The Combustion Characteristics of Biomass Syngas from High Temperature Air, Entrained Flow and Circulating Fluidized Bed Gasifiers

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Abstract

The study has been performed to determine fundamental combustion characteristics of syngas. Three technologies were selected to produce the syngas; High Temperature Agent Gasifier (HTAG), Entrained Flow Gasifier (EFG) and Circulating Fluidized Bed Gasifier (CFBG). Although the material used for production of syngas was the same, wood biomass, the compositions of syngas obtained were different. The adiabatic flame temperatures were determined at different air to fuel ratio. The maximum adiabatic temperature for HTAG, EFG and CFBG syngas at stoichiometric condition were 1846 K, 2250 K and 2234 K respectively. It has been observed that during combustion of CFBG syngas produces more NOx than EFG. The high NOx in CFBG is caused by the high methane content, which increases the adiabatic flame temperature to 2200 K at stoicheometric condition. The lowest NOx emission was observed in HTAG syngas. The adiabatic temperature increased linearly with the preheating temperature, whilst oxygen enrichment increased the adiabatic temperature. It has been concluded that syngas produced from EFG and CFBG are better candidate as gaseous fuel in combustion chamber than HTAG syngas.

Keywords: *Syngas, Adiabatic Temperature, High Temperature Agent Gasifier, Circulating Fluidized Bed Gasifier, Entrained Flow Gasifier, combustion.*

1.0 Introduction

Biomass consists of variable moisture content, fibrous structure (lignocellulose) and carbohydrate or sugar. The major part of biomass is lignocellulose and unlike carbohydrate material type which belongs to food chain, lignocellulose in nature cannot be digested [1]. Since it is not part of the food chain, there has been a growing interest for energy production as it does not threaten the world's food supply.

The lignocellulose consists of cellulose, hemicelluloses and lignin. The composition of these elements in lignocellulose by percentage weight varies in different biomass species. For most lignocellulosic biomass material, the composition of cellulose is in the range of 40 – 50 wt%, whereas hemicelluloses accounts between 25 and 35 wt% and lignin is around 16 – 33 wt% [2]. Biomass possess calorific value lower than that of coal, due to high oxygen content in biomass. The oxygen content in the biomass is about 40%, while that of coal is between 7 to 17% [1].

The conversion of biomass into gaseous fuel (syngas) that can be used in combustion chambers (furnaces) can be achieved through gasification. During this process biomass is partially oxidized at high temperature typically in the range of 800 – 900 ℃ [3]. There are three types of gasifiers; these are fixed bed, fluidized bed and entrained flow gasifiers. This paper discusses the combustion characteristics of biomass syngas from fixed bed, fluidized bed and entrained flow gasifiers, which are represented by High Temperature Agent Gasifier (HTAG), Circulating Fluidized Bed Gasifier (CFBG) and Entrained flow Gasifier (EFG) respectively.

The gasification agent can be air, oxygen, steam or mixture of them, while the available technologies are using air or steam. Figure 1 represents biomass conversion process. The three corners of the triangle represent pure carbon, oxygen and hydrogen. The side opposite to a corner with a pure component represents zero concentration of that component. A biomass fuel is closer to the hydrogen and oxygen corners compared to coal. This means that biomass contains more hydrogen and more oxygen than coal contains. Coal resides further toward the carbon corner and lies far to the oxygen corner in the ternary diagram, suggesting that it is very low in oxygen and much richer in carbon. The ternary diagram can be used to describe the conversion process. Carbonization or slow pyrolyis moves the products toward carbon through the formation of solid char, while fast pyrolysis moves it toward hydrogen and away from oxygen, which implies higher liquid products (hydrocarbons). Oxygen gasification moves the gas toward the oxygen corner, while steam gasification takes the process away from the carbon corner [4].

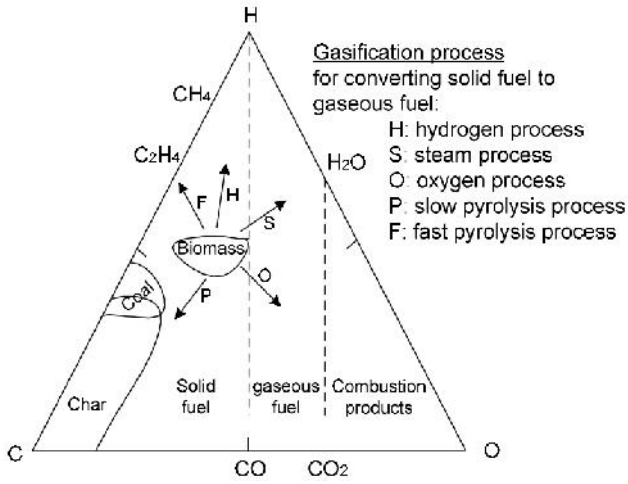

Figure 1: C-H-O ternary diagram of gasification process [4].

