Peer-Reviewed Article

Energetic and Exergetic Evaluation of Biomass Fired Water Heating System

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This paper deals with thermal and exergy efficiencies of biomass fired water heating system. Water heating system is extensively suitable to generate hot water in rural areas. The developed water heating system was tested with Desi babul (*Acacia nilotica*) wood. Thermal and exergy efficiencies of the system were estimated at 54.5 percent and 6.79 percent, respectively.

Keywords: Biomass water heater; Exergy efficiency; Thermal efficiency; Rural applications

Introduction

It is well known fact that biomass is an indirect source of solar energy, and it is a renewable energy resource available where the climatic conditions are favorable for plant growth and production [1-3]. Biomass combustion is going to increase worldwide for a provision of heat and electricity. Approximately 60% of total biomass is used for energy purposes are traditional biomass that is fuel wood, while crop residues and the remaining biomass are used for modern bio-energy. Biomass can play vital role in responding to concerns over the protection of the environment as well as the security of an energy supply [4-5]. From ancient time, biomass is the main fuel which is used for cooking and water heating. But due to urbanization and industrialization, these biomass are replaced by modern fuel like kerosene, LPG and electricity. However, these conventional sources of energy are exhaustible in nature. It is essential to find an economical, convenient and efficient way to replace these conventional sources by renewable sources like biomass and solar as alternate fuel with improved technology to maximize the energy efficiency.

Comprehensive literature is available on various aspects of biomass combustion devices. However, literature on exergy analysis of biomass fired water heating system is limited. Saidur *et al.* performed an exhaustive literature survey on the exergy assessment of various biomass that can be used as fuel for cookstove [6]. Tyagi *et al.* presented an experimental and comparative performance evaluation, using energy and exergy analyses, of four metallic types of cook stoves [7]. Further, Panwar presented a study on assessment of energy and exergy of improved biomass cookstoves [8]. Biomass fired water heating systems are capable to generate hot water whenever it is required, and significantly contribute to reduction of greenhouse gases. Despite these advantages, there is very little literature available on energetic and exergetic analyses of such water heating system.

153

Therefore, the present experimental study was conducted to assess the energetic and exergetic performance of the biomass fired water heating system.

Materials and Methods

System Description

The biomass-fired water heating system consists of two concentric cylinders, *i.e.* the inner cylinder and the outer cylinder made of stainless steel SS 304. Actual combustion takes place in the inner cylinder, which has a diameter of 20 cm, whereas the outer shell has a diameter of 30 cm. During the experiment, the water was poured between these two cylinders. The outer shell was insulated with glass wool to minimize heat loss. The grate was made of a mild steel round bar. To maintain the proper draft during the combustion of the biomass, a chimney was placed on the top of the combustion chamber, as illustrated in Figure 1. One water tap was placed at on the upper side of the water tank to drain hot water, and another tap was placed at the bottom side to drain the water when the system is not in use. The technical specification of the developed water heating system is presented in Table 1.

Table 1. Technical specification of biomass fired water heating system.

No.	Component	Dimension in cm	Material
1.	Inner cylinder	Diameter = 20 Height = 60	SS 304
2.	Outer cylinder	Diameter = 30 Height = 60	SS 304
3.	Chimney	Diameter = 5 Height = 90	Galvanised iron（GI)
4.	Grate	Diameter = 19	Mild steel round bar
5.	Insulation	Thickness = 0.4	Glass wool
6.	Insulation cover	Diameter = 30.8 Height = 90	Aluminum sheet

Thermal Performance

Proximate analysis of the fuel - Desi Babul wood (*Acacia nilotica*), which was purchased from a local market, was carried out prior to the test by using the method suggested by the literature [9]. The physical and thermal properties of the fuel wood are presented in Table 2.

