Implications of Shifting Operation Conditions on the Economics of Biomass Fueled Boilers

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Abstract

The economics of biomass as a fuel for industry and domestic use remain a key challenge to its widespread application. Yet, in view of the numerous advantages offered by the use of biomass as industrial fuel, there continues to be interest in its use. Thus far, efforts at resolving the challenge of the economics of biomass use has centered predominantly on the use of local policy decisions and prudent management of the logistics supply chain of the biomass related business. However, there are other avenues by which the economics of biomass as fuel for industry can be improved such as those related to the efficiency of generation and use of biomass energy. This study examines the implications of varying composition of the biomass input, the chemistry of the biomass combustion, and the efficiency of the boiler on the economics of the operation of biomass fuelled boilers. The work uses a mathematical model previously developed by one of the authors to simulate the effect of these parameters on the expenditure patterns of a biomass fuelled boiler plant. The results showed that changes in these parameters have significant impact on the economics of the plant. The efficiency of the boiler has the most impact on the economics of biomass fueled boilers. A reduction in the boiler efficiency from the manufacturer's stipulated value of 75% to 35% resulted in extra expenditure of 70.3% to the plant.

Key Words: *biomass, boiler, combustion, economics of biomass, operation conditions, mathematical model*

Introduction

The sustainable use of biomass as fuel for industry and for domestic use rests on a number of factors including its impact on the environment, sustainability of supply of biomass sources, and above all the economics of its utility. Whilst it is now established that relative to traditional sources of fuel, that is coal, oil and natural gas, biomass is environmentally friendlier [Saduir et al., 2011],the issues of sustainability and economics of biomass use are management and operational matters that must be planned and worked at on timely basis to attain. The matter of sustainability of biomass use requires long term planning to achieve. The real issues here involve planning for biomass supply through planting of energy crops and planning for storage and transportation of biomass. The issue of economics is a more complex one and depends on factors such as plant operational matters, market forces such as the relative cost of fossil fuel and other renewable energy sources, and policy decisions such as the provision of tax credits

[Strauss, 2013]. A number of researchers [Demirbas, 2010, Caputo et al., 2005, Spliethoff & Hein, 1998] have observed that the application of biomass affords many economic advantages includingconservation of fossil fuel resources, reduction of the dependence on fuel imports, utilization of agricultural and forest residues, reduction of emission of harmful species from fossil fuel combustion, recultivation of non-utilized farming areas, minimization of waste disposal, and local job creation.

Operational factors that impact the economics of biomass plants include the selection and pre-treatment of biomass, selection of the right technology for the conversion of biomass into energy and for efficient harnessing of the energy generated from biomass, the choice of process conditions during the combustion of biomass, and a proper maintenance schedule of plant. Most of the previous studies on the economics of biomass fuelled boilers have focused on the effect of prudent and sustainable provision of logistics and local policy decision and the viability of biomass plants [Strauss, 2013; Verojporn, 2011]. However, the efficient conversion and use of biomass energy can have significant impact on the economics of biomass fuelled plants and therefore the viability of such plants. Indeed, the European Biomass Association (AEBIOM) [Saduir et al., 2011;Daskalakis &. Iyer. 2009]has made the principles of efficiency of biomass energy production and use one of its core goals with respect to the economic utilization of biomass energy.

In this study the effect of changing operational conditions during the operation of a biomass fueled boiler is investigated. It is intended by the study to establish the direct implications of the shifting process conditions on the economics of such plants. The study uses data from an operating biomass fueled boiler plant and a mathematical model previously developed by one of the authors to describe the operations of biomass fuelled boilers [Achaw & Afriyie, 2014]. The model uses mass and energy balances written to describe the boiler system to arrive at correlations that can be used to simulate and evaluate the operations of the boiler plant. This work investigates the effects of variations in the moisture content of the biomass fuel fed to the boiler furnace, the supply of air to the combustion furnace, and the efficiency of the boiler on the economics of biomass fuelled boilers.

Method and Materials

The estimates in the work are based on a mathematical model earlier developed by one of the authors of this work [Achaw & Afriyie, 2014]. The model itself is based on material and energy balances written to describe a model boiler system. The description of the system and its operation are presented in Figure 1 below. Data for the simulation studies were collected from an operating plant based in the Ashanti region of Ghana. The cost of biomass used in this work was based on data from the work by the Forestry Commission of England [http://www.cse.org.uk].

