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PERFORMANCE EVALUATION OF A BIOMASS BOILER ON THE BASIS OF HEAT LOSS METHOD AND TOTAL HEAT VALUES OF STEAM

Anjum Munir*, Jahan Zeb Alvi, Sidrah Ashfaq and Abdul Ghafoor

Department of Farm Machinery and Power, University of Agriculture, Faisalabad, Pakistan
***Corresponding author's e-mail: anjum.munir@uaf.edu.pk**

Pakistan being an agricultural country has large resources of biomass in the form of crop residues like wood, wheat straw, rice husk, cotton sticks and bagasse. Power generation using biomass offers an excellent opportunity to overcome current scenario of energy crises. Of the all biomass resources, bagasse is one of the potential energy sources which can be successfully utilized for power generation. During the last decade, bagasse fired boilers attained major importance due to increasing prices of primary energy (e.g. fossil fuels). Performance of a bagasse fired boiler was evaluated at Shakarganj Sugar Mill, Bhone-Jhang having steam generation capacity of 80 tons h^{-1} at 25 bar working pressure. The unit was forced circulation and bi-drum type water tube boiler which was equipped with all accessories like air heater, economizer and super-heater. Flue gas analyzer and thermocouples were used to record percent composition and temperature of flue gases respectively. Physical analysis of bagasse showed gross calorific value of bagasse as 2326 kCal kg^{-1}. Ultimate analysis of bagasse was performed and the actual air supplied to the boiler was calculated to be 4.05 kg per kg of bagasse under the available resources of the plant. Performance evaluation of the boiler was carried out and a complete heat balance sheet was prepared to investigate the different sources of heat losses. The efficiency of the boiler was evaluated on the basis of heat losses through boiler and was found to be 56.08%. It was also determined that 2 kg of steam produced from 1 kg of bagasse under existing condition of the boiler. The performance evaluation of the boiler was also done on the basis of total heat values of steam and found to be 55.98%. The results obtained from both the methods were found almost similar. Effects of excess air, stack and ambient temperature on the efficiency of boiler have also been evaluated and presented in the manuscript.
Keywords: Biomass, boiler accessories, gross calorific value, heat balance, boiler efficiency

INTRODUCTION

Energy is backbone of a country. Thermal, hydel and nuclear power are major sources of electricity in Pakistan. The country has been facing severe energy crisis for the last one decade. Present demand of energy has exceeded the supply level. Total nominal power generation capacity of Pakistan is 65% by thermal, 33% by hydel and 2% by nuclear (Anonymous, 2012).

Scarcity of energy is not only the problem of Pakistan but also is the problem of the globe as a whole particularly that of the developing countries. As the world faces the energy crisis, therefore researchers from all over the world are in the process of searching alternate sources of energy particularly the currently defined wastes, which in actual is no more are wastes but resources such as bagasse. Therefore, using bagasse not only solves the problem of solid waste disposal but also a significant amount of power is produced (Khan, 2010).

Pakistan is at 5th position in the world sugarcane production having an average annual production of 50 million tons cane and 10 million tons of bagasse (Syed *et al*., 2001). Bagasse is also a cheap source for power generation. Furthermore, processing cost of sugar is decreased much due to self-power generation of sugar industry.

Boiler efficiency is the difference between the amount of energy present in steam and amount of energy in boiler feed water as a percentage of the energy in fuel. It can be calculated by subtracting all heat losses fractions from 100. Major advantage of using heat loss method is that errors in measurement do not make significant change in boiler efficiency (Anonymous, 2012). Important heat losses in the boiler are due to dry flue gases, H_2 and moisture present in the bagasse, moisture present in the air, incomplete combustion and other unaccounted losses. Efficiency of boiler can be improved by minimizing all these heat losses which occur through the boiler (Zeitz, 2003).

Munir *et al.* (2004) determined efficiency of a bagasse fired boiler having steam generating capacity of 60 tons h^{-1} with steam pressure and temperature as 23 kg cm^{-2} and 350°C, respectively. The efficiency was recorded as 77.86% on the basis of net calorific value for 50% moisture content in bagasse.

