PHYS2712 Thermo 5 Laboratory Report

Small Engine Test

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***Abstract*—The performance of a small capacity single cylinder carburettor four stroke internal combustion engine is measured to determine the ideal operating range. The exhaust temperature, torque, power, air/fuel ratio, specific fuel consumption, volumetric efficiency, and thermal efficiency are investigated. These parameters are recorded at six different engine speeds. The engine was found to develop the greatest torque and power at the maximum speed of 3600 rpm, and specific fuel consumption and thermal efficiency were optimised at 3200 rpm.**

***Keywords*—internal combustion engine, specific fuel consumption**

1 Introduction

Evaluating the performance of internal combustion engines (ICE) is an important skill for any mechanical engineer. This laboratory report analyses the performance of a small, single cylinder, four-stroke petrol engine to determine the optimal operating parameters. A multitude of sensors were employed to measure many operating variables and from this data, and by applying thermodynamic principles and equations the engine's performance can be analysed. The engine and water dynamometer are shown in Figure 1.

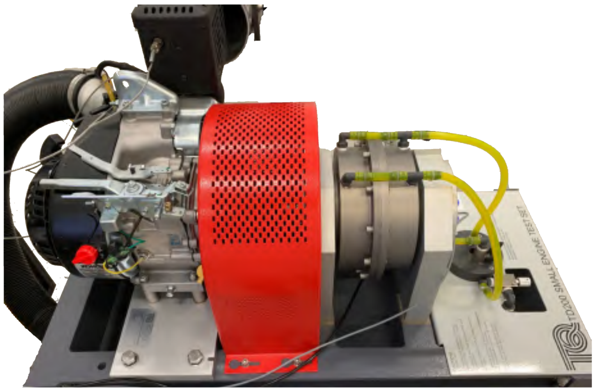


Figure 1: View of experiment apparatus showing from left: intake air hose, internal combustion engine with exhaust exiting from top, coupling shroud, water dynamometer, and water flow control.

1.1 Parameters

Given the density and volume of a material, the mass is given by:

$$m = \rho V \tag{1}$$

where m is the mass, ρ is the density, and V is the volume, and assuming that the material is homogeneous with constant density over time, the mass flow rate is given by:

$$\dot{m} = \rho \dot{V} \tag{2}$$

where $\dot{m}$ is the mass flow rate, ρ is the density, and $\dot{V}$ is the volumetric flow rate.

The volumetric flow rate can be expressed as:

$$\dot{V} = Av \tag{3}$$

where A is the cross-sectional area, and v is the velocity normal to the area.

The air flow velocity is given as [1, 2]:

$$v_a = \sqrt{\frac{2\Delta p}{\rho}} \tag{4}$$

The air passes through a circular opening, having area $A = \pi d^2/4$, and as such a discharge coefficient C_d will apply to the mass flow [1]. Using the ideal gas law $p/\rho = RT$, and Equations 2, 3, and 4, the mass air flow can be given as:

$$\dot{m}_a = C_d \frac{\pi d^2}{4} \sqrt{\frac{2 p_A \Delta p}{R T_A}} \tag{5}$$

where $\dot{m}_a$ is the mass air flow rate, C_d is the coefficient of discharge for the orifice, d is the diameter of the orifice, p_A is the ambient air pressure, Δp is the difference in air pressure between the ambient air and inside the air-box past the orifice, R is the gas constant for air, and T_A is the ambient air temperature.

