PERFORMANCE TESTING
OF LPG-FIRED
MONOTUBE STEAM GENERATOR

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Abstract

Small-sized steam generators are useful in power generation applications such as small scale power generation and utility purposes. The monotube boiler design is one of the safest designs available due to lower operating pressure and well-contained water tubes. In recent years, many optimizations have been done to improve boiler efficiency to reduce emissions and fuel usage. However most of the studies are done on larger boilers where the impact is most significant whereas studies on smaller boilers are few. This paper studies the performance of a specific monotube boiler in terms of efficiency and output. The efficiency and output are plotted against energy input to know the performance characteristics of the monotube boiler. Heat and mass balance was done as verification to the steam output data. It is determined that the specific design of monotube boiler have significant lower efficiency (15-18%) than conventional boilers. Modifications are needed to be made for the boiler to be feasible or commercial or practical usage.

***Index Terms* – Monotube Boiler, Small-Scale Power Generation, Boiler Efficiency, Evaporation Ratio, Heat Balance**

Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree

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Statement 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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Contents

1.0 Introduction

A Monotube steam generator is a type of steam generator consisting of a single tube, usually in a multi-layer spiral. The design of the steam generator is similar with water tube steam generators but in a monotube steam generator, the water passes through the coils in a single chimney structure.

Currently, steam turbine systems are the most used technology for biomass utilization since steam boilers are less sensitive to the amount of moisture, tar and particles contamination associated with biomass combustion [1]. Gasifiers with internal combustion engines and the directly fired gas turbine systems and directly-fired gas turbine engines have the economic potential and the flexibility to cover a wider range from the domestic micro-scale to centralized mega-scale power generation. However, the main problem with these systems is the high cost of operation and maintenance. This presents an opportunity for development of alternative power generation systems such as EFGTs (Externally Fired Gas Turbines) as well as DFGTs (Directly Fired Gas Turbines) [2]. In small-scale gasification systems, a hybrid turbine consisting a gas turbine and a steam generator could potentially be used to reduce the size or temperature of the heat exchanger in heating of the working gas [3].

This present an opportunity for monotube boilers to be utilized in biomass-fired power generation systems. This is due to monotube boilers being primarily used in small-scale applications. The monotube design was not used in large scale as the water-tube designs generally have much higher efficiencies [9]. However, it is much easier to build as the heat exchanger design can be done by simply coiling copper or stainless steel pipes. Development costs can be significant factor in low-income areas and communities. The monotube design offers a low-cost solution to steam generation whether used in utility purposes or power generation.

The monotube design offers a safe operation compared to fire tube boilers. This is due to the high temperature nodes which are the heat exchangers are fully enclosed in the boiler shell. Furthermore, monotube boilers operate in a steady flow instead of large batches as in fire tube boilers. This prevents large bodies of water from flashing [9] and large explosions from occurring.

The many advantages of monotube boiler design made it suitable for various [7] small-scale applications, from water heating, room temperature warming and utility and power generation. Performance characteristics such as evaporation ratio and thermal efficiency of the design are parameters are important to show the feasibility of such system. Hence, the characteristics and the performance of such steam generator is investigated to determine its feasibility in such applications.

2.0 Methodology

2.1 Monotube steam generator specifications

The monotube steam generator consists of 3 main parts: the shell, the heat exchanger coils and the combustion chamber. The heat exchanger is a two-pass system where feedwater travels upwards in a larger coil in the first pass to gain heat. It then travels downwards in a smaller coil in the second pass and turns into saturated steam as the output. The shell of the monotube boiler are insulated by concrete material. Its height measures at 1.7 m. The overall design of the boiler is shown in *Figure 1* and *Figure 2*.