Sosa-Arnao *et al.* (2013) evaluated the performance of a bagasse fired boiler on the basis of both lower heating values (LHV) as well as on the higher heating values (HHV). Efficiency calculated by using both of methods were analyzed and compared as well. Results using both methods showed considerable difference in boiler efficiency. Boiler efficiency determined on the basis of HHV showed the effect of bagasse moisture while it was hidden in other case.

Muhaisen and Hokoma (2012) found that the exhaust gas and feed water temperature have a significant effect over boiler efficiency. Efficiency of boiler can also be improved by 1% by controlling amount of excess air supplied to the boiler (Gupta *et al.,* 2013). Although a great deal of work has been done to determine efficiency of the boiler and factors most affecting boiler efficiency; however, additional work is still required to be done before a precise quantification of the phenomena. Therefore, complete description of heat losses, effect of stack temperature, ambient temperature and excess air on boiler efficiency were also expressed in this paper. Therefore, the main objectives of this study were to determine combustion efficiency of the bagasse fired boiler and to check the effect of excess air, stack and ambient temperature on boiler efficiency.

MATERIAL AND METHODS

This study was focused on the determination of boiler efficiency and to quantify the effect of excess air, stack and ambient temperature on boiler efficiency. Major components of this boiler were grate, bagasse feeders, combustion chamber or furnace, water or mud drum, steam drum, super heater, economizer, air-heater, induced draught (ID) fan, forced draught (FD) fan, secondary draft (SD) fan, boiler feed water pumps and some auxiliary equipments. To conduct the performance analysis, data had been collected for a bagasse fired boiler having steam production capacity of 80 tons h^{-1} and 25 bar working pressure. The boiler heating surface and furnace area were 2386 m^2 and 39.5 m^2, respectively. The boiler bank was comprised of 1096 tubes each having 50.8 mm diameter.

In contrast to conventional gas or oil fired boilers, this boiler has specially been designed to make use of heat present in flue gases. A heat recovery system consisting of air heater, economizer and superheater was installed at the boiler to attain maximum combustion efficiency. In addition, FD (160 kW), ID (1335 kW) and SD (75 kW) fans have been employed to maintain balanced draft in the boiler. In this boiler, bagasse has been kept in suspension using spreader stoker furnace which has considerably low ash contents up to 4%. Small amount of ash is also escaped along with flue gases (Misplon *et al.,* 1996). Air heater utilizing heat from boiler flue gases pre-heats the ambient air up to 250°C when bagasse starts burning (Wienese, 2001). As pressure in boiler was kept very high (25 bar), boiling point of water rises up to its saturation point between 200 to 220°C. As it is sensible heat to raise temperature of water, therefore, exit temperature of economizer is kept well below the boiling pint of water. Excessive water is removed from mud drum of the boiler using blow off valve. Furthermore, wet steam in steam drum is superheated up to 350°C by using heat from flue gases to get dry steam.

Three rectangular shaped bagasse feeders have been used to supply bagasse from main carrier to furnace. Bagasse is a fibrous material which has been left by last mill of the tandem, after juice extraction. The layout of the assessed boiler is shown in Figure 1.

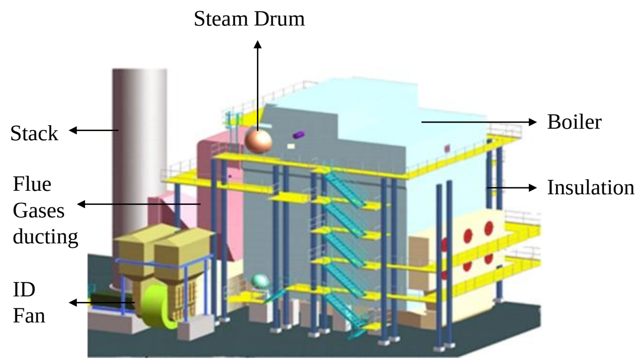

Figure 1. Isometric view of bagasse fired boiler

Firstly, physical analysis of bagasse was carried out to calculate the gross calorific value (GCV) of bagasse. Physical analysis provides quantitative measurement of the physical components of bagasse. The composition of bagasse has been expressed in terms of its fiber, brix and moisture content. GCV of bagasse has been calculated using Equation 1 (Don *et al*., 1977).

