

# A Cost-Effective Teaching and Research Dynamometer for Small Engines\*

ROBERT R. RAINE, KERI MOYLE and GORDON OTTE

*Department of Mechanical Engineering, The University of Auckland, Private Bag 92019, Auckland, New Zealand. E-mail: r.raine@auckland.ac.nz*

JOHN ROBERTSON

*Department of Applied Science, Auckland University of Technology, Private Bag 92006, Auckland, New Zealand*

*A dynamometer suitable for use with model aircraft type engines that enables the measurement of performance, efficiency and emissions under controlled conditions is described. The low cost of both the engine, dynamometer and the fuel measurement system described make it ideal for teaching and undergraduate research projects in situations where a more expensive system may not be suitable. The paper also presents some results from an undergraduate project that demonstrate the capabilities of the equipment.*

## AUTHOR'S QUESTIONNAIRE

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in internal combustion engines
2. The paper describes new equipment useful in the following courses: Thermodynamics, Internal Combustion Engines
3. Level of students involved in the use of the equipment: Undergraduate and postgraduate
4. New aspects of the paper: Measurement methods for small IC engines
5. Method of teaching material presentation: as an experimental facility for undergraduate teaching or for research projects
6. The dynamometer has been used for final year undergraduate experimental projects
7. It is a very low cost experimental arrangement allowing sensitive measurements for small power output engines.

## INTRODUCTION

MODEL AIRCRAFT are often dismissed as 'toys' and their potential for teaching many aspects of engineering is often ignored. This is rather unfortunate because the technology in modern radio controlled model aircraft is leading edge and has considerable potential for productive and interesting projects in a number of areas. These include not only aerodynamics but materials, mechanical engineering, electronics and chemistry. One of the authors flies radio controlled model aircraft and has used many examples of

the technology from modern model aircraft in an introductory materials course.

A typical model aircraft engine is a simple shaft induction two-stroke alloy engine burning a mixture of methanol, nitromethane and castor oil. Sizes range from 0.010 cu in (0.16 cc) to 3 cu in (50 cc) or bigger, with the larger engines often being gasoline fuelled. Four stroke engines are becoming increasingly common and there is also commercial production of multicylinder engines, a Wankel motor and a number of gas turbine models.

As with any internal combustion engines, tuning for particular requirements is possible. For example the power output from a popular 6.5 cc (0.40 cu in) model is typically about 1 hp (750 W) for a budget model and up to 3 hp (2.2 kW) for a very high performance model of the same capacity.

These engines have a number of features that make them a good teaching tool. While they have all the combustion, performance and efficiency characteristics of conventional internal combustion engines, they are relatively inexpensive to buy, with new prices starting at about US\$60 for the common 6.5 cc type. They are readily available and can also be obtained second hand in varying conditions. They are compact and easy to use and maintain.

The typical design of these engines uses a propeller as the 'load' although there are no limits, since some manufacturers produce water cooled models to drive marine models, and there are also motors available to power model cars

A typical modern, single cylinder, 2-stroke, model aircraft engine, using glow ignition as used in this project is depicted in Fig. 1.

Two-stroke engines of this type use a total loss lubrication system, which involves mixing

\* Accepted 25 June 2001.

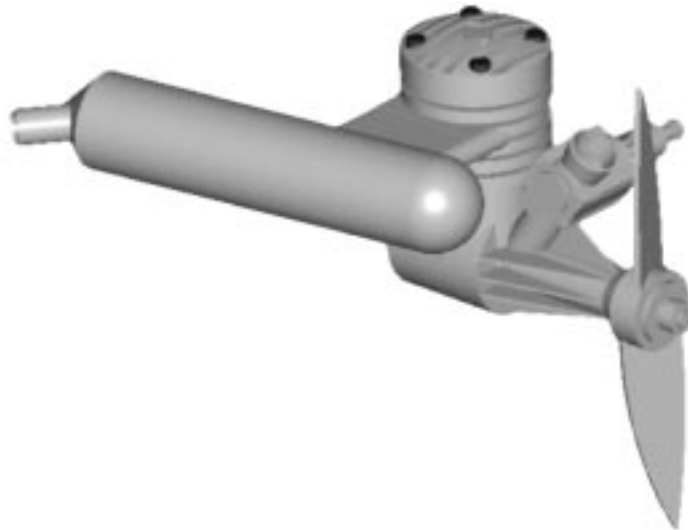


Fig. 1. Diagram of a typical 2-stroke, glow ignition engine.

