Feasibility of High Yield Biomass Fuel for Regenerative Gas Turbine Power Plants in Sudan

Aya Mohammed Hassan Mahjob

Siddharth Pannir

Momin Elhadi Abdalla

Feasibility of High Yield Biomass Fuel for Regenerative Gas Turbine Power Plants in Sudan

Mahjob, Aya Mohammed Hassan[1]; Pannir, Siddharth[2];Abdalla, Momin Elhadi[3*]

Organization(s): 1,3: University of Khartoum, Chemical Engineering Department, Khartoum, Sudan
2: GenH, Somerville, Massachusetts, United States

[1]University of Khartoum, Chemical Engineering Department, Khartoum, Sudan, Aia.moh.hass@gmail.com
[2]GenH Inc, Somerville, Massachusetts, United States,Siddharth.pannir@icloud.com
[3*]University of Khartoum, Chemical Engineering Department, Khartoum, Sudan, mominhadi@yahoo.com, mominhadi@uofk.edu

ABSTRACT

Simulation models were used to characterize the gasification process of a Nilotica Wood Chips Biomass in Sudan. The lower heating value (LHV) of wood chips derived syngas reaches the maximum heating value of 35 MJ/kg for ER=25% at biomass moisture content of 35%, gasification pressure of 30bar, and gasification temperature of 1000°C.An optimum equivalence ratio of ER=25%, achieved a higher regenerative power of 98 MW at a higher regenerator effectiveness of 95%, and a produced syngas rate of 5 kg/s. With air as a gasifier agent, the increase in gasification pressure enhanced the reaction rate and the product's conversion of the gasification reaction, which yielded higher concentrations of the H_2 and CH_4 at the syngas product. As the initial moisture content increases, the results predict a decrease in the gasification temperature and the lower heating value of the syngas., due to change of the syngas composition. The model observed that, the Biomass gasifier's flow rate is higher at lower gasification temperature. Additionally, the biomass flow rate is higher at higher gasifier pressure. At higher gasification pressure of 80 bar, the flow rate of the wood chips reached the maximum value of 11.75 kg/s, for the optimum ER of 25%,with a moisture content of 40% and a gasifier temperature of 1600°C.As the moisture content increases the results predict a decrease in the regenerator gas turbine power due the decrease of the syngas heat value. The results show that, higher the efficiency of the gasifier, the lower the quantity of the biomass flow rate. The predicted data depicted massive decrease in the gasifier efficiency upon increasing the biomass moisture content. For wood chips, the H_2 and CO mole fractions reached the maximum values at the lowest values of the ER, while at the optimum ER the H_2 mole fraction depicted a value of 1.74%,0.7% of CO, and 8.14% of CH_4, for a LHV of 31400 kJ/kg of syngas. The highest value of the syngas composition is depicted by N_2 (53.73%), since air is the gasifier medium.

1. INTRODUCTION

Agriculture is considered the driving force for income and livelihood in Sudan as this sector occupies between 60% and 80% of the population (Farida, 2014), and is also considered as the engine of growth for other economic sectors such as trade, industry and transport (Fig.1). Biomass is considered as a renewable energy source in Sudan because the carbon in biomass is regarded as part of the natural carbon cycle widely produced on land. Biomass is a biological material that consists of forest, agricultural, and paper waste (Prasad et al., 2007, Zabaniotou, et al.,2007). Biomass fuels, such as wood, cow dung, and agricultural residues, are collected mainly from the local environment and have become a traded commodity. Biomass (such as wood, agricultural residue, and municipal waste) with its renewability and worldwide availability is expected to play a key role in future energy scenarios.

Figure 1: Wood Biomass in Sudan (Farida, 2014).

In practice, the gasification of the biomass particle first occurs through a particle drying step, followed by a pyrolytic step (Li et al.,2008, Czernik et al., 2010) which leads to devolatilization and shrinking of the original particle (Hart et al.,2013). With the last step being char gasification, the pyrolysis step occurs gradually from the surface to the center of a biomass particle. In a biomass gasifier, biomass is burned in a limited amount of air. The amount of air supplied is less than the amount of air required for complete burning. This converts the biomass (which consists of carbon, hydrogen, oxygen, etc.) into an inflammable mixture of gases known as producer gas syngas/wood gas (Kollman et al., 1968). The producer gas consists of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4), along with carbon dioxide (CO_2) and nitrogen (N_2).The nitrogen is not combustible; however, it does occupy volume and dilutes the syngas as it enters and burns in an engine. Classification of biomass gasifiers based on the density factor (ratio of dense biomass phase to total reactor volume) is a simple and effective method of classification. In this way the gasifiers can be classified into (a) dense phase gasifiers and (b) lean phase gasifiers. In lean phase gasifiers, for example, apart from the fluidized bed, the biomass occupies very little reactor volume, that is, 0.05−0.2 m^3. Most of the gasifiers employed for decentralized applications in developing countries are dense phase reactors, mostly fixed bed reactors; they have typical density factor of 0.3−0.08 m^3(TERI, Report 2006).The choice of one type of gasifiers over another is dictated by fuel, its final available form, size, moisture content, and ash content. Fixed bed gasifiers are more suitable for small-scale power generation and industrial heating applications (Kouhikamali, et al.,2015). Four types of reactors exist: updraft or countercurrent gasifiers, downdraft or cocurrent gasifiers, cross-draft gasifiers, and fluidized-bed gasifiers. In general, gasification technology is selected on the basis of available fuel quality, capacity range, and gas quality conditions. Downdraft gasifier is suitable for 1kW to 1MW range thermal capacity, whereas updraft is 1.1 MW to 12 MW, fluidized-bed gasifier is 1MW to 50 MW, and cross-draft gasifiers are 10 MW to 200 MW range thermal capacity (Dayton, 2002). A review (Knoef, 2000) of gasifier manufacturers in Europe, USA and Canada concluded that 75% of the designs were downdraft type, 20% of the designs were fluidized bed systems, 2.5% of the designs were updraft type and 2.5% were of various other designs.