For example, given that $C_d = 0.6$, $d = 0.018\,54\,\mathrm{m}$, $p_A = 101\,200\,\mathrm{Pa}$, $\Delta p = 69\,\mathrm{Pa}$, $R = 287\,\mathrm{J\,kg^{-1}\,K^{-1}}$, and $T_A = 289.65\,\mathrm{K}$ then the mass air flow will be:

$$\begin{aligned}
\dot{m}_a &= 0.6 \times \frac{\pi \times (0.018\,54\,\mathrm{m})^2}{4} \\
&\quad \times \sqrt{\frac{2 \times 101\,200\,\mathrm{Pa} \times 69\,\mathrm{Pa}}{287\,\mathrm{J^{-1/2}\,kg^{-1/2}\,K^{-1}} \times 289.65\,\mathrm{K}}} \\
&= 2.10 \times 10^{-3} \left[\frac{\mathrm{m^2\,Pa}}{\mathrm{J\,kg^{-1}}}\right] \\
&= 2.10 \times 10^{-3} \left[\frac{\cancel{\mathrm{m^2}}\,\mathrm{kg}\,\cancel{\mathrm{m^{-1}}}\,\mathrm{s^{-2}}}{\cancel{\mathrm{kg^{1/2}}}\,\cancel{\mathrm{m}}\,\mathrm{s^{-1}}\,\cancel{\mathrm{kg^{-1/2}}}}\right] \\
&= 2.10 \times 10^{-3}\,\mathrm{kg\,s^{-1}}
\end{aligned}$$

The fuel flow rate is determined from Equation 2 by replacing the generic terms with terms for fuel:

$$\dot{m}_f = \rho_f \dot{V}_f \tag{6}$$

where $\dot{m}_f$ is the mass fuel flow rate, ρ_f is the density of the fuel, and $\dot{V}_f$ is the volumetric flow rate of the fuel.

The fuel flow rate is also known as the fuel consumption; this is a key parameter to be minimised in engine development. For this experiment the fuel consumption was measured rudimentarily by measuring the time (with a stopwatch) that an 8 ml vial inline with the fuel line was emptied, giving the fuel volumetric rate. The fuel density is given as $\rho_f = 740\,\mathrm{kg\,m^{-3}}$. From the density, time, and volume the fuel consumption can be calculated, for example:

$$\begin{aligned}
\dot{m}_f &= 740\,\mathrm{kg\,m^{-3}} \times \frac{8\,\cancel{\mathrm{ml}}}{43.09\,\mathrm{s}} \left[\frac{\times 10^{-6}\,\mathrm{m^3}}{\cancel{\mathrm{ml}}}\right] \\
&= 1.37 \times 10^{-4}\,\mathrm{kg\,s^{-1}}
\end{aligned}$$

The fuel consumption per amount of power developed is termed the brake specific fuel consumption, and can be expressed as:

$$\mathrm{BSFC} = \frac{\dot{m}_f}{P} \tag{7}$$

where $\dot{m}_f$ is the mass fuel flow rate, and P is the developed power.

The air/fuel ratio is the ratio of the air mass flow rate to the fuel mass flow rate:

$$\mathrm{AFR} = \frac{\dot{m}_a}{\dot{m}_f} \tag{8}$$

For example:

$$\begin{aligned}
\mathrm{A.F.R.} &= \frac{2.10 \times 10^{-3}\,\cancel{\mathrm{kg\,s^{-1}}}}{1.37 \times 10^{-4}\,\cancel{\mathrm{kg\,s^{-1}}}} \\
&= 15.3
\end{aligned}$$

The volumetric efficiency is defined as the ratio of the actual mass flow of air into the combustion cylinder to the theoretical ideal mass flow rate given no restrictions and quasi-equilibrium process [3–6]:

$$\eta_v = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}} \tag{9}$$

where η_v is the volumetric efficiency, $\dot{m}_{actual}$ is the actual mass flow rate into the cylinder, and $\dot{m}_{ideal}$ is the theoretical mass flow rate into the cylinder without restrictions.

The name is misleading in that it is a ratio of mass flow rates, not volume [3, 4]. It is a measure of the restriction to airflow into the cylinder due to the intake system components, such as valves, intake port dimensions, compression ratio, piston speed, and engine speed [6].

Care should be taken in forced induction engines, whereby the intake air supply is compressed, that the location of the intake air density measurement is well defined, either at atmosphere, or after the compressor. In this experiment the engine is a simple carburettor design and the intake air parameters are measured at the entry into an air-box, at ambient conditions.