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$$GCV = 19605 - 19605(\%moisture) - 19605(\%ash) - 3114(\%brix) \quad kJ.kg^{-1} \qquad (1)$$

Secondly, ultimate analysis of bagasse was performed to calculate actual air supplied (AAS). This analysis has given quantitative measurement on the basic components of bagasse. The AAS has been calculated by the stoichiometric equations of the various elements.

Theoretical air required for complete combustion was calculated using Equation 2.

$$Th_{air} = \frac{11.43C + \left\{34.5\left(\frac{H_2 - O_{2b}}{8}\right)\right\} + 4.32S}{100} \qquad (2)$$

Where Th_{air} is the theoretical air required for complete combustion in kg per kg of bagasse. The C, H_2, O_{2b} and S are the percent of carbon, hydrogen, oxygen and sulfur present in bagasse, respectively.

Excess air supplied (EA) was calculated using Equation 3.

$$EA = \frac{O_{2f}\ percent}{21 - O_{2f}} \times 100 \quad (3)$$

Where O_{2f} is the percentage of oxygen in the flue gases and EA is the excess air supplied.

Actual mass of air supplied was calculated using Equation 4.

$$AAS = \frac{(1 + EA)}{100} \times Th_{air} \quad (4)$$

Mathematical calculations of heat losses**:** While calculating the boiler efficiency, the losses taken into consideration have been presented in Figure 2.

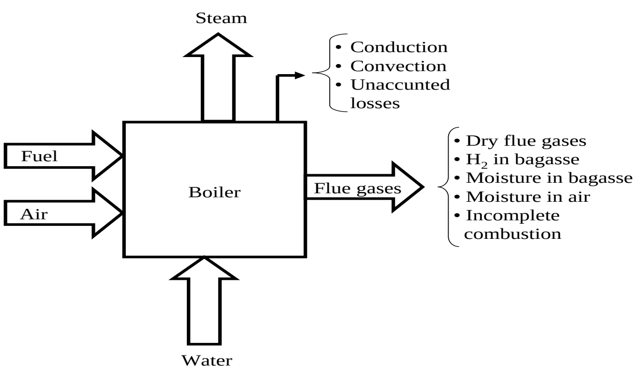

Figure 2. Layout of boiler heat losses

Percent heat loss due to dry flue gases can be calculated using Equation 5 (Anonymous, 2012).

$$L_1 = \frac{m\ C_{P1}(T_f - T_a)}{GCV\ of\ bagasse} \times 100 \quad (5)$$

Where m is the mass of dry flue gas in kg per kg of fuel, L_1 is the percentage heat loss due to dry flue gases, T_f is the flue gas temperature in K, T_a is the ambient temperature in K and C_{p1} is the specific heat of flue gas (average value is taken as 0.23 kCal kg^{-1}) (Anonymous, 2012).

$$m = (\text{mass of dry flue gas per kg of bagasse}) + (\text{mass of N2 per kg of bagasse}) + (\text{mass of N2 in actual mass of air provided}) \quad (6)$$

Percent heat loss due to evaporation of water formed because of H_2 present in bagasse can be calculated using Equation 7.

$$L_2 = \frac{9H_2\{584 + C_{P2}(T_f - T_a)\}}{GCV\ of\ bagasse} \times 100 \quad (7)$$

Where C_{p2} is the specific heat of superheated steam (0.45 kCal kg^{-1}) and L_2 is the percent heat loss due to evaporation of water.

Percent heat loss due to evaporation of moisture present in bagasse can be calculated using Equation 8.

$$L_3 = \frac{M\{584 + C_{P2}(T_f - T_a)\}}{GCV\ of\ bagasse} \times 100 \quad (8)$$

Where M is the moisture present per kg of bagasse, L_3 is the percentage of heat loss due to evaporation of moisture in bagasse.

Percent heat loss due to moisture present in air can be calculated using Equation 9.

$$L_4 = \frac{\mathrm{AAS} \times \text{humidity factor} \times C_{P2}(T_f - T_a)}{\text{GCV of bagasse}} \times 100 \quad (9)$$

Where L_4 is the percent heat loss due to moisture present in air with humidity factor as 0.019 kg water per kg dry air.