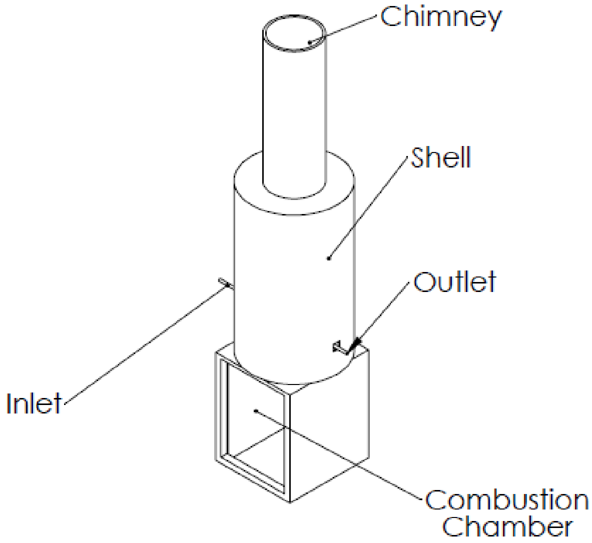

Figure 1: CAD diagram of monotube boiler

Table 1: Monotube boiler specification

Feature	**Description**
No. of passes	2-pass
Type of heat exchanger	Stainless steel coils
Coil length	28.5 m
Coil inner diameter	6 mm
Fuel type	Liquefied propane gas
Chimney height	1.2 m
Total height	1.7 m
Furnace size	30 cm x 30 cm x 45 cm

