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Development of a Biomass Fired Stream Boiler

M.A. Akintunde [1] and K. A. Adetoro[2]

[1]*Mechanical Engineering Department, The federal University of Technology, PMB 704 Akure, Ondo State, Nigeria.*

[2]*Mechanical Engineering Department, Faculty of Engineering, Osun state Polythechnic Iree, P.M.B 301 Iree. Osun state. Nigeria.*

Abstract: *The current trends and future outlook highlights the need for utilization of the vast untapped energy potential of agro-waste and biomass. In this work a mini- biomass fired stream boiler was developed. The aim is to use agro-waste to generate high pressure steam to drive micro turbine for the purpose of generating electricity. The concept of a simple water tube boiler and a free circulation method, where water and stream mixture circulates through the tubes naturally, was used in the design of the boiler. The system was designed to generate steam at pressure of 3 bar and 150 ^oC temperature. After testing the system produces steam at 3 bar and 146^oC. Hence the system has a temperature efficiency of 97.33% and pressure efficiency of 100%. Actual efficiency of the boiler based on the usage (combustion) of fuel wood was estimated to be 61.8%. The overall efficiency was estimated to be 60.02%.*

Keywords*: design, boiler, generation, biomass, fuel-wood, steam, combustion.*

I. Introduction

It is a known fact that, energy consumption is on increase as the world population, inventions of electrical equipment and appliances grow. Another contributing factor is the industrial revolution and advent of sophisticated industrial equipment and instrumentations. Most of the energy utilized by these equipment and instruments are non-renewable. Judging from research outputs, the present use of carbon based non-renewable energy is unsustainable (RC, 2004; Akintunde, M. A. 2002; & Adegoke C. O. and Akintunde, M. A. 2003). On the other hand the issues of atmospheric pollution, carbon loading and climate change put man at a high risk if the usage of non-renewable energy is not controlled.

Biomass, the oldest form of renewable energy, has been used for thousands of years. However, the emergency of fossil fuels has caused the drastic decline in its usage. According to Arvind (2009), only about 13% of the primary energy supply is from biomass though there are regional differences. Developed countries derived around 3% of their energy from biomass, while in Africa the proportion ranges between 70% and 90%. The aims of this work in to design a biomass-fire steam boiler that uses biomass and other industrial wastes as fuel.

Steam boiler is a sealed vessel, purposely designed to generate high pressure steam. The primary function of the boiler, in a heating system, is to transfer heat produced by combustion to a medium, mostly water. Steam is an almost invisible gas generated by heating water in a sealed chamber at a very high temperature and pressure.

II. Design Analysis

The various parts of the machine are as follows: steam water tank; water tubes; superheater; grate; ash collector; DC blower; pressure relief valve and temperature/pressure gauges. The capacity of the system is to produce steam at a temperature of 423 K and 3 bar pressure. The system is to handle 10 liters of water per hour. The amount of heat (Q_t) required to produce steam at the expected temperature and pressure is given by equation (1).

$$Q_t = Q_s + Q_l \tag{1}$$

Where: Q_s is the sensible heat and Q_l the latent heat

Also Q_s is given by equation (2) and Q_l by equation (3).

$$Q_s = m_w C_v (T_h - T_c) = m_w h_f \tag{2}$$

$$Q_l = m_w l \tag{3}$$

Where: m_w is the mass of water, l = h_{fg} = latent heat of vaporization and C_v is the specific heat at constant volume $T_h - T_c$ is the change in temperature under sensible conditions.

The entropy of super-heater steam (h_{sup}) is given by equation (4).

$$h_{sup} = h_f + xh_{fg} \text{ or } h_{sup} = h_f + h_{fg} + c_p(T_{sup} - T_s) \tag{4}$$

The volume of steam generated per unit time is given by equation (5) under superheated conditions.

$$V_{sup} = \frac{V_g T_{sup}}{T} \tag{5}$$

The boiler code of the ASME specifies that the gas side is to be used when calculating heating surfaces. It follows that in determine the heating surface of water tube boilers, the outside diameter or the tube area exposed to the flue gas is used. Hence the quantity of heat transfer through the surface (Q) is given by equation (6).