Description of the boiler system

The boiler system used in this study has been described in an earlier work of Achaw and Afriyie [Achaw & Afriyie, 2014]. The key components of the boiler system are a stoker furnace which can be manually fed or fed through a conveyor arrangement, the boiler drum, and associated inlet and outlet pipings – the water feed pipe, the steam outlet pipe, and the blow down pipe. The boiler is a combination fire tube and water tube design so called Combi Boiler. It was supplied in the by Modipalm Engineering of Malaysia in 2003. The boiler has a capacity to produce 10,000 kg/hr of saturated steam at a pressure of 18 bars. The feed water enters the boiler at a 45^{o}C. The combustion gases from the boiler are led through a cyclone where the accompanying particulates are removed before the gases channeled into the open atmosphere through a stack. A sketch of the set-up of the boiler system is shown in Figure 1.

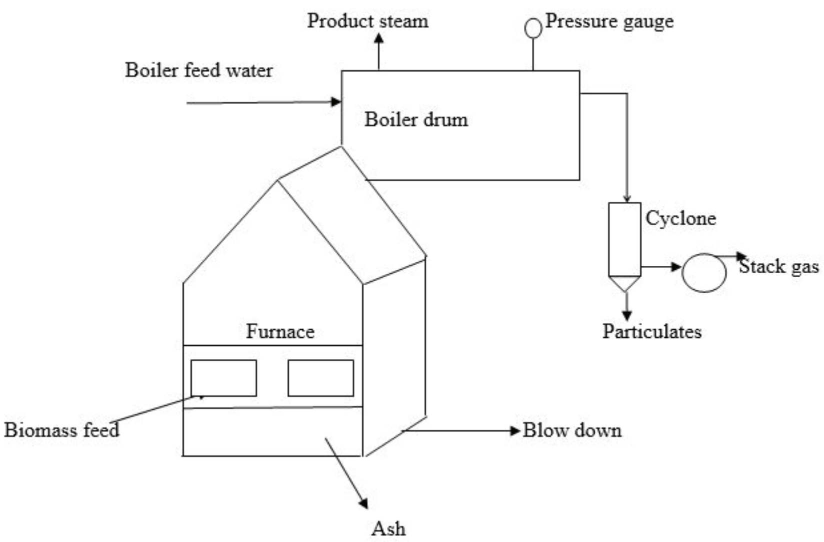


Figure 1. A schematic of the biomass fuelled boiler system [Achaw & Afriyie, 2014]

Mathematical model

Figure 2 is a block diagram of the boiler system indicating material flows into and out of the boiler. Material and energy balance equations were first written to describe the boiler system from which all other relevant parameters were subsequently estimated. The operation of the boileris underlined by the following assumptions [Achaw and Afriyie, 2014].

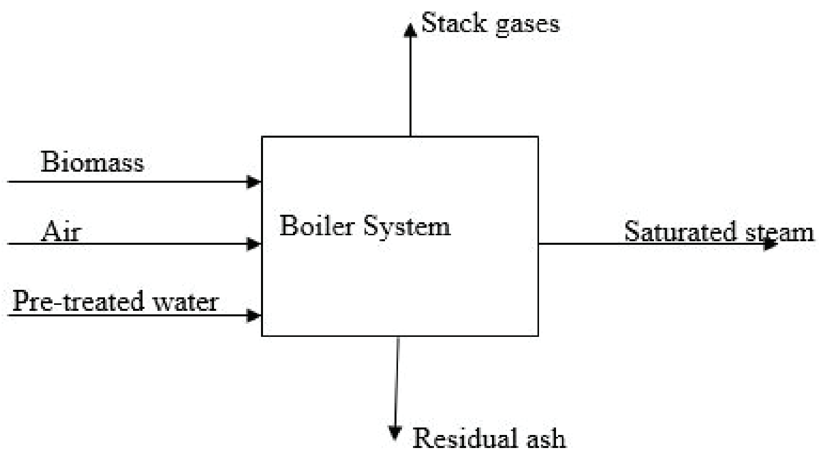


Figure 2. A schematic of the boiler system indicating all material flows

1. The elemental composition of the biomass less its ash and moisture content is taken as 50 wt% carbon, 6 wt% hydrogen and 44 wt% oxygen.
2. The ash content of the biomass is 4.38 wt% dry basis
3. The biomass combustion is represented by the global reactions (1) and (2) of Section 2.2.1

