Statistical Model Development and Analysis for Boiler Performance Evaluation

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Abstract

The present study has been carried out in order to increase the efficiency of the bio mass fired boilers, used in Indian sugar mills. Indirect methods for performance analysis is used in this study and further adjustments have been carried out and analyzed, special attention has been given on the importance of the stoichiometric ratio and steam power on the overall efficiency. Important general rules have been adopted from the complete regular tests following ASME and GOST methodologies and as a result, a simplified statistical model has been obtained. Since Boiler design optimization is very difficult process because efficiency of a boiler depends upon number of variable and it is very difficult to analyze all these variables simultaneously as well as change of any variable effect the performance of other variables also. This problem is analyzed in the current study and the dependency of various boiler losses are evaluated on the basis of various parameters special attention has been paid on stoichiometric air and steam generation rate.

Keywords-Boiler efficiency, stoichiometric ratio, steam generation rate, Statistical Model

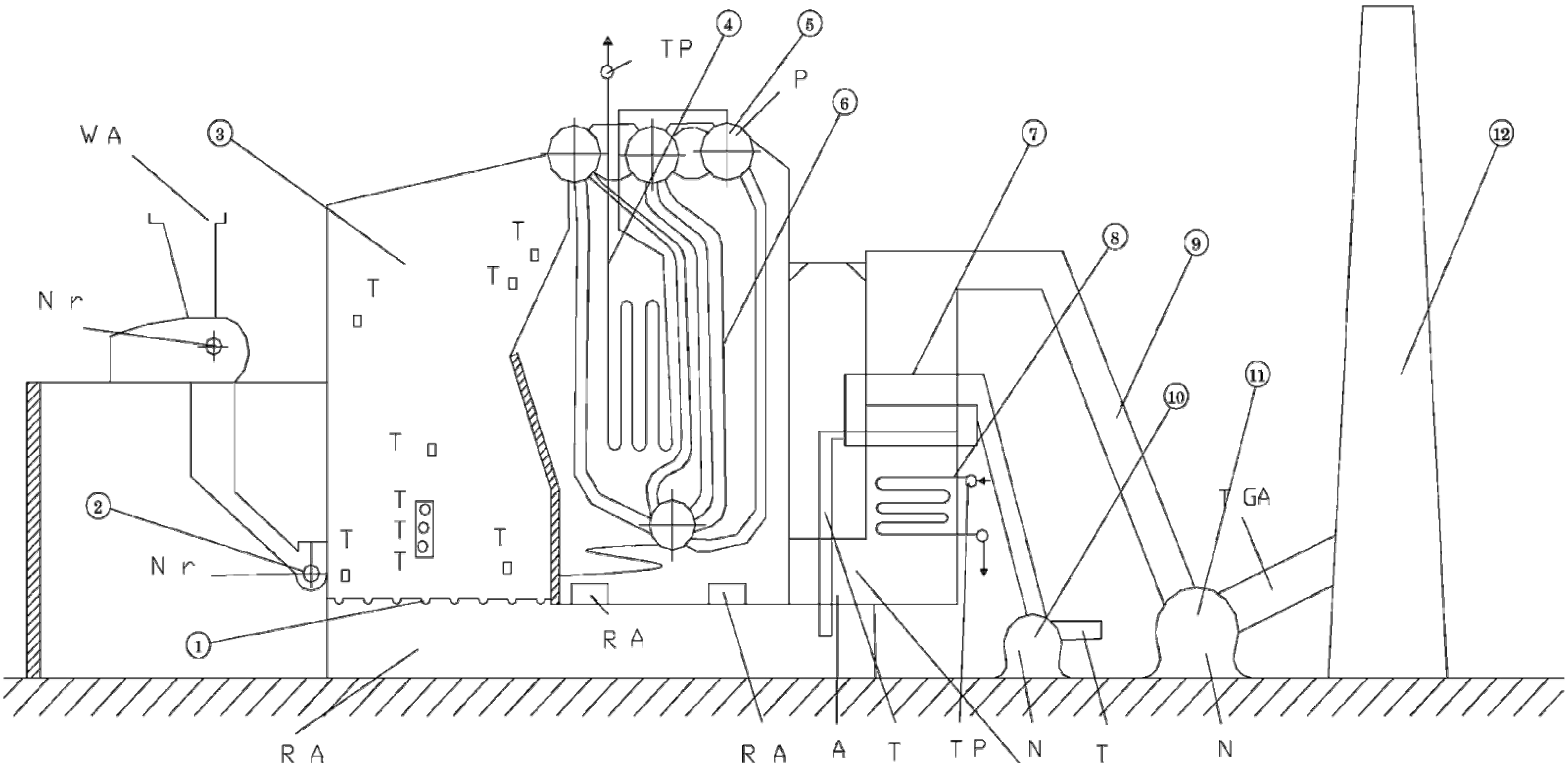
1. Fuel Characteristics-

Sugar cane is a large grass with a stalk that grows 2 –5 m tall. Only the stalk contains sufficient sucrose to be processed into sugar. All other parts of the sugar cane including leaves, roots, etc. are termed ‘trash’, which should be eliminated through the harvesting process. Once inside the mill, juice is extracted in the plant milling section by passing the chopped and crushed cane through a series of grooved rolls. The cane remaining after milling is the bagasse. Usually, it is a biomass-type fuel of varying composition, consistency and heating value. These characteristics depend on the climate, type of soil where the cane is grown, cane type, harvesting method, amount of cane washing and efficiency of the milling plant.

Bagasse is the matted cellulose fiber residue from sugar cane that has been processed in a sugar mill. Previously, bagasse was burned as a means of solid waste disposal. However, as the cost of fuel oil, natural gas, and electricity increased after the energy crisis in 1970, special attention was paid to alternative fuels in an efficient way. Consequently, conception of bagasse combustion changed and it has come to be regarded as a biomass fuel rather than refuse. Another important aspect is the increasing demand of bagasse as raw material for paper, furniture, and other industries. For all these reasons, the saving of this product has become one of the main objectives of the Indian sugar cane industry. The actual tendency is to use bagasse as fuel, especially for co-generation of electric power and steam, to increase its contribution to the country’s energy supply.