On the other hand, the use of gas turbine units to generate electricity has become an attractive endeavor due to the comparatively low initial capital cost as well as its stability of supply under varying circumstances. Another outstanding feature of this equipment is its capability of quick starting using a wide variety of fuels (Monetti et al.,2011) from natural gas, syngas to residual oil or powdered coal (Nag,2008, Sheng L.et al.,2013, ASME, 1992, ISO, 1983).Another feature of the GT equipment is the availability of better materials for construction and the use of adequate blade cooling systems (Sanjay et al.,2014, Bakar RA et al.,2011) to counter the inlet gas temperature which can often exceed 1200°C (Nag,2008,E.J.Ziurys et al.,1959, V. Gansesan,1992, C.F. Taylor,1985). As a result of this, the overall thermal efficiency of a GT plant can be about 35%, which is almost the same as that of a conventional steam power plant. Moreover, the GT normally characterized with its low weight per unit power, was exclusively used to drive aviation systems of all kinds on aircrafts. It is also being increasingly used in land vehicles like buses and trucks and to drive locomotives and marine ships. In oil and gas industries, the GT is widely employed to drive auxiliaries like compressors, blowers, and pumps (Nag,2008, Meherwan, 2002).Researchers have conducted research different methods to increase thermal efficiency of regenerative GT cycles (Perry et al.,1997, Sheng L.et al.,2013), one of which is the reheating process used to increase thermal efficiency of gas and steam turbine cycles. Similarly, regeneration is utilized to increase thermal efficiencies of both the simple GT and the steam turbine cycles. Another important procedure to increase the thermal efficiency of the power plant cycle is the combined cycle, which consists of a GT and a steam turbine cycles (Al-Sayed,2008, Nag,2008, A.McKonkey et al.,1993).

This work aims to reinforce the understanding of a regenerative RGT as a thermal process utilizing the integration of the biomass gasification unit at the combustor, as well as applying similar design parameters of Khartoum North Station (GT,187 MW) (Mast M et al.,2002) in Sudan. The study pushes for establishing a qualified operational and conceptual design procedure for the Integrated Biomass Gasification for Regenerative Gas Turbine Unit "IBGRGT". The work also presents a preliminary strategy to identify the performance and evaluation criterion of the Gasification of Biomass Process utilizing the effect of various operating conditions.

2. MODELING OF COMPONENTS

A schematic of a regenerative gas turbine and Biomass Integrated Unit (BIGT) with the syngas producer is shown in Fig.3. The system consists of a hot air driven gas turbine, compressor, combustor, and regenerator beside gasifier unit. The gasifier in the system produces syngas using gasification of dry biomass. The biomass material will be fed to the gasifier at ambient conditions as described briefly on the Fig.3. Since air is the gasification medium, gasification occurs in the presence of compressed air and produces the syngas, which enters the combustion chamber. A thermodynamic equilibrium method based on a stoichiometric approach according to the method of Jarungthammachote and Dutta (Dutta et al., 2007) , was used for modeling the gasifier. This model is used to predict the syngas composition at the gasifier working temperature and pressure. The gasification global reaction can be written as (Kouhikamali, et al.,2015 , Littlewood,1977 , Perry et al.,1997):

$$CH_xO_yN_z + wH_2O + m(O_2 + 3.76N_2) \rightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + x_6N_2 \quad (1)$$

Since oxidation reactions in the gasifier almost achieve an equilibrium state, by considering their equilibrium constant expression the secondary gas phase reactions can be derived. These reactions are:

$$C + 2H_2 \rightarrow CH_4 \quad (2)$$

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

The above reactions are known as methanation reaction and gas-water shift reaction, which the equilibrium constants for them are given as follows:

$$K_1 = \frac{P_{CH_4}}{P_{H_2}^2} = \frac{x_5}{x_1^2} \qquad (4)$$

$$K_2 = \frac{P_{H_2} P_{CO_2}}{P_{CO} P_{H_2O}} = \frac{x_3 x_1}{x_2 x_4} \qquad (5)$$

Finally, for the calculation of gasification temperature (T_{gasif}) the energy balance is applied as Mc Kendry, 2002) :

$$\bar{h}^{\circ}_{f,Biomass} + w\bar{h}^{\circ}_{f,H_2O} = x_1\left(\bar{h}^{\circ}_{f,H_2} + \Delta\bar{h}\right) + x_2\left(\bar{h}^{\circ}_{f,CO} + \Delta\bar{h}\right) + x_3\left(\bar{h}^{\circ}_{f,CO_2} + \Delta\bar{h}\right) + x_4\left(\bar{h}^{\circ}_{f,H_2O} + \Delta\bar{h}\right) + x_5\left(\bar{h}^{\circ}_{f,CH_4} + \Delta\bar{h}\right) + x_6\left(\bar{h}^{\circ}_{f,N_2} + \Delta\bar{h}\right) \qquad (6)$$

where, $\bar{h}^{o}_{f,i}$ is the formation enthalpy in terms of kJ/kmol, and its value for all the chemical compositions is zero in the reference state and $\Delta\bar{h}^{o}$ is the enthalpy difference value for the given state with reference state. The GT power plants consist of four components including the compressor, combustion chamber (CC),turbine, and generator. The integrated biomass regenerative combined cycle arrangement considered in Fig.3 is a clear presentation on how to utilize the hot turbine exhaust gas. The fresh atmospheric air from the surrounding is filtered and drawn continuously into the circuit, then the energy is added by the combustion of the fuel in the chamber unit. The products of combustion are expanded through the turbine (Rajput,1995) and consequently produce electrical work while the rest of the exhaust gases are discharged into the Biomass Gasifier and Regenerator units.

Table 1: Initial design parameter of the integrated biomass gas turbine system.

Parameter	Value	Unit
Rated Biomass Consumption	4-13	kg/s
Gasification Temperature	1000-1600	^{o}C
Temperature of Gas at Gasifier Outlet	250-400	^{o}C
Biomass Feeding	Machinery	-
Desired Gasifier Operation	Continuous (minimum 300)	days/yr
Gas Turbine Inlet Temperature	1200	^{o}C
Compressor Pressure Ratio	15	-
Biomass Moisture Content	25-80	%
Gasifier Working Pressure	10-80	bar
Air Gasification Mass Flow Rate	15-35	kg/s

Biomass samples were collected from a Mimosaceae Tree (Sunt Tree) available in East part of Sudan (Gedaref State), having a trunk (stem) diameter of 15 cm and height of 75 cm, approximately. The tree was grown in a disturbed forest field located 10 km on a countryside of the Gedaref City. After collection, the raw samples were saved in a plastic container and thereafter processed carefully in the lab using various tools such as hammer mill, electric blender, mesh or filter, small basin, digital scales, bomb calorimeter, high temperature furnaces and watch glasses. The stem sample cultivated 50 cm from the roots, prepared with a size of 2*2*6 cm. The sample was then sieved to obtain a uniform particle size of less than 841 microns (20 Mesh size). The powdered sample was packed separately in airtight bags, ensuring no contact of biomass with ambient air prior to analysis. The sample used in the study are shown in Fig.2.The corresponding proximate and ultimate analysis results are shown in Table 2.