The most common gasification technologies are Circulating Fluidized Bed Gasifier (CFBG) and Entrained Flow Gasifier (EFG), the syngas from these technogies is going to be compaired with the sygan from High Temperature Agent Gasifier (HTAG). In the CFBG, the biomass is added directly to the bed material and is heated

under the oxidation medium (generally air or oxygen, steam is often also included in the mixture). The velocity is sufficient enough to suspend the bed particles throughout the entire reactor. The sand and char which leave the reactor are separated from the vapors by a cyclone and are returned back to the bed. The syngas passes through the cyclone and further on in the system as shown schematically in Figure 2. The CFB is generally operated at temperatures between 1073 K (800℃) and 1273 K (1000 ℃), yielding a gas containing low concentration of tar.

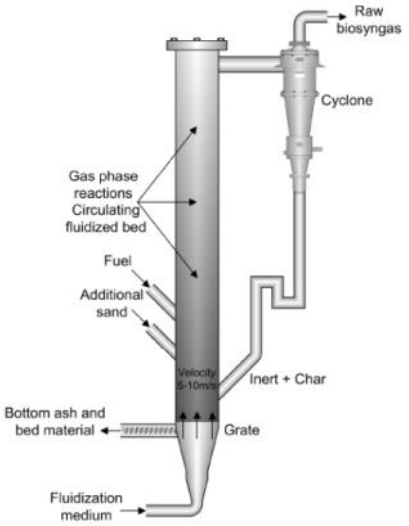

Figure 2: Circulating fluidized bed gasifier

The entrained flow gasifier is shown schematically in Figure 3. It is operated at higher temperature more than 1473 K (1200℃) [5] and residence time in the range of 0.6-2 s [6], which is shorter than other type of gasifiers. Very fine particles of biomass less than 1 mm are required since they have to react at a short residence time. The reaction temperature is above 1473 K at moderate pressure between 20 and 50 bar [5]. The main products of the entrained flow gasifier are hydrogen and carbon monoxide, other products are produced in small amount, and these are carbon dioxide and methane.

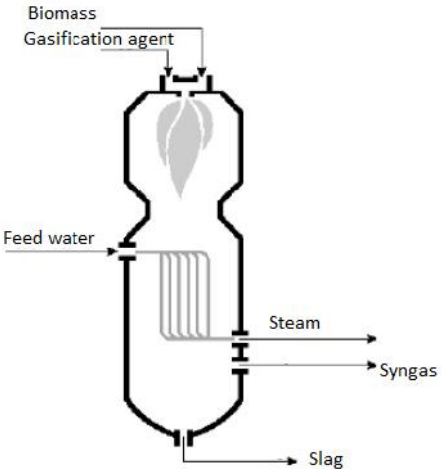

Figure 3: Entrained flow gasifier

Figure 4 shows the principle of the HTAG-concept, by which biomass is fed at the top and the high temperature agent is supplied at the bottom and permeates through the biomass. The biomass lies on a grate through which high temperature agent is introduced.

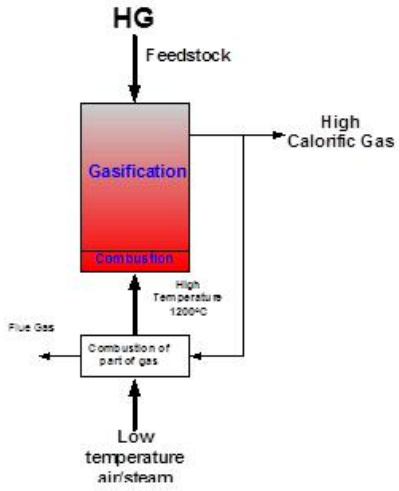

Figure 4: HTAG operation

The bed is divided into four zones due to processes that take place. The first zone is oxidation zone, where combustion takes place at the bottom of the bed, the carbon dioxide and water vapor are formed at this zone and the temperature at this zone is around 1273 K (1000℃). The second zone is reduction zone, where the hot gases from the combustion are

reduced to hydrogen and carbon monoxide at this zone the temperature decreases to 1023 K (750℃). Further up is the third zone, where the reducing gases pyrolyse the downward flowing biomass and produce tars and other products of incomplete gasification. The fourth zone is called drying zone, where gases dries the incoming biomass and then leaves the reactor. The gas leaves the reactor at about 773 K (500℃) and part of the produced gas is used in a regenerative pre-heater. The regenerative pre heater is used to pre heat the temperature agent to about 1273 K (1000 ℃). Yang et al 2006 [7] analyzed the performance of HTAG and observed that increasing of feed gas temperature provides high gasification rate and high molar fraction of hydrogen, carbon monoxide and hydrocarbons, which increases the calorific values of the product gas [7].

