PERFORMANCE OF MICRO STEAM ENGINE

By,

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DECLARATION

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

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

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Acknowledgement

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Abstrak

Enjin stim adalah jenis enjin yang pertama untuk melihat penggunaan meluas. Ia adalah asas kepada revolusi perindustrian. Kajian ini dilakukan untuk mengkaji prestasi dan spesifikasi komponen yang membentuk Engine Steam Micro. Sistem ini terdiri daripada 3 bahagian iaitu dandang, injap tekanan mengawal selia dan enjin stim micro. Dandang adalah dandang tiub api menegak dengan kapasiti 7.5 L dan tekanan operasi maksimum 10 Bar. Injap tekanan mengawal selia ialah Yoshitake GD 45P yang padat, ringan dan dengan tekanan masuk minimum 2 Bar. Enjin wap adalah Micro Wobbler enjin. Prestasi sistem ditentukan dengan mengubah tekanan masuk dan beban manakala mengukur kadar aliran dan tork. Dari eksperimen yang dijalankan, kuasa brek yang paling tinggi, kuasa tertunjuk dan kuasa geseran adalah 4.35 Watts, 17.4 Watts dan 13.05 Watts. Kecekapan haba ditunjukkan tertinggi adalah 0.23% manakala kecekapan mekanik kekal pada 25% dan kecekapan dandang adalah 43%. Keputusan menunjukkan kecekapan keseluruhan sistem yang rendah iaitu 0.056%.

Abstract

Steam engines were the first engine type to see widespread use. It was the foundation of the industrial revolution. This study is done to investigate the performance and specification of the components that make up the Micro Wobbler Steam Engine. The system comprise of 3 parts namely the boiler, the pressure regulating valve and the steam engine. The LPG fired boiler is a vertical fire tube boiler with a 7.5 L capacity and a maximum operating pressure of 10 Bar. The pressure regulating valve is a Yoshitake GD 45P that is compact, lightweight and with a minimum inlet pressure of 2 Bar. The steam engine is Micro Wobbler Steam engine. The performance of the system was determined by varying the inlet pressure and the load while measuring the flowrate and torque. Subsequently, the brake power, indicated power, friction power, brake thermal efficiency and mechanical efficiency were calculated. From the experiment carried out, the highest brake power, indicated power and friction power were 4.35 Watts, 17.4 Watts and 13.05 Watts. The highest indicated thermal efficiency was 0.23% while the mechanical efficiency remained constant at 25%. Whereas the boiler efficiency was 43%. The results indicates a relatively low overall efficiency of the system that is 0.056%.

1.0 Introduction

Steam engines have been attracting a lot of attention in recent years as prime movers in small scale remote area power supply systems utilizing renewable energy. Steam power systems, using steam generated by boilers fueled from biomass fuels or solar energy, have been shown to be rugged, reliable and cost-effective[1]. Steam engine has been in existence since years back and using steam to produce mechanical motion goes back over 2000 years, although early devices were not practical. The first recorded of steam engine was done in the 1606 by a Spanish inventor; Jerónimo de Ayanz. [2, 3] And In 1698 Thomas Savery produce a steam pump that used steam in direct contact with the water being pumped. And also in 1712 Thomas Newcomen's atmospheric engine was the first commercial true steam engine using a piston, and was used for pumping in a mine, in the same year 1712 [4]. In 1781 James Watt produced continuous rotary motion for a steam engine . [5, 6] Watt's ten-horsepower engines enabled a wide range of manufacturing machinery to be powered. The stationary steam engine was a key component of the Industrial replacement, allowing factories to locate where water power was unavailable.

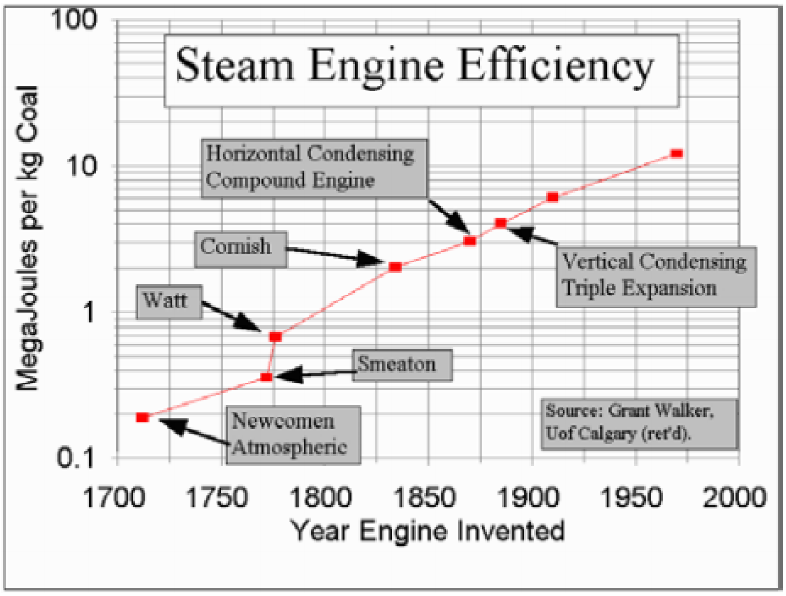


Figure 1. Schematic chart of steam engine efficincy and the year invented [7]

The advantages of the steam engine are it can run at a very low pressure and it can also run in any position Steam engine has no noise or environment impact associated with it and requires no back up power[8].

Reciprocating piston type steam engines remained the dominant source of power until the early 20th century, when design of electric motors was improved and internal combustion engines gradually resulted in the replacement of reciprocating (piston) steam engines for commercial use, and the dominant of steam turbines in power generation[9]. The majority of worldwide electricity generated are produced by steam turbine engines, the "steam age" is continuing with energy levels far beyond those of the turn of the 19th century.

The steam engine works by converting the energy in the steam to useful mechanical work. This is an advantage due to the fact that an enormous variety of fuels can be used to power the steam engine. The fuel is used to heat up the boiler which then turns the water in the boiler into steam that powers the steam engine.

The performance of the steam engine is characterized by its braking torque, mean effective pressure, indicated power, brake power, friction power, mechanical efficiency, brake thermal efficiency and overall efficiency . In order to determine these, the braking torque and the brake power must be determined. The method to determine these 2 parameters is by using a dynamometer. A dynamometer, or “dyno” for short, is a device used to measure torque and rotational speed (rpm) from which power produced by an engine or any other rotating prime mover can be calculated[10]. There are 2 major types of dynamometer which are the absorption dynamometer and the transmission dynamometer. Absorption dynamometer are those that absorbs the power to be measured by friction. The power absorbed in friction is finally dissipated in the form of heat energy[11].

A constant downstream pressure to the steam engine is provided by a steam pressure regulating valve. The steam pressure regulating valve ensures a constant downstream pressure with minimum fluctuations in the pressure, however the flowrate of the steam is not maintained.

