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Design and performance test of a small scale refuse boiler for industrial applications

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ABSTRACT

The huge amount of solid waste (refuse) generated on a daily basis in most cities creates a very big concern for municipal waste management agencies. Energy generation from refuse is an attractive concept (waste to energy technology) which utilizes the heat produced from the combustion of municipal solid waste in a steam boiler system. This paper presents the design and performance evaluation of a small scale refuse boiler for industrial applications. Thermodynamic analysis was used to estimate the heat absorbed by water at the economizer and evaporator sections of the boiler tube. A mathematical modeling was used to establish the relationship between the temperature of the flue gas and the corresponding height of the boiler tube. MATLAB software was used to implement the design of the length of the boiler tube following a structured algorithm. The total heat absorbed by the boiler was estimated as 521.04 kW while the total surface area of the boiler tube required was calculated as 6.68 m^2. Finally, the total length of the boiler tube required to produce steam at the design parameters of 150°C and 5 bar with a mass flow rate of 0.2 kg/s was calculated as 92.03 m.

Keywords: Steam, temperature, pressure, enthalpy, solid waste, energy, boiler tube.

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Nomenclature: F.W., Feed water; **E.S.,** exit steam; **C.G.,** combustion gas; **Re,** Reynolds number; $\mathbf{h_i}$, Inside heat transfer coefficient, kW/m^2°C; $\mathbf{h_o}$, Outside heat transfer coefficient, kW/m^2°C; $\mathbf{U_o}$, Overall heat transfer coefficient, kW/m^2°C; $\mathbf{Q_{EV}}$, Heat absorbed by the evaporator tube, kW; **LMTD,** Log mean temperature difference; **A,** Total area of boiler tube, m^2; **L,** Length of boiler tube, m; $\mathbf{h_{1-3}}$, Enthalpy of fluid, kJ/kg; **H,** Height at a given section of the boiler tube, m; $\mathbf{H_T}$, Total height of boiler tube, m; $\mathbf{H_{EV}}$, Height of evaporator tube, m; $\mathbf{H_{EC}}$, Height of economizer tube, m; $\mathbf{Q_T}$, Total heat absorbed by boiler tube, kW; $\mathbf{Q_{EC}}$, Heat absorbed by economizer tube, kW; ΔT_1, Temp. difference between combustion gas and exit steam, °C; ΔT_2, Temp. difference between combustion gas and steam at the inlet of evaporator, °C; ΔT_3, Temp. difference between combustion gas and steam at the exit of the economizer, °C; ΔT_1, Temp. difference between exit flue gas and inlet feed water, °C.

INTRODUCTION

Refuse boilers most often can be conceived as incinerators equipped with a heat recovery device (boiler tube). They are waste-to-energy (WTE) systems gaining more and more attention as landfill costs and environmental issues (waste disposal) are increasing in many developed countries. The use of municipal solid waste (MSW) as a fuel to generate steam and electricity is receiving renewed attention from communities as a key component of an integrated waste management program (Babcock and Wilcox, 1992). The two proven means for disposal of waste are burying MSW in landfills or combusting it in specially designed chambers at a high temperature, thereby reducing it to one tenth of its original volume (Walter, 2002). MSW also contains combustible elements which are fossil fuel derived materials e.g. plastics and therefore produce high energy during combustion. The heat produced by the combustion of MSW can be used to vaporize water to steam which can be channeled through a turbine to generate electricity or used as process steam in industries. The United State (US) WTE industry has existed for over thirty years and its technology has continuously been improved. Currently there are 86 WTE facilities in the U.S. processing 29 million tons of MSW annually and every ton of MSW processed in a WTE facility avoids the mining of one third ton of coal (9.6 million tons per year) or the importation of one barrel of oil which translate to 29 million barrels per year (Timo, 2009).

Solid wastes come from industrial sources, like mining and manufacturing, and from “municipal” sources (including household and commercial sources) and they we often literally dumped on the ground either near the source, in landfills, in oceans and lakes. The legacy of this dumping is now visible in problems like toxic impacts on groundwater and human health. One of the global energy issues is that the world is running short of the traditional sources of energy, that is, fossil fuels such as methane gas and coal, and future supply may not match the increasing demand. Hence, the need to look for an alternative source of energy and solid waste provide a good alternative.

