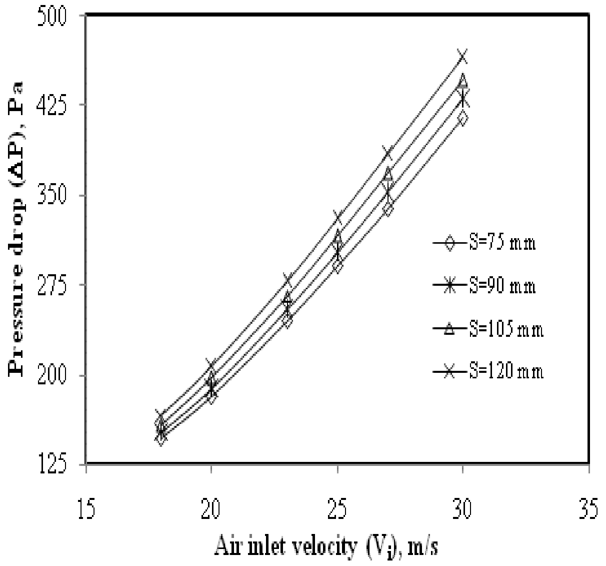


Fig. 4: Effect of vortex finder length on pressure drop in Reactor-4

It is observed from the plot that pressure drop increased with increase in vortex finder height. This may be due to the re-entrainment of secondary flow in to the vortex finder with strong turbulent intensity causing increased frictional losses over the total vortex finder height. Thus, the modification of the vortex finder height affects the pressure drop in the reactors. Similar type of observations has been reported by some investigators while varying the cyclone dimensions, vortex finder heights and other operational conditions [28, 29-32].

B. Comparative evaluation of ash separation efficiencies in the reactors

The ash collection efficiency for the four reactors was plotted against the air inlet velocities in the range of 18-30 m/s and is presented in Fig. 5.

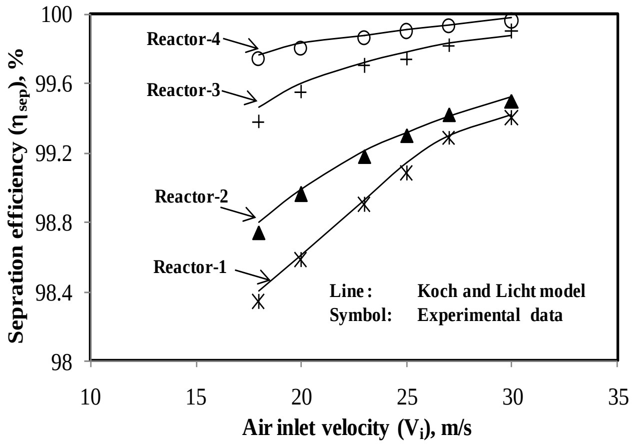


Fig. 5: Ash separation efficiency of the four reactors at different air inlet velocities

It is observed from the Fig.5 that the ash collection efficiency increased with increase in air inlet velocities for the four reactors. Reactor-4 achieved maximum separation efficiency in the range of 99.4-99.8% as compared to other three reactors in the studied range of air inlet velocities of 18-30 m/s. The incorporation of vortex finder in Reacor-4 improves the contact surface area of the flowing fluid inside the cyclone with higher residence time and increased turbulence within the reactor. This may be the reason for obtaining higher collection efficiency in reactor-4 as compared to other reactors. Further, comparison between the calculated separation efficiency using Koch and Licht model and the experimental data, it is observed from Fig. 5 that the model reasonably predicted the experimental data in the studied range of velocities. The experimental data on separation efficiency with different vortex finder height for Reactor-4 is shown in Fig.6.

