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Thermal Simulation and Assessment of Water Tube Boiler for a Biomass Fuel Having Ash Fouling Characteristics

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ABSTRACT: Fossil fuels majorly emits greenhouse gases. The declining reserves, fluctuating prices and environmental harm of fossil fuels led to intensive search for an alternative to replace or complement petroleum derivatives as main fuel resource. Biomass appears as an attractive alternative, as it is renewable and available in abundance. Biomass is unique in its ability to provide solid, liquid and gaseous fuels which can be stored and transported, because of that a comprehensive characterization is needed, but biomass combustion in industrial applications has one of the important challenge of the fouling tendency and it affects performances of the boiler, the classical approach for this challenge is to activate soot blowing cycles with different strategies to clean the boiler. This paper represents the mathematical model for the thermal simulation and prediction on the fouling characteristics of different types of biomass fuels and finding suitability of biomass for the water tube boiler by controlling of its fouling characteristics

NOMENCLATURE

Nu_s	Nusselt number for steam
Nu_g	Nusselt number for gas
Re	Reynolds number
Pr	Prandtl number
Q_r	Radiative heat transfer
Q_c	Convective heat transfer
l	Length of section
w	Width of section
d	Depth of section
T_w	Temperature of water
T_f	Temperature of fuel
T_a	Temperature of air
T_g	Temperature of gas
k	Attenuation factor
L'	Beam length
m_f	Mass flow rate of fuel (kg/s)
C_v	Calorific value of fuel (KJ/Kg °K)
h_f	Enthalpy of fuel
h_a	Enthalpy of air
h_g	Enthalpy of gas
C_{pf}	Specific heat of fuel

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Vol. 7, Issue 8, August 2018

C_{pa}	Specific heat of air
h_{go}	Enthalpy of gas at exit of section
h_o	Gas side heat transfer coefficient (W/m^2K)
h_i	Water side heat transfer coefficient (W/m^2K)
A	Surface area (m^2)
σ	Stefan Boltzmann constant (W/m^2k^4)
ϵ_w	Emissivity of gas
ϵ_g	Emissivity of gas
m_g	Mass flow rate of flue gases (Kg/s)
m_s	Mass flow rate of steam (Kg/s)
C_{pg}	Specific heat of flue gases (J/Kg K).
C_{ps}	Specific heat of steam (J/Kg K).
T_{gi}	Temperature of gas at inlet of section (K)
T_{go}	Temperature of gas at outlet of section (K)
T_{wi}	Temperature of water inlet (K)
T_{wo}	Temperature of water outlet (K)
T_{si}	Temperature of steam inlet (K)
T_{so}	Temperature of steam outlet (K)
T_{sat}	Saturation temperature of water (K)
\ln	Natural log
P_c	Partial pressure of carbon dioxide
P_w	Partial pressure of water vapor
μ	Ash concentration (gm/Nm^3)

I. INTRODUCTION

The steam which is generated in boiler can be used for various purposes like electrical generation & process heating. Combustion of several fuels, such as coal, wood, oil and natural gas are the source of heat for boiler. There basically two types of boiler name as water tube boiler and fire tube boiler. A steam generator is complex integration of furnace, super heater, economizer along with various auxiliaries such as fans, combustors, dust collectors, stack etc. Now a day's biomass fuels are used instead of fossil fuels in boiler. Some of the example of biomass fuel are sugar cane trash, coffee husk, cotton stalk etc. In this paper, the effect of various biomass fuels on the fouling of a water tube boilers is studied.

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Construction of Water Tube Boiler

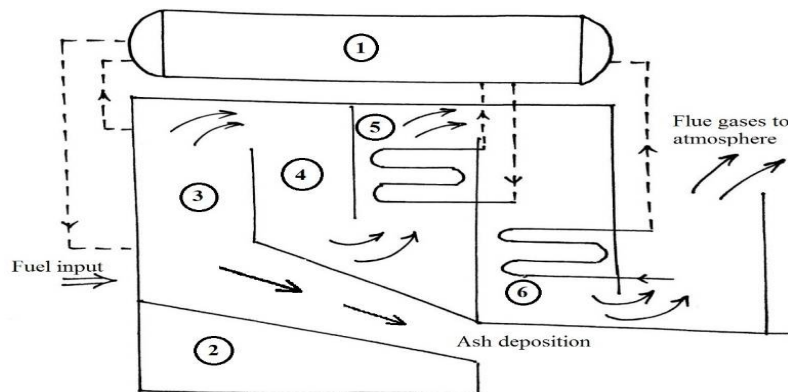


Figure 1: Water Tube Boiler

Fig-1. Shows the basic construction of water tube boiler showing combustor, membrane panel, superheater, evaporator & economizer. Following number notations have been used to show the various part of the boiler.