1.1 Syngas Production and Combustion Technologies

The chemical reactions resulting in syngas takes place in a gasification process, when steam is used as gasification agent are given in Equations 1-4.

$$C + H_2O \leftrightarrow CO + H_2 \quad (1)$$

$$C + CO_2 \leftrightarrow 2CO \quad (2)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (3)$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (4)$$

The evolving syngas can have low heating value of 4 to 6 MJ/Nm^3 when air is the gasification agent. A medium calorific value gaseous fuel with a heating value of 9-13 MJ/Nm^3 is predominant where the gasification agent is oxygen and /or steam. The syngas is suitable for combustion processes, but low calorific syngas cannot attain high temperatures required in some combustion processes. Franscisco *et al.,* 2009 [8] studied the combustion characteristics of gaseous fuel with low calorific value (syngas of different composition) in a porous burner at an equivalent ratio of 0.5. The results revealed that the radiation efficiency of the syngas was between 20 and 30%, which is smaller than that of pure methane at 35%. The flame structure of syngas performed a larger flame length than that of pure methane [8]. Other pioneers in the development of low carlorific gaseous fuels are the Bio-Pro. Bio-Pro have developed FLOX and COSTAIR burners, which have been tested in turbines [9].

2.0 Method and Material

The combustion of syngas was done at different conditions, in order to determine the effect of the following parameters:

- Air to fuel ratio (λ)
- Oxygen concentration
- Pre-heating temperature

During the combustion process the adiabatic temperature, the enthalpy of reactant and the enthalpy of the product were determined. The adiabatic temperature and composition at constant pressure was used in this study. In this method the temperature of the products was adjusted until the equilibrium composition had an enthalpy which was the same as that of the reactants. Under adiabatic combustion the enthalpy of reactants for all combustion reactions is equal to enthalpy of products for all combustion products as shown in Equation 5 [10].

$$H_{reac}(T_i, P) = H_{prod}(T_{ad}, P) \quad (5)$$

Three different compositions of syngas were used during the combustion simulation; syngas from Entrained Flow Gasifier (EFG), High Temperature Air Gasification (HTAG) syngas and Circulating Fluidized Bed Gasifier (CFBG) syngas, the detail composition of the gases is given in the proceeding section. The

experiments were done at different conditions; fuel rich, fuel lean, stoichiometric condition and at different oxygen concentrations.

The combustion process is governed by the chemical reactions in Equation 6 to 8.

$$2H_2 + (O_2 + 3.76N_2) \rightarrow 2H_2O + 3.76N_2 \quad (6)$$

$$2CO + (O_2 + 3.76N_2) \rightarrow 2CO_2 + 3.76N_2 \quad (7)$$

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 2(3.76N_2) \quad (8)$$

REGEMAT 350 FLOX burner shown schematically in Figure 7 was used to study the combustion characteristics of syngas. It is a regenerative type that heats combustion air to 950^{o}C with a cycle time of 10 seconds. During operation, 80% of flue gas is extracted through the regenerator. In order to study the upper extreme of energy utilization efficiency, the regenerative burner was also operated with oxygen enriched and preheated air. Up to 29% of oxygen enrichment was tested in this work. This case was named as OE, (Oxygen Enrichment).

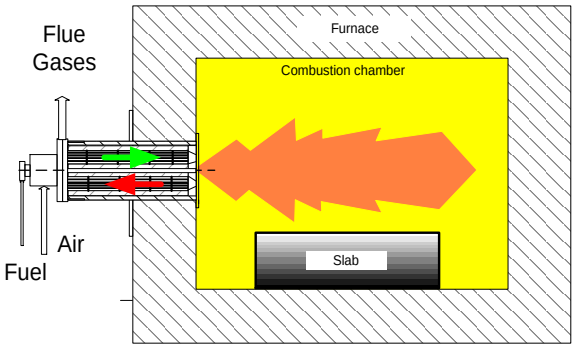

Figure 5 Scheme of flame in REGEMAT 350 FLOX

3.0 Results and Discussion

The composition of syngas produced from EFG, HTAG and CFBG technologies are shown in Table 1. The sygas from EFG has high hydrogen content of 27.2%, CO of 32.1% and CH_4 of 15.2%, syngas from EFG have higher energy content (calorific value) than syngas from CFBG and HTAG. The lower energy content of syngas from HTAG is due to high content of nitrogen.

Table 1: The properties of syngas from EFG, HTAG and CFBG technologies

Component	EFG	HTAG	CFBG
Hydrogen (% wt)	27.2	13.7	14.9
Carbon monoxide (% wt)	32.1	13.1	35.6
Carbon dioxide (% wt)	14.0	8.2	14.6
Methane (% wt)	15.6	10.0	24.9
Nitrogen (% wt)	11.1	55.0	10.0
Low Heating Value (MJ/Nm^3)	9.5	5.6	8.2

3.1 Combustion of Syngas at Different Air to Fuel Ratio (^{a})

The syngas combustion at different air to fuel ratio (λ) enable to analyze the adiabatic temperature, usually the maximum adiabatic temperature of a fuel is obtained, when λ equals to 1, which means at stoichiometric condition. The excess air increases the mass of flue gas relative to mass of fuel, which implies to corresponding reduction in flame temperature. Also when air is deficient (sub-stoichiometric) the temperature is reduced, because the effective calorific value of the fuel is reduced by the amount equivalent to the calorific value of carbon monoxide which is present in the flue gas. Due to that reasons the high adiabatic temperature is obtained under stoichiometric condition.