4. The oxygen required for combustion comes from the oxygen of the air supplied to the furnace and also from the oxygen inherent in the biomass.
5. The operation of the boiler occurs under system steady state.
6. Energy losses from the boiler system occur through the external surface of the boiler, the residual ash in the furnace, the stack gases, and the evaporation of the physical moisture in the biomass.
7. Energy losses from the surface of the boiler is taken as 2.5% of total energy released from the combustion of the biomass.
8. Economic estimates were based on the price of a wood log of £50.0 (fifty U.K. pounds) per ton [http://www.cse.org.uk].

Material and energy balances around the boiler system

Material balances

As shown on Figure 2,the feed to the system are water meant for conversion into steam, the biomass and air. Since the system operates at steady state all the water fed to the boiler is converted into steam. Based on assumptions (1) and (3) the biomass reacts with the air to produce carbon dioxide and water vapor according to equations (1) and (2) below.

$$C + O_2 \longrightarrow CO_2 \qquad (1)$$

$$2H + 1/2O_2 \longrightarrow H_2O \qquad (2)$$

Besides water and carbon dioxide other possible components in the combustion gases are nitrogen and oxygen from the air and water vapor from the physical moisture associated with the biomass. The quantities of each of these in the stack gases were calculated from the stoichiometry of reactions (1) and (2) and the composition of the biomass.

Energy balances

The total energy input to the boiler system is estimated from the grand calorific value (GCV) of the biomass feed (equation 3). This energy is actually released from the biomass following the combustion of the biomass.

$$\dot{Q}_{in} = GCV * \dot{m}_{biomass} \qquad (3)$$

The bulk of this energy goes to generate steam from water in the boiler. The rest ($\dot{Q}_{lost}$) is lost through the stack gases, the residual ash in the furnace, by radiation through the external surface of the boiler, and in evaporating the physical moisture in the biomass. The total energy generated ($\dot{Q}_{in}$)is related to the energy that goes to generate steam ($\dot{Q}$)through the efficiency of the boiler and is given by equation (4) below.

$$\eta = \frac{\dot{Q}}{\dot{Q}_{in}} \qquad (4)$$

($\dot{Q}$) can be estimated from the enthalpy balance on the steam according to equation (5).

$$\Delta \dot{H} + \Delta \dot{E}_{K} + \Delta \dot{E}_{P} = \dot{Q} - \dot{W}_s \qquad (5)$$

ΔH is the enthalpy change between the feed water to the boiler and the exit steam from the boiler, ΔE_K is the kinetic energy change of the fluid at the exit and entrance of the boiler, ΔE_P is the potential energy change of the fluid through the boiler, and W_s is the shaft work of the boiler which is equal to zero.

The energy lost into the environment is the difference between the total energy generated (equation 3) and the energy used to generate steam (equation 5) and is expressed as,

$$\dot{Q}_{in} - \dot{Q} = Q_{lost} = \dot{Q}_{radiation} + \dot{Q}_{bottom.ash} + \dot{Q}_{dry.stack.gas} + \dot{Q}_{moisture} \quad (6)$$

$\dot{Q}_{radiation}$ is the energy lost through the external surface of the boiler

$Q_{bottomash}$ is the energy lost through the residual ash in the furnace

$Q_{dry.stack.gas}$ is the energy lost through the dry gases leaving the stack

$Q_{moisturo}$ is the energy lost to evaporating and heating physical moisture in the biomass

The energy lost through the various avenues are estimated as follows.