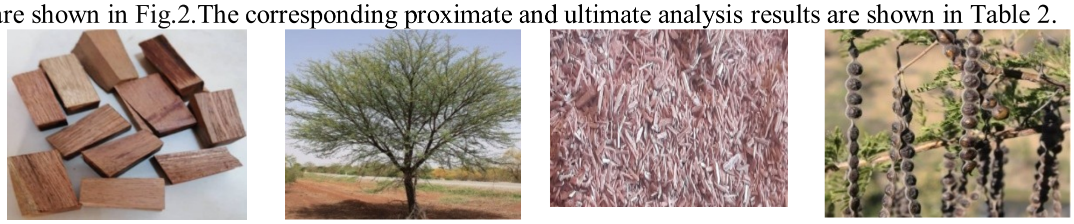

Figure 2: Wood Biomass Sources and Samples.

Table 2: Proximate and ultimate analysis of wood chips.

Proximate Analysis (wt %)				**Ultimate Analysis (wt %)** (Al Qaht et al., 2017)					**Higher Heating Value (HHV)(kJ/kg)**
Water	**Ash**	**Volatile**	**Fixed Carbon**	**C**	**H**	**O**	**N**	**S**	
37.88	1.43	68.49	30.08	48	6	44	0.40	-	19094.94

Ultimate analysis of Acacia Nilotica according to the data of (Al Qaht et al., 2017) , reported the weight percentages of Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen elements are 48%, 6%, 0.40%, 0.00% and 44% respectively. The gasifier's required power output, *Q* (MWth), is an important input parameter specified by the client. Based on this, the designer makes a preliminary estimation of the amount of fuel to be fed into the gasifier and the amount of gasifying medium. The volume flow rate of the *product gas*, V_g(Nm^3/s), from its desired lower heating value, LHV_g(MJ/Nm^3), is found by (Basu,2010):

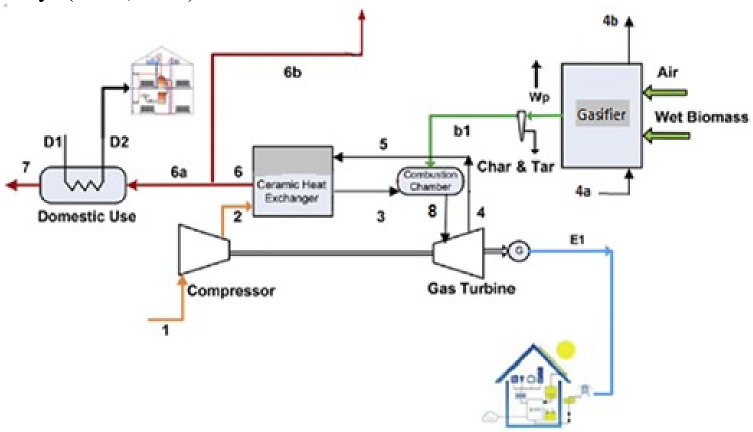

Figure 3: The regenerative gas turbine cycle integrated with Biomass Gasifier Unit.

$$V_{gas} = \frac{Q}{LHV_{gas}} \left(\frac{Nm^3}{sec} \right) \quad (7)$$

The net heating value or lower heating value (LHV) can be calculated from the gas composition (y_i), according to (Basu,2010):

$$LHV_{gas} = \sum_{i}^{N} y_i * LHV_i \quad (8)$$

To find the biomass feed rate, M_f, the required power output is divided by the LHV of the biomass (LHV_{bm}) and by the gasifier efficiency, η_{gef} (Basu,2010):

$$M_f = \frac{Q}{LHV_{Biomass} * \eta_{gef}} \quad (9)$$

The theoretical air requirement for complete combustion of a unit mass of a fuel, m_{th}, is an important parameter. It is known as the *stoichiometric air* requirement. Its calculation is shown in Eq. (10) (Basu,2010):

$$M_{th} = \left[0.1153C + 0.3434\left(H - \frac{O}{8} \right) + 0.0434S \right] \left(\frac{kg.air}{kg.dry\ fuel} \right) \quad (10)$$

For an air-blown gasifier operating, the amount of air required, M_a, for gasification of unit mass of biomass is found by multiplying it by another parameter ER (Basu,2010):

$$M_a = M_{th}.ER \quad (11)$$

For a fuel feed rate of M_f, the air requirement of the gasifier, M_{fa}, is (Basu,2010):

$$M_{fa} = M_{th}.ER.M_f \quad (12)$$

The equivalence ratio (ER) is an important gasifier design parameter. It is the ratio of the actual air-fuel ratio to the stoichiometric air-fuel ratio. This term is generally used for air-deficient situations, such as those found in a gasifier (Basu,2010):

$$ER(<1.0)_{Gasification} = \frac{\text{Actual Air}}{\text{Stoichiometric Air}} = EA(>1.0)_{Combustion} \quad (13)$$

Where *EA* is the excess air coefficient. The quality of gas obtained from a gasifier strongly depends on the *ER* value, which must be significantly below 1.0 to ensure that the fuel is gasified rather than combusted. The oxygen requirement of a gasifier can be met by either air supply or an air-separation unit that extracts oxygen from air. The efficiency of gasification is expressed as cold-gas efficiency or hot-gas efficiency. Cold-gas efficiency is the energy input over the potential energy output. If M_f kg of solid fuel is gasified to produce M_g kg of product gas with an LHV of Q_g, the efficiency is expressed as (Basu,2010):

$$\eta_{cg} = \frac{Q_g.M_g}{LHV_{Biomass}.M_f} \quad (14)$$

Where LHV_f is the lower heating value (LHV) of the solid fuel. The hot-gas efficiency, η_{hg} can be defined as (Basu,2010):

$$\eta_{hg} = \frac{Q_g.M_g + M_{g.}C_{Pg}.(T_f - T_0)}{LHV_{Biomass}.M_f} \tag{15}$$