1. Steam drum
2. Reciprocating grate (Combustor)
3. Membrane wall
4. Superheater
5. Evaporator bank
6. Economizer

When the combustion takes place above the grate, the products of hot gases rise above combustion chamber and flow through the furnace of the boiler transferring heat to the membrane wall of the furnace. The partially cooled flue gases then transfer the heat to the steam in super heater section. The flue gas then flows to evaporator section and vaporizes the water into steam inside the tubes; the steam and water mixture formed then enters the boiler drum. The flue gas then goes to economizer section through insulated duct section to pre-heat the water. Flue gas finally exits from chimney to the atmosphere through the induced draft fan.

The water in boiler is pumped by a feed pump and it enters the economizer and then to the drum. The fed water is pre-heated in economizer. The water from drum enters to the membrane wall and evaporator bank through down comer and receives heat of the flue gas for evaporation. The water steam mixture rises due to buoyancy effect to induce natural circulation and reenters steam drum through the risers.

Biomass Used as Fuel

Biomass fuel is used to reduce the discharge of the greenhouse gases from the combustion. Biomass is fuel that is developed from organic materials. It is a sustainable and renewable source of energy used to create forms of power. It is considered to be as renewable source of energy because water and carbon dioxide contained inside the plants and animals are released back to the atmosphere when they are burned [1]. In this paper biomass fuels are used as bagasse, sugar cane trash, press mud, ground nut shell, soya husk, saw dust, coffee husk, chili spent and cotton stalk. For the case study done in this paper, briquette biomass is considered as a fuel.

The main challenges which occur while combustion of biomass fuels is fouling and slagging. Fouling is defined as the deposition or commonly known as collection of ash on the surface of the heat transfer equipment whereas slagging characteristics deposits on the furnace wall or other surface exposed to predominantly radiant heat. Fouling, slagging and corrosion occur due to ash composition together with Sulphur and chlorine contents which facilitates to move freely with many inorganic compounds especially with alkali compound including with potassium and sodium. Corrosion can be also caused either directly by deposits, by gas phase species or by a combination of both [2-5].

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Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

Biomass ash- related problems are not due to chlorine and alkaline metals but are also due to biomass ash fusion characteristics (AFC). AFC is an important factor in causing the tendency of fuels to form fused or partly fused slag deposition on surfaces of boiler. AFC increases MgO, CaO, Fe₂O₃, Al₂O₃ and K₂O content in ash. There is test which is based on a continuous process that can be characteristics by different temperatures. This test is known as ash fusion temperature (AFT). These temperatures are named as deformation temperature, sphere, hemisphere temperature and flow temperature.

A) Deformation temperature (DT) is that temperature at which rounding occurs, due to melting of tips or edges of test piece.

B) Hemisphere temperature (HT) is that temperature in which the test piece is approximately hemispherical and the height being equal to the base diameter.

C) Flow temperature (FT) is that temperature at which the test piece material has spread out so that its height is one-third of that at its hemispherical temperature [6].

To overcome the problems of slagging, fouling and corrosion, we can predict various temperature profiles at various sections of the boiler and also to predict biomass with less amount of moisture, silicon and many more content with respect to the boiler design so that to control slagging, fouling and corrosion of boiler and also to increase the efficiency of the boiler.

A biomass goods seems to be alternator fuel as it is renewable and abandoned. The only disadvantage of biomass combustion is it create ash which causes fouling and slagging in boiler. As fouling and slagging reduces the heat transfer rate, there is no specific method or tool to overcome this problem. So create a mathematical model which will predict in every section of water tube boiler using different biomass fuel and reduce the formation of fouling and slagging.

Mathematical modeling

A mathematical model is a used to simulate the heat transfer performance of the different section of the boiler and to predict the gas, water, steam and metallic wall temperature profile. This temperature profile is used to predict the boiler performance and the possibility of slagging and fouling of the boiler.

A development of a mathematical model consists of understanding the physical phenomenon, generation of governing equations, simultaneous solution of these equations and the validation of the mathematical model with experimental results. Fig-2 shows the flow chart of the mathematical model development process.

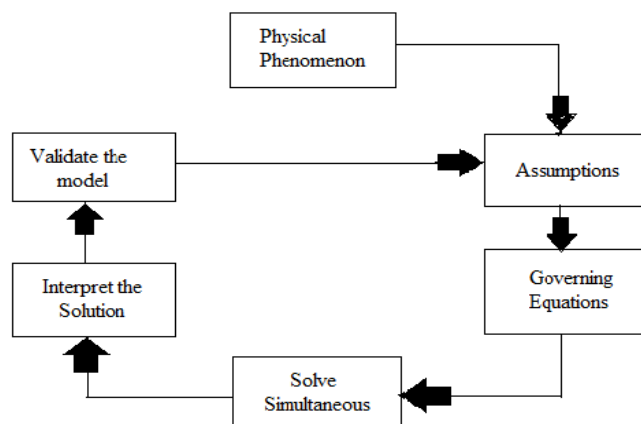


Figure 2

International Journal of Innovative Research in Science, Engineering and Technology

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Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

1) Physical Phenomenon

In water tube boiler air fuel is injected into the furnace. Due to combustion, the resulting high temperature flue gases produced in the furnace rejects partial heats to the surrounding water by luminous radiation. The flue gases at the end of the furnace enter into reversible chamber rejecting heat to the surrounding water by non-luminous radiation heat transfer. After transferring heat in reversal chamber flue gases into superheater section of water tube boiler. In this section majorly heat transfer takes place by convection. The flue gases from superheater section enter into the evaporator section through another reversible chamber. In the evaporator section, the dominant mode of heat transfer is convection. Finally, the flue gases enter to the economizer, where the flue gas heat is transferred to the feed water before exiting to chimney.