$$Q = 2\pi r_o L h_o (T_1 - T_0) = \frac{2\pi k L (T_0 - T_1)}{ln\left(\frac{r_0}{r_1}\right)} = 2\pi r_1 L h_1 (T_1 - T_2) \tag{6}$$

The U-values for both outside and inside of the heat transfer surface is as given respectively by equations (7) and (8).

$$\frac{1}{U_0} = \frac{1}{h_0} + \frac{r_0}{k} + \frac{r_0}{k} ln\frac{r_0}{r_1} + \frac{1}{h_1}\frac{r_0}{r_1} \tag{7}$$

$$\frac{1}{U_1} = \frac{1}{h_1} + \frac{r_1}{k} + \frac{r_1}{k} ln\frac{r_0}{r_1} + \frac{1}{h_1}\frac{r_1}{r_0} \tag{8}$$

The gas mass velocity G was calculated form equation (9).

$$G = \frac{12W_g}{N_w L(S_t - d_0)} \tag{9}$$

The design of combustion chamber is to a large extent determined by the burner capacity. In order to determine the heat transfer in the combustion chamber, it was assumed that radiation is the dominant process of heat transfer. Simplifying the flow inside the combustion chamber, by assuming a plug flow results in heat balance given by equation (10).

$$Q_m C_p(T).dT - \pi D_{cl} \ddot{q_{rad}}(x)\,dx = 0 \tag{10}$$

Where: $\ddot{q_{rad}}(x) = E\sigma T^4$

The method suggested by Hottle (1981) was used in estimating the emission coefficient (E). Assuming O_2 and H_2O as the radiation gas species; the emission coefficient is related to the concentration temperature of the gas and the geometry of the chamber. The latter is expressed by a mean beam length, L_b. Solving equation (10) and assuming a constant heat capacity results in equation (11).

$$T_e = \sqrt[3]{\frac{Q_m c_p T_s^3}{3\epsilon\sigma\pi(DL_b)_{cl}T_b^3 + Q_m c_p}} \tag{11}$$

Pressure drop along the pipe of length (L) is given by equation (12).

$$P_1 - P_2 = f\left(\frac{L}{D}\right)\left(\frac{\rho U_{av}^2}{2g_c}\right) \tag{12}$$

Where: $f = \frac{64}{Re}$

Pressure drop (ΔP) across the tube banks is given by equation (13).

$$\Delta P = Nf\left(\frac{\rho U_{av}^2}{2g_c}\right) \tag{13}$$

The expression for *f* is as shown in equation (14).

$$f = 4\left(0.004 + \frac{0.08\left(\frac{S_t}{D}\right)}{\left(\frac{S_t - D}{D}\right)\left(0.43 + \frac{1.13D}{S_t}\right)}\right) Re_{e\,max}^{-0.15} \quad (14)$$

The design entails a lot of equations. All these equations cannot be presented in this article. The rest of design equations for heat transfer, flue gases, stress due to internal pressure, circumferential or hoop stress and other parameters can be found in the works of Olumide et al., (2012).

Some of the results of the design calculations are as shown in Table 1. Some of these results were obtained by using charts and steam Tables in connection with the governing equations.

Table 1. Result of Design calculation

Parameters	H_{sup} (kJ/kg)	Q_T (kJ/kg)	t (mm)	V_{sup} (m^3/hr)	Q_t (kJ)	M_f (kg/hr)	σ_t (MPa)	σ_c (MPa)	τ (MPa)	D (mm)
Design value	2761.3	2656.8	1.1	0.6303	26,568	1.6605	385	665	308	282

The combustion chamber is to house 17 kg of wood chips per hour. It was found that average composition of wood (organic) is: 50% C; 6.1% H and 43.9% (O+N), (Saidur, et al., 2008). The minimum air requirement for complete combustion was expressed as $\left(\frac{8}{3}C + 8H + s\right) kg$ while for complete combustion is $\left(\frac{100}{28}\right)\left(\frac{8}{3}C + 8H + s\right) kg$ (Chagger, et al., (1998). Substituting values for C, H, and S, the minimum value of required air was found to be 6.01 kg and for complete combustion 1.1 kg. The developed biomass-fired steam boiler is shown in Plate 1.