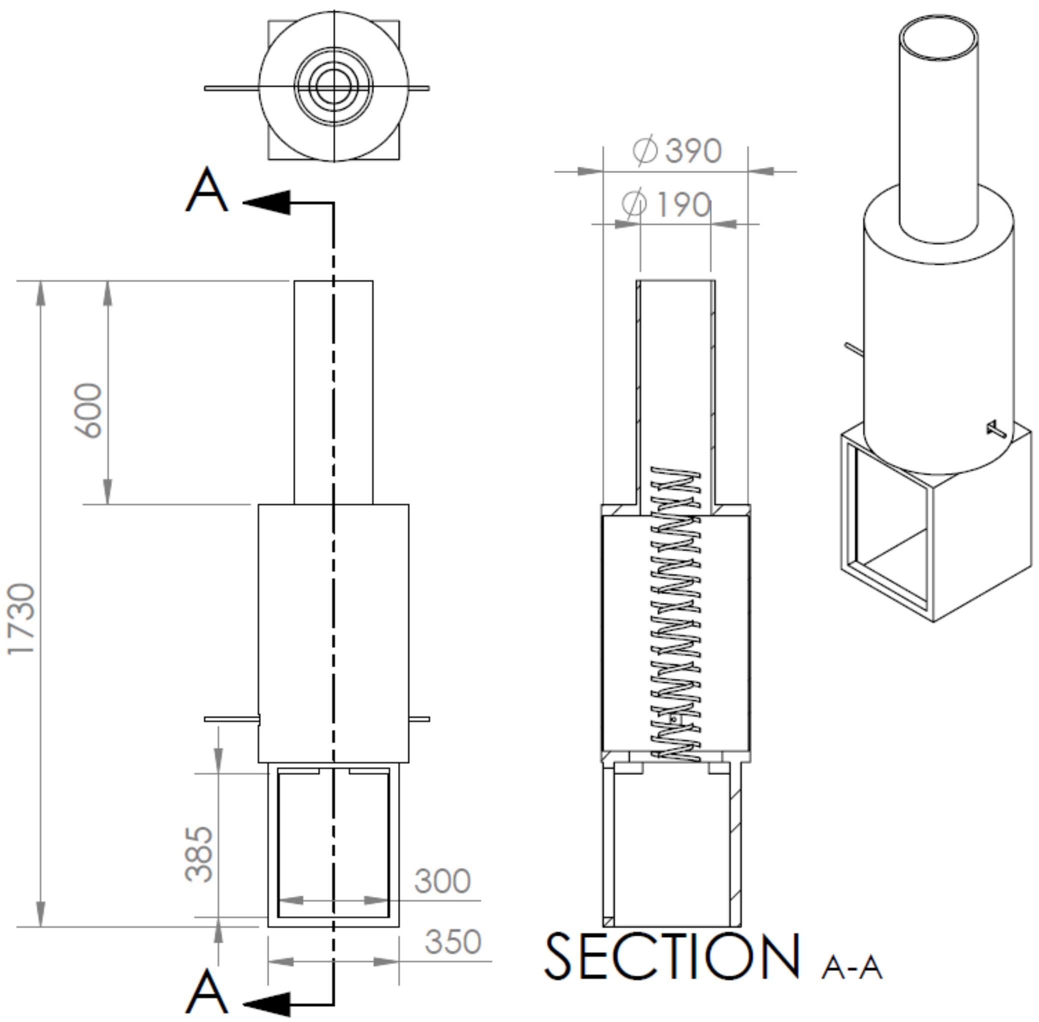

Figure 2: CAD drawing of monotube boiler

2.2 Reference standard

ASME Standard: PTC-4-1 Power Test Code for Steam Generating Units

Referring to ASME standards, there are two methods of boiler efficiency determination:

2.2.1 Direct method (also called as input-output method)

Direct method is the measurement of useful output (steam) and the input (fuel) directly to evaluate the efficiency. The energy gain of the working fluid (water) is compared to the energy content of the boiler fuel (LPG) directly. However, the direct method does not compute the sources of heat loss in the system.

2.2.2 Indirect method (also called as heat loss method)

The efficiency can also be measured by measuring all the losses occurring in the boiler. The losses from all the different sources is then summed to obtain overall thermal efficiency. The method is viable because the mechanism of the heat losses in boiler are known and can be measured or calculated theoretically.

There are various sources of heat loss that result in lower thermal efficiency of the monotube steam generator.

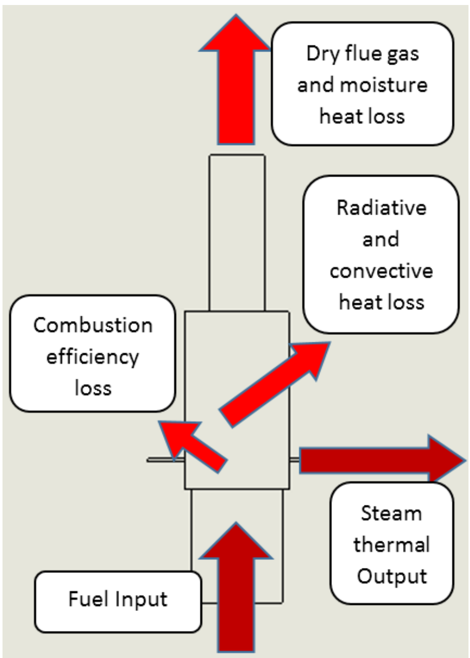

Figure 3: Heat balance of boiler

Loss of heat to flue gases

The dry flue gas is the major contributor towards heat loss. The flue gasses are the dry products of the chemical reactions between fuel and oxygen, but also include natural draft that is induced by stack effect, due to open stove system used in monotube design. During the reaction, these gases are liberated and flow against the heat exchanger which are stainless steel coils and escape through the chimney. Due to the heat exchanger not absorbing all the heat in the flue gases, up to 10 to 30 % [4] of the heat energy generated in combustion are lost.

Loss of heat to moisture

When the fuel and air is not completely dry, some of energy is expended in evaporating water. At the same time, there are also moisture content in the air that is fed into the combustion chamber. Hence, the atmospheric relative moisture also contributes in heat loss.

Loss of energy due to unburnt fuel

The loss of energy due to unburnt fuel are significant (up to 2%) in solid fuels, but since LPG gas is used, the loss of energy is insignificant.

Radiation and convection losses

Radiation and convection losses are losses that occurs by the heat escaping the heat combustion chamber and chimney through radiation and convection mechanisms. To minimize these losses, the chimney of the monotube boiler is insulated with at least 4 cm thick concrete, which has lower heat transfer coefficient. The typical losses are up to [4] 2-5% of the energy input to the furnace.