Figure 6, Figure 7 and Figure 8 show the variation of adiabatic temperature with λ of EFG, HTAG and CFBG syngas, while Figure 9 shows the comparison of the syngas combustion.

The maximum adiabatic temperatures were 2250 K, 1846 K and 2234 K of the respective syngas, also the adiabatic temperature was above 1700 K when λ was between 0.5 to 1.2 for EFG and CFBG syngas, while for HTAG syngas the temperature above 1700 K was obtained when λ is between 0.9 and 1.1. Figure 9 shows the comparison of adiabatic temperatures of the syngas combustion from the three technologies.

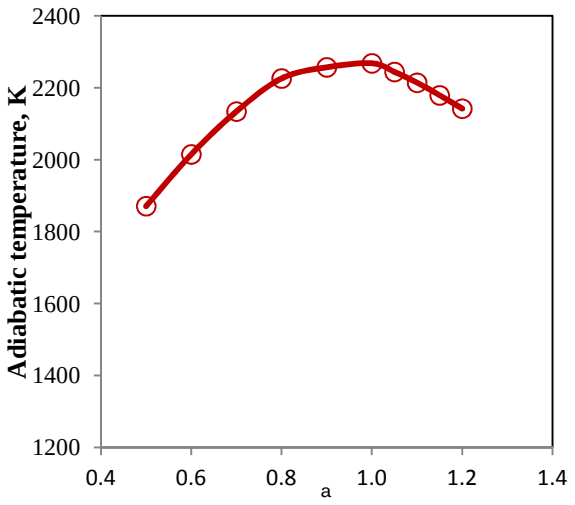

Figure 6: Adiabatic temperature of EFG syngas at different [a]

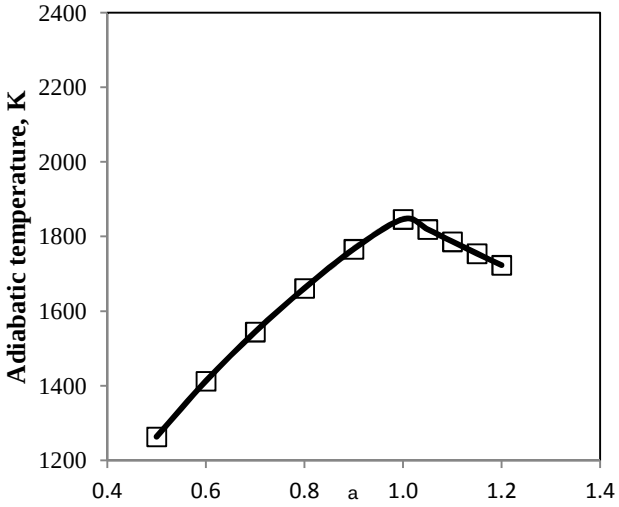

Figure 7: Adiabatic temperature of HTAG syngas at different [a]

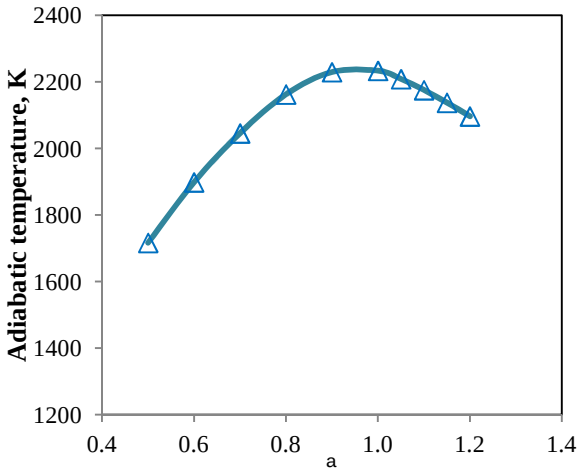

Figure 8: Adiabatic temperature of CFBG syngas at different [a]

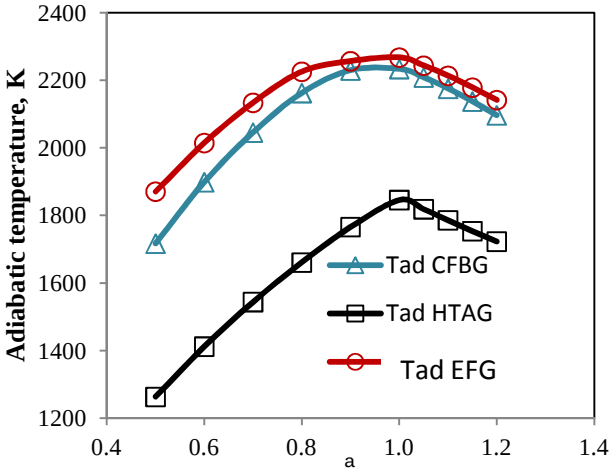

Figure 9: Comparison of adiabatic temperature of syngas from EFG, HTAG and CFBG technology

3.2 Effect of Oxygen Enrichment during Syngas Combustion

High adiabatic temperature was obtained by oxygen enrichment. During this process the fuel is easily oxidized since the amount of nitrogen is small, causes the high adiabatic temperature and reduces the mass of the flue gas. Figure 10 shows the oxygen enrichment of the syngas from HTAG, EFG and CFBG.