Seven trials were undertaken under different conditions to study the thermal efficiency of the developed system. The calorific value of fuel wood was calculated by using a digital bomb calorimeter (Advance Research Instruments Company, Delhi, India). A multi-channel temperature scanner (ADI-Vadodara, Gujarat, India) with calibrated NiCr–Ni thermocouples was used to measure the ambient air temperatures, water inlet and out temperature.
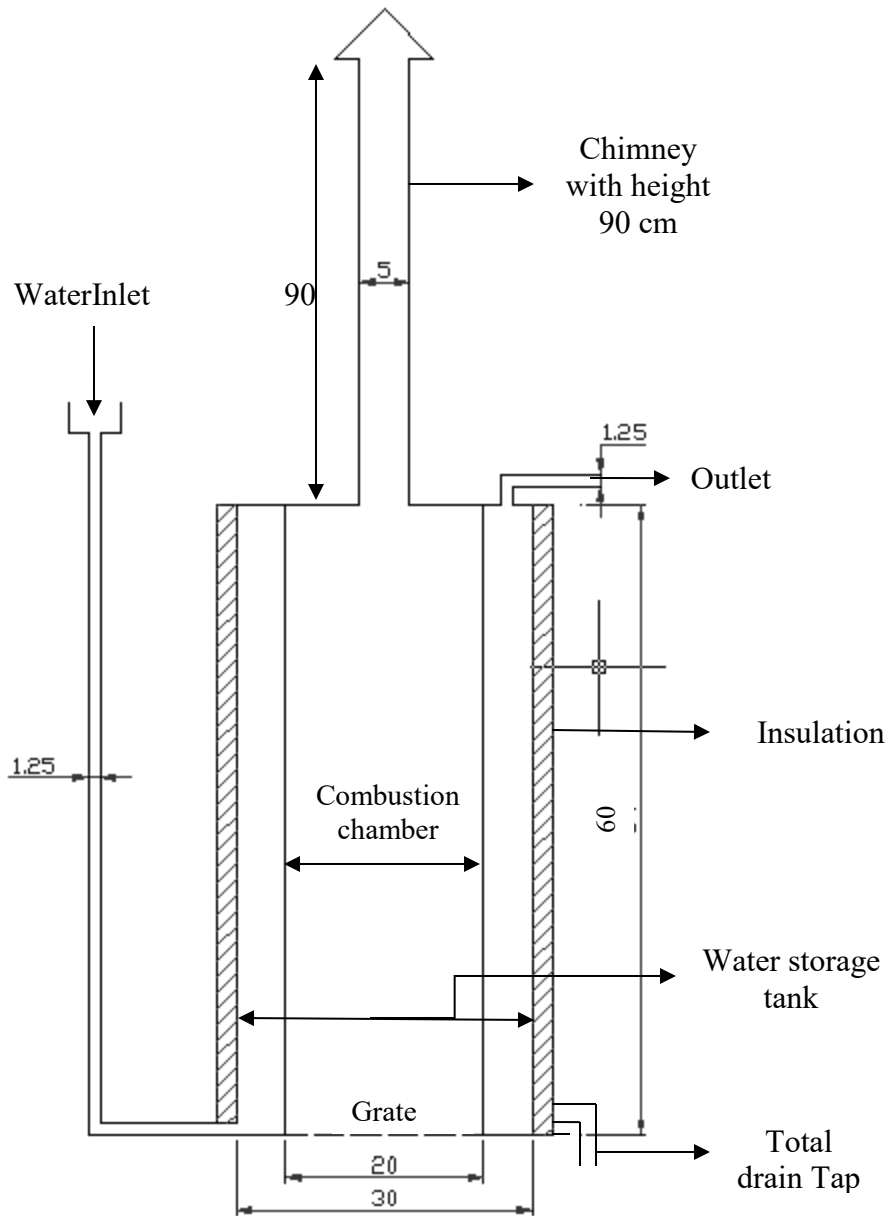
Figure 1. Schematic of biomass fired water heating system (all dimension in cm).