2) Assumptions

Furnace modeling is based on stirred reactor model, where a uniform flue gas temperature is assumed inside the complete furnace and heat transfer calculation is done on the uniform gas temperature. This model ignores the temperature gradient in the furnace. This model provides a fairly accurate result for a short furnace with high degree turbulence caused by secondary air injection. Semi luminous model of emissivity calculation is recommended in the combustion chamber and non-luminous model is assumed for the reversal section.

3) Governing Equations

The governing equations are the basic heat transfer equations and energy balance equations. In furnace and reversal zone 1 radiative heat transfer is considered while in superheater, evaporator and economizer convective heat transfer equations are used. Energy balance equations in each section are depending upon the number of elements that carry the energy.

Combustion Analysis

In combustion analysis, the input parameters for fuel properties and elemental composition in percentage are as shown in table. This fuel composition is used for the stoichiometric calculation to estimate the flue gas quantity and composition.

Table 1. Fuel Property

Parameter	Value
Fuel firing rate	1349.059(kg/hr)
Calorific value of fuel	3357(kcal/kgK)

Table 2. Elemental composition of fuel

Elements	Percentage
Carbon	41
Hydrogen	3.57
Sulphur	0.13
Moisture	16.36
Nitrogen	0.415
Oxygen	31.53
Mineral matter	7

International Journal of Innovative Research in Science, Engineering and Technology

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Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

Estimation of Gas Properties

Transport properties like specific heat (C_p), dynamic viscosity (μ) and thermal conductivity (K) play very important role in thermal modeling. These properties are estimated for individual gases as a function of temperature and the transport properties of gas mixture is calculated by using following equations [7].

1. Specific Heat at Constant Pressure

$$C_{pmax} = \frac{\sum(m_k \times C_k)}{\sum m_k} \quad (1)$$

Where,

m_k = mass fraction of flue gas component in kg/kg

C_k = mean specific heat of flue gas component in kJ/kg

2. Dynamic Viscosity

$$\mu_{mix} = \frac{\sum(\mu_k \times y_i \times \sqrt{M_i})}{\sum(y_i \times \sqrt{M_i})} \quad (2)$$

Where,

μ_k = dynamic viscosity of flue gas component in kg-m/s

y_i = mass fraction of flue gas component in kg/kg

M_i = Molecular mass of flue gas component in kg/mol

3. Thermal Conductivity

$$k_{mix} = \frac{\sum(k_i \times y_i \times \sqrt[3]{M_i})}{\sum(y_i \times \sqrt[3]{M_i})} \quad (3)$$

Where,

k_i = thermal conductivity of flue gas component in W/m °C

y_i = molecular fraction of flue gas component in kg/kg

M_i = molecular weight of flue gas component in kg/mol

Heat Transfer Calculation

The heat generated by combustion of fuel is utilized for heating up the circulating water in the different sections of boiler. The mentioned sets of equations are solved using Successive approximation method. Heat transfer and heat balance equation in different sections of the boiler depends on the heat transfer process in those sections.

1. Furnace

In furnace region, semi luminous radiation heat transfer is considered and the temperature profile is determined from the semi luminous radiation heat transfer equation and energy balance equation as follows respectively [8].

$$Q_r = \frac{\sigma A(T_{avg}^4 - T_w^4)}{\left(\frac{1}{\epsilon_g} + \frac{1}{\epsilon_w}\right) - 1} \quad (4)$$

Emissivity of gas is depended on attenuation factor and beam length which is calculated using following equation [8].

International Journal of Innovative Research in Science, Engineering and Technology

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Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

$$\epsilon_g = 0.9(1 - e^{-kL}) \quad (5)$$

Attenuation factor is depended upon the type of flame; the flame is of three types –luminous, semi-luminous, and non-luminous. A semi-luminous flame model is assumed for solid fuel fired boiler for the calculation of attenuation factor [8].

For semi-luminous flame-

$$k = \frac{(0.8 + 1.6P_W) \left(1 - \frac{0.38T_g}{1000}\right) (P_C + P_W)}{\sqrt{(P_C + P_W)L'}} + 7\mu' \sqrt{1/d_m^2 T_g^2} \quad (6)$$

Mean beam length (L') can be approximated by using following equation [8].

$$L' = 3.4 \left(\frac{\text{Volumne}}{\text{Surface area}} \right) \quad (7)$$

Energy equation is used to calculate the enthalpy of gas (h_g)

$$m_f h_f + m_a h_a + m_f C_v = Q_r + m_g h_g \quad (8)$$

Where, enthalpies of fuel, air and gas are approximated as follows [9].