The CFBG and EFG curve overlapped each other; this means they almost produced the same adiabatic temperature. It has been observed that adiabatic temperature above 2200 K was obtained during combustion of EFG and CFBG

syngas under oxygen enrichment and HTAG has adiabatic temperature below 2500 K. Rapid increase of adiabatic temperature was observed between 21% and 40% oxygen enrichment, a slow increment of the adiabatic temperature was observed above 40% oxygen enrichment.

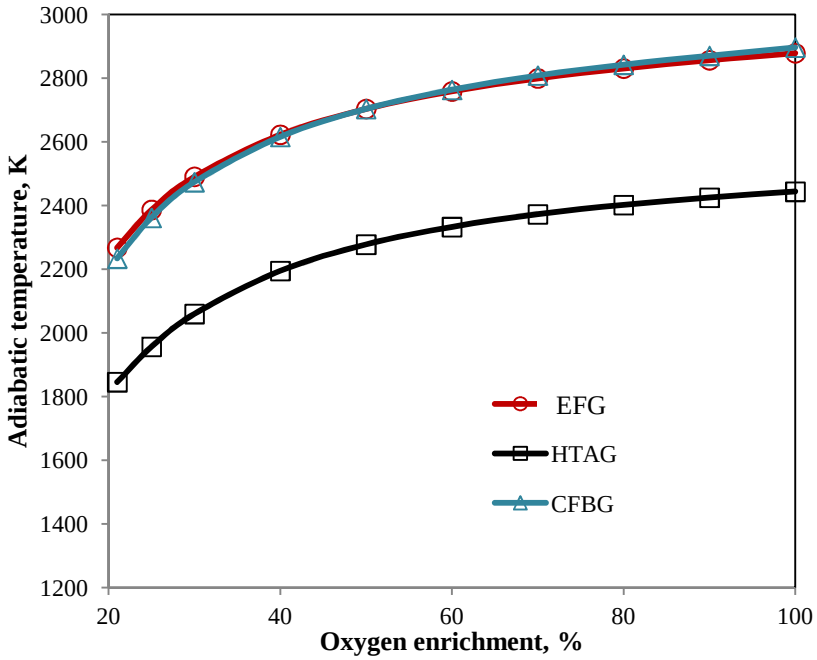

Figure 10: Adiabatic temperature vs oxygen enrichment during syngas combustion

3.3 Effect of Pre-Heating Temperature

The preheating process increases the adiabatic temperature linearly, as shown in Figure 11. The EFG syngas has higher adiabatic temperature than other syngas. HTAG syngas has low adiabatic temperature because it contains nitrogen; the nitrogen is an inert gas.

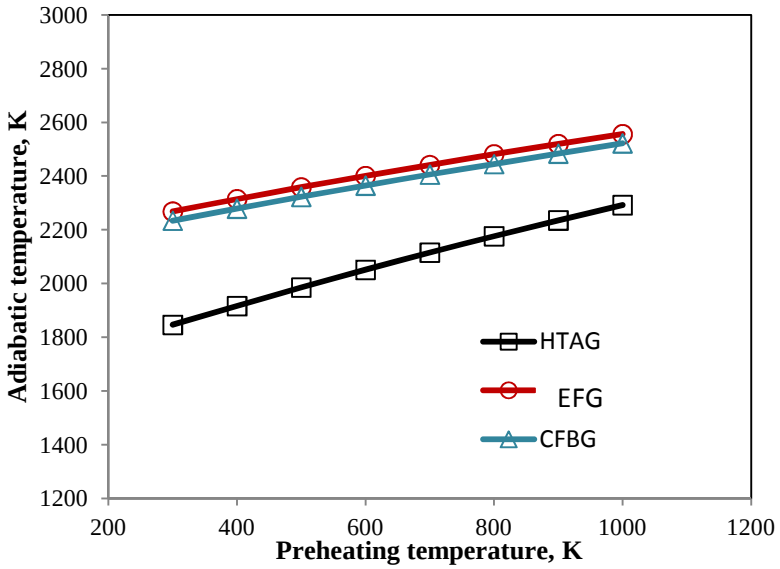

Figure 11: Variation of adiabatic temperature at different preheating temperature

Although oxygen enrichment increases the adiabatic temperature, the preheating temperature seemed to increases the adiabatic temperature linearly, by combining these two process high adiabatic temperature can be obtained as shown in Figure 12 to Figure 15. If both oxygen enrichment and preheating temperature were used, they produced high adiabatic temperature.