The major problems identified from the previous work done on the study of the performance of the micro steam engine were that there were high frictional losses between the rope of the dynamometer and the flywheel. This is because the rope used was a steel wire. The flywheel is made of aluminium. Steel and aluminium has a high coefficient of friction which is 0.61. The contact surface of the rope with the flywheel was also very large due to the large diameter of the flywheel. This resulted in a high friction power and low efficiency.

Operating and testing the micro steam engine was also cumbersome due to absence of a proper steam pressure regulating valve. The operator has to meticulously operate the control valve so that the steam pressure to the steam engine is maintained at the desired pressure. This was particularly difficult because the pressure in the boiler will drop quickly once the valve is opened. The range of pressure drop should not exceed 0.2 bar so that the result is acceptable. The usage of the control valve also contributed to errors because it was not possible to accurately maintain the pressure to the steam engine. This might have cause inaccuracies in the data recorded. The objective of this project is to determine the performance of the micro steam engine and the boiler. The performance of the micro steam engine must also be increased by fabricating an improved version of the rope brake dynamometer than has been used previously and also replacing the rope material from steel to leather. This is to reduce the friction power and increase the efficiency of the micro steam engine. The control valve should also be replaced by a suitable steam pressure regulating valve that would simplify the operation of the steam engine and to provide a more accurate reading.

2.0 Methodology

2.1. Apparatus

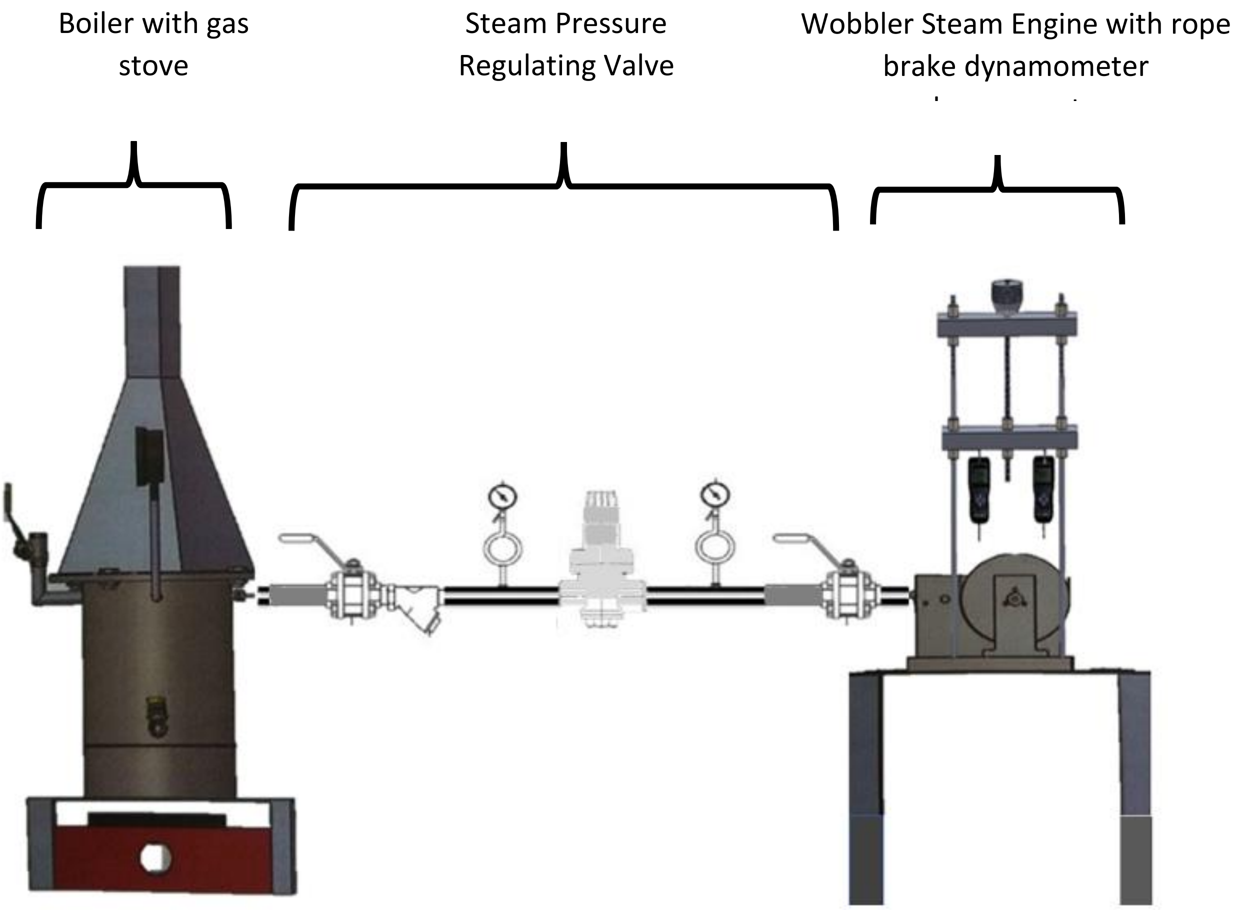


Figure 2. Complete setup of the Wobbler Steam Engine together with a vertical fire tube boiler and a steam pressure regulating valve

Figure 2 shows the complete setup of the system which consist of 3 main parts that are the boiler, steam pressure regulating valve and the micro steam engine together with the rope brake dynamometer attached to it.

2.1.1. Boiler

Figure 3 shows the boiler used which is a vertical fire tube boiler. It has a maximum capacity of 7.5 liters and a maximum operating pressure of 10 bar. It is made of stainless steel. The components attached to the boiler are a pressure gauge (10Bar), water level indicator, and a safety valve.