The theoretical ideal mass flow rate, m_{ideal} can be determined by firstly determining the theoretical volume:

$$\dot{V}_{ideal} = \frac{2 \times V_{cyl} \times N}{n} \tag{10}$$

where $\dot{V}_{ideal}$ is the ideal volumetric flow rate, V_{cyl} is the engine displacement, N is the engine speed, and n the number of strokes per cycle of the engine.

Then, by Equation 2:

$$\dot{m}_{ideal} = \frac{\rho_a \times V_{cyl} \times 2N}{n} \tag{11}$$

However as the air density ρ_a is not know, the ideal gas equation will be used again to substitute known parameters:

$$\dot{m}_{ideal} = \frac{2p_a V_{cyl} N}{nRT} \tag{12}$$

And so the volumetric efficiency is:

$$\eta_v = \frac{\dot{m}_{actual} nRT}{2p_a V_{cyl} N} \tag{13}$$

The heat energy that is developed by the combustion process is determined by:

$$H_f = \dot{m}_f \times C_L \tag{14}$$

where H_f is the heat energy, m_f is the mass fuel flow rate, and C_L is the energy density of the fuel. This relation implies complete combustion such that all chemical energy stored within the fuel is converted to heat (achieved at the stoichiometric air/fuel ratio).

The enthalpy of the inlet air is found by:

$$H_a = \dot{m}_a c_p T_A \tag{15}$$

where H_a is the enthalpy of intake air, $\dot{m}_a$ is the mass air flow rate, c_p is the specific heat of air at constant pressure, and T_A is the temperature of the intake air.

The thermal efficiency of an engine is a measure of the amount power developed compared to the amount of energy stored within the fuel that can be converted with combustion, and can be expressed as:

$$\eta_T = \frac{P}{H_F} \tag{16}$$

where η_T is the thermal efficiency, P is the engine power, and H_F is the heat energy of combustion for petrol.

The brake mean effective pressure is the average pressure developed within the cylinder during the power stroke that would develop the actual output power:

$$\text{BMEP} = \frac{Pn}{2NV_{cyl}} \tag{17}$$

where P is the power developed by the engine, n is the number of strokes per cycle, N is the rotational speed of the engine, and V_{cyl} is the cylinder volume (the engine capacity).

Brake parameters are based on the actual measured performance of an engine. The term originates from the use of a brake dynamometer attached to the engine's crankshaft to measure the actual produced torque; such a device is also used in the experimental setup [4, 7]. This term is in contrast with *indicated*, which is the theoretical performance, or the value that is indicated should the system by operating without losses.

2 Methods

2.1 Equipment

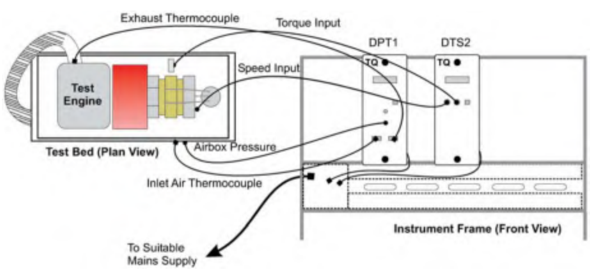


Figure 2: Plan view of apparatus showing from left: engine and dynamometer on test bench, sensor connections to interface modules. Adapted from TecQuipment Ltd. [2].

The experimental equipment consists of a small capacity 208cc, single cylinder, four-stroke petrol engine securely mounted to a test bench to which a water dynamometer is affixed via the crankshaft. The engine has a cylinder pressure sensor that is mounted in a small opening drilled into the cylinder head next to the spark plug, a crankshaft angular position sensor that is connected via a small belt to the crankshaft, and an exhaust gas temperature sensor mounted in the exhaust path. The engine air intake is fed from large diameter corrugated tube from an air-box positioned under the engine, within the frame. The air-box has an interchangeable opening orifice that allows for the diameter to be adjusted. The air-box has a temperature and pressure sensor within the air-box and a pressure sensor outside of the air-box near the orifice opening. The basic layout can be seen in Figure 2.