Where T_f is the gas temperature at the gasifier exit or at the burner's entrance, and T_0 is the temperature of the fuel entering the gasifier. The isentropic outlet temperature leaving the compressor is modeled by the equation (Alsanousi et al.,2017, Nag,2008, Konstantin Volkov, 2012, Prasad, L. (2012):

$$\frac{T_1}{T_{2s}} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma_a - 1}{\gamma_a}} \tag{16}$$

The specific heat ratio for air γ_a was taken as 1.4 and was predicted at $\gamma_g = 1.3$ for the gas.The isentropic efficiency of the compressor and turbine was taken to be in the range of 85% to 90%. The isentropic compressor efficiency is expressed by the equation (Shapiro et al.,2008, Abdalla et al.,2011):

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1} \tag{17}$$

Where, T_1 and T_2 are the compressor inlet and outlet air temperatures respectively and T_{2s} is the compressor isentropic outlet temperature. The specific work required to run the compressor work (W_C) is modeled with the following equation (Abdalla et al.,2011):

$$\dot{W}_c = \dot{m}_a C_{P_a}(T_2 - T_1) = \dot{m}_a C_{P_a} T_1 \left[\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right] \tag{18}$$

The energy balance in the combustion chamber (Nag,2008):

$$\dot{m}_a C_{P_a} T_x + \dot{m}_f LHV + \dot{m}_f C_{P_f} T_f = (\dot{m}_a + \dot{m}_f) C_{Pg} TIT \tag{19}$$

Where $\dot{m}_f$ is the fuel mass flow rate in (kg/s), $\dot{m}_a$ is the air mass flow rate (kg/s), LHV is the fuel's low heat value, TIT is the turbine inlet temperature, C_{P_f} is the specific heat of fuel, and T_f is the temperature of the fuel. The specific heat of the flue gas was modeled with $C_{P_g} = 1.07\ kJ/kg.K$; efficiency was set at 95%, and a pressure drop of $\Delta P_{C,C} = 0.4785\ bar$ in the combustor. Accordingly, the efficiency of the combustor was modeled as (Nag,2008):

$$\eta_{C,C} = \frac{\dot{m}_g C_{Pg} TIT - \dot{m}_a C_{P_a} T_x}{\dot{m}_f LHV_g} \tag{20}$$

The regenerator effectiveness ε was modeled according to the equation (Shapiro et al.,2008):

$$\varepsilon = \frac{T_3 - T_2}{T_4 - T_2} \tag{21}$$

The network from the GT unit was expressed by the equation (Abdalla et al.,2011, Nag,2008,Tariq et al., 2014):

$$\dot{W}_{RGT,Net} = \dot{W}_{RGT} - \dot{W}_c = \dot{m}_g C_{Pg} TIT \eta_t \left[1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}}\right] - \dot{m}_a C_{P_a} T_1 \left[\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right] \tag{22}$$

The output power from the GT is expressed with the equation (Nag,2008,Tariq et al., 2014):

$$P_{RGT} = [\dot{W}_{RGT} - \dot{W}_c] * \eta_{Mech} \eta_{Gen} \tag{23}$$

The mechanical (η_{Mech}) and generator (η_{Gen}) efficiencies were taken to be 92% and 95% respectively. The heat supplied (per kg. air) to the combustor was modeled according to the equation (Nag,2008):

$$\dot{Q}_{add} = \frac{\dot{m}_f LHV_g \eta_{C,C}}{\dot{m}_{air}} = \frac{LHV_g * \eta_{C,C}}{AFR} \tag{24}$$

The GT efficiency was determined by the equation (Nag,2008, Straznicky et al., 2009):

$$\eta_{over,RGT} = \frac{\dot{W}_{RGT,Net}}{\dot{Q}_{add}} \tag{25}$$

3. RESULTS AND DISCUSSIONS

The gasification process was simulated using wood chips as biomass available in Sudan. Detailed energy analysis derived to investigate the optimal design conditions of the system that integrate the Biomass unit with the Regenerative Gas Turbine Power Plant. The work executed the Thermodynamics Engineering Equation Solver

(EES) codes. The work investigates air as a gasification medium to produce syngas fuel for wood chips (Acacia Nilotica).

The composition of the products determines the quality of the syngas produced. Normally,CH_4,CO,H_2 are the major constituents of the final product. As can be observed in Fig.4, the increase of the equivalence ratio (ER) in a gradual range of ER=5-50% leads to an increase in the lower heating value of the syngas. However, the results revealed that there is an optimum equivalence ratio (ER), for each heat value. The lower heating value (LHV) of wood chips derived syngas reaches the maximum heating value of 35 MJ/kg for ER=0.25 at a gasification pressure of 30bar,biomass moisture content of 35%,and gasification temperature of 1000°C. However, after the ER of 25% , the results depict massive decrease of the lower heating value of the syngas. This can be regarded as the point of the optimal design of the system to derive the amount of the needed air for the assigned biomass quantity at the gasifier. The amount of air used is the key parameter for designing the gasifier unit. Higher values of the equivalence ratio (ER), leads to excessive air, which revealed a complete combustion of the biomass. The complete combustion of the biomass revealed higher concentrations of CO_2 ,water vapor, and low heat values of the syngas.

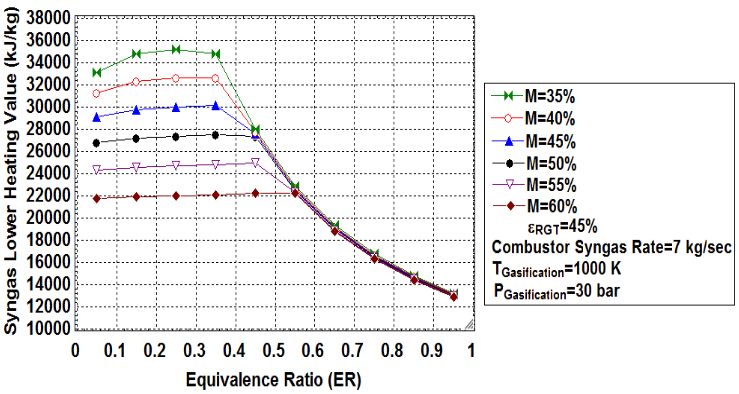

Figure 4: Equivalence Ratio versus syngas lower heating value for different biomass moisture contents (M).