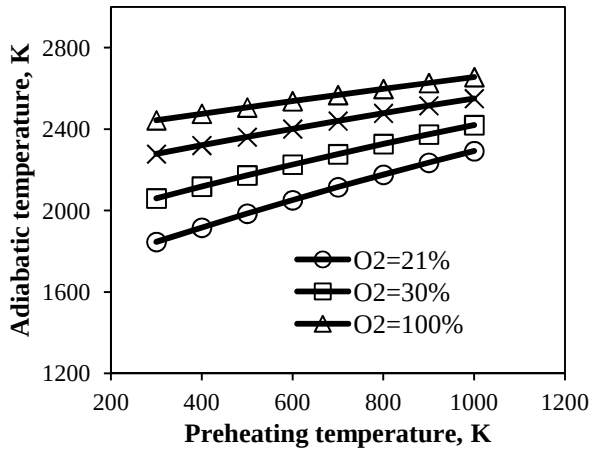

Figure 12: Oxygen enrichment during HTAG syngas combustion

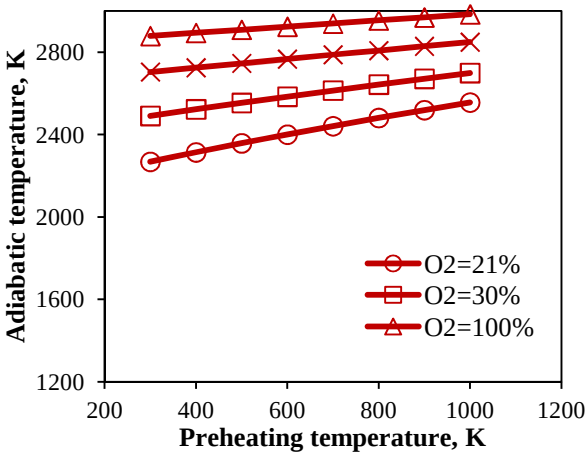

Figure 13: Oxygen enrichment during EFG syngas combustion

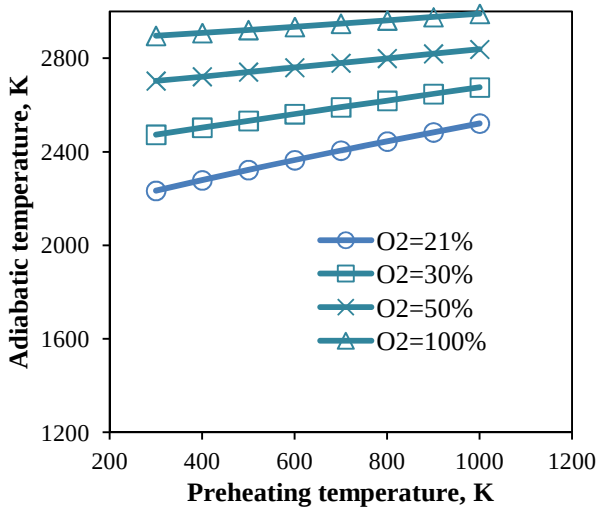

Figure 14: Oxygen enrichment during CFBG syngas combustion

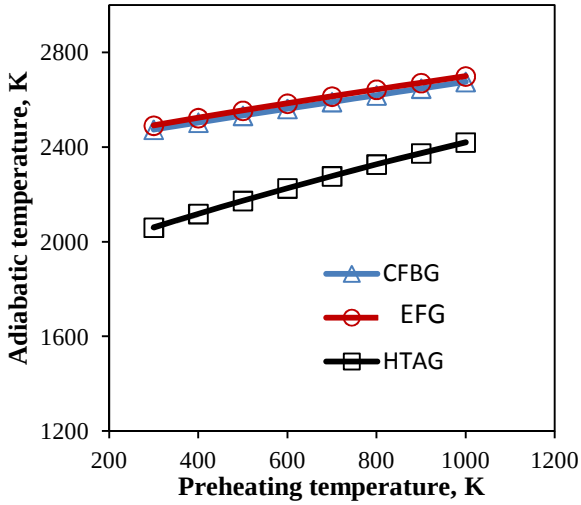

Figure 15: 30% Oxygen enrichment for EFG, HTAG and CFBG syngas combustion

The increase of the adiabatic temperature during oxygen enrichment is due to increase of enthalpy change between the reactant and product as shown in Figure 16 and Figure 17. The energy released is obtained by taking the difference between enthalpy of product and the enthalpy of reactant at same temperature, so the area between the curves of enthalpies of reactants and products is the energy released during combustion process, the area covered during oxygen enrichment is larger than that during stoichiometric condition as shown in the combined diagram of Figure 18.