- Enthalpy of fuel

$$h_f = C_{pf} T_f \quad (9)$$

- Enthalpy of air

$$h_a = C_{pa} T_a \quad (10)$$

- Enthalpy of gas

$$h_g = C_{pg} T_g \quad (11)$$

From the above equation, the value of T_g is obtained.

These equations are simultaneously solved by successive substitution to calculate the final gas temperature and heat transfer.

2. Reversal Zone

The Reversal zone shown in figure has non-luminous radiation heat transfer as the combustion occurs in furnace zone. Emissivity and radiation heat transfer can be calculated in the same way, as it is done in furnace. The attenuation factor is calculated for non-luminous flame as follows [8].

$$k = \frac{(0.8 + 1.6P_W) \left(1 - \frac{0.38T_g}{1000}\right) (P_C + P_W)}{\sqrt{(P_C + P_W)L'}} \quad (12)$$

Following equation represents energy balance in the reversal zone.

$$m_g h_g = Q_r + m_{go} h_{go} \quad (13)$$

From above equation, the value of Enthalpy of gas at exit of reversal zone (h_{go}) is obtained.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

Where,

- Enthalpy of gas [9]

$$h_{go} = C_{pg} T_{go} \quad (14)$$

From the above equation, the value of gas outlet temperature and heat transfer are obtained by successive substitution method.

3. Superheater

The temperature profile in super heater is calculated using convective heat transfer equation and heat capacity equation as follows [9].

$$Q_c = U A LMTD \quad (15)$$

U is Overall heat transfer co-efficient which is depended on the internal and external heat transfer co-efficient [9].

$$U = \frac{1}{\frac{1}{h_o} + \frac{1}{h_i}} \quad (16)$$

The external and internal heat transfer co-efficient are depended upon the Nusselt number of fluid which is further depended upon Prandtl number and Reynolds number of the fluid.

In the superheater, flue gas flows over the tube bank and Nusselt number is calculated by following equation [7].

$$Nu_g = 0.287 Re^{0.6} Pr^{0.33} \quad (17)$$

Nusselt number for steam is calculated by following equation, as steam flows inside the tubes [7].

$$Nu_s = 0.023 Re^{0.8} Pr^{0.4} \quad (18)$$

Steam and flue gas side Nusselt number is used for the calculation of flue gas and steam side heat transfer coefficients. LMTD (Log mean temperature difference) is calculated by using following equation.

$$LMTD = \frac{(T_{gi} - T_{so}) - (T_{go} - T_{si})}{\ln \left(\frac{T_{gi} - T_{so}}{T_{go} - T_{si}} \right)} \quad (19)$$

where T_{gi} is inlet gas temperature, T_{go} is outlet gas temperature, T_{si} is inlet steam temperature and T_{so} outlet steam temperature.

Following equations represent heat balance of steam and flue gas [9].

$$Q_c = m_g C_{pg} (T_{go} - T_{gi}) \quad (20)$$

$$Q_c = m_s (h_2 - h_1) \quad (21)$$

Where,

h_2 = Steam enthalpy of superheated steam (At T_{si})

h_1 = Vapour enthalpy at saturated steam (At T_{so})

T_{si} = Temperature of saturated steam

T_{so} = Temperature of superheated steam

International Journal of Innovative Research in Science, Engineering and Technology

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Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

The above equation heat transfer and heat balance equations are simultaneously solved to estimate heat transfer and flue gas and steam exit temperatures.

4. Evaporator

Temperature profile in evaporator is calculated using convective heat transfer equation as follows [9].

$$Q_c = U A \text{ LMTD} \quad (22)$$

The process of calculation is similar to that of super heater section with the exception of the formula of LMTD. The different formula is used as there is no phase change in the evaporator and the temperature of fluid inside the tube i.e. steam remain the same. This temperature of steam is equal to the saturation temperature at the corresponding pressure [9].

$$\text{LMTD} = \frac{(T_{gi} - T_{sat}) - (T_{go} - T_{sat})}{\ln \left(\frac{T_{gi} - T_{sat}}{T_{go} - T_{sat}} \right)} \quad (23)$$

Where, T_{gi} is inlet gas temperature, T_{go} is outlet gas temperature and T_{sat} is saturation temperature of steam.

5. Economizer

Temperature profile in evaporator is calculated using convective heat transfer equation (15). The process of calculation is similar to that of super heater section with the exception of the formula of LMTD. In this formula, instead of temperature of steam, take temperature of water as the fluid is in liquid state in economizer inside the tube [9].

$$\text{LMTD} = \frac{(T_{gi} - T_{wo}) - (T_{go} - T_{wi})}{\ln \left(\frac{T_{gi} - T_{wo}}{T_{go} - T_{wi}} \right)} \quad (24)$$

Where, T_{gi} is inlet gas temperature, T_{go} is outlet gas temperature, T_{wi} is inlet water temperature and T_{wo} is outlet water temperature.