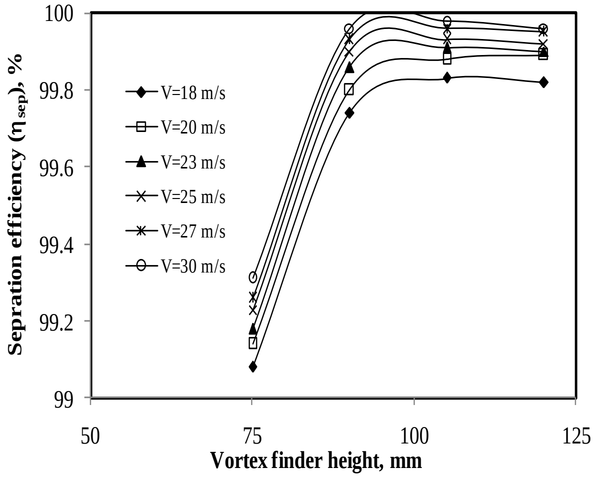


Fig. 6: Effect of vortex finder height on separation efficiency in Reactor-4

It is observed from the Fig.6 that the ash collection efficiency increased with increase in vortex finder length in the studied range of air inlet velocities of 18-25 m/s. The increase in collection efficiency at higher velocities and increased length of vortex finder may be due to increased turbulence and disruption of vortex within the reactor. Further, an increase in the height of the vortex finder causes an increase in particle residence time and increases the effective collection area in the reactor resulting in an appreciable improvement in collection efficiency. It is also indicated that collection efficiencies of more than 99 % was obtained in Reactor-4 with vortex finder height of 90 mm and more in the studied range of air inlet velocities. Restricting the height of vortex finder to 90 mm can be useful in reduction of pressure drop across the cyclone reactor for economic operation of such gasifier reactors.

C. Theoretical evaluation of the performance for the prototype gasifier

Based on the cold model studies, a prototype gasifier having a barrel internal diameter 0.325 m and L/D ratio 6.5 with a furnace volume of 0.13 m^3 was designed. The gasifier reactor was conceptualized as a reverse flow type cyclone with the insertion of a vortex finder. The performance of the prototype entrained flow reactor for gasification of blended coal and dolochar as feedstock material were evaluated with respect to Equivalence Ratio (ER), adiabatic flame temperature, steam to fuel ratio on gas composition, cold gas efficiency, turndown ratio and conversion rates etc.

1) Equivalence ratio (ER)

Equivalence ratio is the ratio of the amount of air used for partial combustion to stoichiometric amount of air required for full combustion. Complete combustion is the process of reacting coal gasification with the surplus amount of oxygen so that all the reactant gets converted into carbon dioxide and water. The empirical formula for the blended feedstock has been approximated as $C_{3.207}H_{2.37}O_{0.486}$ from the ultimate analysis of coal and dolochar by blending 80% low grade coal with 20% Dolochar. Thus, the dolochar fraction in the blended feedstock was kept as 0.2. For partial and complete combustion of the feedstock, the following reactions have been considered:

Partial oxidation:

$$C_{3.207}H_{2.37}O_{0.486}+0.889O_2+3.34N_2= 2.264CO+1.185H_2+3.34N_2+0.943CS \quad (7)$$

Complete oxidation:

$$C_{3.207}H_{2.37}O_{0.486}+3.557O_2+13.37N_2=3.207CO_2+1.185H_2O+13.37N_2 \quad (8)$$

For complete combustion 3.557 moles of oxygen is required where as for gasification 0.889 moles of oxygen is required. Therefore the equivalence ratio for the gasification of the blended feedstock was computed as 0.889 moles/3.557 moles=0.25. Similarly, the computed values of ER at dolochar fractions of 0.1, 0.3 and 0.4 in the blended coal-dolcochar mixture were determined to be 0.2, 0.3 and 0.35 respectively.