2.2.2.1 Combustion Mass Balance

In the study, heat loss due to flue gas and moisture can be estimated by firstly measuring the temperature of the flue gas, followed by calculating the rate of air intake of the boiler. Since the air intake of the boiler is by natural draft, the stack effect equation can be used to compute the induced draft into the furnace due to temperature difference. The equation is given by:

$$Q = CA\sqrt{2gh\frac{T_i - T_o}{T_i}}$$

Equation 1: Induced draft by stack effect

Where:

Q	= Stack effect draft flow rate, m^3/s
A	= Minimum cross-section of chimney, m^2
C	= Discharge coefficient
g	= Gravitational acceleration, 9.81 m/s^2
h	= Height of furnace, m
T_i	= Average temperature of flue gas, K
T_o	= Atmospheric air temperature, K

After air in induced into the combustion chamber, the air reacts with propane for combustion. The stoichiometric combustion of LPG is given by *Equation 2.*

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

Equation 2: Stoichiometric combustion of propane

The resulting flue gas composition can be determined by the resulting mass fraction of oxygen, nitrogen, water vapor and carbon dioxide. Consequentially, the specific heat capacity of the flue gas can be determined by mass fractions of the gas composition. Finally, the heat loss of the dry flue gas and heat loss in moisture content were determined.

$$Q_{loss} = m_{flue}c_{p\ flue}T_{flue} - m_{air}c_{p\ air}T_{air}$$

Equation 3: Heat loss in flue gas

Where:

m_{flue}	= Stack effect draft flow rate, m^3/s
$c_{p\ flue}$	= Weighted specific heat capacity of flue gas
T_{flue}	= Temperature difference of flue gas
m_{air}	= Stack effect draft flow rate, m^3/s
$c_{p\ air}$	= Weighted specific heat capacity of flue gas
T_{air}	= Temperature difference of flue gas

2.3 Experimental Conditions

For the experiment, the boiler is operated under fixed fuel and feedwater conditions for 20 minutes to achieve steady-state. The determination of thermal efficiency is by the direct method. It is used due to fewer quantity of instruments required for the investigation. The method is also known as the 'input-output' method since it needs only the useful output (steam) and the heat input) for evaluating the efficiency. The efficiency can be evaluated using the formula:

$$Boiler\ Efficiency = \frac{Steam\ flow\ rate \times (steam\ enthalpy - feed\ water\ enthalpy)}{Fuel\ consumption\ rate \times Lower\ heating\ value}$$

Equation 4: Efficiency determination by direct method

Specifically,

$$Thermal\ Output, Q = \mathrm{V} \times \rho \times (\mathrm{Qout} - \mathrm{Qin})$$

Equation 5: Thermal Output

$$Boiler\ thermal\ efficiency, \eta\mathrm{thermal} = \frac{\mathrm{V} \times \rho \times (\mathrm{Qout} - \mathrm{Qin})}{(\mathrm{Vf} \times \rho\mathrm{f} \times \mathrm{LHV})} \times 100$$

Equation 6: Thermal efficiency

$$Evaporation\ ratio = \frac{\mathrm{V} \times \rho}{\mathrm{Vf} \times \rho\mathrm{f}}$$

Equation 7: Evaporation Ratio

Where:

V	= Volumetric flowrate of feedwater, m^3/s
ρ	= Density of water, kg/m^3
Q_{out}	= Enthalpy of steam, kJ
Q_{in}	= Enthalpy of feedwater, kJ
V_f	= Volumetric flowrate of LPG, m^3/s
ρ_f	= Density of LPG gas, kg/m^3
LHV	= Lower heating value of LPG, kJ/kg·K