lubrication oil with the fuel in order to lubricate the bearings and piston in the crankcase, and means that some of this oil will be burned with the fuel. This type of engine should always operate on the rich side of a stoichiometric air-fuel mixture for prolonged use [1] in order to achieve maximum power, to ensure an adequate supply of lubricant and to avoid the piston overheating, causing damage to itself and the cylinder walls.

This type of engine is known as 'glow ignition engines', or just 'glow engines' [2] because of the 'glow ignition' method of combustion in this type of engine. During engine starting, a voltage is applied to the 'glow plug' and is disconnected once the engine is running.

The typical fuel used is a mixture of methanol, nitromethane and castor oil in approximate proportions of 70%:10%:20%. The original purpose of the experimental programme that forms the basis of this work involved investigation of the effects of varying fuel composition on engine performance. The programme involved variation of the proportions of nitromethane, and the addition of water to the fuel to see how this affected the operation of the engine.

### ENGINE DETAILS AND DYNAMOMETER DESIGN

The engine used here was a K&B .45 Sportster engine, having a piston displacement of 7.44 cc (0.45 cub. in.). Experimental testing confirmed that the engine had a maximum power output of 620 W at 11 500 rpm in static upstream air using a 10% nitromethane fuel.

For the project, the engine drove an APC (Advanced Poly-Carbonate, a name brand) 11 × 6 propeller as the load. This propeller has a nominal diameter of 11 inches, (279 mm), and a nominal pitch of 6 inches (152 mm) (The pitch is defined as a measure of the forward distance

travelled in one complete revolution of the propeller when turned as a screw through a solid material.)

The engine was attached to gimbals and mounted on a trolley together with the fuel supply and a pendulum system to measure torque. A small plate was attached to the engine with three locating holes to allow the location of a rod from the throttle at nominal idle, mid-throttle and wide open throttle (WOT) positions.

The propeller posed a hazard, spinning at speeds of up to 12 000 rpm. As a precaution, the propeller tips were painted white and a guard designed and constructed that provided protection from the propeller.

A method of measuring exhaust emissions was devised that allowed for the removal of excessive lubricating oil from the gas and compensated for the small exhaust flowrate that would not be sufficient for the conventional exhaust gas analysers used.

### MEASURING EQUIPMENT

#### Torque

Torque was measured by means of a pendulum arrangement (Fig. 2). The engine was mounted in gimbal bearings so that it was free to rotate. The torque dissipated by the propeller induced an equal and opposite torque on this freely rotating shaft. A pendulum weight that rotated from the vertical position provided a reaction torque. A pointer reading against a protractor indicated the angle rotated from the vertical, enabling calculation of the torque.

$$\tau = mgL \sin \theta$$

where  $\tau$  = torque (N.m)

$L$  = distance to centre of mass (COM) (m)

$\theta$  = angular deflection ( $^{\circ}$ )