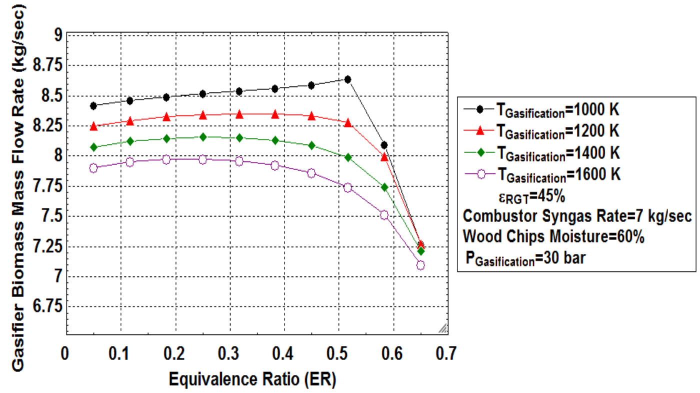

Figure 5: Variation of equivalence ratio with gasifier biomass mass flow rate at different gasification temperatures.

As the initial moisture content increases, the results predict a decrease in the gasification temperature and the lower heating value of the syngas, due to a change in the syngas composition. Fig.5 depicts the variation of the equivalence ratio (ER) and the gasifier Biomass flow rate at different gasification temperatures. As observed, the biomass gasifier's flow rate is higher at lower gasification temperature. Higher value of the biomass flow rate reached at 8.65kg/s, which yielded 7 kg/s of syngas. The results show that, there is a turning point of the equivalence ratio (ER),however with a further increase in ER will lead to a decrease in the biomass flow rate at the gasifier. As observed in Fig.6, at constant gasification pressure of 30 bar, and wood chip moisture content of 40%, the increase of the temperature exhibited an increase in the rate of combustion inside the gasifier, which revealed a decrease of the syngas heat value and a massive reduction of the biomass flow rate. Fig.7 shows the equivalence ratio (ER), and the released syngas LHV for wood chips at different gasification pressure (P=10-80 bar). As observed, increasing the ER resulted in an increase of the syngas LHV for an optimum set of points of ER. At biomass moisture content of 40%, a gasification pressure of 80 bar, temperature of 1600°C, and optimum ER of 25%, the LHV of the syngas delivered a highest value of 31 MJ/kg among the predicted data.

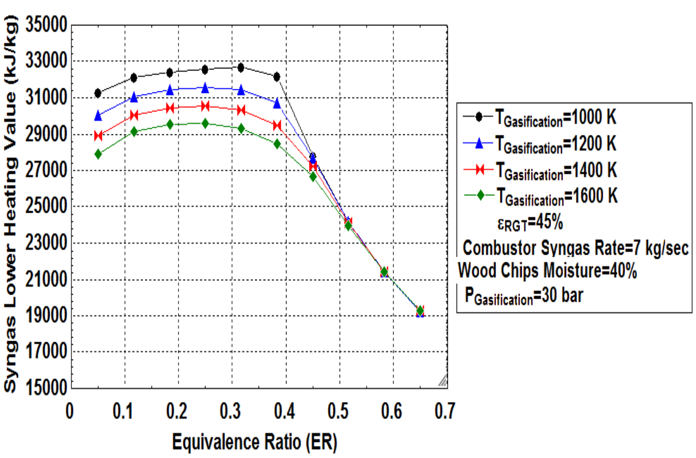

Figure 6: Equivalence ratio versus syngas lower heating value for different gasification temperatures.

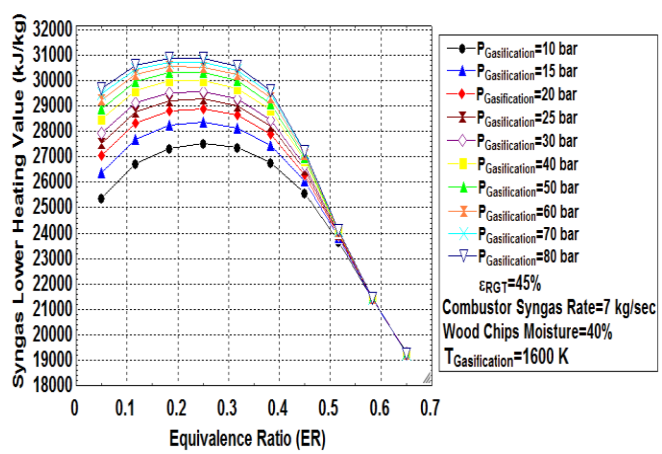

Figure 7: Effect of the equivalence ratio on syngas lower heating value for different gasification pressures.

The excessive rate of the ER, led to a decline in syngas LHV due to the increased rate of combustion products in the composition of the syngas. For air as a gasifier agent, it was observed that the increase of the gasification pressure enhanced the reaction rate and the product's conversion of the gasification reaction, yielding higher concentrations of the H_2 and CH_4 at the syngas product. As is evident, the gasification pressure is strongly dependent on the gasification temperature and the composition of the syngas product. Fig.8 displays the influence of the ER varying between 5-65%, on the gasifier biomass flow rate at different gasification pressure varying from 10-80 bar. As observed, the biomass flow rate is higher at higher gasifier pressure. At higher gasification pressure of 80 bar, the flow rate of the wood chips reached the maximum value of 11.75 kg/s, for the optimum ER of 25% at a moisture content of 40% and a gasifier temperature of 1600°C. Beyond ER of 25%, the results depict gradual decrease of gasifier mass flow rate due increasing of combustion rate and decreasing of the syngas heat value.