The combustion of solid waste in a refuse boiler produces steam; this is a critical resource in today’s industrial world which can be used in brewery, textile, cement, food and chemical industries. Common applications for steam are heating/sterilization, propulsion/drive motive, atomization, cleaning, moisturization, humidification (Woodruff et al., 2004). The aim of this work is to design a refuse boiler and carry out performance test using MSW such as plastic, paper, wood chips, textile, rubber and leather.

METHODOLOGY

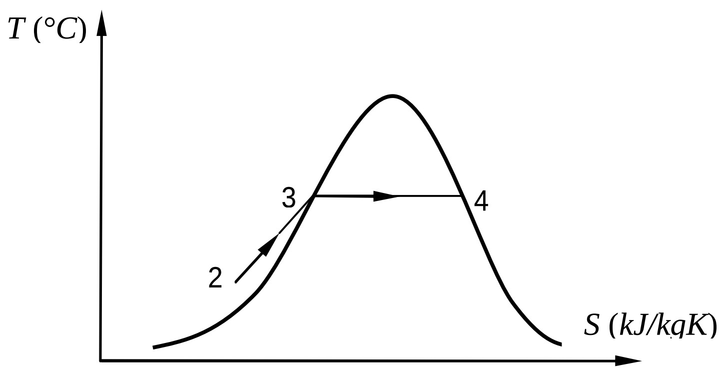
Thermal design of the boiler tube

The design of the boiler tube involves the following calculations:

i) The heat absorbed by water in each section of the tube
ii) The logarithmic temperature difference
iii) The sizing of the boiler tube

Heat absorbed by water in each section of the tube

The heat absorbed by water in each section of the tube can be illustrated graphically with the *T-S* diagram shown in Figure 1 while Table 1 shows sections of the boiler tube with their values.



From the thermodynamic properties table
$h_2 = 194.48\ kJ/kg$;
$h_3 = 908.8\ kJ/kg$
$h_4 = 2799.5\ kJ/kg$

Figure 1. *T* - *S* diagram of the cycle.

Table 1. Values at the sections of the boiler tube.

Section of the boiler tube	Height occupied by the tube (m)	Temperature of flue gas = (−250.8*H* + 701.6)	Temperature of water (°C)	Heat absorbed
Section 2-3: Economizer	$H_{EC} = \frac{Q_{EC} \times H_T}{Q_T} = 0.34$	285.27°C (entry) 200°C (exit) (for *H* = 1.66 to 2.0)	38 to 150	$Q_{EC} = m_s(h_3 - h_2)$ = 142.9 kW
Section 3-4: Evaporator	$H_{EV} = \frac{Q_{EV} \times H_T}{Q_T} = 1.66$	701.6°C (entry) 285.27°C (exit) (for *H* = 0 to 1.66)	150 to 150	$Q_{Ev} = m_s(h_4 - h_3)$ = 378.14 kW

Variation of fluid temperatures

The variation of fluid temperatures (flue gas and water temperature) in the evaporator and the economizer sections of the tube are shown in Figures 2 and 3, respectively.