2) Computation of Adiabatic flame temperature

The maximum adiabatic flame temperature for a given fuel and oxidizer combination occurs with a stoichiometric mixture (correct proportions such that all fuel and all oxidizer are consumed). This is the maximum temperature that can be achieved for given reactants. Heat transfer, incomplete combustion, and dissociation all result in lower temperature. The amount of excess air can be tailored as part of the design to control the adiabatic flame temperature. Adiabatic flame temperature for the blended coal-dolochar mixture was calculated using gasification reactions such as partial oxidation, steam gasification, water gas reaction and shift reaction with thermodynamic relationship of conservation of enthalpies. The computed values of adiabatic flame temperatures at different moisture contents and with different dolochar fractions in the blended coal and dolochar are illustrated in Fig.7

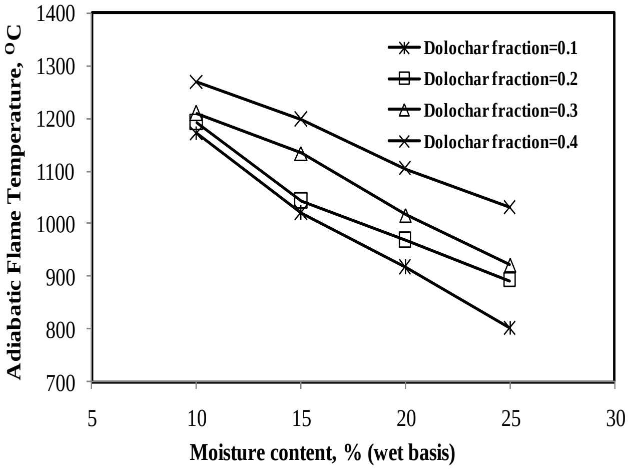


Fig. 7: Adiabatic flame temperature at different moisture contents

It is observed from Fig. 8 that, the adiabatic flame temperature decreased with increase in moisture content of the fuel. This may be due to large heat capacity of water molecules and a good amount of energy is required to evaporate them from the fuel. Further, the trend in decrease of adiabatic flame temperature with increased dolchar fractions in the blended feedstock was evident due to lesser amount of carbon available for partial oxidation.

3) Effect of steam to blended coal-dolochar ratio on gas composition

The entrainment of steam promotes the overall gasification process via the endothermic steam-carbon reactions to form hydrogen and carbon monoxide. Thus, steam to fuel ratio has much importance in steam gasification process. Fig.8 shows the result of product gas behaviour by increasing the steam/blended coal-dolochar ratio at a fixed dolochar fraction of 0.2 in the feedstock.

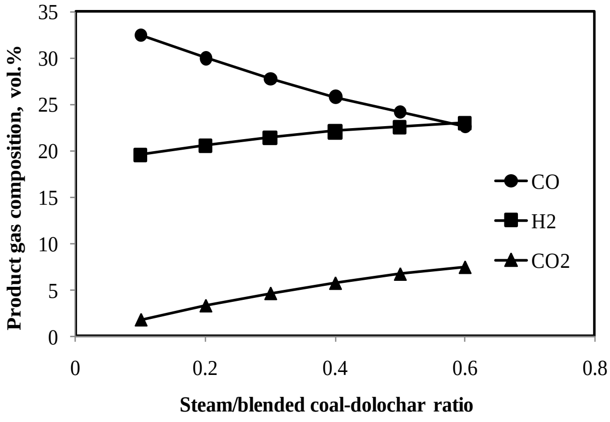


Fig. 8: Effect of steam/blended coal-dolochar ratio on product gas, Fuel feed rate: 30 kg/h; Dolochar fraction in the blended feedstock: 0.2

It is observed from the Fig.8 that by increasing steam to fuel ratio from 0.1 to 0.6, the hydrogen concentration increased and CO concentration decreased. The increase of H_2 and CO_2 content in the produced gas could have come as a result of steam reaction with CO ($H_2O + CO = H_2 + CO_2$). Therefore, steam injection in the gasifier favours the production of hydrogen and this effect is supported by the gasification chemistry [33].