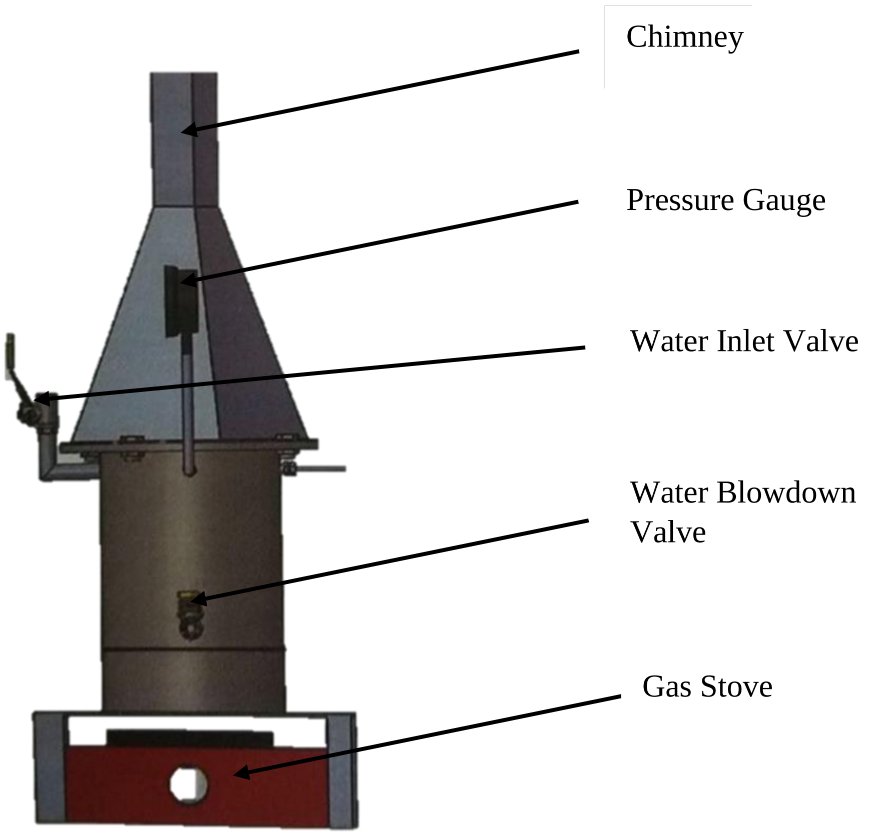


Figure 3. Vertical fire tube boiler

2.1.2. Steam Pressure Regulating Valve

Figure 4 shows the steam pressure regulating valve. The model is a Yoshitake GD-45P.45. Applicable to inlet pressure of up to 2.0MPa. A screen (60 mesh) is incorporated to protect the valve from dirt. The maximum operating temperature is 220°C.[12] Attached to the PRV are 2 pressure gauges and 2 valves.

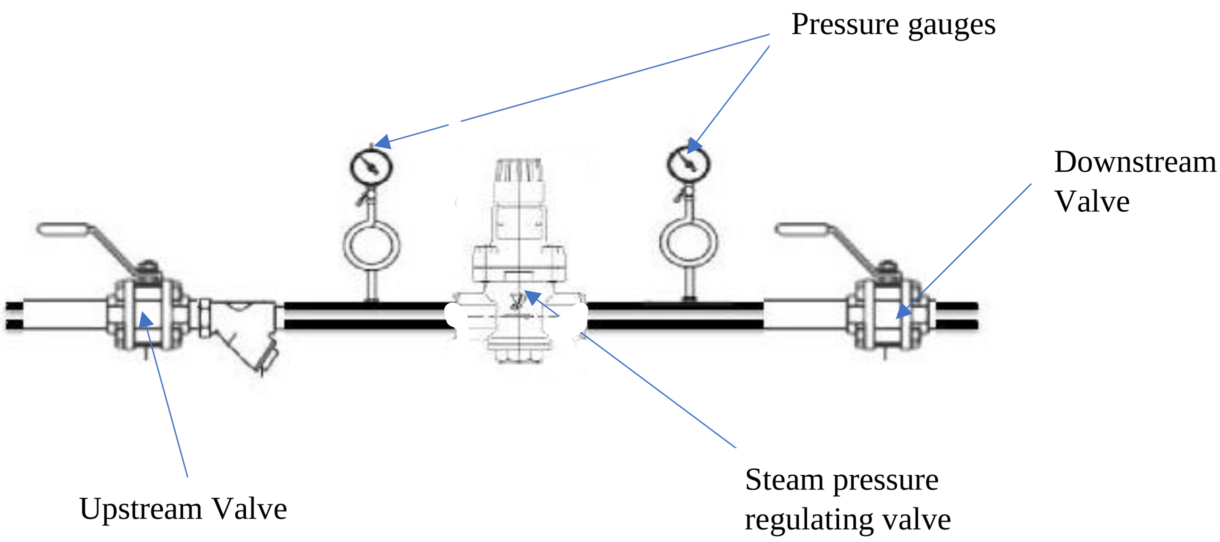


Figure 4. Schematic Diagram of the Steam Pressure Regulating Valve

2.1.3. Steam Engine and Rope Brake Dynamometer

Figure 5 and Figure 6 shows the Steam Wobbler engine used which is a 2 stroke reciprocating engine. The Wobbler engine has no valve gear which makes it easy to manufacture. The Wobbler engine is compact than other engines of the same capacity and has the added advantage of simplicity. The engine works by the rocking motion of the cylinder block. As the cylinder rocks up and down about the pivot point, it allows steam to flow into the cylinder block by aligning the inlet hole to that of the steam flow path. As the cylinder block moves downwards, the steam is forced out of the exhaust port. The rope brake dynamometer attached to the steam engine is employed to measure the torque of the steam engine. The dynamometer applies the load by turning the adjustment knob at the top to adjust the height of the rope. 2 weight gauges both having a maximum capability of 50kg each are attached to the rope brake dynamometer. The rope chosen is made of leather which has a coefficient of friction of 0.2. This is to ensure a low frictional loss between the flywheel and the leather rope.

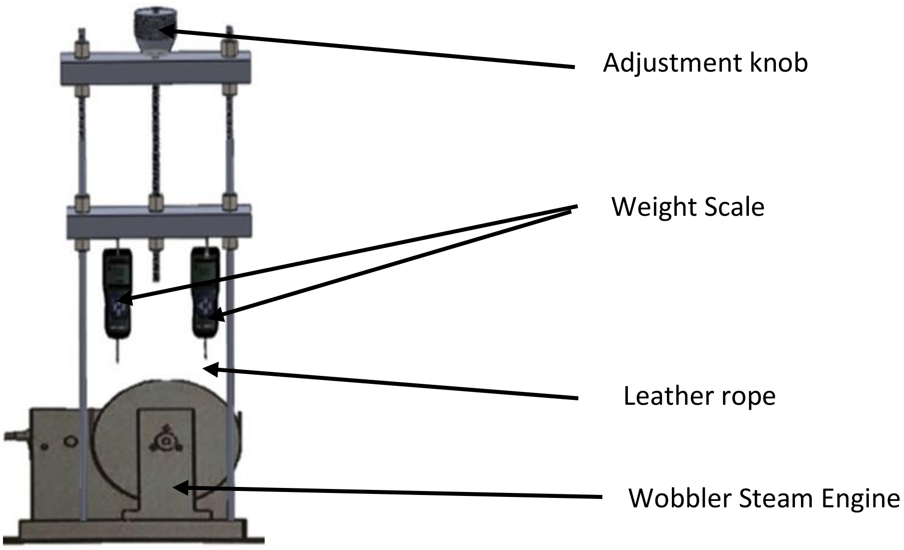
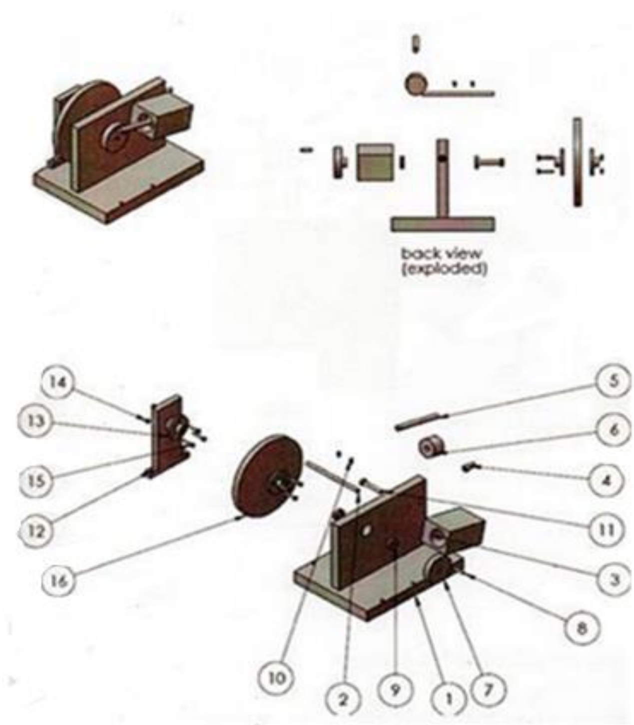