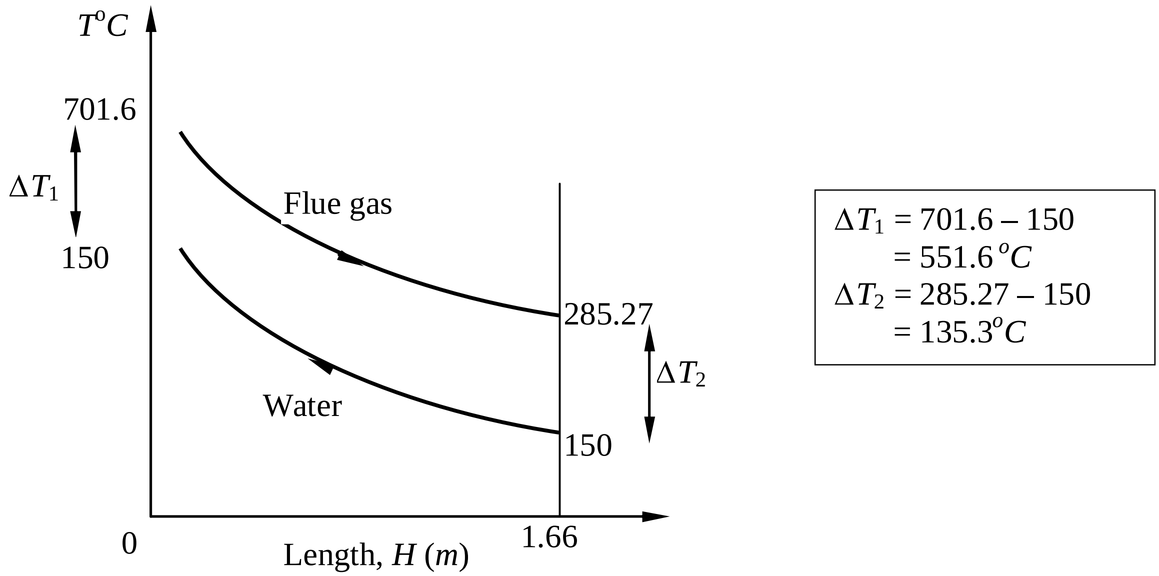


Figure 2. Variation of fluid temperatures in the evaporator tube section.

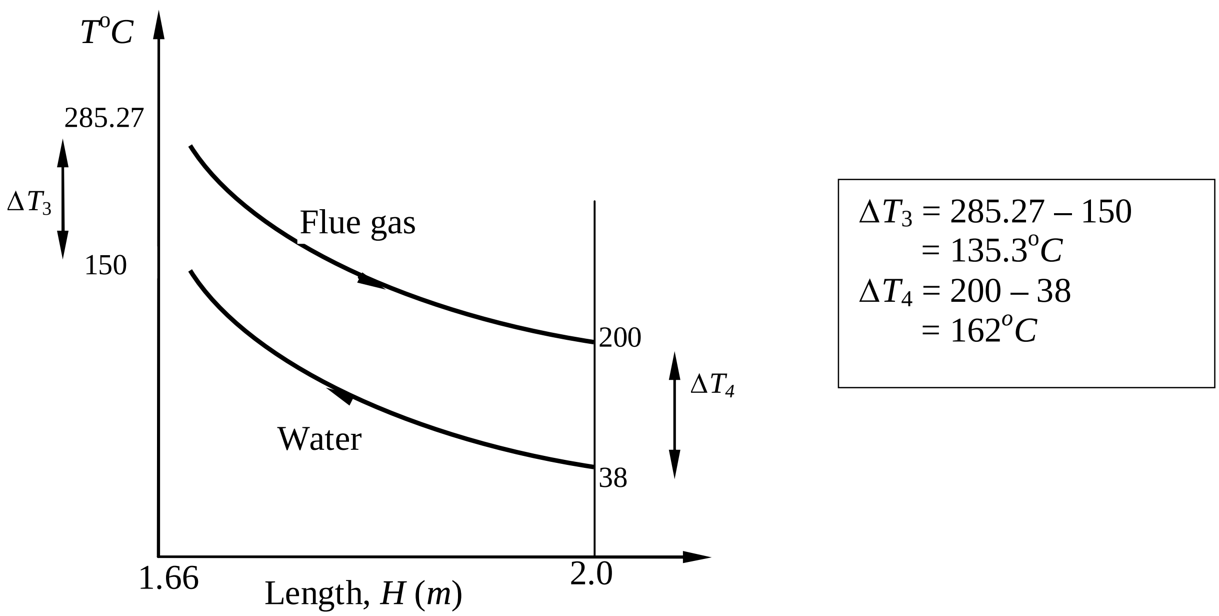


Figure 3. Variation of fluid temperatures in the economizer tube section.