2.3 Experimental setup

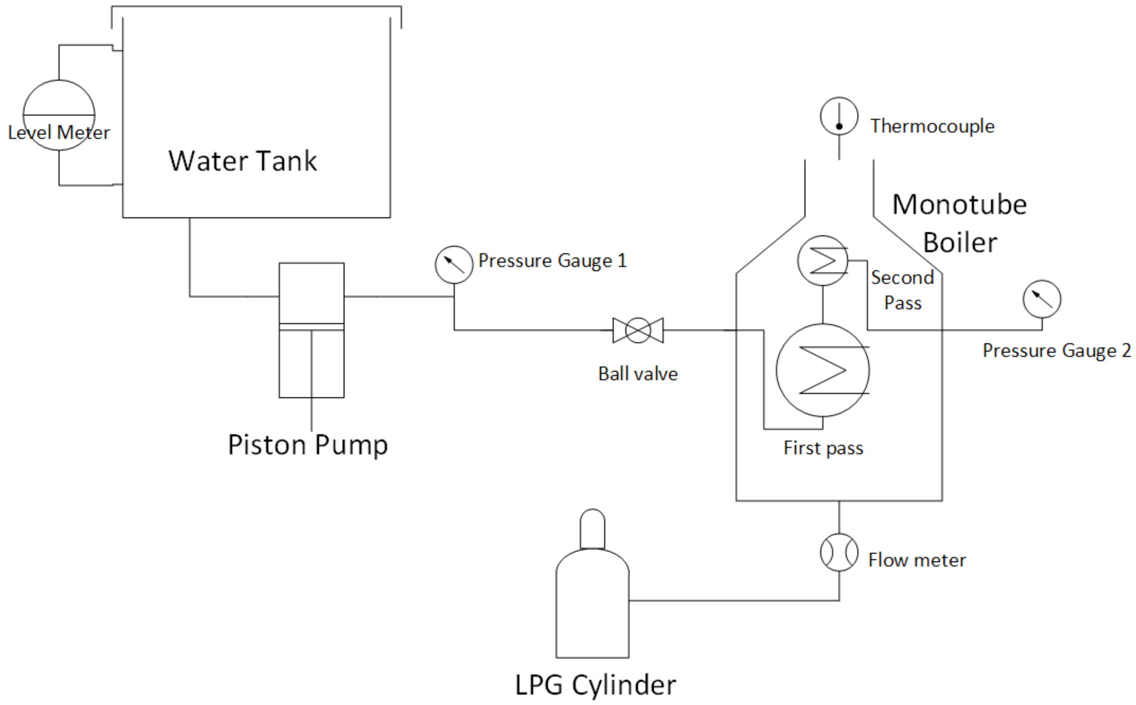

Figure 4: Schematic diagram of Experiment Setup

The experiment setup is shown as in Figure 3. The large water tank was used to supply water to the monotube water. Normal tap water which had not been further treated was refilled into the water tank only when exhausted. Water was pumped into the monotube boiler by a piston pump powered by 1KW motor on constant speed of 300 RPM. A ball Valve was used to control the flowrate of feedwater as necessary. Two pressure gauges were installed at the inlet and outlet of the monotube boiler respectively to obtain the averaged pressure of the steam. A gas flowmeter was installed at the input of the fuel (liquefied propane gas) to measure the fuel consumption. The test range of the experiment is limited by the range of input LPG and the head provided by the pump. The fuel input rate is increased gradually until steam generation is at steady-state and increased at 2 LPM data points to tabulate the changes in output.

3.0 Result & Discussion

In boiler performance analysis, the specifications of interest are thermal output, thermal efficiency and evaporation ratio. The efficiency of the boiler under different flowrates were investigated. The evaporation ratios were also determined for each of the cases.

3.1 Performance Characteristics

Water consumption and LPG gas consumption data were measured directly using a volumetric cylinder and gas flowmeter respectively. The enthalpy of feedwater and steam are obtained from a steam table while other parameters are listed in *Table 2*:

Table 2: List of parameters

Temperature of Feedwater	30 °C
Pressure of Feedwater	1 Bar
Lower Heating Value of LPG gas	46.35 MJ
Density of LPG gas	0.58 kg/m^3

Table 3 and *Table 4* shows the performance characteristics of the monotube steam generator. The two tables represent characteristics of the thermal output for 2 different flowrates: 0.5 LPM and 0.7 LPM (0.03 and 0.042 tones per hour). The enthalpy of the steam is determined by referring to steam table while thermal output, efficiency and evaporation ratio are determined using *Equation 3, Equation 4 and Equation 5* respectively.