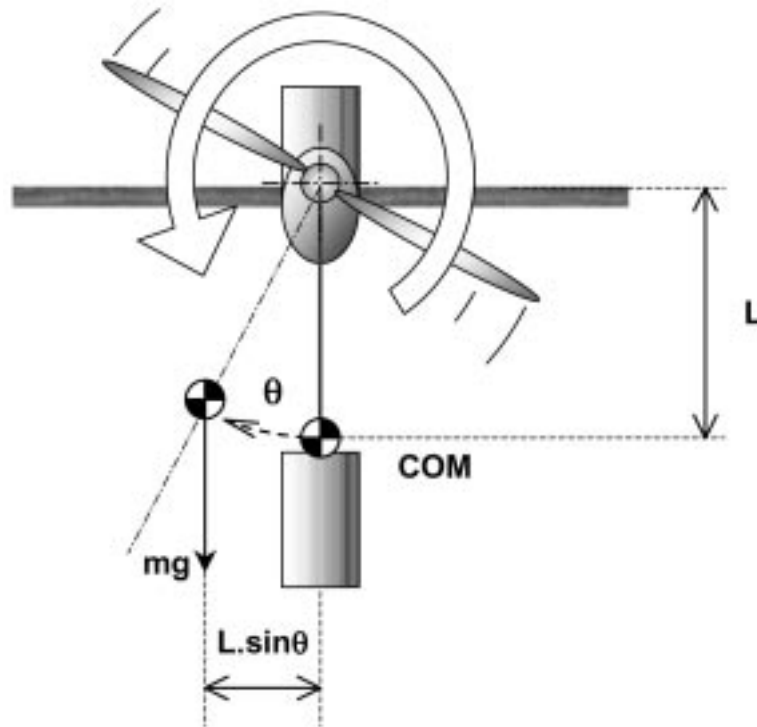


Fig. 2. Diagram of torque measuring system.

$m$  = mass of weight (kg)  
 $g$  = acceleration due to gravity =  $9.81 \text{ (m.s}^{-2}\text{)}$

#### Fuel flow rate

Fuel flow rate is measured by the following method (Fig. 3). As the engine uses fuel, air must be replaced into the fuel container to keep the pressure constant. This replacement air flows from the atmosphere through a length of tube, with calibration markings of known volume (10 ml), into the fuel container. Water droplets were placed in this air line, and their progress tracked.

Air could not flow past the droplets, so the time the droplet took to pass the calibration markings gave the corresponding volume flow rate of fuel.

A break consisting of an empty plastic container that was identical to the fuel container prevented the water used to measure the flow rate from reaching the fuel container and contaminating it.

#### Exhaust gas flowrate and composition

Exhaust gas composition can give information on the relative air-fuel ratio of the engine operation

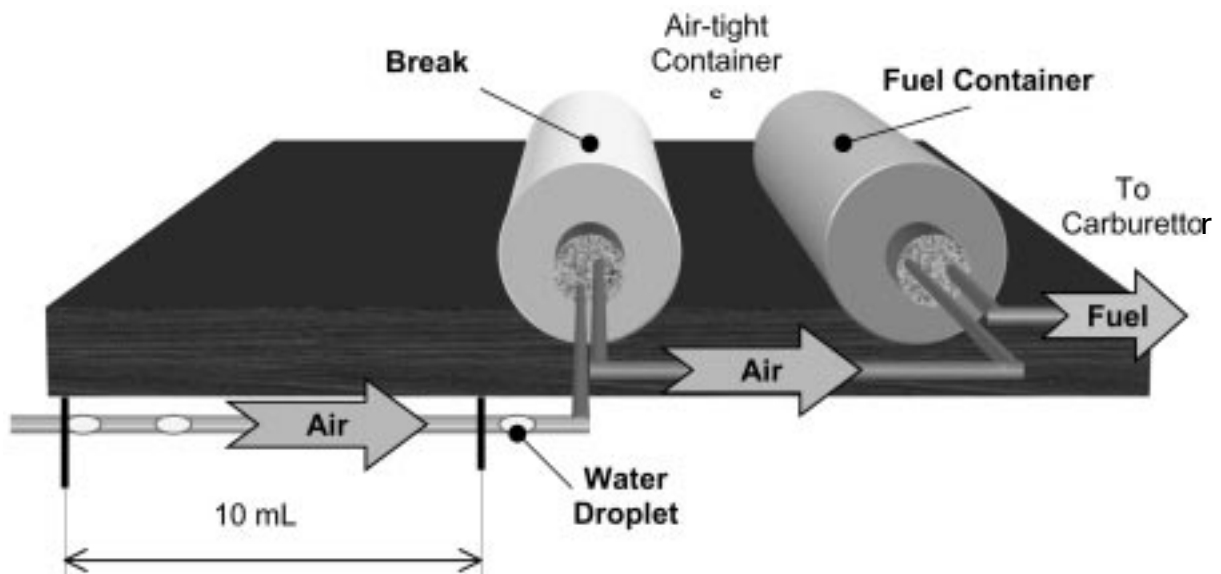


Fig. 3. Schematic of the fuel flow rate measuring system.

and an appreciation of the completeness of combustion in relation to engine efficiency.