Sizing of the boiler tube

The sizing of the boiler tube involves determination of the length of the tube that is required to produce steam at the temperature of 150°C and pressure of 5 bar with a mass flow rate of 0.2 kg/s from a feed water at a temperature of 38°C and atmospheric pressure. In this work an algorithm (Figure 4) was created to calculate the required length of the boiler tube, this was then implemented with a MATLAB software.

Fabrication and performance test of the refuse boiler

A prototype water tube refuse boiler shown in Figure 5 was designed and fabricated (in accordance with the ASME Standard Code) with a 3 mm thick mild steel sheet for the inner and outer shells while the boiler tubing was made of stainless steel pipe of 19 mm diameter and 2 mm thickness having thermal conductivity of 15 W/m°C. The performance testing of the potential for waste to energy was carried out to evaluate the practically

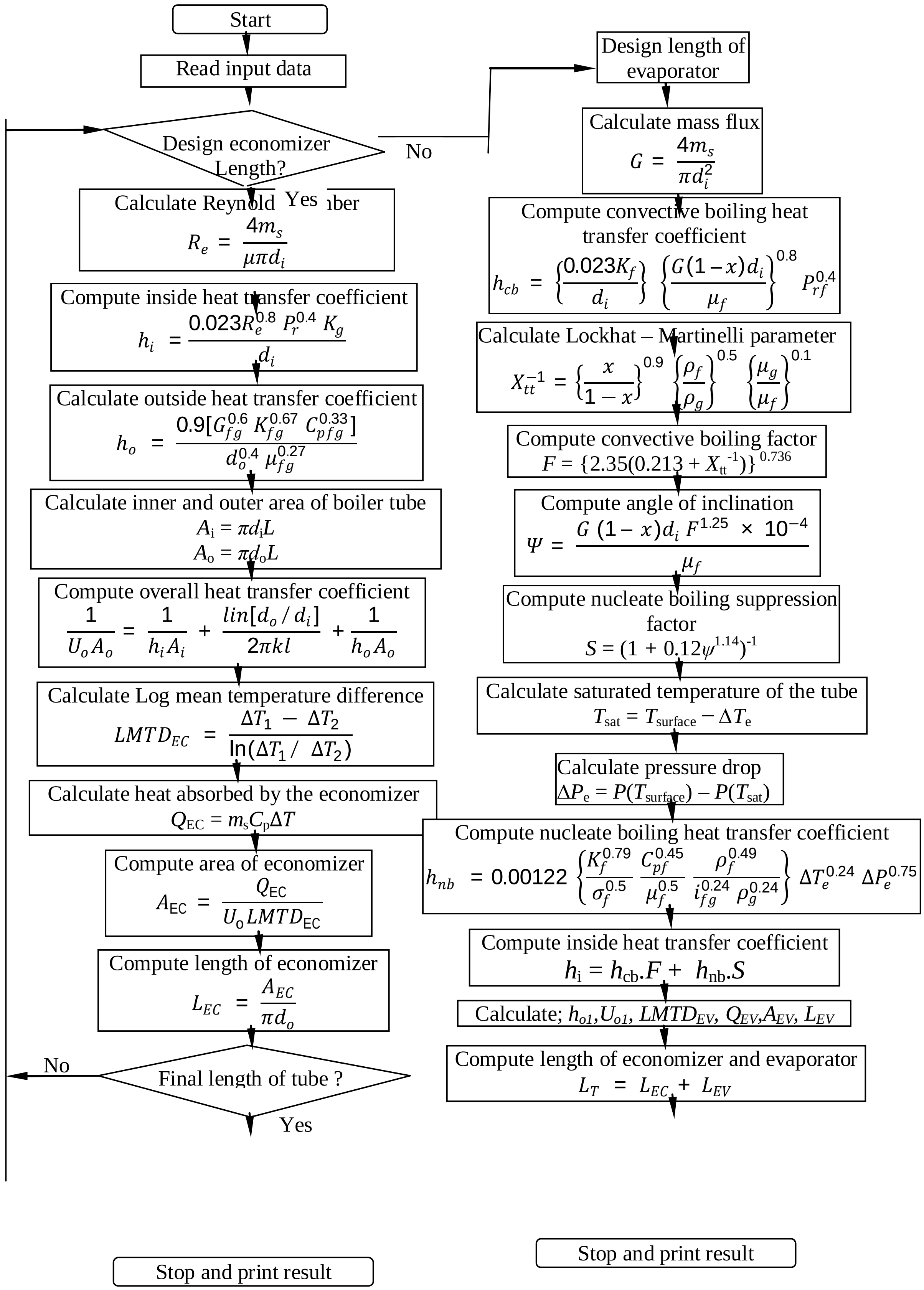


Figure 4. Flow chart for estimating the length of the boiler tube.

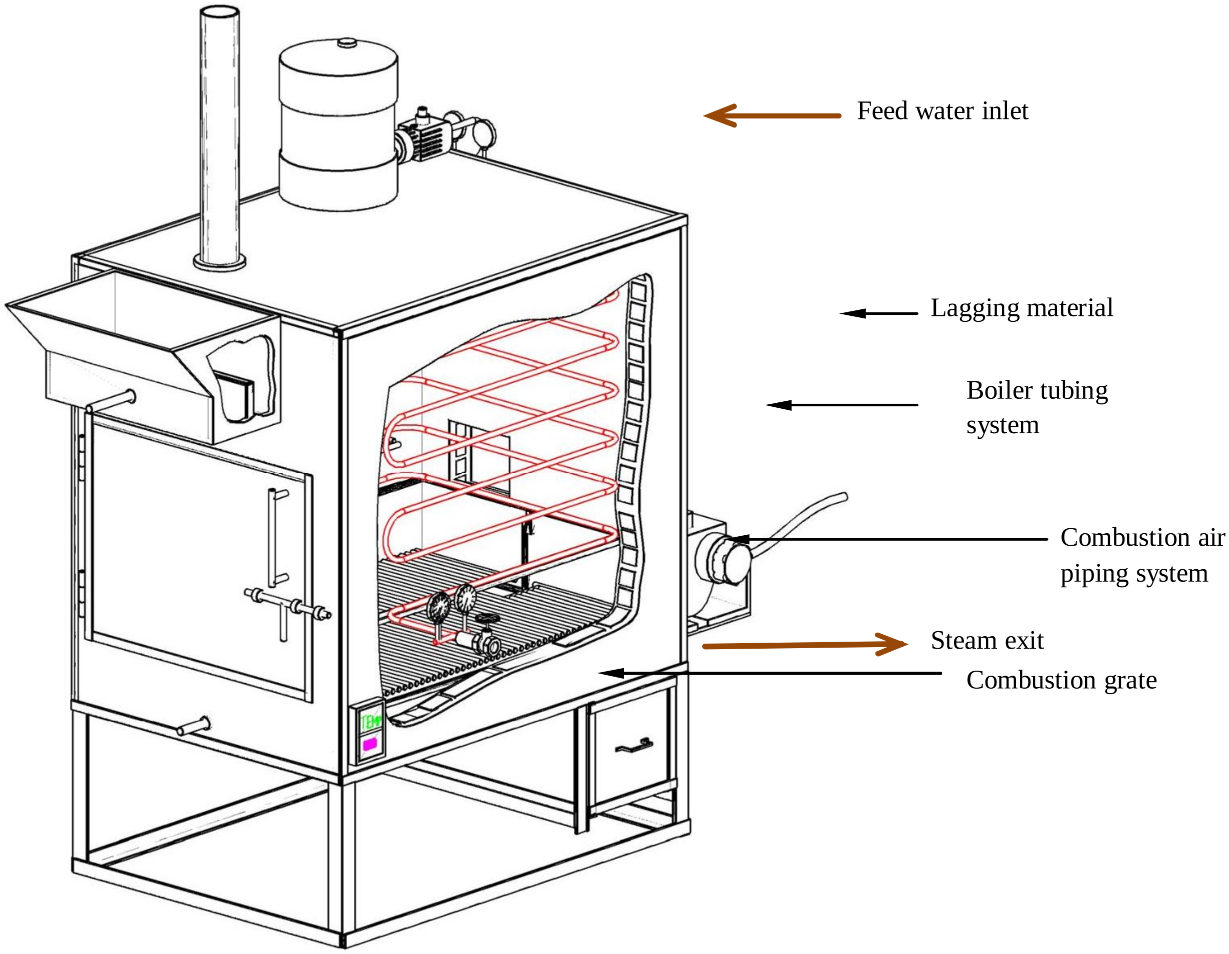


Figure 5. A prototype refuse boiler.