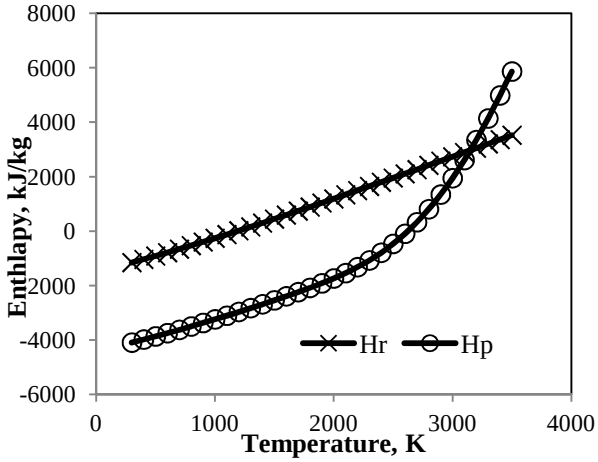

Figure 16: Syngas combustion under stoichiometric condition

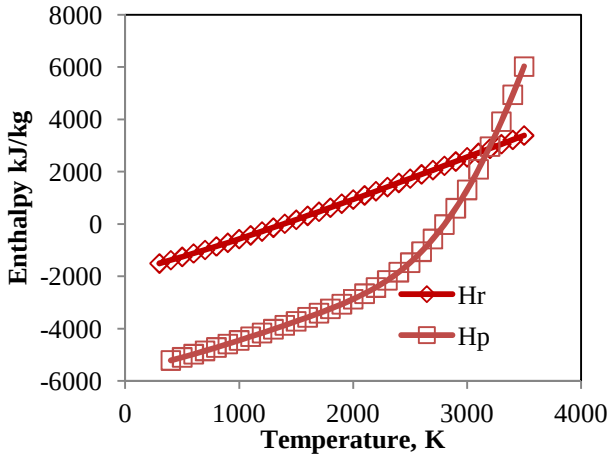

Figure 17: Enthalpy change under Oxygen enrichment 30%

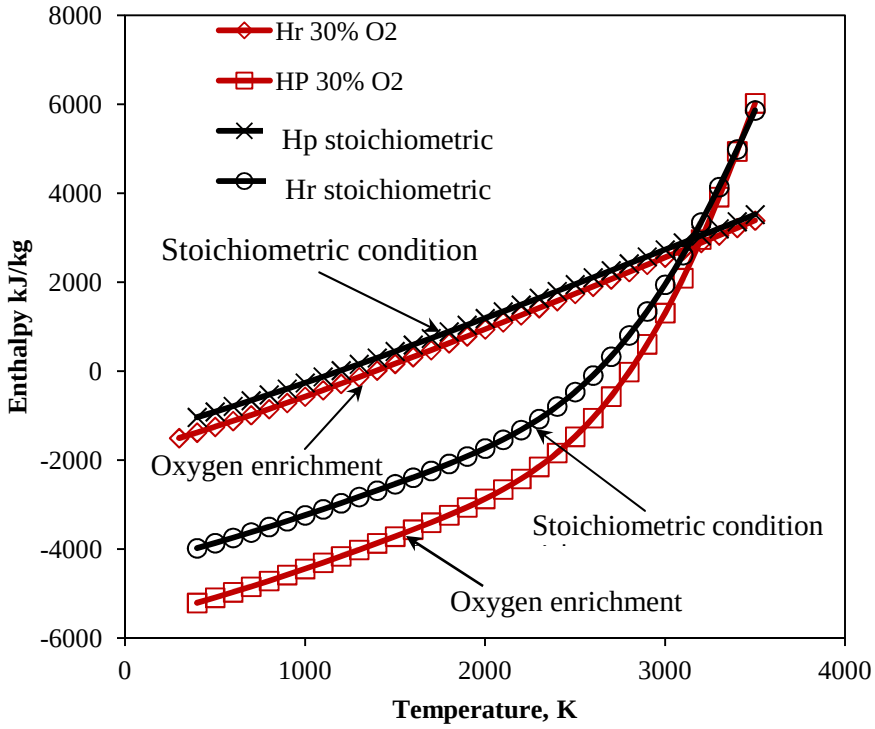

Figure 18: Combined enthalpy changes during stoichiometric and oxygen enrichment condition

3.4 NOx Formation during Syngas Combustion

The NOx Figure 19, that was produced during the syngas combustion is thermal NOx produced due to high temperature. Thermal NOx generally takes place above 1500 K [11] and those fuels that have high adiabatic temperature produce high thermal NOx. In Figure 20, the EFG and CFBG syngas produce more NOx than HTAG syngas. It has also been observed that during combustion of CFBG syngas produces more NOx than EFG, the high NOx in CFBG is caused by the high methane content, because the adiabatic flame temperature of methane (CH_4) is high at 2223 K, thus causing high thermal NOx [12].