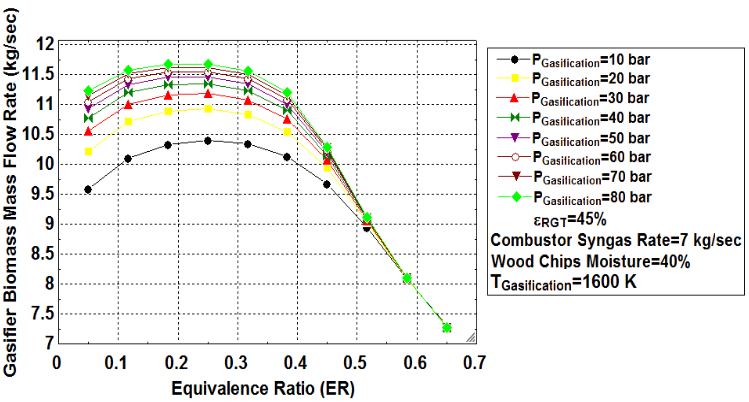

Figure 8: Influence of equivalence ratio on gasifier biomass mass flow rate at different gasification pressures.

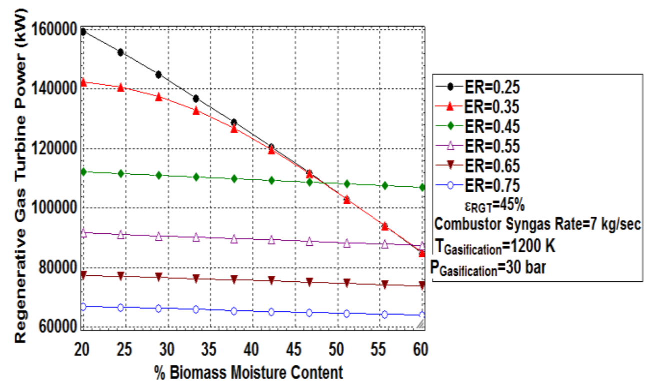

Figure 9: Effect of biomass moisture content and equivalence ratio (ER) on regenerator gas turbine power.

The relationship between the Biomass moisture content varying from 20-60% and the regenerative gas turbine power at different equivalence ratios (ER=25-75%), is plotted in Fig.9. At the lowest biomass moisture content of 20%, gasifier temperature of 1200 °C, pressure of 30 bar, regenerative effectiveness of 45%, and a produced amount of 7 kg/s of the syngas, the optimum ER of 25% depicted a higher value of the regenerator gas turbine power at160 MW.As the moisture content increases, the results predict a decrease in the regenerator gas turbine power due to a decrease in the syngas heat value. The amount of the moisture content in the feedstock plays a major role on identifying the quality of the biomass. High quantity of moisture effects the cellular parts of the wood chips (Mc Kendry, 2002, Liu et al.,2007) resulting in a decrease of the energy content inside the cells of the wood. Moreover, the gasifier system will require additional heat to remove the biomass's moisture. Fig.10 plots the effect of ER varying between 5-95%, on the wood chip mass flow rate at different gasifier efficiency ranging from 65-95%.As observed, at a gasification temperature of 1200°C, pressure of 30 bar, turbine compression ratio of 15, moisture content of 40%, an optimum ER of 25%, depicted a maximum wood mass flow rate of 12.70 kg/s at a gasifier efficiency of 65%.

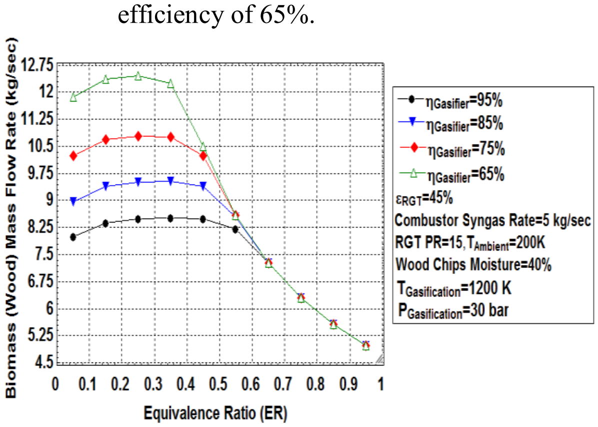

Figure 10: Variation of equivalence ratio with the biomass mass flow rate at different gasifier efficiencies.

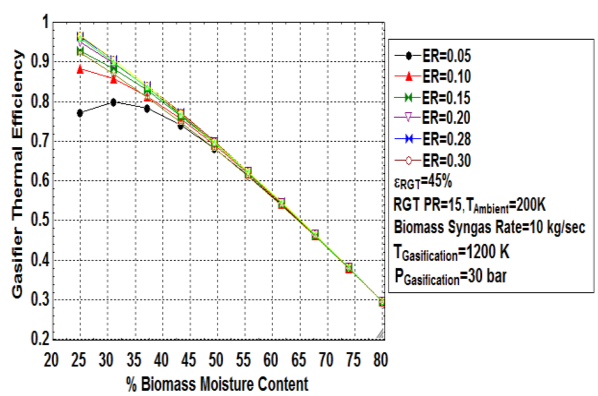

Figure 11: Variation of biomass moisture content with gasifier thermal efficiency at different equivalence ratios.

Beyond an ER of 25%, the model predicts a massive decrease of the biomass flow rate, from increasing combustion rate. The results show that, higher the efficiency of the gasifier, lower the biomass flow rate. The gasifier efficiency is a major design parameter of the gasifier system. Increasing the gasifier's efficiency will reduce irreversibilities and other losses at the gasifier unit. Fig.11shows the influence of the Biomass moisture content varying in a range of

25-80%, on the gasifier thermal efficiency at different values of equivalence ratios (ER=5-30%).The results depict massive decrease on the gasifier efficiency upon increasing the biomass moisture content due losses of the energy content at the Biomass and syngas heat values. As observed, at a gasification temperature of 1200°C, pressure of 30 bar, a maximum gasifier efficiency of 95% has been achieved at the lowest values of the Biomass moisture content (M=25%). As evident, the irreversibilities of the gasifier is increasing due the higher quantity of the Biomass moisture content. At a gasification temperature of 1200°C, pressure of 30 bar, moisture content of 40%, Fig.12 realized that increasing of the regenerator effectiveness will result in increasing the regenerative turbine power at different compressor's air flow rate. An optimum equivalence ratio of ER=25%, achieved a higher regenerative power of 98 MW at a higher regenerator effectiveness of 95% and production amount of 5 kg/s of the syngas. Beyond the optimum ER, massive decrease of RGT power occurred from a change in the syngas composition.