Table 3: Results for 0.5 LPM steam flowrate

LPG Gas Flowrate (L/min)	Q_{in} (W)	P1 (Bar)	P2 (Bar)	P avg. (Bar)	hf (J/kgK)	ΔP (W)	ηthermal (%)	Evaporation Ratio (kg steam/kg LPG)
22	33990	22	1	12	815171	5715.33	16.81	0.0392
24	37080	24	2	13	830515	5842.55	15.76	0.0359
26	40170	30	2	16	872203	6188.22	15.41	0.0332
28	43260	32	3	17.5	891071	6344.66	14.67	0.0308

Table 4: Results for 0.7 LPM steam flowrate

LPG Gas Flowrate (L/min)	Q_{in} (W)	P1 (Bar)	P2 (Bar)	P avg. (Bar)	hf (J/kgK)	ΔP (W)	ηthermal (%)	Evaporation Ratio (kg steam/kg LPG)
26	40170	14	2	8	743238	7171.48	17.85	0.0332
28	43260	19	3	11	798931	7818.43	18.07	0.0308
30	46350	26	3	14.5	852093	8435.99	18.20	0.0287
32	49440	32	3	17.5	891071	8888.78	17.98	0.0269

3.1.1 Thermal Output

The performance curve of the power output shows that the highest power output is achieved at highest LPG input attainable for standard 12 kg LPG gas tank and 3-ring burner. The boiler produces significantly lower output when the feed water flow is restricted by the ball valve. This shows better output performance when feedwater flow is higher.

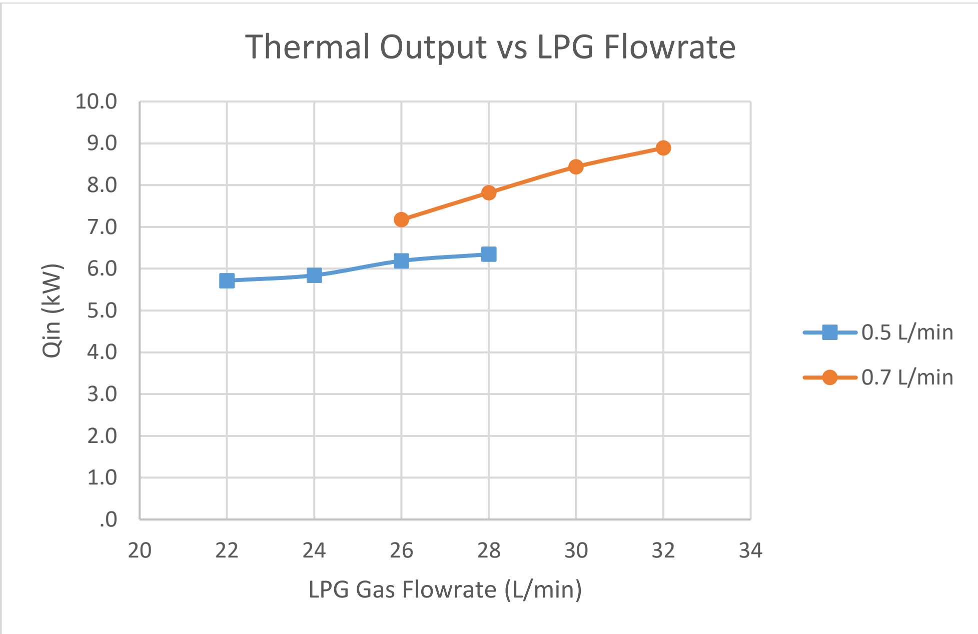

Figure 5: Graph of power output against LPG flowrate

3.1.2 Thermal Efficiency

The steam generator attains the highest efficiency at 30 LPM of the LPG gas flow. This shows that the optimum efficiency occurs when flowrate of water is at 0.7 LPM. At lower feedwater flowrate of 0.5 LPM, the thermal efficiency of boiler is significantly lower. It indicates the flow of water is not pumped to a sufficient head to allow good heat transfer. Higher power motor could be used to ensure the head is sufficient.