$$\dot{Q}_{radiation} = 2.5\% \dot{Q}_{in} \quad (7)$$

$$\dot{Q}_{bottom.ash} = \dot{m}_{ash} * GCV_{ash} \quad (8)$$

$$\dot{Q}_{dry.stack.gases} = \dot{m}_{dry.stack,gases} * C_{p,dry.stack.gases} * (T_{stack.gases} - T_a) \quad (9)$$

$$\dot{Q}_{moisture} = \dot{m}_{moisture} * (2243.6 + C_{p,H2O}) * (T_{stack.gases} - T_a) \quad (10)$$

m_{ash} is the mass of residual ash from the combustion of the biomass, $m_{dry.stack.gas}$ is the mass of dry stack gas leaving the stack of the boiler, $m_{moisture}$ is the mass of water vapor leaving the stack. All these quantities are estimated from the stoichiometry of reactions (1) and (2). $C_{p,i}$ is the specific heat capacity of component i, T_a is the temperature of ambient air, x_i is the composition of component i in the mixture, and $T_{dry\ stack\ gas}$ is the temperature of the dry gases leaving the stack. The moisture leaving the stack is from two sources, namely, the free moisture in the biomass (m_{free}) and the moisture produced as a result of reaction (2), $m_{reaction}$.

Also,

$$\dot{m}_{moisture} = \dot{m}_{free} + \dot{m}_{reaction} \quad (11)$$

$$C_{p,drystackgas} = \sum_{i=1}^{n} x_i * C_{p,i} \quad (12)$$

Knowing the elemental composition and flow rate of biomass into the furnace, the capacity and state of the boiler, and the chemistry of the combustion reactions in the furnace, it is possible to estimate the composition and temperature of the stack gas using equations (1) to (12) [Achaw & Afriyie, 2014]

Economic and environmental implication of changing operation conditions

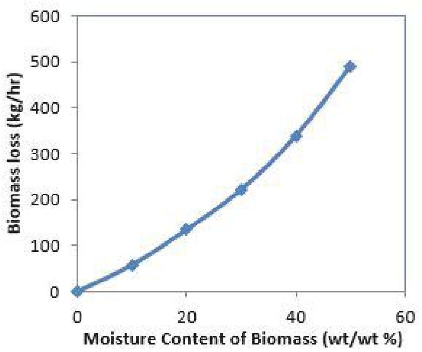
The key parameters that are liable to change during the operation of the boiler and which when not regulated could engender loses in the system include the moisture content of the biomass, the air flow rate to the furnace and the efficiency of the boiler which could change as a result of fouling and slagging and corrosion of heat exchange surfaces of the boiler drum. The magnitude of energy loses and its immediate implications on the economy of the plant and the environment can similarly be tracked using the foregoing correlations (equations 1 – 12). Using data from an existing boiler plant in rural Ghana, Table 1, these estimates have been made and presented in Figures 3 – 11.

Table 1. Data used in calculating boiler energy flows and stack gas composition

Parameter	Value
Diameter of outlet steam pipe, m	0.20
Diameter of inlet water pipe, m	0.05
Elevation between steam outlet and water inlet (Δz), m	3
Flow rate of inlet water, , kg/h	10,000
Flow rate of steam, $\dot{m}$, kg/h	10,000
Pressure of product steam (saturated steam)	18 bar
Ambient temperature, (T_a), °C	31
Efficiency of boiler, η	0.75
Moisture in biomass, wt%	variable
Ash content of biomass, wt%	4.38
Gross calorific value of biomass, MJ/kg	19.78
Gross calorific value of ash, MJ/kg	3.03
Heat capacity of dry stack gas ($C_{p,dst}$), kJ/kg.K	1.77
Heat capacity of water ($C_{p,H2O}$), kJ/kg.K	4.23

Results and discussions

On Figures 3-5 are plots of the effect of the moisture content of biomass on the energy lost through the stack gases as a result of the combustion of the moisture laden biomass, the effect of increase in moisture in biomass on the extra biomass burnt to achieve a required steam production, and the effect of increasing moisture in the biomass on the cost of generating steamin the boiler respectively.