Table 2. Physical and thermal properties of the fuel wood

Characteristic	Biomass (Desi Babul wood, *Acacia nilotica*)
Size (mm)	25-40
Length (mm)	50-75
Bulk density (kg·m⁻³)	350
Moisture content (wt% wet basis)	5.6
Volatile matter (wt% dry basis)	82.52
Ash content (wt% dry basis)	1.05
Fixed carbon (wt% dry basis)	16.43
Calorific value (Higher heating Value, HHV, unit: MJ/kg)	19.157

Thermal efficiency of system is calculated by the following formula:

$$H_{out} = M_w Cp_w \Delta T \qquad \text{Eqn. 1}$$

$$H_{in} = M \times Cv \qquad \text{Eqn. 2}$$

$$\eta_{th} = \frac{heat\ utilized\ by\ system}{total\ thermal\ energy\ avialable\ in\ wood} = \frac{H_{out}}{H_{in}} \qquad \text{Eqn. 3}$$

Exergy Analysis

Energy assessment is the customary method of assessing the way that energy is used in an operation involving the physical or chemical processing of materials and the transfer and/or conversion of energy. Energy analysis is based on the first law of thermodynamics: Net heat supplied is converted in order to work. Thus, energy analysis ignores reductions of energy potential and can provide sound management guidance for those applications in which the usage effectiveness depends exclusively on energy quantities. Such analyses are suitable for sizing and analyzing of systems using only one form of energy [10].

The exergy contents of biomass can be calculated by using their higher heating or lower heating values. Both higher and lower heating values are the function of the weight fraction (wt%, dry) of the chemical composition of biomass such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), etc. The higher heating value (HVV) of biomass can be calculated by using the correlation proposed by [11-12].

$$HHV = [33.5(C) + 142.3(H) - 15.4(O) - 14.5(N)] \times 10^{-2} \qquad \text{Eqn. 4}$$

Similarly, lower heating value (LHV) can be computed using correlation proposed by [13].

$$LHV = HHV(1 - H_2O_i) - 2440(H_2O_i + 9H_i) \qquad \text{Eqn. 5}$$

where H_2O_i and H_i state the moisture content of biomass and the weight of hydrogen in biomass.

Correlation can be used for estimating the exergy of biomass suggested by [14].

$$Ex_{biomass} = \beta \times LHV_{biomass} \qquad \text{Eqn. 6}$$

where β is the quality factor and can be calculated as follows:

$$\beta = \frac{1.0412 + 0.2160\left(\frac{H}{C}\right) - 0.2499\left(\frac{O}{C}\right)\left[1 + 0.7884\left(\frac{H}{C}\right)\right] + 0.0450\left(\frac{N}{C}\right)}{1 - 0.3035\left(\frac{O}{C}\right)} \qquad \text{Eqn. 7}$$

Exergy output of improved cookstove is depended on the heat utilized to boil the water and amount of water evaporated. It can be written as follows:

$$Ex_{out} = H_{out}\left(1 - \frac{T_o}{T_{aw}}\right) \qquad \text{Eqn. 8}$$

where T_{aw} state for average water temperature

Therefore, exergy efficiency (ψ) can be written as follows:

$$\psi = \frac{Ex_{out}}{Ex_{biomass}} \qquad \text{Eqn. 9}$$

Results and Discussion

Thermal Performance

Thermal efficiency of the developed system was estimated using equations (1-3). To assess the thermal performance, total 80 liters of water was used to raise the temperature from 30°C to average temperature about 61°C in one hour, and one kg of babool (*Acacia nilotica*) wood was consumed. The developed biomass fired system illustrated in Figure 2. Thermal efficiency was estimated at about 54.50 %.

Figure 2. Developed biomass fired water heater

Exergy Assessment

Ultimate analysis of Desi babul (*Acacia nilotica*) was carried out to assess the exergetic performance of cookstoves as presented in Table 3. Exergy efficiency was calculated using equation (9). The exergy efficiency of biomass fired water heating system was about 6.79 %

Table 3. Ultimate analysis of biomass (wt%)

Biomass	C	H	O	N
Acacia nilotica	48.82	4.78	0.28	46.12

Conclusions

Biomass is the most convenient form of renewable resources. A country's socio-economy cannot show progressive development unless energy is explored, developed, distributed and utilized in an efficient and appropriate way. In this study, the performance of the developed system was tested with Desi babul (*Acacia nilotica*) wood. Efficiency was determined through water heating tests. The developed system delivers 80 litres of hot water per hour per one kg of biomass at average temperature 61°C. The developed water heating system brings potential benefits like reduced emission of the greenhouse gases and reduced fuel demand with economic and time saving benefits to the household, and increases sustainability of the natural resources.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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