4) Solving Simultaneous Equations and Validating Model

Gas and steam temperatures in each section are assumed to calculate gas properties, heat transfer coefficients and heat transfer. These values are used for the calculation of new value of gas and steam temperatures for successive substitutions. Finally, a converged solution is obtained for the gas and steam temperatures.

Fouling Index

Empirical equations in proposed in mathematical model have been derived to relate biomass ash melting temperature under reducing atmosphere. It can also be used for prediction ash melting temperature of bio mass with addition of various types of additives with known chemical composition [6].

The equation for ash melting temperatures i.e. shrinkage temperature(ST), deformation temperature(DT), hemisphere temperature (HT), flow temperature(FT) prediction under reducing atmosphere is depended upon three factors, namely Dolomite, CMK and PH. These factors can be calculated using following equations respectively [6].

- Dolomite Index-

$$D_{1x} = \frac{\%CaO + \%MgO}{\%SiO_2 + \%CaO + \%K_2O + \%MgO + \%Al_2O_3} \quad (25)$$

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

- Factor CMK-

$$f_{CMK} = \frac{\%CaO + \%MgO}{\%K_2O} \quad (26)$$

- Factor PH-

$$f_{PH} = \frac{\%CaO + \%MgO + \%K_2O}{\%SiO_2 + \%Al_2O_3} \quad (27)$$

The equation for ash melting temperatures i.e. shrinkage temperature (ST), deformation temperature (DT), hemisphere temperature (HT), flow temperature (FT) prediction under reducing atmosphere is- [6]

$$t = b_0 + b_1 \cdot SiO_2 + b_2 \cdot CaO + b_3 \cdot K_2O + b_4 \cdot MgO + b_5 \cdot Al_2O_3 + b_6 \cdot D_{1X} + b_7 \cdot f_{CMK} + b_8 \cdot f_{PH} \quad (28)$$

In above equation b_0 [°C] is a constant and $b_1 - b_8$ [°C] are regression coefficients which are different for DT, ST, HT and FT. These values are obtained from table given below.

Table 3. Fouling and slagging index^[6]

Indication	Variables	DT	ST	HT	FT
b0	CONST	854.7001827	959.55144	1005.429562	1172.865022
b1	SiO2	-10.20767818	33.128529	161.6122538	300.0681685
b2	CaO	368.138734	285.91131	-361.896417	-855.8003084
b3	K2O	35.4651134	-400.6883	-42.36404369	-921.9924019
b4	MgO	115.2004821	134.69116	-216.323586	-359.0323222
b5	Al2O3	1043.827256	977.81951	749.419564	682.7742762
b6	Dix	762.9269328	640.55331	588.3611569	411.2205704
b7	Fcmk	1.229534564	-3.27702	0.023970513	3.064078364
b8	Fph	-67.61601605	-32.84441	24.72771191	69.24627947
Sigma		51.62	52.11	59.32	59.8
R		0.935	0.937	0.892	0.914

Several theoretical indices that predict slagging and fouling behavior of a biomass fuel were calculated. In the base-to-acid ratio (B/A) (Equation (29)) the compounds of group B (the oxides in the numerator) are basic in nature and it has

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

low melting temperature, whereas the compounds of group A (the oxides in the denominator) are acidic in nature and it has higher melting temperature [10].

$$B/A = \frac{Fe_2O_3 + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} \quad (29)$$

This base-to-acid ratio can be used in a simplified form as $(B/A)_{simp}$ (Equation (30)) However, this deposition rate has been created for fuels with low phosphorus content, such as coal, it is not the case of biomass [10].

$$B/A (simp) = \frac{Fe_2O_3 + MgO + CaO}{SiO_2 + Al_2O_3} \quad (30)$$

Biomass contains phosphorus. The base-to-acid ratio plus phosphorus $(B/A(+P))$ was calculated (Equation (31)) for biomass [10].

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5}{SiO_2 + Al_2O_3 + TiO_2} \quad (31)$$

These above 3 ratios indicate the potential tendencies for slagging and fouling. Even, there are more ratios to calculate slagging and fouling – [10]

- Slagging Index

$$R_s = (B/A) \cdot S^d \quad (32)$$

Approx. range - $R_s < 0.6$ low slagging, $R_s = 0.6 - 2.0$ medium slagging, $R_s = 2.0 - 2.6$ high slagging, $R_s > 2.6$ extremely high slagging.

- Slag ratio

$$S_r = \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO} \cdot 100 \quad (33)$$

Approximate range- $S_r > 72$ low slagging, $72 \geq S_r > 65$ medium slagging, $S_r < 65$ high slagging.

- Fouling Index

$$F_u = (B/A) \cdot (Na_2O + K_2O) \quad (34)$$

Approximate range- $F_u \leq 0.6$ low fouling, $0.6 < F_u \leq 40$ high fouling, $F_u > 40$ extremely high fouling.