Figure 5. Steam engine and rope brake dynamometer



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Body Support	Aluminium	1
2	Shaft	Aluminium	1
3	Cylinder Block	Aluminium	1
4	Pipe Fitting		1
5	Piston Rod	Aluminium	1
6	Piston	Aluminium	1
7	Mass Balancer	Aluminium	1
8	Lock Pin	Aluminium	1
9	Bearing		3
10	Shaft Support Lock Pin		2
11	Piston Pin Lock		1
12	Support Station		1
13	Shaft Support		3
14	Shaft Support Nut		6
15	Shaft Support Bolt		6
16	Flywheel	Aluminium	1

Figure 6. Details and Design of the Wobbler Steam Engine

2.2. Determining performance of the micro steam engine.

Firstly, the adjustment knob of the dynamometer was rotated to apply a load of 0.15N on the flywheel. Approximately 4L of water was poured into the boiler. The volume of water in the boiler was recorded. Once the boiler is filled with water, the gas stove was then turned on. Time to reach the pressure of 3.0 bar in the boiler was recorded. The pressure in the boiler is allowed to rise till 6.0 bar. Once, the boiler pressure reaches 6.0 bar, the steam pressure regulating valve's knob was turned till the downstream pressure to the micro steam engine's inlet was at 3 bar. A tachometer was used to measure the speed of the flywheel. The valve was adjusted till the speed of the flywheel was maintained at steady 1000 rpm. The time was recorded from the moment the valve was opened till the valve was closed. After the valve is closed, the water level in the boiler was again recorded. The experiment was repeated by increasing the load to 0.20N, 0.25N and 0.30N at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar. The formulae for calculations are as below;

Braking Torque, $T_b = (W1-W2) \times r$ (Nm) (Eq. 1)

W1 : Weight of digital weighing scale 1 (N)
W2 : Weight of digital weighing scale 2 (N)
r : radius of rope and radius of flywheel (m)

Mean effective pressure, $P_m = 2\pi n T_b/V_d$ (Nm^{-2}) (Eq. 2)

n : number of stroke
Vd : Swept Volume (m^3)
N : rpm of flywheel

Indicated Power = $2 \times P_m \times V_d \times N/60$ (Watt) (Eq. 3)

Brake Power, $P_b = T_b \times (2\pi N/60)$ (Watt) (Eq. 4)

Friction Power, Pf = Indicated Power – Brake Power (Watt) (Eq. 5)

Mechanical Efficiency = (Brake Power/ Indicated Power) x 100 (Eq. 6)

Brake thermal Efficiency = (Brake Power/ $\dot{m}_{fuel}$ x LHV) x 100 (Eq. 7)

$\dot{m}_{fuel}$: mass flow rate of fuel (kg/s)

Indicated Themal Efficiency = (Indicated Power/ $\dot{m}_{fuel}$ x LHV) x 100 (Eq. 8)
$\dot{m}_{fuel}$: mass flow rate of fuel (kg/s)

2.3. Determining efficiency of boiler

The Boiler was initially filled with 4.25 liters of water. The LPG tank was then placed on a weighing scale to measure it's intial weight. After 10 minutes the weight of the LPG was again recorded to measure the mass flow rate of the fuel. Once the initial weight of the LPG tank has been recorded, the stove was switched on to it's maximum setting. The time taken for the pressure to reach the pressure of 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar were recorded. The pressure was allowed to increase to 7.0 bar to ensure the pressure remains higher than the pressure being tested. The steam pressure regulating valve's knob is rotatated to adjust the downstream pressure to a pressure of 3.0 bar. The downstream valve was then opened for 5 minutes. To identify the mass flow rate of the steam, the water level was recorded before and after the valve was opened for 5 minutes. The experiment was repeated for pressures 3.5 bar, 4.0 bar, and 4.5 bar and 5.0 bar. The formula used to calculate the efficiency of the boiler is given in Eq. 9.

Boiler Efficiency, $\eta = \frac{Steam\ Flowrate\ x\ hg}{Fuel\ mass\ flow\ rate\ x\ LHV}$ x 100 (Eq. 9)

Steam Flowrate(kg/hour)
Fuel mass flow rate (kg/hour)

3.0 Result and Discussion

3.1. Performance of Steam Engine

The performance of the steam engine can be studied based upon the power generated by the engine. The 3 powers investigated are the brake power, indicated power and the friction power. The flywheel is maintained at 1000rpm. Brake power is the available power at the flywheel without any friction loss. Indicated power is the power developed in the piston cylinder whereas friction power is the difference between indicated power and brake power. Figure 7 to Figure 10 shows that brake power, indicated power and friction power increases linearly as the load is increased. The indicated power is the highest followed by friction power and then brake power for pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar. The brake power is always less than the indicated power due to frictional loss. The friction power is higher than the brake power due to high friction losses that occur in the system. The frictional loss happens mainly between the cylinder block and the body support, between the piston and the cylinder block and rope of the dynamometer and the flywheel. The brake power should be higher than the frictional power so that the efficiency of the engine can be increased.