An average ultimate (dry) analysis of the fuel used in the tests gave a 46.27% (in weight) of carbon, 6.4% of hydrogen, 43.33% of oxygen, 0% of nitrogen, 0% of sulphur and 4% of ash. The moisture content of the bagasse ranged from 48 to 52% for all the analyzed samples.

2) Bagasse (low density bio mass) fired Boilers –

Figure.1 shows a detailed sketch of the main thermal surfaces of these facilities. The total height and depth of the boiler are 10.6 and 10.92 m, respectively, and the width (not shown in the figure-1) is 8 m. summarizing the main characteristics, a nominal steam power of 45Tons/hr is achieved for an approximate bagasse consumption of 22Tons/hr with a pressure and temperature of superheated steam of 32.5 bar and 420^{o}C respectively.



Bagasse fed to these boilers enters the furnace through five fuel chutes and is spread mechanically. The major part of the bagasse characterized by small and light pieces, burns in suspension. Simultaneously, large pieces of fuel are spread in a thin even bed on a stationary grate.

Major heating surfaces and important accessories used in this boiler is as shown in figure-1 are as follows-

1) Furnace grill
2) Spreader stoker
3) Furnace
4) Super heater
5) Drums
6) Generating tubes
7) Air pre heater
8) Economizer
9) exhaust gas duct
10) FD Fan
11) ID Fan
12) Stack
13) Ash hopper

The alphabets are used to denote some important data which is collected from the different equipment are as follows with their locations, as shown in figure-1

A ash concentration
GA exhaust gas composition analysis
N motor power
P pressure
r revolutions per minute
R residual weight
T temperature
W bagasse moisture percentage.

Nomenclature

η = Boiler efficiency
q = Heat losses of boiler in different sections
I = Enthalpy
α= Stoichiometric ratio
Q_1= Bagasse heating value
Suffix
eg = Exhaust gas stack
ea = External air

3. Performance Evaluation

As it is well-known, the overall efficiency of a boiler can be calculated using both direct and indirect methodologies. The direct measurement of the bagasse consumption is always subjected to many error sources. For this reason, in the present study, efficiency has been calculated using the indirect methodology. In general, this method relates the efficiency (η) of the boiler with the different heat losses through the equation

$\eta\ (\%) = 100 - \sum q$ ------- (1)

Where $\sum q = q_1 + q_2 + q_3 + q_4$
q_1=exhaust gas heat loss
q_2=chemical carbon loss
q_3=fixed carbon loss
q_4=conduction, convection and radiation heat losses
To quantify these losses following equations can be used [2]

$$q_2\ (\%) = (I_{eg} - \alpha_b I_{ea})\left(\frac{100 - q_4}{Q_1^P}\right) \quad \text{---- (2)}$$

$$q_3\ (\%) = \frac{\Delta H_C^{CO}}{Q_1^P} R_{CO/f} \times 100 \quad \text{--- (3)}$$

$$q_4\ (\%) = \frac{\Delta H_C^C A^P}{Q_1^P}\left[\sum a_i \frac{(100 - A_i)}{A_i}\right] \quad \text{---- (4)}$$

$$q_5\ (\%) = \frac{\sum \gamma_T F_i (t_i - t_{ea})}{B Q_1^P} \quad \text{---- (5)}$$