II. CASE STUDY

Simulation of a biomass fuel was carried out while doing this project. In this case study a biomass fuel was considered named as briquette for the simulation of water tube boiler. Briquettes are made from agricultural waste and are a replacement for fossil fuels such as oil or coal and can be used to heat boilers in manufacturing plant. The following data shows the composition and properties of biomass briquette: -

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 8, August 2018

Table 4. Composition and properties

Elements	Percentage
Carbon (%)	41
Hydrogen (%)	3.57
Nitrogen (%)	0.415
Oxygen (%)	31.53
Sulphur (%)	0.13
Moisture (%)	16.36
Mineral mater (%)	7
Calorific value	3357

The following data shows the input data of boiler: -

Table 5. Input data

Excess air (%)	50
Fuel consumption (kg/hr)	1349.059
Pressure	35

Developed mathematical model is used to simulate the design condition and the result is validated against the experimental results. Following table presents the comparison of experimental and simulation result.

Table 6. OUTPUT DATA

Furnace	Theoretical(°C)	Experimental(°C)
Flue gas outlet	1077.137	1073
Reversal zone		
Flue gas outlet	880.2064	877
Superheater		
Flue gas outlet (stage1)	739.1788	720
Steam outlet (stage1)	463.3507	445
Flue gas outlet (stage2)	617.1107	594
Steam outlet(stage2)	331.8607	313
Evaporator		
Flue gas outlet	405.7953	386
Water outlet	242.7232	230
Economizer		
Flue gas outlet	266.4627	243
Water outlet	170.9765	160

The error occurring in the furnace section and reversal zone section is about +3°C. The error in superheater, evaporator and economizer section is comparatively more but acceptable within limit (< 10 %). Mathematical model is used to study the effect of the various operating parameter on the performance of the biomass boiler.

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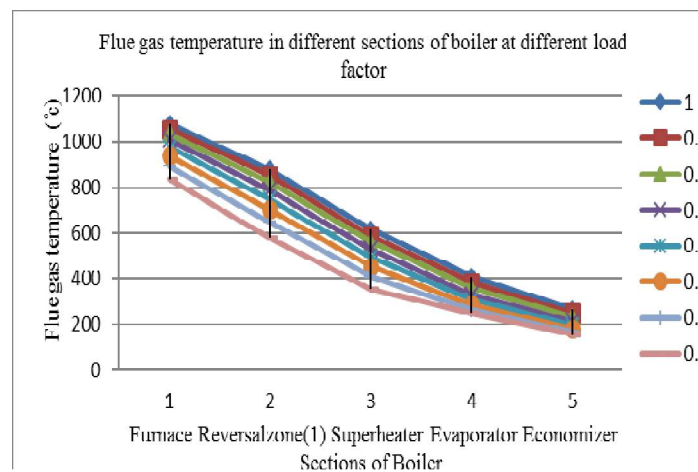
Vol. 7, Issue 8, August 2018

III. RESULTS

Effect of Input Parameter on the boiler Performance

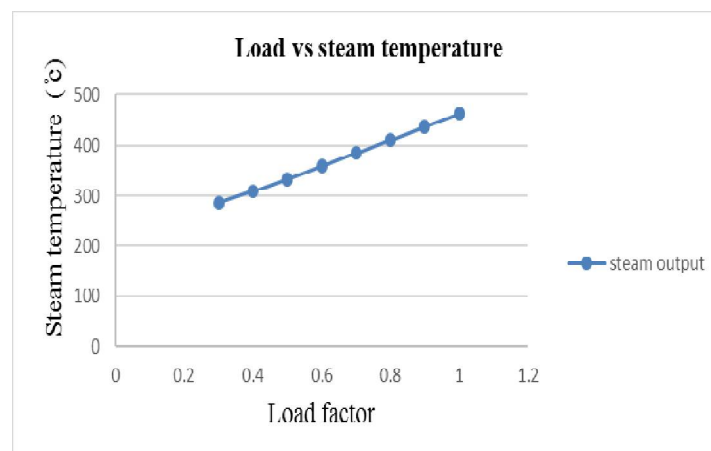
Variation in Load

The temperature of different section of boiler is calculated for different load conditions of the boiler by keeping another variable constant.



GRAPH 1

Graph 1 shows the different lines representing the temperature profile in different sections of boiler at different load conditions. From above graph, it is clear that flue gas temperature in different section of boiler increases with load. This can be primarily attributed to linear increase in the heat generation as a function of heat load.



GRAPH 2

The graph 2 shows that the superheater steam outlet temperature increases with increase in load. This is primarily due to increase in flue gas temperature at higher load condition.