The water dynamometer is a device that consists of a rotor within a casing, which are both mounted to a frame through bearings and are free to spin. The rotor and casing have ribs, or fins, which allow interaction between the rotor and casing though a fluid. The rotor is mechanically attached to the engine crankshaft. The area within the casing is filled with water and as the engine turns, the rotor acts on the water. The movement of the water is resisted by the fins on the casing and and casing will begin to rotate. To the outside of the casing is a short lever arm that acts on a force meter. From this meter the torque applied to the casing by the engine through the rotor and water can be measured. A position sensor is also mounted to the rotor that measures the engine speed as the rotor is affixed directly to the crankshaft.

The level of water in the dynamometer controls the amount of torque that can be transferred to the casing. The water within the casing is provided by mains water supply and is continually filled and drained at a set rate to provide constant water volume within the casing. This water flow provides cooling to the dynamometer and any heat generated by the water motion is discarded through the water outlet.

The fuel flow rate is measured manually by visually watching a fluid drain from a vial of set volume. As the fuel level passes a mark indicating the beginning of the volume a stopwatch is started, as the fuel level passes the second mark the time elapsed is recorded and from this the volume per time can be calculated. The fuel density is known and from this the mass flow rate can be determined. A front view of the fuel meter apparatus can be seen in Figure 3

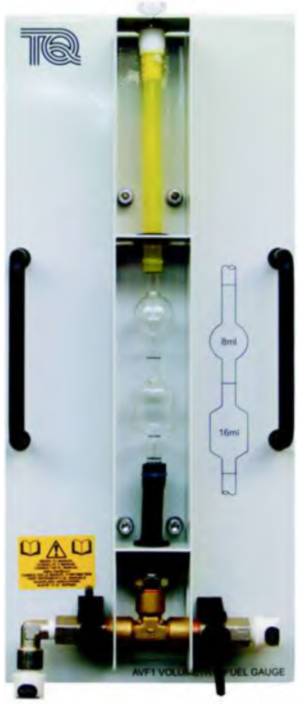


Figure 3: Front view of fuel flow metering device. Adapted from TecQuipment Ltd. [2].

The sensors are fed into control boxes that then interface with a personal computer that records and displays the sensor data.

2.2 Procedure

The engine is provided in a setup state, with all sensors and devices connected and ready to run. Prior to the testing the engine had been idling to allow it to warm up and come to operating temperature. The fuel tank cock is opened to allow the flow meter vial to fill. As the engine is run only for a short period of time the fuel within the fuel gauge is sufficient to run the engine for the duration of the test and so once the vial is full, the fuel tank is closed.

The engine is started and run at a fixed speed by adjusting the air flow via a throttle until the fuel is used within the vial. Once the fuel is depleted the engine speed is reduced back to idle and the fuel vial is filled again.

The sensor data is recorded for each run. The process is run again at a different engine speed in approximately 300 rpm steps from 2000 to 3500 rpm yielding six data points.

2.3 Assumptions

Energy loss through the water dynamometer is negligible.

3 Results

Seven different parameters are plotted against the engine speed in Figures 4 and 5. The exhaust temperature increases as engine speed increases. The torque and power show linear correlations. The air/fuel ratio begins at 15.3 and then drops to be fairly consistent around 12.9 as engine speed increases. The specific fuel consumption follows an unusual curve where there is a significant drop between 2750 and 3000 rpm. The volumetric efficiency increases linearly with engine speed after 2250 rpm. The thermal efficiency indicates a large jump between 2500 and 3000 rpm.

The maximum torque and power is available at maximum engine speed. The specific fuel consumption, and by association the thermal efficiency is optimised around 3000 rpms. The volumetric efficiency is highest at maximum engine speed.

A full set of values can be found in Appendix A Table 1.