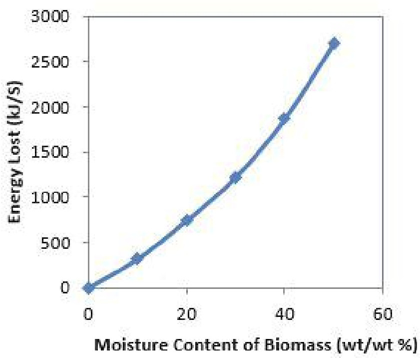


Figure 3. Moisture content vrs biomass lost

Figure 4. Moisture content vrs energy lost

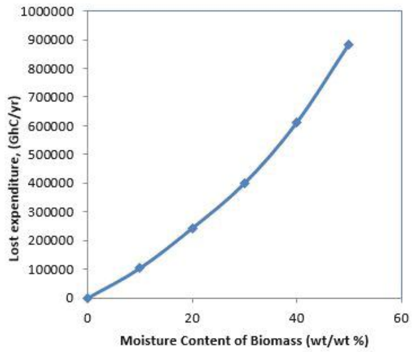
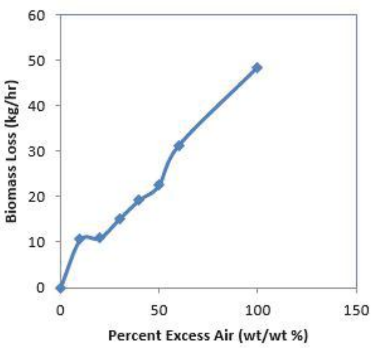


Figure 5. Moisture content vrs lost expenditure

The effects of the extra air fed to the furnace on the extra energy, extra biomass burnt, and the extra cost to the plant are shown on Figures 6-8, while the effects of the boiler efficiency on the extra energy, extra biomass burnt, and the extra cost to the plant are shown on Figures 9-11.



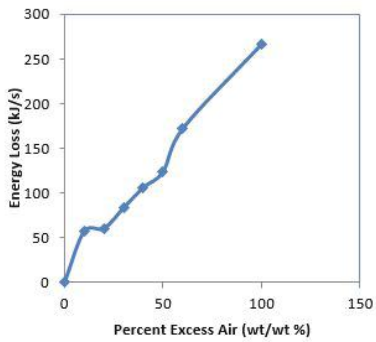


Figure 6. Excess air vrs fuel lost

Figure 7. Excess air vrs energy lost

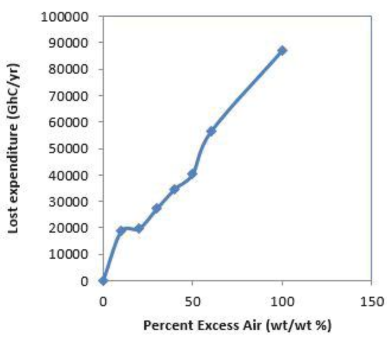


Figure 8. Excess air vrs expenditure lost

It is evident from Figures 3 – 11 that increases in all the operational parameters studied in this work affected the energy lost, the amount of biomass burnt in the furnace of the boiler and the expenditure at the plant, albeit to different degrees and along different directions. While increases in the moisture in the biomass and extra air supplied to the furnace resulted in increases in expenditure at the plant, the opposite was the case for changes in the efficiency of the boiler, namely, decreases in the boiler efficiency resulted in increase expenditure at the plant. Changes in the boiler efficiency had the most effect of the three objective parameters under study. A change in boiler efficiency from the manufacturer's recommended figure of 75% to 35% resulted in loss of energy and biomass of 18089.2 kJ/s and 3292.23 kg/hr respectively (see Figures 9 &10). The corresponding cost implications stand at Gh₵5,926,014.00 per year (Five million, nine hundred and twenty six thousand, and fourteen Ghana Cedis per year, see Figure 11).This figure represents 70.3% of the cost of energy required to generate steam assuming the boiler is operated under ideal conditions (Conditions of no moisture in the biomass, stoichiometric supply of air to the furnace and boiler operation at the manufacturer's stipulated efficiency of 75%.In other words when the boiler operates at 35% efficiency, it costs more than one and half times in biomass to generate the same amount of steam as would be required if the plant operated at the manufacturer's efficiency. Evidently, this extra cost incurred as a result of a drift in the boiler efficiency is quite considerable. This cost has direct effect on the cost of operating the plant. Avoiding this extra cost requires that the boiler is operated at or near the manufacturer's efficiency. The drift in efficiency of the boiler is brought about as a result of fouling, corrosion and slag formation of especially the heat exchanger surfaces of the boiler. Preventing and getting rid of fouling and slagging of the heat exchanger tubes requires that the heat exchanger surfaces of the boiler are cleaned on regular basis. Fouling, corrosion and slagging are caused by inorganic chemicals in the biomass that following combustion are transported to and deposited on the heat exchanger surfaces of the boiler [Miles et al., 1995]. One approach to avoiding these chemicals reaching these surfaces is to pre-treat the biomass to remove these unwanted chemical before combustion of the biomass [Bakker, 2000; Khan et al., 2009]