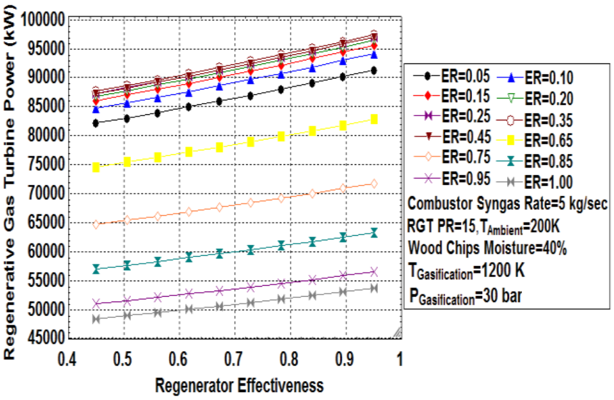

Figure 12: Variation of regenerator effectiveness with regenerator gas turbine power at different equivalence ratios.

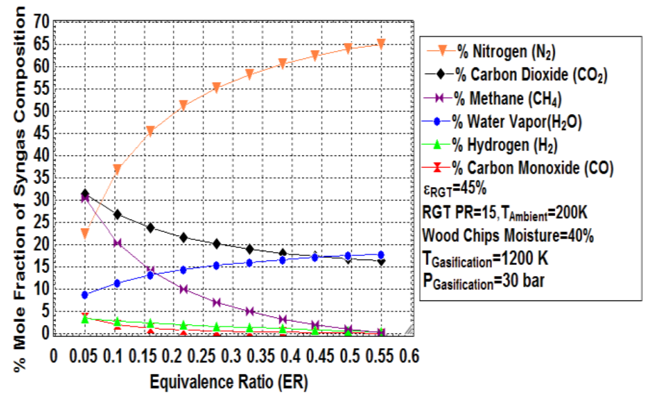

Figure 13: Effect of equivalence ratio on the Wood Chip syngas composition.

Fig.13 depicts the variation of ER in the range of ER=5-55%, with the percentage mole fraction of the syngas, at a gasification temperature of 1200°C, pressure of 30 bar, regenerator effectiveness of 45%, compressor air temperature of 200K, biomass moisture content of 40%, and a production amount of 5 kg/s of the syngas. At the final product of the syngas composition, it was observed that, the N_2 and water vapor formation increases with the increase of the ER, while the formation of CO_2,CH_4,H_2 and CO exhibited decreases upon increasing of the ER. For wood chips, the H_2, CH_4 and CO mole fractions reached the maximum values at the lowest values of the ER, while at the optimum gasifier's ER the H_2 mole fraction depicted a value of 1.74%, 0.70% of CO, and 8.14% of CH_4, for a LHV of 31400 kJ/kg syngas. The highest value of the syngas composition is depicted by N_2.Due to the high nitrogen content in the producer gas, air gasification produces a low heating value syngas. As can be noted, the nitrogen content in the producer gas can be significantly reduced by using steam or oxygen as the oxidizing agent.

CONCLUSIONS

This work discussed and investigated the integration of the Biomass Gasifier unit with a Regenerative Gas Turbine power plant, including the effect of various parameters. Simulation models were used to characterize the gasification process of a Wood Chips Biomass in Sudan. This type of Biomass (Wood) is of great interest in the country due wide domestic use and presence of agricultural lands. A parametric analysis of the released syngas composition, temperature, pressure, LHV, Moisture content, Equivalence Ratio and Regenerative Gas Turbine Power were investigated carefully to identify the optimal design points of the gasifier system available for such type of Biomass. With an average syngas LHV of 30 MJ/kg, the results revealed that such type of Biomass (Wood Chips) can achieve a highly thermal efficiency and be a valuable energy saving process for Regenerative Gas Turbine Unit.

NOMENCLATURE

Symbols

T	Temperature	(K)	T_x	Combustor Inlet Temperature	(K)	T_S	Compressor Isentropic Temperature	(K)
$\dot{m}_f$	Fuel Mass	(kg.fuel)	ε	Regenerator Effectiveness	-	P_{GT}	GT Power	(MW)

P	Pressure	(kPa)	$\eta_{C,C}$	Combustor Efficiency	-	$\dot{W}_C$	Specific Compressor Work	(MW)
M_a	Gasifier Actual Air Flow Rate	(kg air)	$\dot{m}_g$	Gas Mass	(kg.gas)	$\dot{Q}_{add}$	Heat Supplied	(kW)
γ	Specific Heat Ratio	-	$\dot{W}_{GT}$	Turbine Shaft Work	(MW)	$\dot{m}_a$	Air Mass	(kg air)
η_C	Isentropic Compressor Efficiency	-	η_T	Turbine Efficiency	-	C_{P_a}	Heat Capacity of Air	(kJ/kg.K)
η_{gef}	Gasifier Efficiency	-	y_i	Syngas Mole Fraction	-	C_{P_g}	Heat Capacity of Gas	(kJ/kg.K)
M_{th}	Gasifier Stoichiometric Air Flow Rate	(kg air/kg dry fuel)	C_{P_f}	Heat Capacity of Fuel	(kJ/kg.K)			

Subscripts

ER	Equivalence Ratio
RGT	Regenerative Gas Turbine
Mech	Mechanical
Gen	Generator
EES	Engineering Equation Solver
CC	Combustion Chamber
ATM	Atmospheric
LHV	Lower Heating Value
TIT	Turbine Inlet Temperature