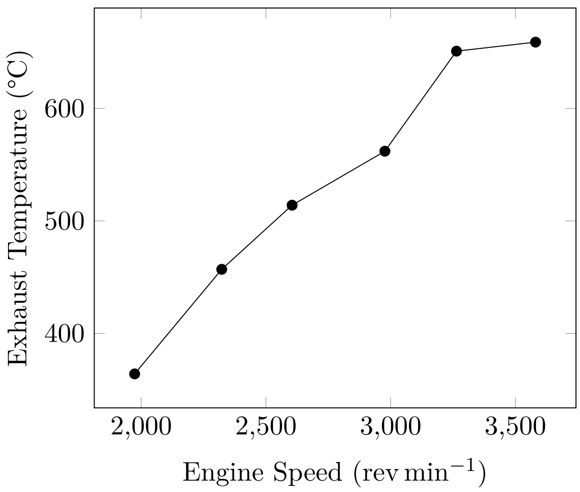


Figure 4: Plot of exhaust gas temperature vs engine speed.

4 Analysis

As the speed of the engine increased, the exhaust temperature, torque and power increased with relative linearity. The volume available in the cylinder during the induction stroke is constant. To increase power, the engine will either need to alter the mixture of air and fuel to facilitate greater expansion, or the frequency at which the four strokes occur will need to increase.

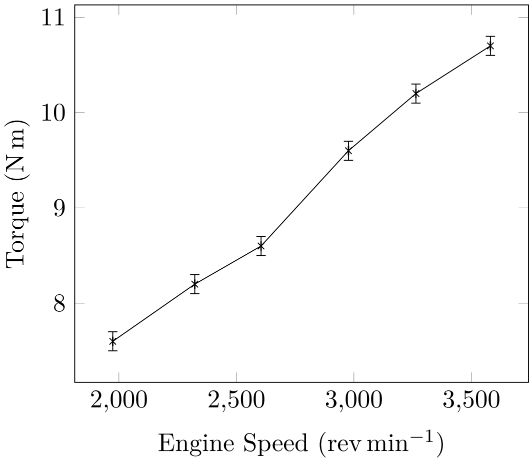
After each power stroke the heated gas is evacuated in the exhaust stroke. With an increase in engine rpm, these strokes are performed more frequently leading to a larger volume of heated exhaust fumes being evacuated within a given time interval. Since the volume of the pipes and cooling system is constant, the raise in temperature is expected.

The amount of torque produced was increased linearly with the speed of the engine. A typical engine will increase the torque output as the speed of the engine increases until the maximum brake torque (MBT) is achieved [8]. The MBT is typically achieved near 3500 rpm which is the maximum speed that was used in this experiment. This would suggest that the measured torque of 10.7 N m is approximately equal to the MBT.

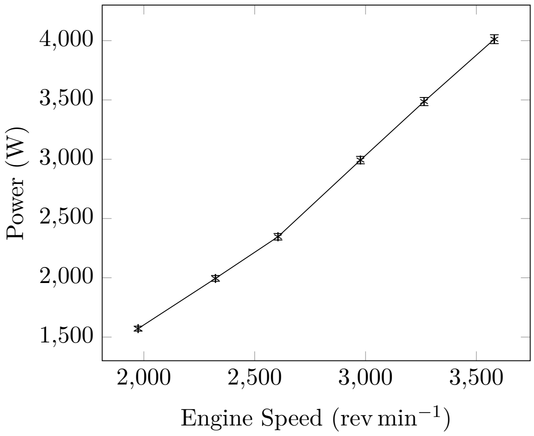
The air/fuel ratio maintained relative levels, at an average of 12.9, throughout the various speeds tested. However, at 1974 rpm, the mixture had a ratio of 15.3. The ideal stoichiometric air/fuel mixture is 14.7, however, engines typically require a slightly richer mixture of approximately 14.1 [9]. This suggests that the average air/fuel ratio was slightly rich.