Percentage heat loss due to incomplete combustion can be calculated using Equation 10.

$$L_5 = \left\{\frac{(\%CO \times C)}{(\%CO + \%CO_2)}\right\} \times \frac{5744}{\text{GCV of bagasse}} \times 100 \quad (10)$$

Where *%CO*, *%CO₂* and *L₅* are the percentage volume of CO gas leaving the boiler, actual percentage volume of CO_2 gas leaving the boiler and percent heat loss due to incomplete combustion, respectively.

Percent heat loss due to radiation and other unaccounted loss can be calculated using Equation 11.

$$L_6 = 0.548\left\{\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right\} + 1.957(T_s - T_a)^{1.25}\sqrt{\frac{(196.85V_m + 68.9)}{68.9}} \quad (11)$$

Where L_6 is the percent heat loss due to radiation and other unaccounted loss in Wm^{-2}, V_m is the wind velocity in m s^{-1}, T_s is the surface temperature of the boiler in K.

However, the actual radiation and convection losses are difficult to assess because of particular emissivity of various surfaces, its inclination, airflow patterns etc. Typically these losses were considered between 2-3% (Anonymous, 2012).

The boiler efficiency (η) was calculated using Equation 12.

$$\eta = 100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6) \quad (12)$$

Effect of stack and ambient temperature on boiler efficiency was also observed using thermocouples. Similarly, the effect of excess air on boiler efficiency was also recorded. The boiler efficiency was also checked on the basis of total values of steam using steam table against working pressure and temperature of the boiler. At the end, the results were compared by using both methods.

RESULTS AND DISCUSSION

The present research was conducted for a water-tube biomass boiler comprising of steam and mud drum and bank tubes. This paper presents an algorithm to calculate the efficiency of all types of biomass boilers on the basis of heat losses through the boiler as well as total heat values of steam. The experimental data were recorded affecting the boiler efficiency such as excess air, ambient and stack temperature. Physical and ultimate analysis of bagasse were also carried out. Different instruments like thermocouples, draft gauges, probe type flue gas analyzer, anemometers were used to measure different parameters.

In order to determine GCV of bagasse, physical analysis of the bagasse was performed and the results have been shown in Figure 3. Physical analysis of bagasse gives quantities of physical components of bagasse.

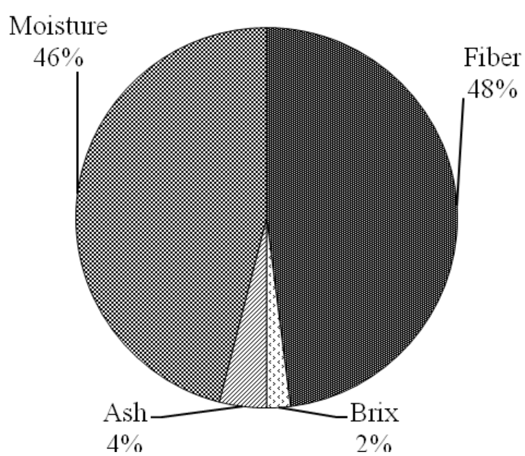

Figure 3. Physical analysis of Bagasse

Figure 3 depicts that bagasse is mainly composed of water contents (moisture) and fiber. However, small amounts of ash and brix have also been noticed. Wenise *et al*. (2000) also calculated percentage of fiber, moisture, ash and brix in bagasse and found to be 44, 50, 4 and 2 percent respectively. Results also verified that bagasse has major portion of fiber and moisture while ash and brix are on minor side. The experiments were replicated six times and the average value (GCV) of bagasse was calculated to be 2326 kCal kg^{-1}(9738 kJ kg^{-1}) using Eq. (1)

The ultimate analysis performed to calculate theoretical air required for complete combustion of bagasse has been shown in Figure 4.