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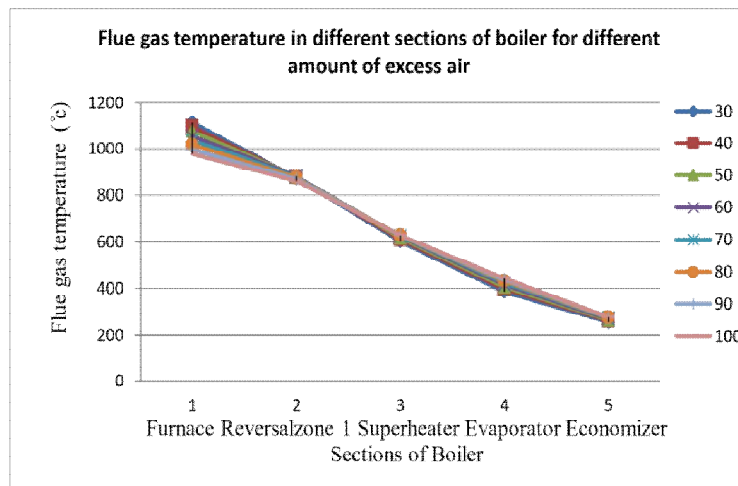
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Vol. 7, Issue 8, August 2018

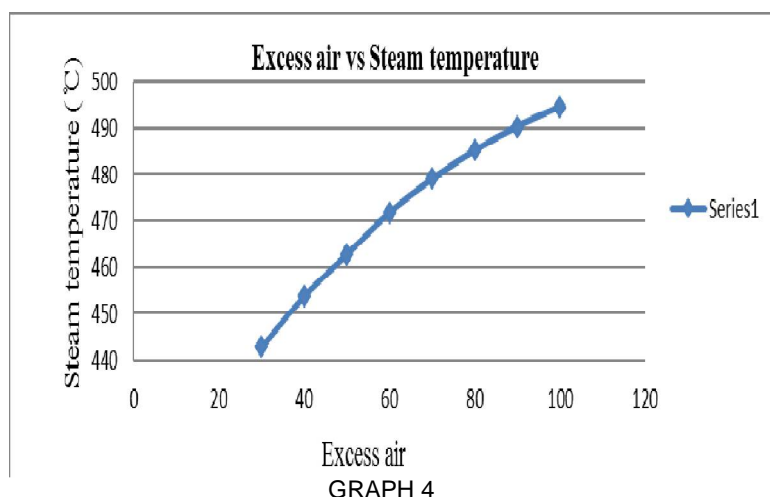
Variations in Excess Air

The temperature of different section of boiler is calculated by giving different amount of excess air to the boiler.



GRAPH 3

Graph 3 shows the different lines representing the temperature profile in different sections of boiler at different amount of excess air. From above graph, it is clear that providing high amount of excess air, the flue gas exit temperature in furnace and reversal chamber decreases.



GRAPH 4

The graph 4 shows that the steam output temperature rises with increasing amount of excess air. Increase in excess air increases heat transfer rate and thus increases steam temperature.

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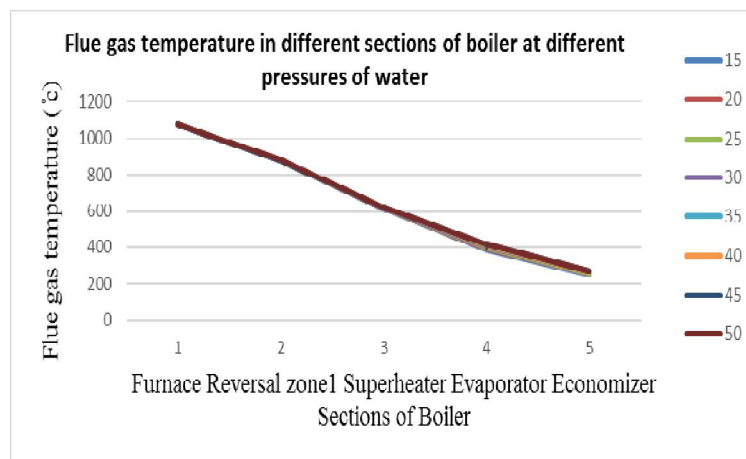
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Vol. 7, Issue 8, August 2018

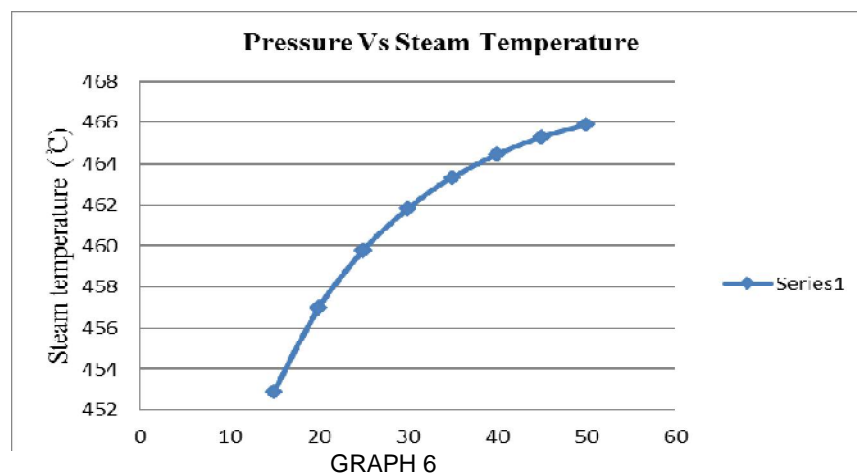
Variations in Pressure

The temperature of different section of boiler is calculated for different pressure conditions in the boiler.