The specific fuel consumption started out high and experienced a sudden drop around 2900 rpm. After 3300 rpm the specific fuel consumption increased again. This dip around 3000 rpm created an increase in thermal efficiency. The thermal efficiency has an inverse relationship with the specific fuel consumption, as can be seen from Equations 7, 14, and 16 [7]. The thermal efficiency is less than 30% for all tested speeds, this is expected as there are large heat losses caused by friction [10]. The results suggest that the engine tested was the most thermally efficient between 2900-3300 rpm.

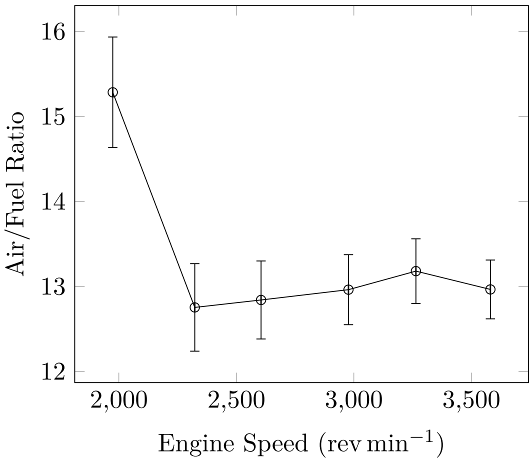
The volumetric efficiency experienced a



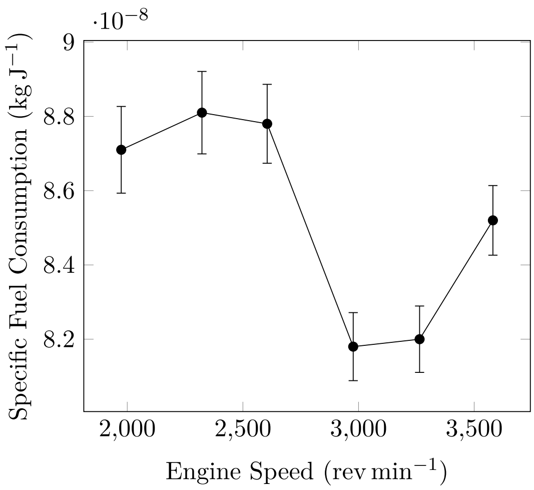
(a)



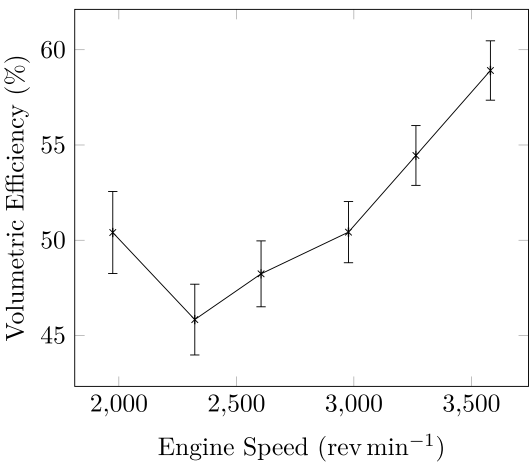
(b)



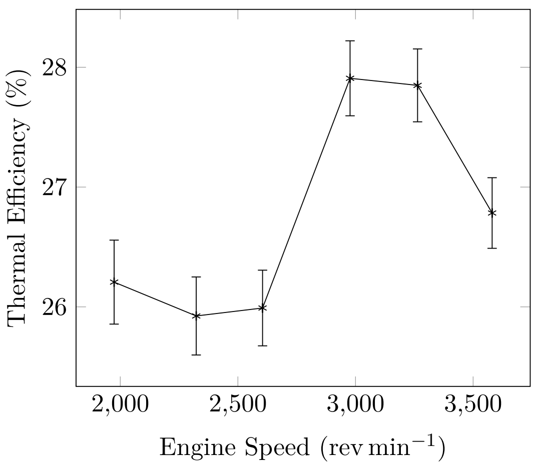
(c)



(d)



(e)



(f)

Figure 5: Plots of (a) torque, (b) power, (c) air/fuel ratio, (d) specific fuel consumption, (e) volumetric efficiency, and (f) thermal efficiency vs engine speed.

small drop at approximately 2350 rpm but linearly increased with rpm after this. This suggests the engine experienced the greatest resistance to air flow at around 2350 rpm. The linear increase in volumetric efficiency increases the total amount of airflow into the engine. As the air/fuel ratio is maintained more fuel is therefore burned increasing the overall power output.