From Figure5 the extra cost incurred when the moisture content of the biomass is 50 wt% is Gh₵880,000.00 per year (Eight hundred and eighty thousand Ghana Cedis per year.) which equals 37.8% of the cost of energy used when the plant is run under ideal conditions. This sum is considerable and may represent difference between the profitability or otherwise of the plant. Therefore, there is sufficient incentive to dry the biomass prior to burning in the furnace. In tropical climates, drying of the wood can conveniently be done in the sun, thus avoiding incurring any cost associated with drying of the wood. Alternatively, the energy of the stack gasses can be used to dry the biomass before feeding into the furnace. Under the normal operating conditions of zero moisture content of biomass, boiler efficiency of 75% and stoichiometric supply of air, the temperature, the flow rate and enthalpy of the stack gas were estimated from the material and energy balances (equations 1,2 and 9) to be716.4 K, 8.47 kg/s and 3772.5 kJ/s respectively. In this state, the stack gas can be deployed to dry the biomass rather than be discharged into the open atmosphere with the attendant adverse consequences on the environment.

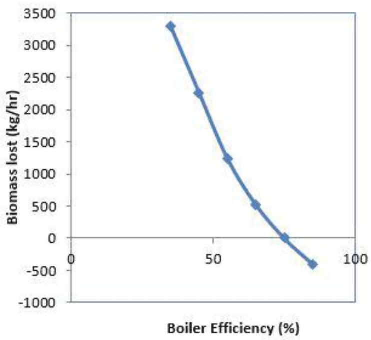


Figure 9. Boiler efficiency vrs biomass lost

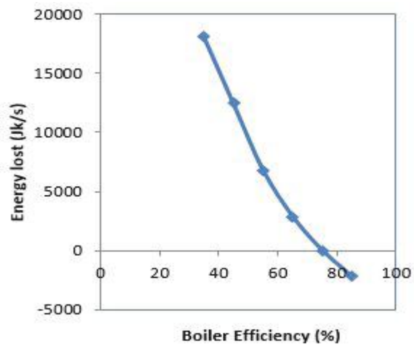


Figure 10. Boiler efficiency vrs energy lost

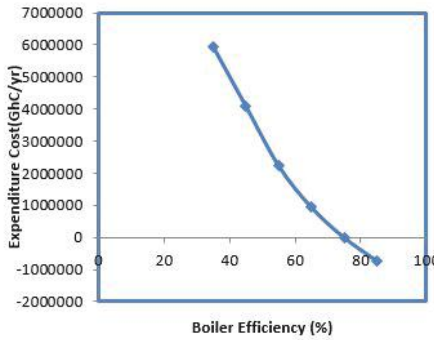


Figure 11. Boiler efficiency vrs expenditure lost

From Figure 8, at excess air supply of 100%, the extra cost over the normal conditions of operation of the boiler is only GhȻ87,246.00 per year(Eight hundred and seventy two thousand Ghana cedis).Compared to the expenditure loses due to decrease in efficiency of the boiler or as a result of the moisture content of the biomass, this figure is relatively small. This figure is equal to 3.7% of cost of energy required to operate the boiler under ideal conditions. While this sum is noticeable, it is probably not large enough to influence the economics of the plant any significantly. The immediate implication of this result is that it might be better to supply excess air to the furnace in order to achieve complete combustion of the fuel than to restrict air supply to the furnace for fear of energy being carried away by the excess air.

Another consequence of the deteriorating operational conditions of a biomass fuelled boiler plant is the adverse effect on the environment. Tables 3 and 4 show estimated data on the combustion gases at boiler efficiencies of 75% and 45% respectively. It is evident from the tables that as the efficiency of the boiler deteriorates from 75% to 45 %, the amount of combustion gases released into the environment increases from 290.2 mols/s to 486.20 mols/s. This increase in gaseous emission is unfavorable to the environment, further strengthening the need to operate the plant so as to avoid adverse shifting of the operational conditions.