REFERENCES

1. Farida Mahgoub: Current Status of Agriculture and Future Challenges in Sudan, Nordiska Afrika Institutet, Uppsala, 2014.
2. Y. Sanjay, O. Singh, B. Prasad, Energy and exergy analysis of steam cooled reheat gas steam combined cycle, Appl. Therm. Eng. 27 (2007) 2779e2790.
3. O. Ioannidou, A. Zabaniotou, Agricultural residues as precursors for activated carbon production—a review, Renew. Sust. Energ Rev., 2007, 11, 1966–2005.
4. M. Garcia-Perez, X. S. Wang, J. Shen, M. J. Rhodes, F. Tian, W.-J. Lee, H. Wu, C.- Z. Li, Fast pyrolysis of oil mallee woody biomass: Effect of temperature on the yield and quality of pyrolysis products, Ind. Eng. Chem. Res., 2008, 47, 1846– 1854.
5. R. French, S. Czernik, Catalytic pyrolysis of biomass for biofuels production, Fuel Process. Technol., 2010, 91, 25–32.
6. Kollman, F.F.P, Cote, W.A. 1968. Principle of wood science and technology, vol. I, Solid Wood.Springer-Verlag.
7. TERI, "Thermal applications of biomass gasifier in SMiEs," Project Report 2005BE28,The Energy and Resources Institute, New Delhi, India, 2006.
8. S. Khanmohammadi, K. Atashkari, R. Kouhikamali, Performance assessment and multi-objective optimization of a trigeneration system with a modified biomass gasification model, Modares Mech. Eng. 15 (9) 209e222,2015.
9. D. Dayton, A Review of the Literature on Catalytic Biomass Tar Destruction: Milestone Completion Report, NREL/TP, Golden,Colo, USA, 2002.
10. Knoef HAM. Inventory of biomass gasifier manufacturers and installations. Final report to European Commission, Contract DIS/1734/98-NL, Biomass Technology Group B.V., University of Twente, Enschede,2000 (see http://btgs1.ct.utwente.nl/).
11. Littlewood, K., 1977. Gasification: theory and application. Progress in Energy and Combustion Science 3 (1), 35–71.
12. Perry, R.H., Green, D.W., 1997. Perry's Chemical Engineer's Handbook, 7th ed. McGraw-Hill,pp. 2-161–2-169.
13. R.K.Rajput , A. Text Book of Power Plant Engineering, Laxmi Publications, New Delhi, 1995.
14. Prabir Basu. (2010): Biomass Gasification and Pyrolysis, Practical and Theory, Elsevier Inc, Boulevard, Langford Lane, UK.

15. HossinOmar,AlyKamel,MohammedAlsanousi ,Performance of Regenerative GT Power Plant, Energy and Power Engineering, 2017,9,136-146, https://doi.org/10.4236/epe.2017.92011.
16. Al-Sayed AF (2008). Aircraft Propulsion and GTEngines, Taylor and Francis, ISBN 978-0-8493-9196-5.
17. Nag, P.K. (2008) Power Plant Engineering. Tata McGraw-Hill Publishing Company Limited, New Delhi.
18. Farouk N, Sheng L. Effect of Fuel Types on the Performance of GTs. International Journal of Computer Science Issues (IJCSI). 2013; 10(1):436.
19. ASME GT Fuels B 133.7M Published: 1985 (Reaffirmed year:1992).
20. ISO, Natural Gas-Calculation of Calorific Value, Density and Relative Density, International Organization for Standardization ISO 6976-1983(E).
21. A.K. Mohapatra, Sanjay:Thermodynamic assessment of impact of inlet air cooling techniques on GT and combined cycle performance, Energy 68 (2014) 191-203.
22. Rahman MM, Ibrahim TK, Kadirgama K, Mamat R, Bakar RA (2011).Influence of operation conditions and ambient temperature on performance of GT power plant. Adv. Mater. Res., 189-193:3007-3013.
23. P.W. Gill, J.H. Smith, Jr., E.J.Ziurys, Fundamentals of Internal Combustion Engines, Fourth Edition, Oxford &IBH Publishing Co.,1959.
24. V. Gansesan, Internal Combustion Engines, Tata McGraw-Hill, New Delhi,1992.
25. C.F. Taylor, The Internal Combustion Engine in Theory and Practice,Vol. I and II, MIT Press, Cambridge, Mass.,1985.
26. Meherwan P. Boyce (2002). GT Engineering Handbook, Gulf Professional Publishing, New Delhi.
27. T.D. Eastop and A.McKonkey, Applied Thermodynamics for Engineering Technologists, Fifth Edition, Addison-Wesley Longman Ltd., U.K.,1993.
28. Johnke T, Mast M (2002). GT Power Boosters to enhance power output. Siemens Power for generation, Siemens Power J.
29. Konstantin Volkov (2012): Efficiency, Performance and Robustness of GTs, Published by InTech, ISBN 978-953-51-0464-3, Croatia.
30. Mohapatra, A.K. and Prasad, L. (2012) Parametric Analysis of Cooled GT Cycle with Evaporative Inlet Air Cooling. International Journal of Scientific & Engineering Research, 3, Issue 3.
31. Moran, M.J. and Shapiro, H.N. (2008): Fundamentals of Engineering Thermodynamics. John Wiley & Sons, INC, New York.
32. M.M. Rahman, Thamir K.Ibrahim, Ahmed N. Abdalla, Thermodynamic Performance Analysis of GT Power Plant, International Journal of the Physical Sciences Vol.6(14), pp. 3539-3550,2011.
33. Omar Shakir Mahmood, Mohammad Tariq (2014), Analysis of a Regenerative GT Cycle for Power Plant, International Journal of Scientific Engineering and Technology Research, ISSN 2319-8885, Vol.03,Issue 4, pp. 611-616.
34. Mc Kendry P., Energy Production from Biomass, part 3: Gasification Technologies, Bioresource Technology, 83, p.55-63 (2002).
35. Wei,L.,Xu,S.,Zhang,L.,Liu,C.,Zhu,H.,Liu,S.,Steam gasification of Biomass for hydrogen rich gas in a free fall reactor. International Journal of Hydrogen Energy,32,24-31, 2007.
36. Muhammad Saleem, Mehmood Ali, Zia Siddiqi & Abdulrahman Saud Al Qaht, Preparation of Activated Carbon from Acacia (Vachellia seyal) Tree Branches and Application to Treat Wastewater Containing Methylene Blue Dye, Modern Applied Science; Vol. 11, No. 12; 2017, ISSN 1913-1844, Published by Canadian Center of Science and Education.
37. Jarungthammachote S., Dutta A., 2007, Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier, Energy, 32, 1600–1669.

ACKNOWLEDGMENTS

The authors greatly acknowledge the technical support of Chemical Engineering Department and the Energy Research Centre of the University of Khartoum, Faculty of Engineering for providing laboratory and facilitating the field of works. The Financial, technical and academic supervisions of the World Academy of Science (TWAS) and the Islamic Development Bank (IsDB),grant number “506798/2019” under the scheme of the Postdoctoral Fellowship program, is greatly appreciated.