Exhaust analysis posed the serious problem of unburnt castor oil in the exhaust sample. This oil, if allowed to enter the emissions testing equipment would cause problems. After several attempts at methods of real-time exhaust sampling, a simple but effective system was developed in which the exhaust gases were captured in a bag, thence allowing the volume flowrate and composition of the gas to be measured at a later stage.

The exhaust was collected in black plastic rubbish bags of approximately 60 litre capacity over a measured period of time. A copper tube was connected to the muffler outlet and the bag and tube were coupled by means of a modified plastic jar: one lid had a hole cut out of the middle, through which the copper tube was glued, and this formed the exhaust connection. The bag was taped to the jar body, which had its bottom cut off to allow the gas into the bag. When the bag was full, it was disconnected from the hose by unscrewing the jar, and an unmodified lid screwed onto the jar to seal it. The bag was twisted near the jar whenever the lids were removed to prevent gas leakage.

The bagged exhaust gas was allowed to cool for several hours to condense any oil and water vapour and to have the sample at ambient temperature for the volume measurement. The exhaust flowrate was determined from the measured exhaust volume and the time taken to collect the sample.

The volume was measured by placing the bag into a large plastic crate of known dimensions and a flat aluminium plate was lowered on top of it until the bag was snug against every side of the crate. The distance from the top of the crate to the plate was then measured, and the volume enclosed under this plate calculated to give the volume inside the bag. The bags could not be overfilled, because then the bag would not fit snugly into the rectangular shape of the crate. However, it was still necessary to capture enough gas for the analysers to read, so there was a trade-off in the optimal amount of gas to capture.

Analysis of the composition of the exhaust sample was made with standard laboratory analysers for carbon dioxide, carbon monoxide and oxygen. After the contents were left to settle for several hours the bag was shaken to promote a homogeneous mixture.

Engine speed was measured with an optical tachometer held in front of the propeller blades to read from the white-painted stripes on the blade tips. This reading was divided by two to account for the two blades.

Different throttle settings or different fuel mixtures meant that the engine needed tuning. Adjustment of the needle valve on the engine gave maximum propeller speed. The sound of the propeller, the exhaust note, and the optical tachometer all aided the identification of this region of

maximum speed. Testing commenced after tuning and warm up.

*Propeller power*

The power produced by the engine to spin the propeller in air of zero upstream velocity ('static' air) is given by the following theoretical formula [3], adapted from [4]:

$$P = c \cdot \text{RPM}^3 \tag{2}$$

where P = static power (W)  
 c = constant for given propeller  
 RPM = rotational propeller speed (rpm).

Also given [4] is:

$$c = (\text{constant}) \times (\text{pitch}) \times (\text{diameter})^4$$

where pitch and diameter are in feet.

For an APC 11 × 6 propeller:

constant = 1.12 × 10<sup>-9</sup>  
 pitch = 6/12  
 diameter = 11/12.

Therefore, for the propeller used in these experiments, the constant is given as: c = 3.954 × 10<sup>-10</sup>. Figure 4 shows the predicted power curve for the APC 11 × 6 propeller used in our experiments, as defined above, Equation (2).

An early objective of this project was to verify the above equation for our particular propeller.