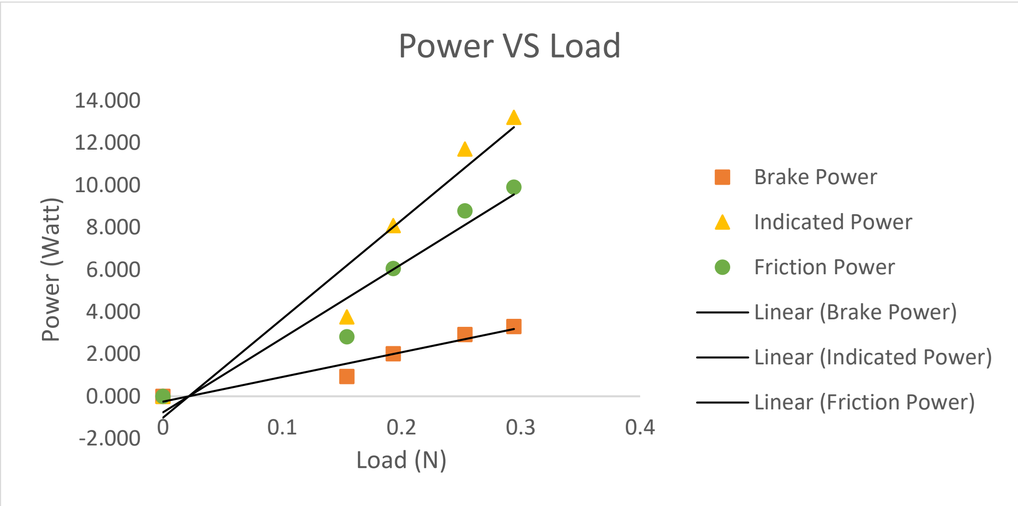


Figure 7. Power generated as load is increased at a constant pressure of 3 Bar

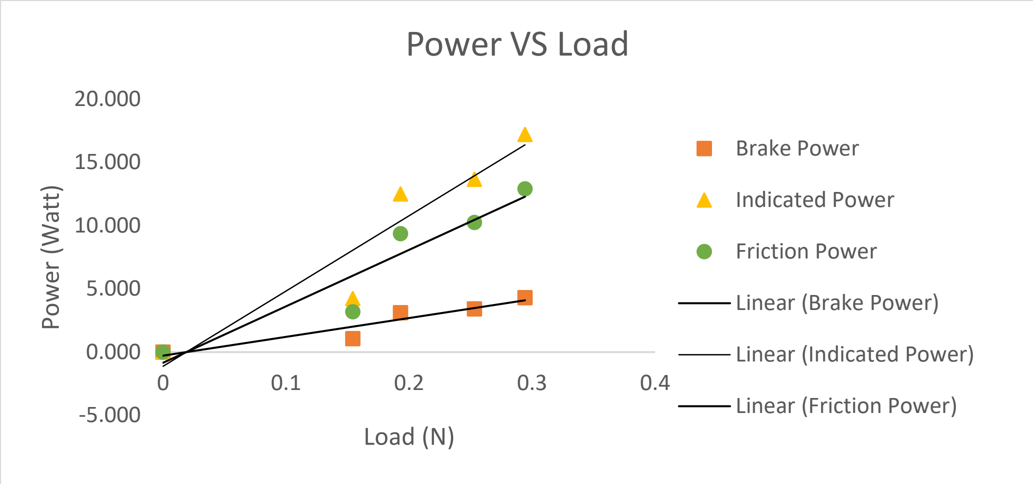


Figure 8. Power generated as load is increased at a constant pressure of 3.5 Bar

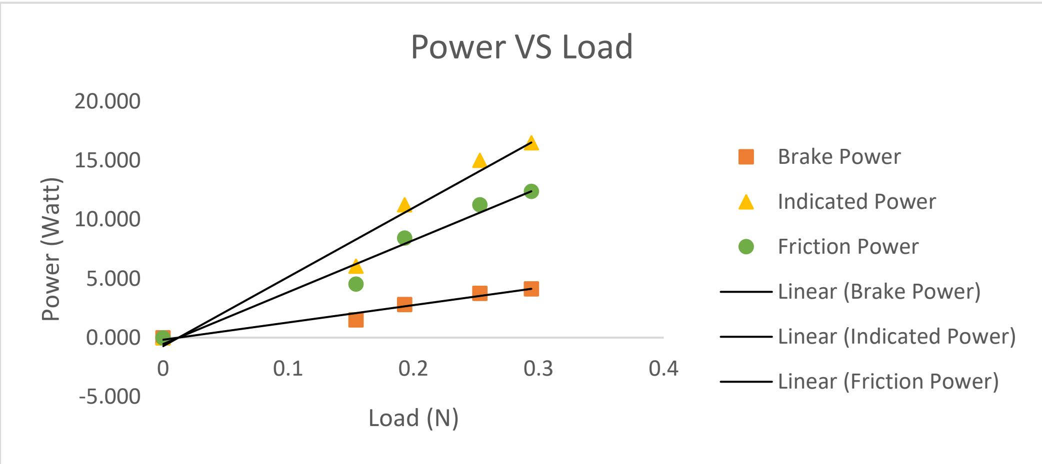


Figure 9. Power generated as load is increased at a constant pressure of 4.0 Bar

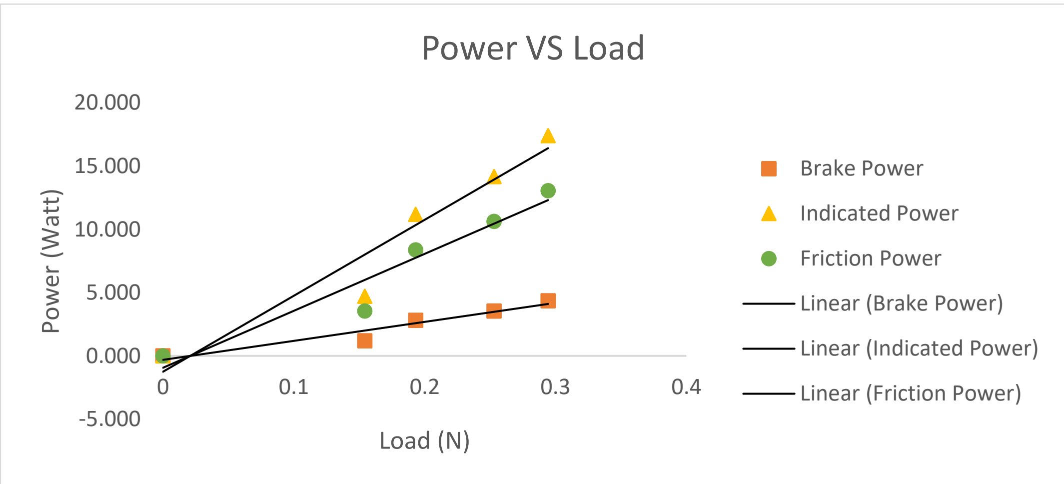


Figure 10. Power generated as load is increased at a constant pressure of 4.5 Bar

3.2. Brake Power

The variation of brake power with varying load at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar is shown in Figure 11. It can be observed that the brake power increases with increasing pressure at the same load. The highest brake power recorded is 4.35 Watts at 4.5 bar and a load of 0.2942 N.

