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 derivates 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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Nuₜₕ</td>
<td>Nusselt number for steam</td>
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<tr>
<td>Nuₔₕ</td>
<td>Nusselt number for gas</td>
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<tr>
<td>Re</td>
<td>Reynolds number</td>
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<td>Pr</td>
<td>Prandtl number</td>
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<td>Qₑ</td>
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<tr>
<td>l</td>
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<td>Temperature of water</td>
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<td>L’</td>
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<tr>
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<td>Mass flow rate of fuel (kg/s)</td>
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<tr>
<td>Cᵥ</td>
<td>Calorific value of fuel (KJ/Kg°k)</td>
</tr>
<tr>
<td>hᵢₕ</td>
<td>Enthalpy of fuel</td>
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<td>hₔ</td>
<td>Enthalpy of gas</td>
</tr>
<tr>
<td>Cₚₑ</td>
<td>Specific heat of fuel</td>
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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.
Construction of 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].
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 a test which is based on a continuous process that can be characterized 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.
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>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel firing rate</td>
<td>1349.059(kg/hr)</td>
</tr>
<tr>
<td>Calorific value of fuel</td>
<td>3357(kcal/kgK)</td>
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</table>

<table>
<thead>
<tr>
<th>Elements</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Carbon</td>
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<tr>
<td>Hydrogen</td>
<td>3.57</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.13</td>
</tr>
<tr>
<td>Moisture</td>
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</tr>
<tr>
<td>Nitrogen</td>
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<tr>
<td>Oxygen</td>
<td>31.53</td>
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<td>Mineral matter</td>
<td>7</td>
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</table>
Estimation of Gas Properties
Transport properties like specific heat \((C_p)\), dynamic viscosity \((\mu)\) 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**

\[
C_{p_{\text{max}}} = \frac{\sum (m_k \times C_k)}{\sum m_k} \quad (1)
\]

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**

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

Where,
- \(\mu_k\) = 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**

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

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].

\[
Q_r = \frac{\sigma A (T_{avg}^4 - T_w^4)}{\left(\frac{1}{r_g} + \frac{1}{r_w}\right)} - 1 \quad (4)
\]

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

\[ k = \frac{0.8 + 1.6P_w}{\sqrt{(P_c + P_w)I'}} + 7\mu'\sqrt{\frac{1}{d_m^2T_g^2}} \]  

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

\[ L' = 3.4 \left( \frac{\text{Volume}}{\text{Surface area}} \right) \]  

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

\[ m_fh_f + m_ah_a + m_Cv = Q_r + m_gh_g \]  

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

- Enthalpy of fuel
  \[ h_f = C_{pf}T_f \]  

- Enthalpy of air
  \[ h_a = C_{pa}T_a \]  

- Enthalpy of gas
  \[ h_g = C_{pg}T_g \]  

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].

\[ k = \frac{0.8 + 1.6P_w}{\sqrt{(P_c + P_w)I'}} \]  

Following equation represents energy balance in the reversal zone.

\[ m_g h_g = Q_r + m_{go}h_{go} \]  

From above equation, the value of Enthalpy of gas at exit of reversal zone \( (h_{go}) \) is obtained.
Where,
- Enthalpy of gas [9]

\[ h_{go} = c_{pg} T_{go} \]  \hspace{1cm} (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 superheater is calculated using convective heat transfer equation and heat capacity equation as follows [9].

\[ Q_c = U \cdot A \cdot \text{LMTD} \]  \hspace{1cm} (15)

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

\[ U = \frac{1}{\frac{1}{h_o} + \frac{1}{h_i}} \] \hspace{1cm} (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].

\[ N_u_g = 0.287 \cdot \text{Re}^{0.6} \cdot \text{Pr}^{0.33} \] \hspace{1cm} (17)

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

\[ N_u_s = 0.023 \cdot \text{Re}^{0.9} \cdot \text{Pr}^{0.4} \] \hspace{1cm} (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.

\[ \text{LMTD} = \frac{(T_{gi} - T_{so}) - (T_{go} - T_{si})}{\ln \left( \frac{T_{gi} - T_{so}}{T_{go} - T_{si}} \right)} \] \hspace{1cm} (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].

\[ Q_c = m_g c_{pg} (T_{go} - T_{gi}) \] \hspace{1cm} (20)

\[ Q_c = m_s (h_2 - h_1) \] \hspace{1cm} (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
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].

\[
Q_c = UA \text{ LMTD}
\]  

(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].

\[
\text{LMTD} = \frac{(T_{gi} - T_{sat}) - (T_{go} - T_{sat})}{\ln \left( \frac{T_{gi} - T_{sat}}{T_{go} - T_{sat}} \right)}
\]

(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].

\[
\text{LMTD} = \frac{(T_{gi} - T_{wo}) - (T_{go} - T_{wi})}{\ln \left( \frac{T_{gi} - T_{wo}}{T_{go} - T_{wo}} \right)}
\]