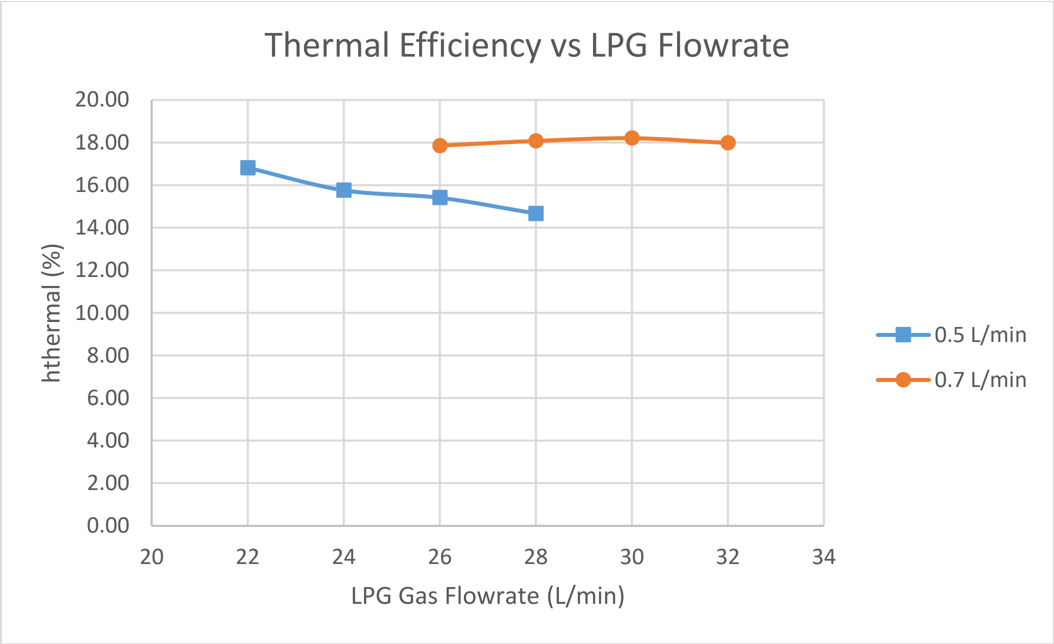

Figure 6: Graph of thermal efficiency against LPG flowrate

3.1.3 Evaporation Ratio

The evaporation ratio drops significantly as the fuel input increases. Design flaws are possible for this result. An increase in length of the heat exchanger should result in improved results. Another factor to be considered is the wetness of the steam. The pressure gauge might have condensation issues that causes water carryover. This can cause misleading of the output for generated steam.