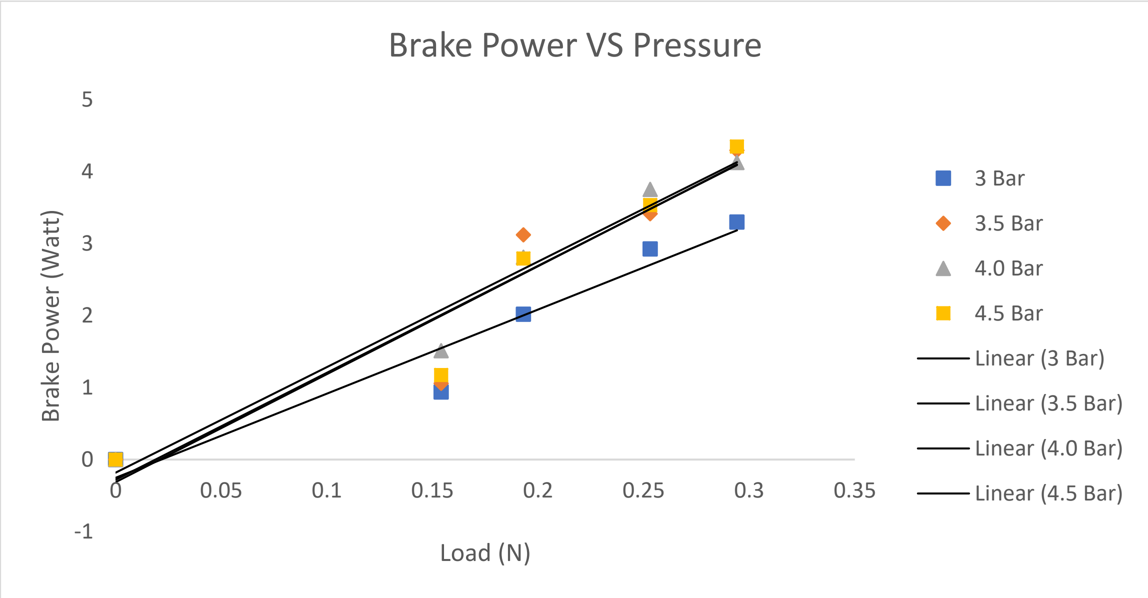


Figure 11. Brake power generated when load is increased at 3.0 bar, 3.5bar, 4.0 bar and 4.5 bar

3.3. Indicated Power

The variation of indicated power with different loads at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar is shown in Figure 12. The plot reveals generally that as the pressure increases the indicated power increases at the same load. The highest indicated pressure recorded is 17.4 Watts at 4.5 bar and a load of 0.2942N.

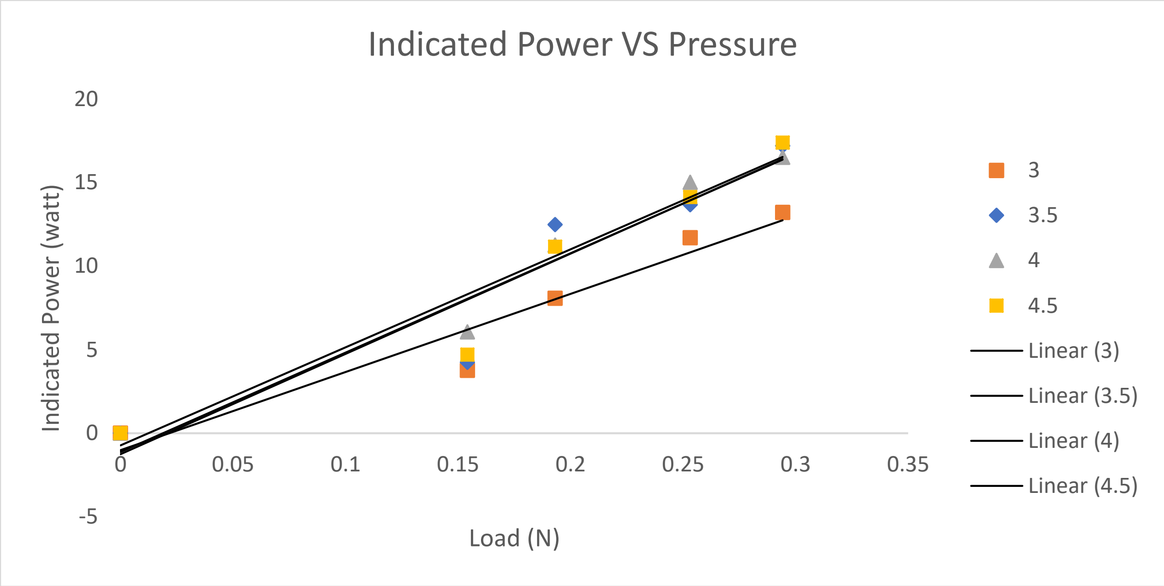


Figure 12. Indicated power generated when load is increased at 3.0 bar, 3.5bar, 4.0 bar and 4.5 bar

3.4. Friction Power

The variation of friction power with different loads at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar is shown in Figure 13. The plot shows that as the pressure increases the friction power increases at the same load. The highest friction pressure recorded is 13.05 Watts at 4.5 bar and a load of 0.2942N.

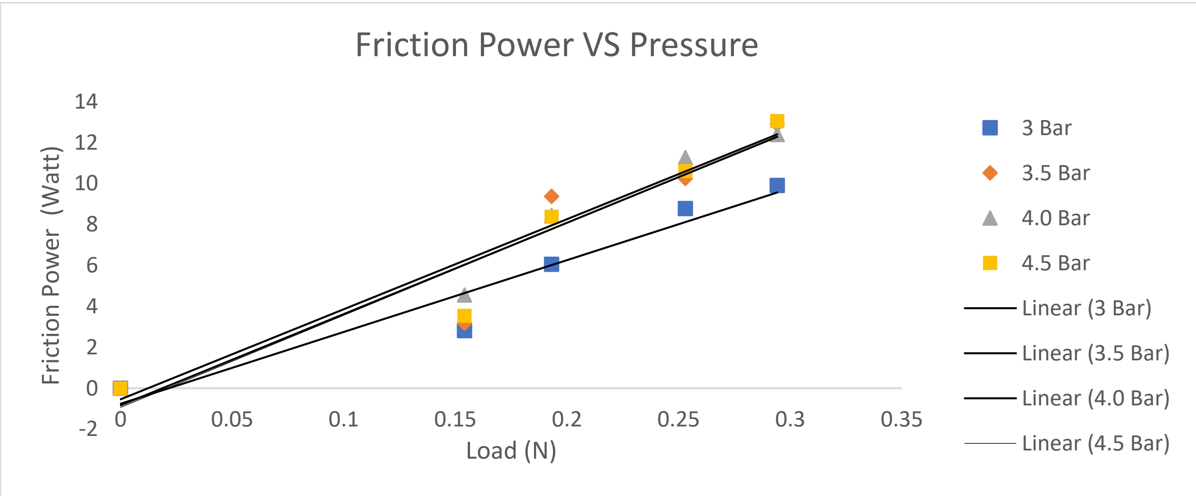


Figure 13. Friction power generated when load is increased at 3.0 bar, 3.5bar, 4.0 bar and 4.5 bar