4) Effect of Equivalence Ratio (ER) on Cold Gas Efficiency (CGE)

Cold gas efficiency (CGE) is defined as the percentage of the fuel heating value converted into the heating value of the producer gas and by using the following equation the CGE of the gasifier was computed.

$$CGE = \frac{[LHV]_g V_g}{[LHV]_f} x100\%$$

where $[LHV]_g$ and $[LHV]_f$ are denoted as the lower heating value of the producer gas and blended coal and dolochar mixture feedstock respectively in MJ/Nm^3. V_g denotes the specific dry gas volume, in Nm^3/kg fuel. The effect of ER on the CGE at different dolochar fractions in the blended feedstock of coal and dolochar is shown in Fig. 9.

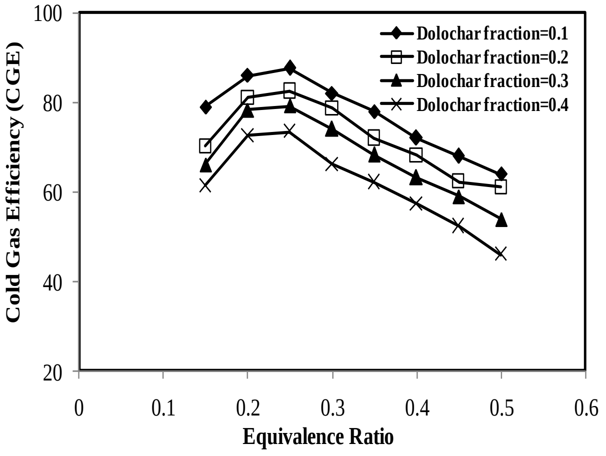


Fig. 9: Effect of Equivalence ratio on cold gas efficiency at different dolochar fractions in the blended feedstock.

It is seen from the Fig.9 that the CGE value decreased with increase in dolochar fraction in the blended coal-dolochar feedstock at a fixed equivalence ratio. This is quite obvious as the net carbon content in the blended fuel available for gasification decreases with increase in dolochar fractions. Further, at low ER, the CGE low due to low conversion of feedstock. As the amount of air supplied to the gasifier increases, the CGE increases due to the production of combustible gases in the product gas. But, when the ER is further increased beyond the practical limit (0.25-0.35) the CGE decreased due to re-combustion of product gas such as CO, H_2 and CH_4 and non-availability of enough heat to activate the endothermic gasification reactions [34]. This resulted in formation of more CO_2 with lesser production of combustible gas. Maximum CGE is shown to be in the vicinity of ER of around 0.25. The computed values of cold gas efficiencies for the blended coal-dolochar feedstock were found to be in the range of 73.45 -87.6% at a equivalence ratio of 0.25 with different dolochar fractions.

5) Turn down ratio (TR)

Turn down ratio is defined as follows:

$$TR = \frac{Dessigned\ thermal\ output}{Minimum\ thermal\ output} \qquad (9)$$

This ratio is generally varied between 3-20 and must be specified in terms of gas quality required. Too low a value generates a very dirty quality gas and too high a value yields low energy gas. TR is also important for load varying applications. Typically, TR for fixed bed gasifier is about five and for fluidized bed is three. Turn down ratio is primarily affected by the moisture content in the fuel. Reactor size and insulation also influence the turn down ratio. In our case, a TR value of 2.5 has been adopted considering a designed fuel feeding rate of 30 kg/hr. and moisture content of 15% on wet basis.

6) Conversion Rate

The conversion rate is also an important parameter for comparing gasifiers with different sizes and estimating the size requirement. It is defined either output energy per area or as energy per volume. The area refers to the cross-sectional area of the gasifier throat and volume refers to the volume of the reduction zone. The computed value of the conversion rate for the proposed gasification system was found to be in the range of 2590-3410 kW/m^2 or 1679-2211 kW/m^3 for all fractions of dolochar in the blended coal-dolochar feed stocks.

V. CONCLUSIONS

The cold model studies indicated that the pressure drop and ash separation efficiencies are very much affected by vortex finder length in the studied range of air inlet velocities (15-30 m/.sec.). To handle high ash content blended coal-dolochar feedstock for entrained flow gasification, the vortex finder length and air inlet velocity may be compromised to minimize pressure drop and maximize ash separation. The operating parameters and performance of the prototype entrained flow gasification system with a designed fuel (blended coal and dolochar) feeding rate of 30 kg/hr. were evaluated. The study indicated that the proposed gasifier can achieve cold gas efficiency in the range of 73.45-87.6% at a fixed equivalence ratio of 0.25 with different fractions of dolochar in the blended coal and dolcohar feed stock by steam reformation reactions.