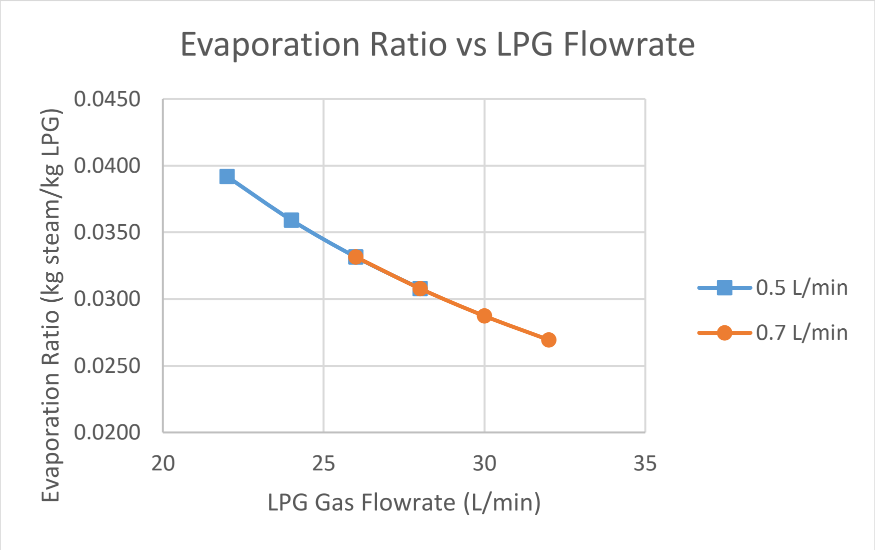

Figure 7: Graph of evaporation ratio against LPG flowrate

3.2 Heat Loss

The temperature of flue gas was measured for the feedwater flowrate of 0.7 LPM and LPG flowrate of 30 LPM. Air flowrate of into the combustion chamber was determined by *Equation 1*. Hence, the constituents of flue gas are calculated using mass balance on stoichiometric basis of the combustion. The humidity of the air is also considered. It is determined that for 30 LPM of LPG flowrate, 1.65 g/s CO_2, 57 g/s 189.45 g/s N_2, and 0.675 g/s H_2O are the constituents of the flue gas. Using *Equation 3*, the heat loss in dry flue gas and heat loss in moisture are estimated, as shown in *Table 5* and *Table 6*.

Table 5: Combustion mass balance

Flue gas flowrate	30 LPM
Flue gas temperature	395 K
Induced volumetric airflow	0.185 m^3/s
Induced mass airflow	0.227 kg/s

Table 6: Heat losses

Heat loss in dry flue gas	30720 J	66.28%
Heat loss in moisture	1031 J	2.09%
Heat loss by radiation and convection	[4]	2-5 %
Total heat loss	34.06 kJ	73.36%
Experimental heat loss	37.91 kJ	81.80 %
Other heat loss	**3.85 kJ**	**8.44 %**

As tabulated in *Table 6*, there was some discrepancy between the expected heat loss and the experimental heat loss determined using direct method of measuring the steam enthalpy. Some of the difference can be caused by [6] incomplete combustion of the propane gas and formation of CO and NOx. Other differences may be related to accuracy of the instrument and incorrect assumptions of moisture level in atmosphere, stoichiometric combustion, and the accuracy of theoretical induced flow equation.

3.2 Accuracy of Results

One of the challenge faced is the back-pressure problem experienced during the testing of the monotube boiler, saturated steam flow that is desired cannot be achieved. To achieve steady, continuous steam output, the inlet pump preferably need to provide high head (20-30 bar) at a relatively low flow rates of water (1-2 LPM) and achieve higher pressure to prevent the back-flow. The evaporation ratio and efficiency data may also mislead, if the steam is highly wet due to water carryover. A significantly wet steam can cause the pressure gauge to measure inaccurate pressure levels.

4.0 Conclusion

This project determines important performance characteristics of the boiler. The highest power output of 8.89 kW is attained at maximum firing of 32 LPM of LPG at 0.7 LPM feedwater flowrate. The highest efficiency of 18.2 % is achieved at 30 LPM of LPG and 0.7 LPM feedwater input. The highest evaporation ratio of 0.0392 is achieved at 22 LPM of LPG and 0.5 LPM feedwater input. The heat loss in flue gas determined by mass balance shows close agreement with the low efficiency (8.44 %) with direct determination.

The very low [9] efficiency of the monotube boiler reveals that the design of the monotube boiler needs an overhaul. High flue gas temperature (120 °C) implies inadequate heat transfer in the heat exchangers. Measures that should be implemented are increasing the length of heating coil and changing the coil material into stainless steel. For future studies, flue gas analysis can be done to determine flue gas composition and combustion efficiency much more accurately. Flue gas temperatures can also be determined for all the data points for a more complete data set.

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