(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**-

\[
D_{1x} = \frac{\% \text{CaO} + \% \text{MgO}}{\% \text{SiO}_2 + \% \text{CaO} + \% \text{K}_2\text{O} + \% \text{MgO} + \% \text{Al}_2\text{O}_3}
\]

(25)
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]

\[ t = b_0 + b_1 \cdot \text{SiO}_2 + b_2 \cdot \text{CaO} + b_3 \cdot \text{K}_2\text{O} + b_4 \cdot \text{MgO} + b_5 \cdot \text{Al}_2\text{O}_3 + b_6 \cdot D_{1X} + b_7 \cdot f_{\text{CMK}} + b_8 \cdot f_{\text{PH}} \]  

(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]

<table>
<thead>
<tr>
<th>Indication</th>
<th>Variables</th>
<th>DT</th>
<th>ST</th>
<th>HT</th>
<th>FT</th>
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<tr>
<td>b0</td>
<td>CONST</td>
<td>854.7001827</td>
<td>959.55144</td>
<td>1005.429562</td>
<td>1172.865022</td>
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<tr>
<td>b1</td>
<td>SiO2</td>
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<td>33.128529</td>
<td>161.6122538</td>
<td>300.0681685</td>
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<tr>
<td>b2</td>
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<td>285.91131</td>
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<td>K2O</td>
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<td>-921.9924019</td>
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<td>MgO</td>
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<td>134.69116</td>
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<tr>
<td>b5</td>
<td>Al2O3</td>
<td>1043.827256</td>
<td>977.81951</td>
<td>749.419564</td>
<td>682.7742762</td>
</tr>
<tr>
<td>b6</td>
<td>Dix</td>
<td>762.9269328</td>
<td>640.55331</td>
<td>588.3611569</td>
<td>411.2205704</td>
</tr>
<tr>
<td>b7</td>
<td>Fcmk</td>
<td>1.229534564</td>
<td>-3.27702</td>
<td>0.023970513</td>
<td>3.064078364</td>
</tr>
<tr>
<td>b8</td>
<td>Fph</td>
<td>-67.61601605</td>
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<td>24.72771191</td>
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<td>Sigma</td>
<td></td>
<td>51.62</td>
<td>52.11</td>
<td>59.32</td>
<td>59.8</td>
</tr>
<tr>
<td>R</td>
<td></td>
<td>0.935</td>
<td>0.937</td>
<td>0.892</td>
<td>0.914</td>
</tr>
</tbody>
</table>

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

\[
\frac{B}{A} = \frac{\text{Fe}_2\text{O}_3 + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2} \tag{29}
\]

This base-to-acid ratio can be used in a simplified form as \(\frac{B}{A}_{\text{simp}}\) (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 \[10\].

\[
\frac{B}{A}_{\text{simp}} = \frac{\text{Fe}_2\text{O}_3 + \text{MgO} + \text{CaO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3} \tag{30}
\]

Biomass contains phosphorus. The base-to-acid ratio plus phosphorus \(\frac{B}{A} + \text{P}\) was calculated (Equation (31)) for biomass \[10\].

\[
\frac{B}{A} = \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{P}_2\text{O}_5}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2} \tag{31}
\]

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**
  
  \[R_s = (\frac{B}{A}) \cdot S^4\] \tag{32}

  Approx. range - \(R_s < 0.6\) low slagging, \(0.6 \leq R_s < 2.0\) medium slagging, \(R_s = 2.0 \sim 2.6\) high slagging, \(R_s > 2.6\) extremely high slagging.

- **Slag ratio**
  
  \[S_r = \frac{\text{SiO}_2}{\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO}} \cdot 100\] \tag{33}

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

- **Fouling Index**
  
  \[F_u = (\frac{B}{A}) \cdot (\text{Na}_2\text{O} + \text{K}_2\text{O})\] \tag{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:
Table 4. Composition and properties

<table>
<thead>
<tr>
<th>Elements</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (%)</td>
<td>41</td>
</tr>
<tr>
<td>Hydrogen (%)</td>
<td>3.57</td>
</tr>
<tr>
<td>Nitrogen (%)</td>
<td>0.415</td>
</tr>
<tr>
<td>Oxygen (%)</td>
<td>31.53</td>
</tr>
<tr>
<td>Sulphur (%)</td>
<td>0.13</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>16.36</td>
</tr>
<tr>
<td>Mineral mater (%)</td>
<td>7</td>
</tr>
<tr>
<td>Calorific value</td>
<td>3357</td>
</tr>
</tbody>
</table>

The following data shows the input data of boiler:

Table 5. Input data

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess air (%)</td>
<td>50</td>
</tr>
<tr>
<td>Fuel consumption (kg/hr)</td>
<td>1349.059</td>
</tr>
<tr>
<td>Pressure</td>
<td>35</td>
</tr>
</tbody>
</table>

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

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

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.
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 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 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.
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 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.

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.
Variations in Pressure

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

![GRAPH 5](image-url)

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](image-url)

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.
In above three tables 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.
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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