The boiler tank, pipes, super-heater and water tubes were made of galvanized mild steel. The frame structure, boiler body, fuel grate, ash tray and blower housing were made of mild steel. Kaolin (clay) was used as thermal insulation for boiler body. Also fiber was used as thermal insulator for boiler tank. The sizes and shapes of all the components can be found in the works of Olumide et al,. (2012). The construction of the boiler was carried out at both the Federal University of Technology, Akure Central Workshop and at the workshop of the Engineering Materials Development Institute, Akure.

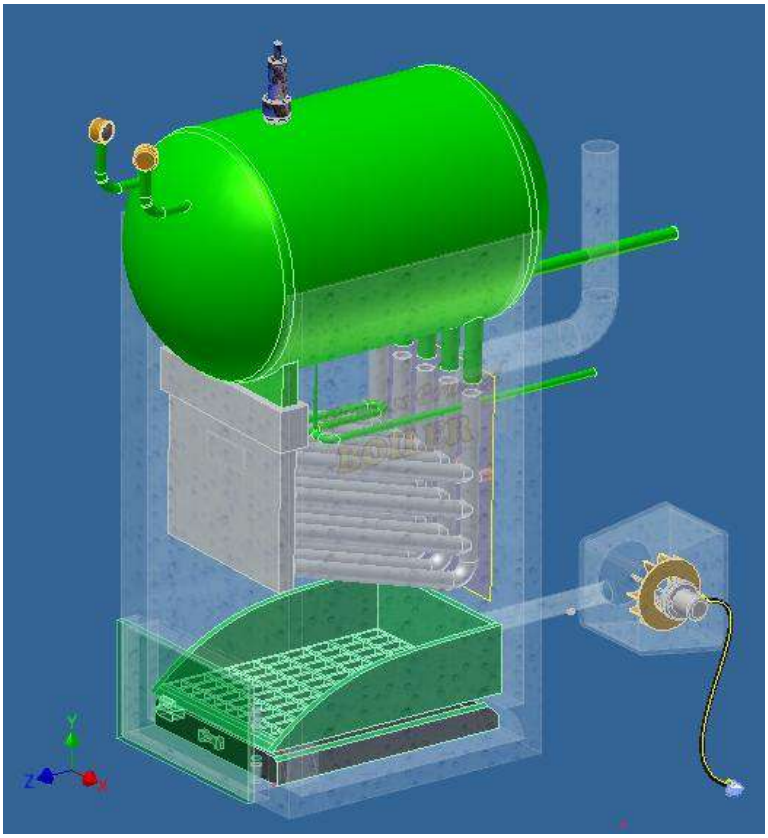

Plate 1 The designed biomass-fired steam boiler geometric

III. Results And Discussion

Plates 2 and 3 show the experimental set-up and incomplete combustion in the combustion chamber respectively. During the test; although the system was designed for 3 bar and 150^{o}C; a pressure of 3 bar was achieved while the maximum temperature was 146^{o}C. It takes 30 minutes before a steady state was reached. The temperature efficiency was estimated to be 97.33%. The system is capable of producing current and voltage enough to charge 12 V battery.

Plate 2. Experimental set-up of the biomass boiler.

Plate 3.The boiler showing incomplete combustion of biomass

During the experimentation a total biomass of 2.686 kg was used as against the designed value of 1.6605 kg. This is attributed to losses and the incomplete combustion of the fuel-wood in the chamber (Plate 3). The boiler efficiency was then estimated to be 61.8%.

IV. Conclusion

In this work a biomass-fired steam boiler was designed and constructed. The machine uses wood chips as fuel. It has a capacity of producing steam at 3 bar and 146^{o}C. The system was designed to generate steam at 3 bar and 150 ^{o}C. Hence the system has a temperature efficiency of 97.33% and pressure efficiency of 100%. The deferent in temperature was attributed to the incomplete combustion experienced in the combustion chamber and heat loss, since there is no perfect insulator of heat energy. Actual efficiency of the boiler based on the usage of fuel wood was estimated to be 61.8%. The overall efficiency was estimated to be 60.02%.

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