Here I_{eg} and I_{ea} are the exhaust gasses and external air enthalpy respectively, α_b is the stoichiometric ratio at the exit of the boiler,Q_1^P is the bagasse heating value (as received), ΔH_c^c is the carbon heat of combustion, ΔH_c^{co} is the CO heat of combustion, A^P is the ash content of bagasse from ultimate analysis of fuel and $R_{CO/F}$ is the rate of Kg of CO produced during the combustion of 1 Kg of fuel. Stoichiometric ratio $\alpha = m_{a/f} / m^0_{a/f}$ denotes the ratio of actual air fuel to the theoretical one. A_i refers to ash percentage in the different section of boiler obtained through laboratory analysis. In the same way a_i refers to the ratio ash content in different samples collected from the different sections of the boiler, to the total as in fuel(Kg $_{\text{of ash in sample}}$/Kg $_{\text{of ash in fuel}}$) Fi (surface areas of different wall sections),Ti wall temperature of these surfaces.

Simplified Statistical Model for Boiler Performance Evaluation-

Since the above equation which is used for boiler efficiency calculation involves number of operating variables which has to be measured for efficiency calculation. This difficulty makes the job tedious and requires lots of efforts. Problem can be solved by developing a mathematical model with single variable dependency. In present study efforts has been done to develop such model for the performance evaluation of bio mass fired boiler. Past experience shows that the major constituents of boiler heat loss shows strong dependency on two important operating parameters (α, D_{sh}) which measure in day to day operation.

i. In the above model equation (5) is used for the calculation of conduction, convection and radiation losses from boiler surfaces. Since these losses shows strong dependency on steam generation rate as compared to any other operating parameter and the best suited model which can be used for this purpose is [2]

$$q_5\ (\%) = \left(\frac{D_{sh}^{nom}}{D_{sh}}\right)\sqrt{\frac{100}{D_{sh}^{nom}}} \quad \text{------- (6)}$$

Practical result obtained from actual plant operation using equation (5) and (6) gives a very good agreement between the exact thermal analysis and the simplified one with an error of 5to10%.

ii. Equation (4) is used for the calculation of fixed carbon loss which gone in terms of ash. For the term inside the bracket in this equation, practical results show following inequality.

$$a_{fa}\frac{(100 - A_{fa})}{A_{fa}} \ggg a_{ah}\frac{(100 - A_{ah})}{A_{ah}} + a_{ba}\frac{(100 - A_{ba})}{A_{ba}}$$

Which means that the term corresponding to ash hopers and bottom ash can is neglected when compared to the fly ash. The term (100 -A_i) at any section of boiler can be replaced by the relation (C_{uf}=100 -A_i) and equation (4) now can be written as

$$q_4\ (\%) = \frac{\Delta H_C^C A^P}{Q_1^P}\left(\frac{C_{uf}}{100 - C_{uf}}\right) \quad \text{----(7)}$$

In order to obtain a simplified model, the influence of the stoichiometric ratio in the furnace (α_f) and steam generation rate (D_{sh}) on the unburnt cabon in fly ash $C_{uf,}$ has been plotted. Result of the experimental measurement are as shown in figure-2. As can be seen that the unburned carbon decreses with increases in steam power and increses with increase in stoichiometric ratio taking into account all the experimental data number of statistical model has been tried but the best suited model with minimum error is given by

$$C_{uf}\,(kg_c/kg_{fa}) = 0.854965 + 0.002724D_{sh} - 0.592243\sqrt{\alpha_f + \frac{1.3416}{\sqrt{D_{sh}}}}$$ ------ (8)

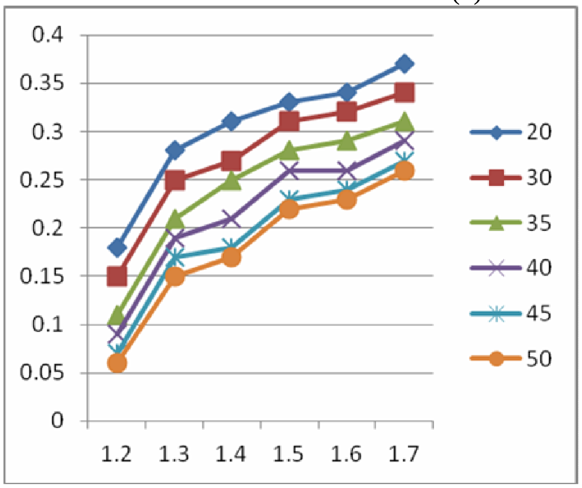


Figure-2

Now with the help of this equation fixed carbon losses can be easily estimated by measuring only two operating parameters that is stoichiometric ratio and steam generation rate.