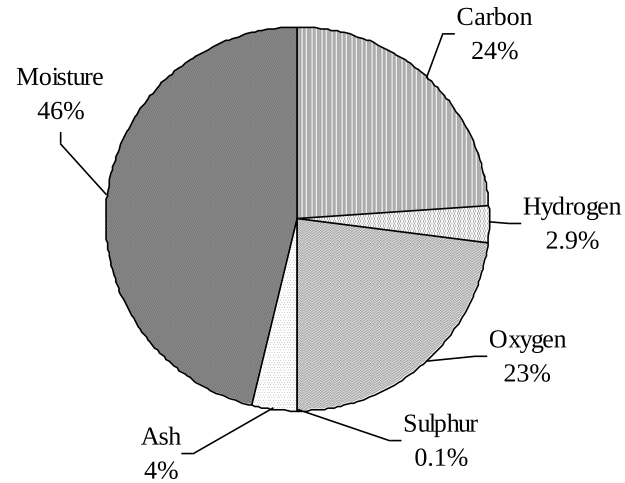

Figure 4. Ultimate analysis of bagasse

This analysis resulted basic chemical elements of bagasse. This analysis has been used to obtain the actual air needed for combustion based on the stoichiometric equations for various elements. Mass of dry flue gases was calculated to be 4.02 kg per kg of bagasse using Equation 6.

Finally, it formed the corner stone in the calculation of the boiler efficiency using the heat loss method. A comprehensive heat balance sheet has been prepared to calculate all heat losses using Eq. (5) to Eq. (10) as shown in Table 1.

Table 1 shows that boiler efficiency was calculated to be 56.08% for 80 tons h^{-1} steam generating capacity operated using bagasse (biomass) on the basis of gross calorific value. Remaining 43.95% were assumed as the heat losses from the boiler in the form of dry flue gases, moisture, hydrogen and due to incomplete combustion. The biomass boiler losses due to moisture and partial combustion of C to CO are comparatively higher as compared to moisture in air and heat loss due to radiation and other unaccounted losses. However, these losses could be reduced using controlled condition. The results obtained in this study are in accordance with the findings of Sosa-Arnao *et al.* (2013).

***Boiler efficiency based on total heat values of steam*:** This method is based on determination of bagasse and steam flow rates separately. The boiler was equipped with all necessary instrumentation like pressure gauges, thermocouples, water level indicators, Pyrometer, steam and bagasse flow meters. The mass flow rates of steam and bagasse were determined using steam and bagasse flow meters. Table 2 shows complete data sheet recorded from 09:00 to 16:00 hours for

Table 1. Heat balance sheet of biomass bolier

Input /Output Parameter	kcal per kg of bagasse	%
Heat Input in bagasse	2326	100
Various heat losses in boiler		
Dry flue gas loss	184.21	7.92
Loss due to hydrogen in bagasse	175.61	7.55
Loss due to moisture in bagasse	309.35	13.30
Loss due to moisture in air	7.44	0.32
Partial combustion of C to CO	310.05	13.33
Loss due to radiation and other unaccounted loss	34.89	1.50
Total losses	**1021.55**	**43.92**
Boiler efficiency = 100 - (L1+L2+L3+L4+L5+L6) = 56.08%		

Sr. No.	Time	Ambient Temp		Fuel		Feed Water		Steam			Flue gas analyzer			
		Dry bulb (°C)	Wet Bulb (°C)	Flow Rate (kg h^{-1})	Temp. (°C)	Flow Rate (kg h^{-1})	Temp. (°C)	Flow Rate (kg h^{-1})	Pressure (kg cm^{-2})	Temp. (°C)	O_2 (%)	CO_2 (%)	CO (%)	Temp. (°C)
1	9:00	28	24	34500	35	69000	95	69000	25	350	5.7	12.6	3.5	235
2	10:00	29	25	36500	35	76000	96	73000	25	350	5.5	13.2	3.6	232
3	11:00	30	26	36000	36	750000	95	72000	25	350	5.6	12.9	3.6	230
4	12:00	30	26	38000	36	76000	97	76000	25	350	5.8	12.5	3.7	233
5	13:00	30	26	33000	36	68000	95	66000	25	350	5.9	11.5	3.8	236
6	14:00	30	26	35000	36	72000	96	70000	25	350	5.6	12.3	3.5	232
7	15:00	29	25	33000	36	67000	96	66000	25	350	6.2	11.9	3.4	235
8	16:00	29	26	36000	35	73000	97	72000	25	350	6.1	12.4	3.9	234
Avg.		29.4	25.4	35250	35.6	72000	95.5	70500	25	350	5.8	12.4	3.6	233

80 tons h^{-1} steam generating capacity boiler at Shakrganj Sugar Mills Bhone- Jhang.