3.5 Efficiency

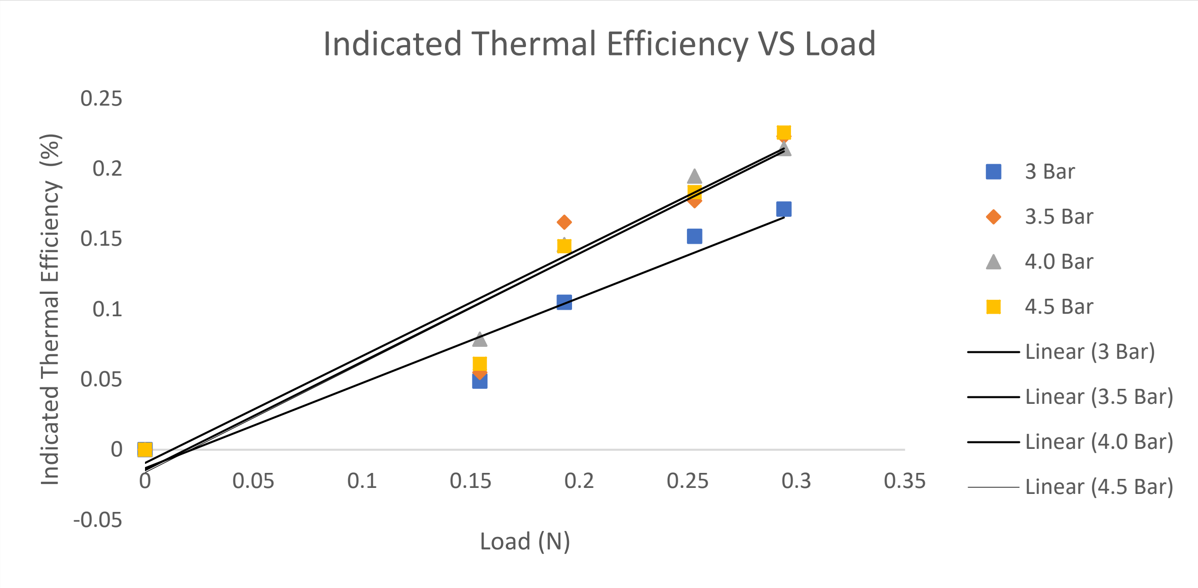


Figure 14. Indicated Thermal Efficiency with varying load at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar

Indicated thermal efficiency is the ratio of indicated power to the heat input at the boiler. Figure 14 shows the variation of Indicated Thermal Efficiency with different loads at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar. From the plot, it can be seen that the indicated thermal efficiency increases with increasing pressure at the same load. The indicated thermal efficiency also increases with increasing load at the same pressure. The highest recorded indicated thermal efficiency is 0.23% at a pressure of 4.5 bar and a load of 0.294 N. The indicated thermal efficiency is a function of the indicated power thus demonstrating the similar trend to that of the indicated power. The low efficiency of the system can be attributed to high amounts of steam loss. Steam is largely loss at the connection between the inlet to the cylinder block. Steam is also lost via the gap between the piston and the piston cylinder. The diameter of the piston is 1mm smaller compared to the diameter of the piston cylinder. This contributes greatly to the vast amount of steam loss. Further heat loss to the surrounding due to poor insulation of the boiler and the pressure regulating valve contributed to a very low thermal efficiency. Leakages at points of connection of the valves, pipes and pressure gauges could have also contributed to a low indicated thermal efficiency.

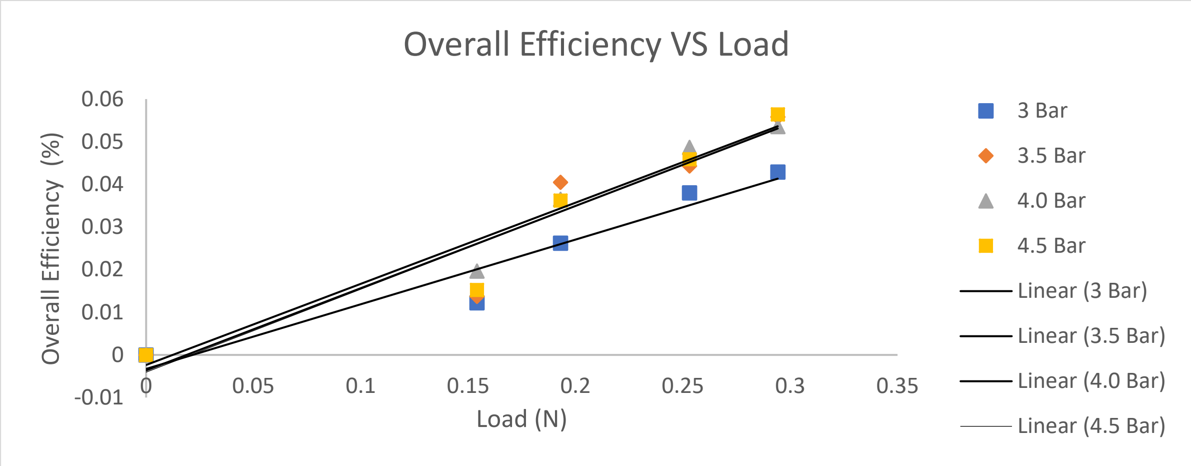


Figure 15. Overall Efficiency with varying load at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar

Figure 15 shows the variation of overall efficiency with different loads at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar. Overall efficiency is the ratio of brake power to the heat input at the boiler. A good range of overall efficiency is about 5-10% for a steam engine[1]. From the plot it can be seen that the overall efficiency increases with increasing pressure at the same load whereas the similar trend can be seen as the load is increased while keeping the pressure constant. The highest recorded overall efficiency is 0.056% at 4.5 bar and at a load of 0.294N which is very low. The overall efficiency is lower when compared to the indicated thermal efficiency. This is because of the high friction power. As stated previously, high frictional loss occurs at mainly the 2 moving components of the system that are between the cylinder block and the body support and also between the piston and the cylinder block. The influence of temperature on the coefficient of friction for metal-metal contact may have been an influencing factor that lead to low efficiency and high friction power.

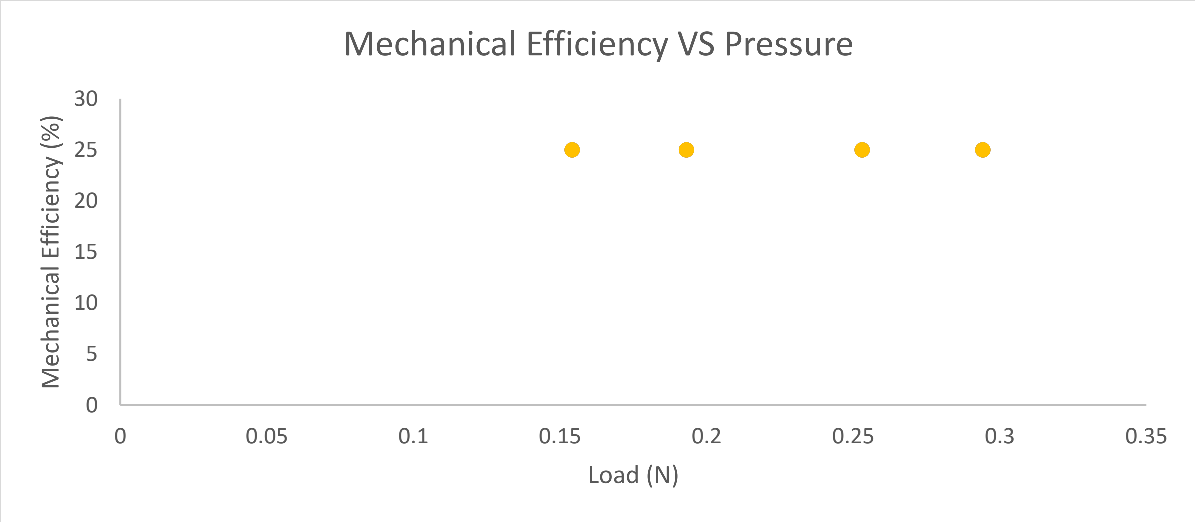


Figure 16. Mechanical Efficiency with varying load at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar