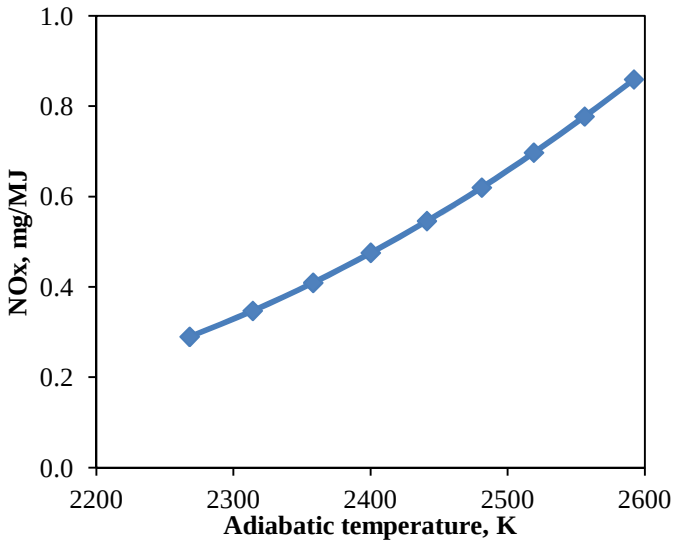

Figure 19: Thermal NOx produced at different adiabatic temperature

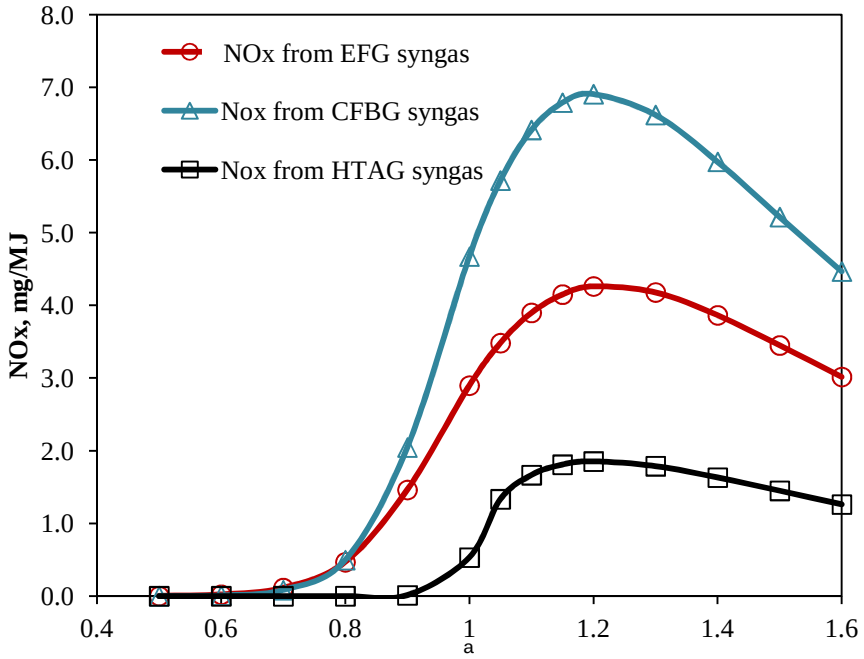

Figure 20: Variation of NOx formation with air to fuel ratio

Figure 20 shows that in fuel rich less NOx is formed, this is because all the oxygen is consumed by fuel, while in fuel lean there is excess of oxygen, therefore some part of it is used to oxidize nitrogen to form NOx. The thermal NOx can be reduced by one of the following technologies; flameless, HiTAC or air staging combustion.

4.0 Conclusions

The high adiabatic temperature is obtained, when air to fuel ratio is equal to one (stoichiometric condition), increasing and reduction of air reduces the flame temperature. Syngas from EFG and CFBG produce high adiabatic temperature between 2200 and 2900 K, while the syngas from HTAG has adiabatic temperature below 2500 K during oxygen enrichment combustion. The preheating temperature of sygan is linearly related to the adiabatic temperature, but also the syngas from CFBG and EFBG have higher adiabatic temperature than syngas from HTAG. The lower adiabatic temperature of syngas from HTAG is due to high nitrogen content. In addition to that the energy release was high during oxygen enrichment, which causes higher adiabatic temperature than stoichiometric condition. Therefore syngas from EFG and CFBG are more suitable to be used as gas fuel in combustion chambers than syngas from HTAG. On the other hand high thermal NOx was observed during combustion of EFG and CFBG syngas, but the NOx of CFBG syngas is higher than EFBG due to high content of methane.

5.0 Acknowledgement

The authors wish to thank the staff and students of University of Dar es Salaam toward this research.

6.0 Nomenclature

CFBG	Circulating Fluidized Bed Gasifier
EFG	Entrained Flow Gasifier
HiTAC	High Temperature Air Combustion
HTAG	High Temperature Agent Gasifier
OE	Oxygen Enrichment
H_{reac}	Enthalpy of reactant
H_{prod}	Enthalpy of products
T_{ad}	Adiabatic Temperature
T_i	Temperature of reactant
P	Pressure
λ	Air to fuel ratio

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