iii. To obtain the chemical carbon loss by using conventional model which is given by the equation (3) the parameter $R_{CO/F}$ needed to be evaluated which can be given by the equation

$$R_{CO/f} = \mu_{CO/C}\left(\frac{C^P + 0.375S^P}{100}\right)\left(\frac{CO}{CO + CO_2}\right)\left(\frac{100 - q_4}{100}\right)$$

------ (9)

Where $\mu_{co/c}$ is the CO to C molecular weight ratio. C^P and S^P, are the carbon and sulphur contents of bagasse from ultimate analysis. CO and CO_2 are the carbon monoxide and Dioxide concentration in the stack gasses respectively. By putting this value of $R_{CO/F}$ in equation (3) only the term CO and CO_2 remains to be determined from the experiments in order to establish a correlation for the chemical carbon loss.

Again in order to get the influence of the stoichiometric ratio in the furnace (α_f) and the steam generation rate (D_{sh}) on CO and CO_2 a curve has been plotted between[CO/(CO+CO_2)], α_f and D_{sh} results are as shown in figure-3. The best statistical model which satisfy these practical results is given by

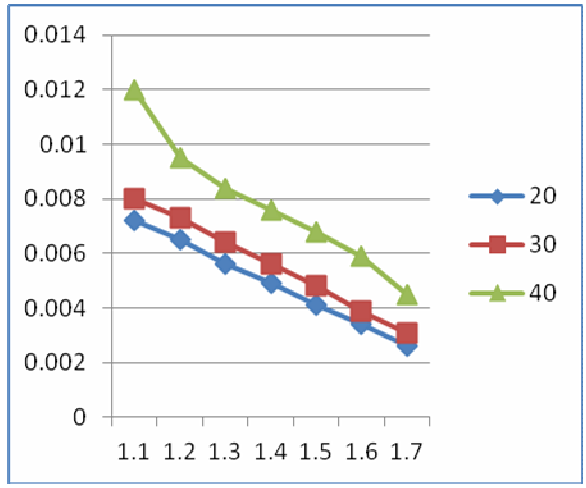


Figure-3

$$\frac{CO}{CO + CO_2} = 0.0275 - 0.01485\alpha_f - \frac{0.0165}{\sqrt{D_{sh}}}$$

------------- (10)

iv. Finally, to calculate the exhaust gasses heat loss q_2 the exhaust gas enthalpy I_b needs to be calculated which further depends upon stack temperature $T_{eg.}$ Again the results of T_{eg} are plotted against α_f and D_{sh} which are as shown in figure-4. Results shows linear dependence of T_{eg} on stoichiometric ratio while antiproptional to the steam generation rate. The best model which suited these results with minimum error is given by

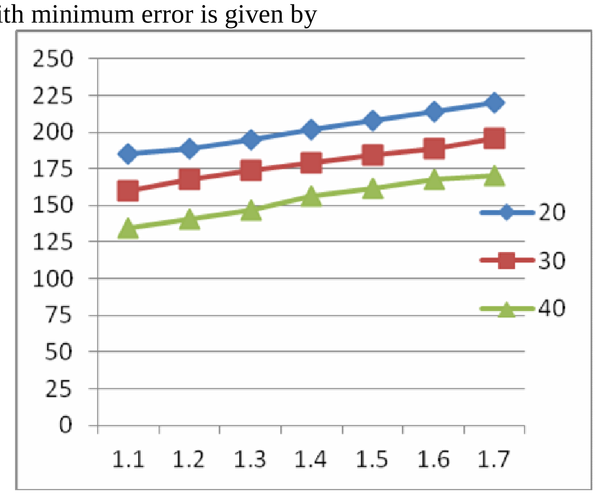


Figure-4

$$T_{eg}\,(^{\circ}C) = 172.32 + 24.76\alpha_f + \frac{43.22}{\sqrt{D_{sh}}} - 0.213(D_{sh})^{0.33}$$

---------- (11)

By putting this model in equation (2) the dependency of exhaust losses on stoichiometric ratio (α_f) and steam generation rate (D_{sh}) can be analyzed.

4) Conclusion-

A methodology for the determination of heat losses and efficiency of a bio mass fired boilers has been established and a simplified model developed for the performance evaluation of the boilers using bagasse as fuel, as a result three statistical-based model given by the equations. (6), (10) and (11), have been obtained, which can be used for the calculation of fixed carbon, chemical carbon, and exhaust gas heat losses, as a function of stoichiometric ratio in the furnace α_f and the steam generation rate D_{sh}.

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