achievable energy that can be produced from the combustion of a given mass of the solid waste materials (refuse). This entails incinerating several different batches of the waste materials and basically determining the mass flow rate, temperature and pressure of the feed water and exit steam.

RESULTS AND DISCUSSION

The MATLAB results for the refuse boiler are given in Table 2. This reveals a total of 521.4 kW heat energy was absorbed by the water to produce steam at a designed specification temperature of 150°C and pressure of 5 bar using a boiler tube having a total surface area of 6.68 m^2 and a length of 92.03 m.

The result of the performance testing of the potential for waste to energy is shown in Table 3. The performance testing of the potential for waste to energy showed that steam was produced at a mass flow rate of 0.2 kg/s with a temperature of 120°C and pressure of 2 bar. A considerable average temperature difference of 83°C (31 to 114°C) was recorded between the inlet and exit temperature, this compares well with results obtained by Unachukwu and Anyanwu (2010) in which 53°C (32 to 85°C) was recorded between the inlet and exit temperature of a small scale incinerator for hot water production. In addition the quantity of steam produced (0.2 kg/s) was considerably high compared to 0.18 kg/s obtained by Ujam and Eboh (2012) from a small scale

Table 2. MATLAB results for the boiler tube.

Parameter	Economizer	Evaporator
R_e	2.2259×10^{-3}	
h_i (kW/m^2°C)	0.4956	5.5362
h_o (kW/m^2°C)	0.0155	0.0032
U_o (kW/m^2°C)	0.0140	0.0052
LMTD	164.69	317.50
Q_{EV} (kW)	142.9	378.14
A_{EC} (m)	1.83	4.85
L_{EC} (m)	30.73	61.30

Table 3. Result of the performance testing of the potential for waste to energy.

Weight of solid waste (40 kg)	Combustion time (min)	Solid waste charging rate (kg/s)	Temperature (°C)			Pressure (bar)	Mass flow rate of steam (kg/s)
			F.W	E.S	C.G		
Paper: 7.12 Plastic: 19.68 Rubber: 3.4 Textile: 6.12 Wood: 1.68 Leather: 2.12	20	0.033	31.0	115	406	1.70	0.2
Plastic: 14.0 Rubber: 13.0 Leather: 13.0	23	0.029	31.0	112	401	1.57	0.2
Paper: 13.0 Textile: 13.0 Wood chips:14.0	19	0.035	31.0	116	431	1.75	0.2
Wood chips: 40	17	0.039	31.0	120	437	1.93	0.2
Plastic: 40	21	0.032	31.0	111	426	1.50	0.2
Leather: 40	19	0.035	31.0	113	430	1.61	0.2
Rubber: 40	22	0.030	31.0	116	386	1.75	0.2
Paper: 40	20	0.033	31.0	110	392	1.43	0.2
Palm kernel bunch: 40	19	0.035	31.0	112	432	1.57	0.2
Textile: 40	20	0.033	31.0	113	389	1.61	0.2

municipal solid waste fired steam generator of 2 m^3 capacity.

CONCLUSION

The required length of the boiler tube required to produce steam at a temperature of 120°C and pressure of 2 bar was determined. The steam produced by this boiler can be used for various applications in process industries like the brewery, cement, sugar and textile industry. Finally, this work has demonstrated to a large extent that the incineration of solid waste can solve the challenges of solid waste disposal which is a major problem facing many cities. The heat released from the combustion process can be used to produce steam; hence, solid waste can be used as an alternative fuel for firing a steam boiler.

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