Table 3. Stack gas components and composition (Stoichiometric air requirement; moisture content of biomass = 0.0 wt%; η=0.75)

Component	Molar flow rate (mol/s)	Mass flow rate (kg/s)	Molar Composition (% mol/mol)
N_2	200.9	5.6	69.2
CO_2	51.9	2.28	17.9
H_2O (moisture)	0.0	0.0	0.0

H_2O (generated)	37.4	0.67	12.9
TOTAL	**290.2**	**8.55**	**100**

Table4. Stack gas components and composition (Stoichiometric air requirement; moisture content of biomass = 0.0 wt% η=0.45)

Component	Molar flow rate (mol/s)	Mass flow rate (kg/s)	Molar Composition (% mol/mol)
N_2	336.73	9.43	69.26
CO_2	86.90	3.82	17.87
H_2O (moisture)	0.0	0.0	0.0
H_2O (generated)	62.57	1.13	12.87
TOTAL	**486.20**	**14.38**	**100**

Conclusions

The results from this study indicate that all the three operational parameters studied affected the economics of biomass fuelled plants. Increases in the moisture content of the biomass and the excess air fed to the boiler furnace all resulted in increase in the cost of running the plant. A decrease in the efficiency of the boiler similarly leads toan increase in the cost of running the plant. Changes in the boiler efficiency has the most significance on the cost of running the plant. For a reduction in boiler efficiency from 75% to 35%, the increased cost in running the boiler is 70% compared to 37 % when the moisture content of the biomass increased from 0 wt % to 50 wt %. The parameter with the least impact on the cost of running the plant was the excess air fed to the boiler furnace. For a 100% increase in excess air to the furnace, the extra expenditure cost in running the plant is only 3.7%. The study further established that the conditions of operation of the boiler plant affected the quality and quantity of combustion gases released into the environment.

References

Online Document

Achaw, O.W. and J. K. Afriyie. (2014). Effects of changes in the operating conditions on the stack gas temperature and stability of biomass fuelled boilers. Chem Eng Commun.**DOI :**10.1080/00986445.2014.886199.

Daskalakis M., V. Iyer. (2009). Finding energy savings with a biomass boiler. http://hpac.com/bse/finding-energy-savings-0609 [Accessed: 20th September, 14].

Forestry Commission, (2014). A guide to small-scale wood fuel (biomass) heating systems. Englandhttp://www.cse.org.uk/pdf/guide%20to%20small-scale%20wood-fuelled%20heating.pdf (Accessed: 19th September, 2014)

Strauss, W. (2013). An Analysis of the Effects of a 30% Credit on the Expected Demand for High Efficiency Wood Pellet, Wood Chip, and Agricultural Residue Fueled Boilers: The Cost/Benefit to the Treasury, and the Jobs Created. http://biomassthermal.org/pdf/Strauss_BTU_Act.pdf(Accessed: 10th September, 2014)

Thesis

Bakker, R. R. 2000. Biomass fuel leaching for the control of fouling, slagging, and agglomeration in biomass power generation. PHD Thesis, University of California, Davis, USA.

Verojporn S. (2011). Technical and Economic Feasibility of Using Waste Wood as Biomass Fuel for Small Scale Boiler and CHP in Solway Precast, Scotland. MSc Thesis, University of Strathclyde, Glasgow, UK.

Journal

Caputo, A. C., M. Palumbo, P. C. Pelagagge, F. Scacchia. (2005). Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass Bioenerg.28:35–51.

Demirbas, A. (2010). Social, economic, environmental and policy aspects of biofuels. EnergyEduSciTechnolPartB–EnergySci.2(1–2):75–109.

Khan, A. A.,W. D. Jonga, P. J. Jansens, and H. Spliethoff (2009). Biomass combustion in fluidized bed boilers: potential problems and remedies. Fuel Process Technol. 90:21 – 50.

Miles,T.R,L. L. Baxter, R.W. Bryers. 1995.Boiler deposits from firing biomass fuels. Biomass Bioenerg.10:125–38.

Saidura, R., E.Abdelaziza,A.Demirbasb,M.S.Hossaina,S.Mekhile. (2011). .A review on biomass as a fuel for boilers. Renew and Sust Energ Rev. 15:2262 – 2289.

Spliethoff, H.,K. R. G. Hein. 1998. Effectofco-combustion of biomass on emissions in pulverized fuel furnaces. Fuel Process Technol. 54:189-205.