The work done by the engine can be calculated analytically from a p-V diagram by finding the area enclosed within the closed loop that represents the process cycle [11]. The p-V diagram can be created from pressure within the cylinder. An example p-V diagram can be seen in Figure 6. For the experiment, insufficient data was gathered to be able to evaluate the work done in this way.

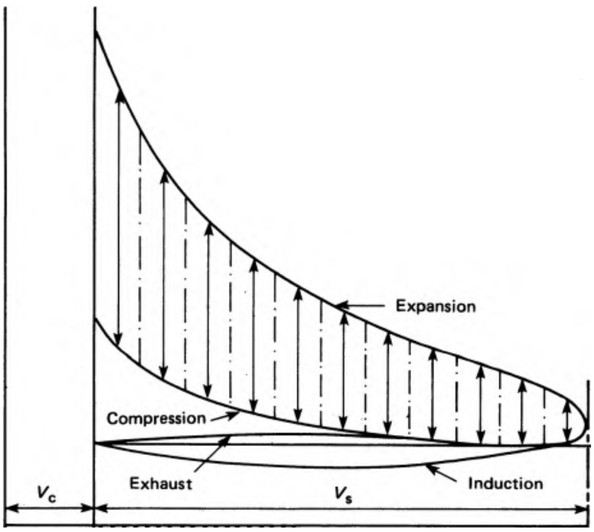


Figure 6: Pressure vs volume diagram showing one thermodynamic cycle of the engine. Work done by the combustion process is positive, while the lower shape accounts for work done by the engine in drawing and exhausting gasses. Adapted from Kett [7].

5 Conclusion

As the volumetric efficiency linearly increased with rpm. It is suggested that the optimum performance for the engine is different for power and efficiency. If more power output was favourable to fuel economy then a speed of around 3500 rpm or greater would be optimal. If efficiency was the priority, the engine would function optimally between 3200-3300 rpm.

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Appendix A Data

Table 1: Experimental results.

	Energy		Air and Fuel				Efficiency		
Engine Speed N [rev.min-1]	**Heat Of Combustion** H_f [W]	**Inlet Air Enthalpy** H_a [W]	**Air Mass Flow Rate** $\dot{m}_a$ [kg s^{-1}]	**Fuel Consumption** $\dot{m}_f$ [kg s^{-1}]	**Air/Fuel Ratio**	**Specific Consumption** [kg J^{-1}]	**Thermal Efficiency** [%]	**Volumetric Efficiency** [%]	**BMEP** [Pa]
1974	6.02×10^3	608	2.10×10^{-3}	1.37×10^{-4}	15.3	8.71×10^{-8}	26.21	50.40	4.61×10^5
2323	7.73×10^3	651	2.25×10^{-3}	1.76×10^{-4}	12.8	8.81×10^{-8}	25.92	45.83	4.97×10^5
2605	9.04×10^3	767	2.65×10^{-3}	2.06×10^{-4}	12.8	8.78×10^{-8}	25.99	48.23	5.20×10^5
2977	1.07×10^3	918	3.17×10^{-3}	2.45×10^{-4}	13.0	8.18×10^{-8}	27.91	50.42	5.79×10^5
3264	1.25×10^3	1086	3.75×10^{-3}	2.84×10^{-4}	13.2	8.20×10^{-8}	27.85	54.45	6.13×10^5
3581	1.50×10^3	1289	4.45×10^{-3}	3.43×10^{-4}	13.0	8.52×10^{-8}	26.78	58.91	6.49×10^5