The power developed by the engine could be determined experimentally from measurements of torque and speed according to:

$$P = \tau \times \omega$$

$$= \tau \times \text{RPM} \times (2\pi/60) \tag{3}$$

where τ = torque (from Equation (1))  
 and ω = rotational speed (rad/s)

Data for the measured power, calculated using Equation (3), are plotted in Fig. 5 together with the calculated power from Equation (2), but with a constant c = 4.095 × 10<sup>-10</sup>. We see that there is

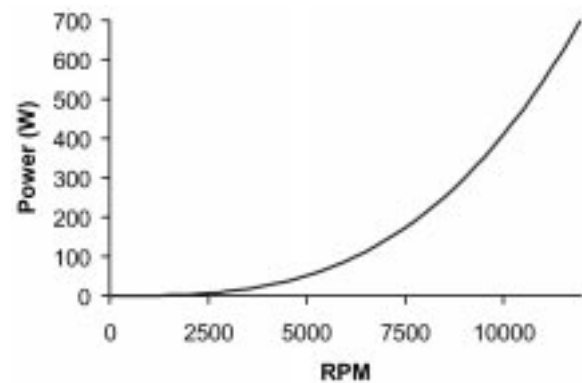


Fig. 4. Plot of static power versus propeller speed for an 11 × 6 APC propeller.

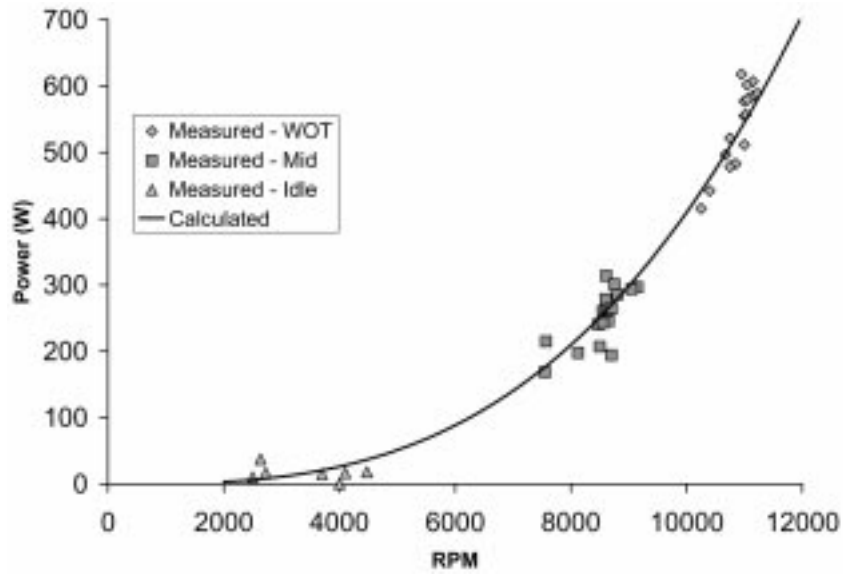


Fig. 5. Comparison of power output calculated by Equation (3) ('measured'), and Equation (2) ('calculated').

very good correlation with the propeller constant,  $c$ , adjusted by 3.5% compared with the reference value of  $3.954 \times 10^{-10}$ .

This result gives confidence in the accuracy and sensitivity of the torque and speed measurement methods.

#### *Exhaust composition—changes with throttle opening*

Figure 6 presents the average of our measured emissions data against throttle setting. Emissions are undoubtedly changing over the range of operating conditions, from idle to wide open throttle. Carbon dioxide,  $\text{CO}_2$ , is low at idle ( $\sim 2\%$ ) and carbon monoxide,  $\text{CO}$ , is high ( $\sim 9\%$ ), indicating incomplete combustion and a rich fuel-air mixture.  $\text{CO}_2$  increases and  $\text{CO}$  decreases at mid- and wide open throttle indicating improved combustion and leaner mixture under these conditions.

Oxygen,  $\text{O}_2$ , content is high, lying between 6 and 10% at all throttle settings. Considering that the ambient oxygen fraction is 21%, we conclude that about one third of the air has passed through the engine unreacted, as would be expected in a two-stroke engine [5].

At idle, corresponding to low engine speeds, there is a relatively long time when both the transfer and exhaust ports are open and air can pass straight through the cylinder, that is 'short-circuiting' [5]. As speed increases, there is less time for this to occur, and we would expect the oxygen content of the exhaust to decrease. However, we find that oxygen levels fall from idle to mid throttle, but rise again at WOT. It is likely that the increase in oxygen concentration at WOT is associated with leaner operation, as deduced from the reduced  $\text{CO}$  emissions.