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REFERENCES

[1] Dwari RK, Rao DS, Swar AK, Reddy PSR & Mishra BK (2012). Characterization of dolochar wastes generated by the sponge iron industry, *Int. J. of Minerals, Metallurgy, and Materials,* **Vol 19(11)**, pp. 992-1003

[2] Breault RW **(**2010). Gasification Processes Old and New: A Basic Review of the Major technologies, *Energies*, **Vol 3**, pp. 216-240.

[3] Fletcher DF, Haynes BS, Christo FC & Joseph SD (2000). CFD based combustion model of an entrained flow biomass gasifer, *Applied Mathematical Modeling,* **Vol 24**, pp.165-182.

[4] McKendry P (2002). Energy production from biomass (Part II); Conversion technologies, *Bioresource Technology*, **Vol 83**, pp. 47-54.

[5] Peng-Mei L, Jie C, Yan F, Tie-Jun W, Yong C & Jing-xu Z (2003). An experimental investigation of hydrogen production from biomass, *The Chinese J. of Process Engineering 3*, **Vol 5**, pp. 464-470.

[6] Dasappa S, Paul PJ, Mukunda HS, Rajan MKS, Sridhar G & Sridhar HV (2004). Biomass Gasification Technology-A root to Energy Need,. *Current Science-87*, **Vol 7**, pp. 908-916.

[7] Senapati PK & Behera S (2012). Experimental investigation on an entrained flow type biomass gasification system using coconut coir dust as powdery biomass feedstock, *Bioresource Technology*, **Vol 117**, pp. 99-106.

[8] Wang P & Massoudi M (2013). Slag Behaviour in Gasifiers. Part 1: Influence of Coal Properties and Gasification Conditions, *energies*, **Vol 6**, pp. 784-806.

[9] Shin YS, Choi SM & Ahn DH (2000). Pressurized drop tube furnace tests of global coal gasification characteristics. *Energy Research*, **Vol 24**, pp. 749-758.

[10] Wu XJ, Zhang ZX & Piao GL (2009). Gasification characteristics of coal with high ash fusion temperature in lab-scale down-flow gasifier, *Journal of Combustion Science and Technology*, **Vol 15(2)**, pp. 182-186.

[11] Wu XJ, Zhang ZX & Xu XY (2011). Experimental study on gasification and ash fusion characteristics of coal with high ash fusion temperatures, *Journal of Chinese Society of Power Engineering*, **Vol 31 (7)**, pp. 557-562.

[12] Lou T, Zhang ZX, Fan J-Jie, An H-quan, Zhou Z-hao & Yue P.-jie (2013). Experimental research on gasification character of pulverized coal at medium temperature, *Energy and Power Engineering*, **Vol 5**, pp. 315-318.

[13]Bain RL, Overend RP & and Craig KR (1998). Biomass-fired Power Generation. *Fuel Processing Technology*, **Vol 54**, pp. 1-16.

[14] Risberg M, Ohrman OGW, Gebart BR, Nilsson PT, Gudmundsson A & Sanati M (2014). Influence from fuel type on the performance of an air-blown cyclone gasifier, *Fuel*, **Vol 116**, pp. 751-759.

[15] Barnhart JS & Laurendeau NM (1982). Pulverized coal combustion and gasification in a cyclone reactor, 1. *Experiment, Ind. Eng. Chem. Process Des. Dev*., **Vol 21**, pp. 671-680.

[16] Fredriksson C (1999). Exploratory experimental and theoretical studies of cyclone gasification of wood powder, Doctoral Thesis, ISSN 1402-1544, Lulea University of Technology, Sweden.