Figure 16 shows the variation of Mechanical Efficiency with different loads at pressures 3.0 bar, 3.5 bar, 4.0 bar and 4.5 bar. Mechanical efficiency is the ratio of brake power to indicated power. From the plot in Figure 10, it can be deduced that the mechanical efficiency remains constant with increasing load at the same pressure and also with increasing pressure at the same load. The mechanical efficiency remained constant at 25%. An efficient steam engine should have mechanical efficiency in the range of 70-80%[1]. The low efficiency was due to high frictional loss. This resulted to the brake power being lower than the friction power.

3.6. Boiler Efficiency

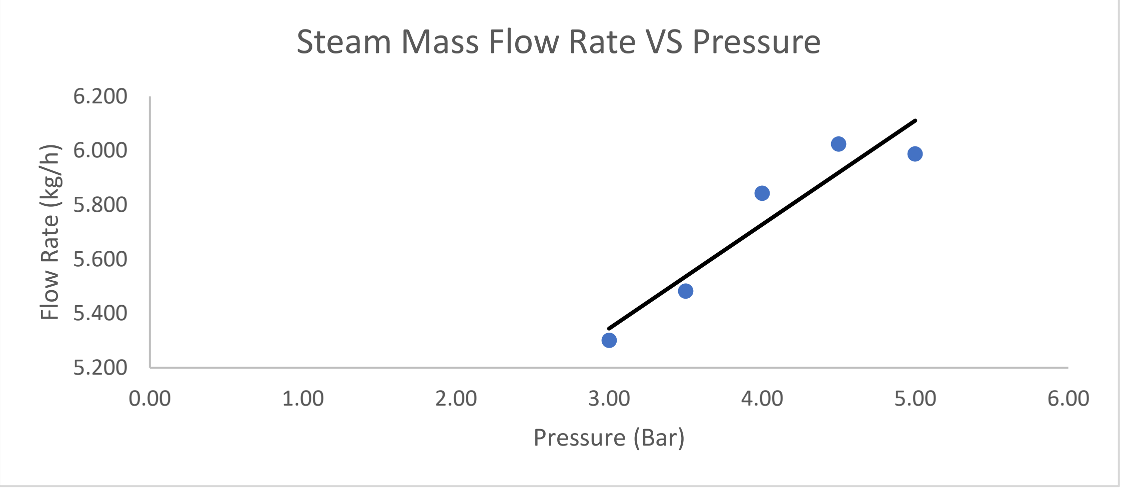


Figure 17. Steam Mass Flow Rate VS Pressure of Boiler

Figure 17 shows the variation of steam flow rate with increasing boiler pressure. The plot reveals that the flowrate increases with increasing pressure. The mass flow rate is a function of velocity, density and flow area. As the pressure increases, the velocity of the steam increases. This results to a higher mass flow rate with increasing pressure. The highest steam mass flow rate is approximately 6kg/h.

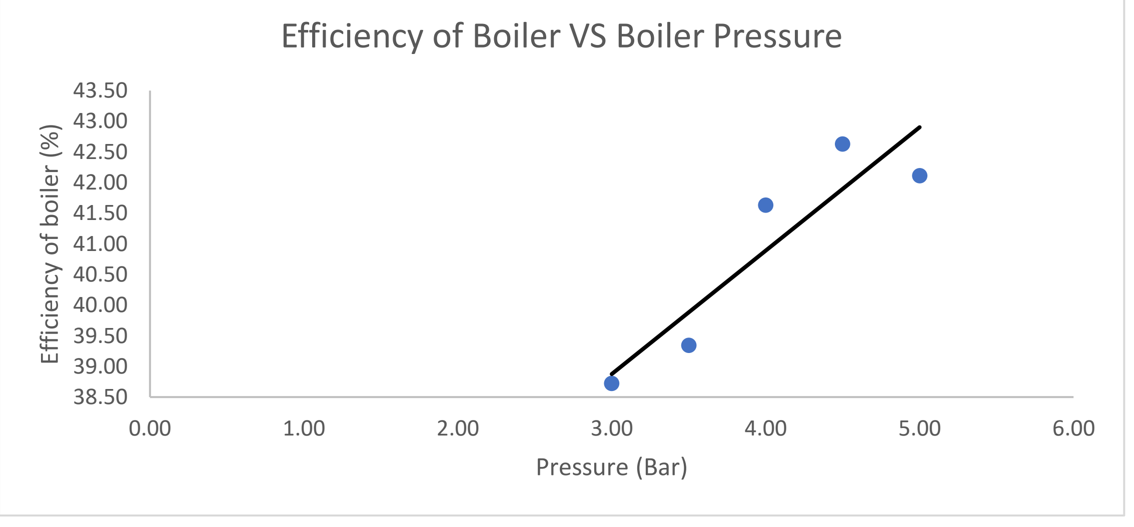


Figure 18. Efficiency of boiler at pressure 3-5 bar

Figure 18 shows that the efficiency of the boiler increases as the pressure increases. The efficiency of the boiler is a function of the mass flow rate of the steam and the mass flow rate of fuel. As previously stated, as the pressure increases, the mass flow rate of the steam increases thus increasing the boiler efficiency. The highest recorded efficiency of the boiler is 43%. The efficiency of the boiler is low due to the flame from the stove not focused towards the bottom surface area of the boiler. Some parts of the flame may not be used to heat the boiler. The boiler maybe lacking sufficient insulation. Thicker insulations can be used to increase efficiency.

4.0. Conclusion

The performance of the micro steam engine and the efficiency of the boiler were measured experimentally. Parameters including brake power, indicated power, friction power, mechanical efficiency, brake thermal efficiency and indicated thermal efficiency were then determined. From the experiments carried out, it has been identified that the highest brake power is 4.35 Watt, highest Indicated power is 17.4 Watt and the highest friction power is 13.05 Watt. The highest mechanical efficiency is 25%, highest Indicated Thermal Efficiency is 0.23% whereas the overall efficiency of the system is 0.056%. The boiler efficiency is approximately 43%. The low efficiency was largely due to significant loss of steam to the cylinder block and the high frictional loss between the body support and the cylinder block and between the cylinder block and the piston. From the observations made throughout the project, a few suggestions to increase the efficiency of the system such as changing the material of the piston and the cylinder block to that of Teflon. Teflon's lubricative properties may reduce the frictional loss. Another suggestion is to ensure the steam does not escape through the gap between the piston and the cylinder block. This can be done by using a rubber fitting around the piston.

‘

5.0. References

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