The average steam and bagasse flow rates were recorded to be 70500 and 35250 kg h^{-1}, respectively. The average values of steam pressure and temperature were recorded to be 25 kg cm^{-2} and 350°C, respectively. Total heat value at 25 kg cm^{-2} and 350°C was determined from steam table and found to be 3126 kJ kg^{-1}. The average value of feed water temperature was 95.6°C. The average value of steam produced per kg of bagasse was found to be 2.0 kg per kg of bagasse.

The total heat put into one kg of steam was calculated by subtracting the enthalpy of feed water (sensible heat) from enthalpy of steam (sensible + latent) (Munir *et al*., 2004).

The sensible heat of feed water is always equal to rise in temperature from freezing point.

So, total enthalpy of steam is found to be 3126 kJ kg^{-1}.

Total enthalpy of water $= m\,C_p\,\Delta T$

$= 1 \times 4.187 \times 95.6$

$= 400.28$ kJ kg^{-1}

Total heat put into one kg of steam $= 3126 - 400.28$

$= 2725.72$ kJ kg^{-1}

Total heat put into one kg of bagasse $= 2725.75 \times 2$

$= 5451.44$ kJ kg^{-1}

Boiler efficiency $= 5451.44/9738$

$= 55.98\%$

The boiler efficiency on the basis of total steam value of the boiler was calculated to be 55.98% and the results had been similar with that calculated on the basis of heat loss method. Results have shown that boiler is in good working condition.

Effect of excess air on boiler efficiency: The effect of excess air on boiler efficiency is shown in Figure 5.

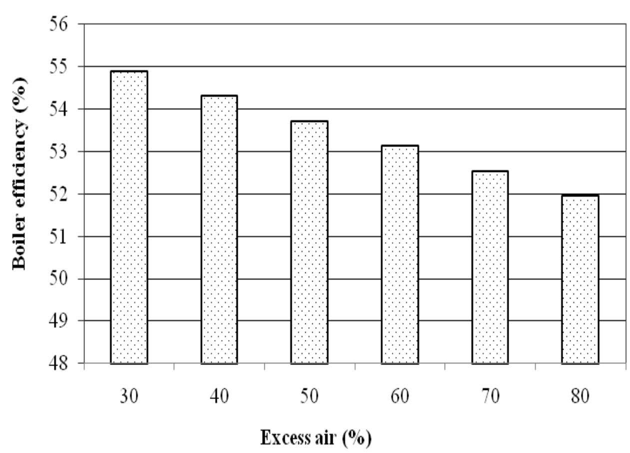

Figure 5. Effect of excess air on boiler efficiency

Figure clearly indicates that decreasing the excess air to the boiler increased the boiler efficiency. In fact, for the best performance of a boiler, the stoichiometric air-fuel ratio is required. However, the designer increases the quantity of air so that each bagasse particle should have contact with air for complete combustion. In this case, the excess quantity of air does not take part in any combustion process. Consequently, the surplus air along with other flue gases reaches the same temperature and it will be assumed as the sensible heat losses by flue gases. So higher the quantity of excess air, greater will be the sensible heat losses and consequently lower will be the boiler efficiency. This concludes that an optimum air fuel ratio should be maintained to ensure complete combustion as well as to decrease the excessive losses due to surplus air.

***Effect of ambient temperature on boiler efficiency*:** Efficiency of boiler varies slightly with variation in ambient temperature (Fig. 6). This variation is due to the fact that under the same boiler conditions, the high temperature air entering the boiler increases the air temperature in the air-heater to a higher degree comparatively. So the heat recovery from the heat produced by bagasse is reduced and resultantly boiler efficiency increases.