[17] Gabra M, Nordin A, Ohnam M & Kjellsteron B (2001a). Alkali retention/separation during bagasse gasification; A comparison between a fludized bed and a cyclone gasifier, *Biomass and Bioenergy*, **Vol 21**, pp. 461-476.

[18] Syred C, Fick W & Griffiths AJ (2004). Cyclone gasifier and Cyclone combustor for the use of biomass derived gas in the operation of a small gas turbine in co-genration plant, *Fuel*,**Vol 83**, pp. 2381-2392.

[19] Thorn R (1998). Reengineering the Cyclone Separator, *Metal Finishing*, **Vol 96**, pp. 30-45.

[20] Chen CJ & Wang LFS (2001). Cost-benefit analysis of electro cyclone and cyclone, *Resources, Conservation and Recycling*, **Vol 31**, pp. 285-292.

[21] Maynard AD (2000). A simple model of axial flow cyclone performance under laminar flow conditions, *Journal of Aerosol Science*, **Vol 31**, pp. 151-167.

[22]Ma L, Ingham DB & Wen X (2000). Numerical modeling of the fluid and particle penetration through small sampling cyclones, *Journal of Aerosol Science***, Vol 31**, pp. 1097-1119.

[23] Solero G & Coghe A (2002). Experimental fluid dynamic characterization of a cyclone chamber, *Experimental Thermal and Fluid Science*, **Vol 27**, pp. 87-96.

[24] Gimbun J, Chuah TG, Choong TSY & Razi FI (2006). Evaluation on empirical models for the prediction of cyclone efficiency, *Journal- The institution of Engineers, Malaysia*, **Vol 67(3)**, pp. 54-58.

[25] Chen J & Shi M (2007). A universal model to calculate cyclone pressure drop, *Powder Technology*, **Vol 171**, pp. 184-191.

[26] Hemdan H (2007). On the potential of large eddy simulation to simulate cyclone separator. Technischen Universitat Chemnitz, Available at: http:/ www.qucosa.de/ fileadmin/data/qucosa/ documents /5333/data/diss.pdf, 2007.

[27] Marinuc M & Rus F (2011).The effect of particle size and input velocity on cyclone separation process, Bulletin of the Transilvania University of Brasov, Series II: Forestry, Wood Industry, *Agricultural Food Engineering*, **Vol 4(53)**, no. 2, pp. 117-122.

[28] Valverde MR, Coury JR & Goncalve JA (2011). Modeling the effect of the vortex finder height on pressure drop in the cyclone using computational fluid dynamics, *Asociacion Argentina de Mecanica Computacional*, **Vol xxx**, pp. 525-533.

[29] Hoffmann AC & Stein LE (2002). *Gas Cyclones and Swirl Tubes*; 2nd ed., Springer.

[30] Chuah LA, Gimbun J, Thomas SY & Fakhru'l-Razi A (2009). A CFD analysis on the effect of vortex finder and cylindrical length on cyclone hydrodynamics, *Journal-The Institution of Engineers*, Malaysia, **Vol 71(2)**, pp. 51-58

[31] Ficici F, Ari V & Kapsiz M (2010). The effect of vortex finder on the pressure drop in cyclone separators, *International Journal of the Physical Sciences*, **Vol 5(6)**, pp. 804-813.

[32] Elsayed K & Lacor C (2010). The effect of vortex finder diameter on cyclone separator performance and flow field, V European Conference on Computational Fluid Dynamics, ECCOMAS CFD, J.C.F. Pereira and A. Sequeira (Eds.), Lisbon.

[33] Crnomarkovic N, Repic B, Mladenovic R, Neskovic O & Veljkovic M (2007). Experimental Investigation of Role of Steam in Entrained Flow Coal Gasification, *Fuel*, **Vol 86**, pp. 194-202.

[34] Lee H, Choi S & Perk M (2011). A simple process modeling for a dry feeding entrained bed coal gasifier, *J. Power and Energy*, **Vol 225(10)**, Part A pp.74-84.