GRAPH 5

The graph 5 shows the different lines representing the temperature profile in different sections of boiler at different pressure conditions. From above graph, it is seen that not much difference in flue gas temperature profile occurs at different pressure conditions of water.



GRAPH 6

The above graph 6 shows that the steam output temperature increases with increase in pressure of water.

Variations in Fuel

The temperature of different section of boiler is calculated for different types of biomass. This study is conducted to understand the effect of different biomass on boiler performance. Flue gas temperature at the exit of the furnace and reversal chambers are calculated and compared with deformation temperature of the biomass to check the possibility of fouling in convective tubes. The input conditions for load, excess air and pressure are taken same as that of the case study.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

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Vol. 7, Issue 8, August 2018

TABLE.7

	Bagasse	Sugar cane trash	Press mud	Ground nut shell	Soya husk	Coffee husk	Cotton stalk	Saw dust	Chili spent
Moisture	5.65%	6.36%	9.08%	7.66%	8.29%	10.95%	10.13%	12.74%	11.18%
Ash content	4.35%	8.55%	2.99%	3.51%	5.58%	7.58%	7.20%	11.08%	11.57%
Carbon as C	45.96%	43.87%	51.83%	48.19%	44.34%	45.78%	43.71%	47.70%	47.52%
Hydrogen as h	6.91%	6.69%	6.30%	6.93%	7.13%	6.54%	5.41%	6.45%	6.89%
Nitrogen as N	0.17%	0.31%	0.40%	0.91%	0.68%	1.39%	0.63%	0.13%	2.79%
Sulphur as S	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Oxygen as O	42.51%	40.48%	38.38%	40.36%	42.17%	38.61%	42.95%	34.54%	31.13%
NCV	3727	3449	4038	3823	3314	3051	3028	3171	3180
Furnace flue gas Output	1028.835	996.598	1036.01	1020.693	951.412	891.0577889	952.195	890.952327	875.709
Reversal zone flue gas output	879.3491	853.5410	899.183	879.9689	825.256	787.1694017	814.58	792.679835	785.349
DT	1073.132	983.736	1028.69	1061.44	1038.4214	732.2502567	652.200	1097.42559	1013.790
Fouling	No	Yes	Yes	No	No	Yes	Yes	No	No
Slagging	No	No	No	No	No	Yes	Yes	No	No

In above three tables 7 the temperatures for furnace and reversal zone are compared with deformation temperature of the respective fuel so as to know if the fuel causes fouling or slagging. As per above results obtained, we get to know that some fuels such as press mud, coffee husk and cotton stalk may cause fouling and slagging which reduces the efficiency of the

boiler. The low ash melting temperatures in these biomass fuels occur due to high content of potassium and low content of silica. To overcome the slagging and fouling for the above respective fuels of the boiler, different load condition can be a possible solution.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

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Vol. 7, Issue 8, August 2018

TABLE. 8

	Sugar cane trash	Sugar cane trash	Press mud	Press mud	Coffee husk	Coffee husk	Cotton stalk	Cotton stalk
Load factor	0.5	0.75	0.5	0.75	0.5	0.75	0.5	0.75
Furnace flue gas Output	885.264	952.422	799.236	834.020	674.356	699.54	696.965	724.465
Reversal flue gas zone output DT	702.6329	792.034	718.9407	770.9585	619.4398	657.380	636.1261	677.4042
	983.736	983.736	1028.69	1028.690	732.2502	732.250	652.2005	652.2005
Fouling	No	No	No	No	No	No	Yes	Yes
Slagging	No	No	No	No	No	No	No	Yes

From the table 8, it is seen that press mud and coffee husk can be used at partial load condition without occurrence of fouling and slagging. While in case of cotton stalk the load factor needs to be reduced less than 50% but at the risk of getting even lower temperature of steam.

IV. CONCLUSION

1. A mathematical model is developed in which calculation are carried out to find outlet temperature of different section of water tube boiler and to predict the fouling characteristics of different type of biomass.
2. For various biomass fuel, temperature calculations are carried out for different section of water tube boiler under different conditions like load factor, amount of excess air and pressure.
3. Temperature of each section of boiler and outlet steam temperature of superheater increases when load factor and pressure increases. Steam temperature also increases with increase in load factor and pressure.
4. Temperature of each section of boiler decreases with the outlet steam temperature of superheater increases, when amount of excess air increases. Steam temperature increases with increase in amount of excess air.
5. The deformation temperature is compared with furnace and reversal zone so as to know fuel causes fouling or slagging and to overcome fouling and slagging for different fuels of the boiler, different load conditions can be a possible solution.
6. From results two biomass fuels press mud and coffee husk can be used at partial load condition without occurrence of fouling and slagging and for cotton stalk the load factor needs to be reduced less than 50% but at the risk of getting low temperature of steam.
7. Theoretical temperature values which are calculated are validated with experimental temperatures values given by Thermax company with an error of +3 °C which are in acceptable range.

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Vol. 7, Issue 8, August 2018

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