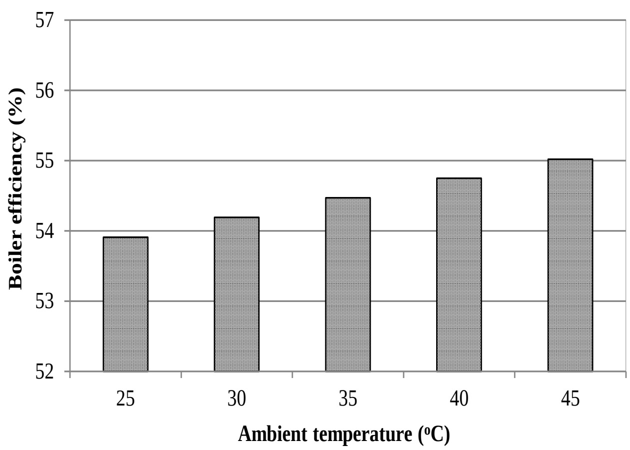

Figure 6. Boiler efficiency against different ambient temperatures

***Effect of stack temperature on boiler efficiency*:** Effect of stack temperature on boiler efficiency is shown in Figure 7. The theoretical efficiency of a heat engine is increased by increasing the heat supplied and decreasing the heat rejected. In boiler section, the main object is to reduce the heat as minimum as possible. However, this figure should not be reduced below 200°C in order to prevent it from corrosion due to presence of sulfur in the flue gases. In fact, the flue gases contain moisture contents as a part of combustible gases. At lower temperature, the sulfur reacts with water and forms fumes of dilute sulfuric acid which can corrode the stack if maintained for a prolong period of time. Keeping all facts in view, the temperature is maintained at 200°C. Boiler efficiency is a function of stack temperature and it decreases by increasing stack temperature as shown in Figure 7.

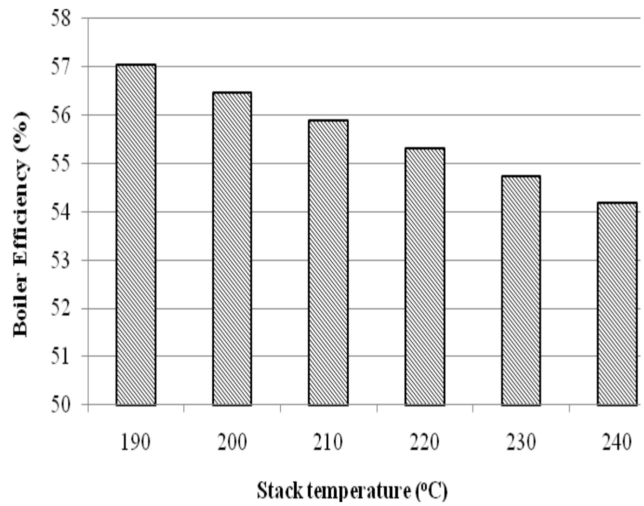

Figure7. Boiler efficiency against different stack temperature

***Conclusions*:** This paper provides the complete detail to determine the boiler efficiency of a biomass boiler on the basis of total heat values of steam (direct method) as well as heat loss method (indirect method). A complete algorithm along with formulae has been presented in the paper to determine sources of heat losses. In this paper, the performance evaluation of an 80 tons h^{-1} steam generation capacity was calculated using the total heat values of the steam and using heat loss method. Boiler efficiency was calculated to be 54.07% on the basis of gross calorific value of the bagasse which shows that boiler is in good working. The major losses were due to incomplete combustion, moisture in the fuel and dry flue gas loss. About 10 percent reduction in excess air increases boiler efficiency by 0.5 percent. About 20°C reduction in flue gas temperature increases the boiler efficiency by 1%. It was also noted that the boiler efficiency was increased by 1% by decreasing the temperature difference of flue gas temperature by 22°C. The results have shown that two kg steam was produced per kg of the bagasse for the biomass boiler using bagasse as fuel at 46% moisture content. The efficiency of the boiler was also calculated on the basis of total steam value and found to be 55.98% under the existing condition of the boiler. This value is approximately the same as obtained by using the heat loss method (indirect method) thus showing the accuracy of the indirect method for the performance evaluation of any biomass boiler.

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