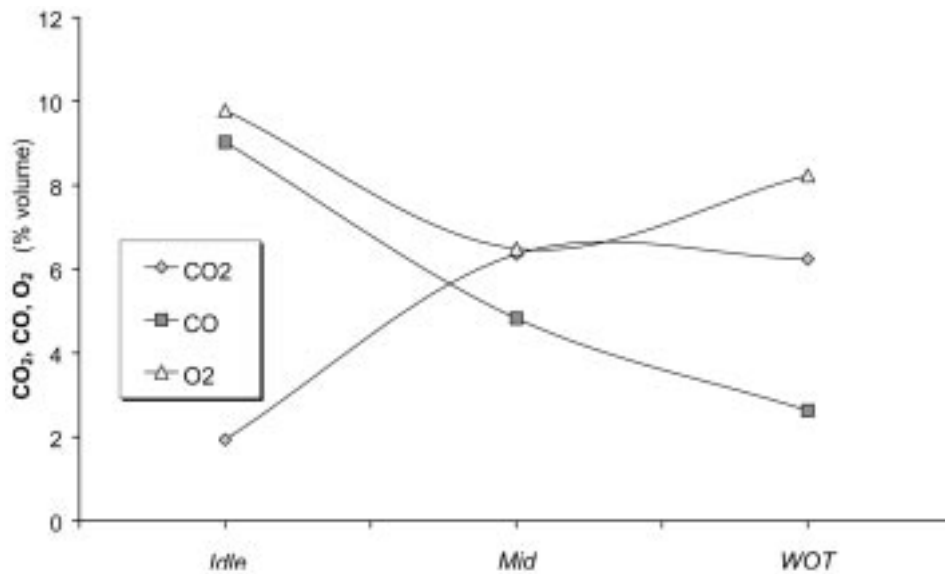


Fig. 6. Average Emissions measured as a function of throttle opening.

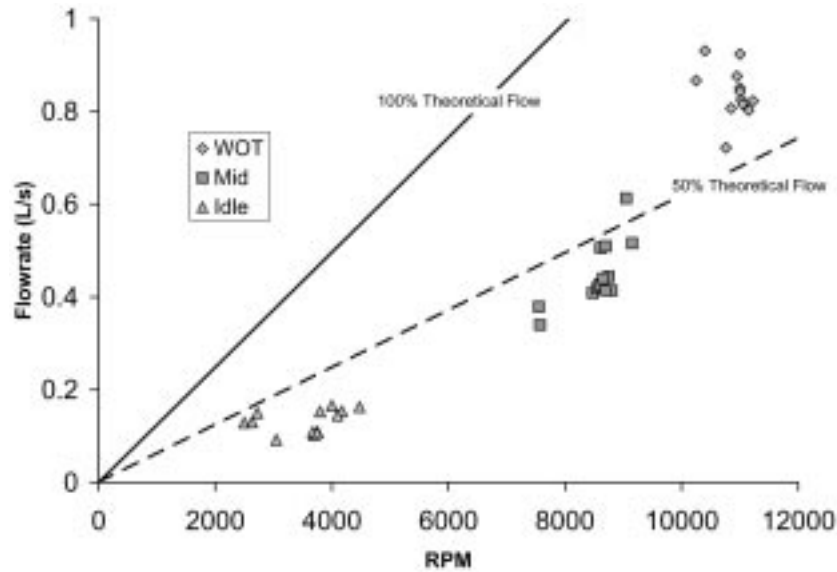


Fig. 7. Measured exhaust gas flowrate versus engine speed.

#### Measured exhaust flowrate

Figure 7 shows results of the measured exhaust gas flowrate plotted against engine speed. For comparison, the theoretical displaced volume flowrate is also plotted, as well as the line corresponding to 50% 'delivery ratio', that is the measured flowrate as a proportion of the theoretical displaced volume flowrate [5]. The displaced flowrate is calculated by treating the engine as an air pump, assuming that the volume displaced by the piston is the volume of air displaced at atmospheric pressure and temperature for every revolution of the engine.

Therefore, the displaced volume flowrate is:

$$\dot{V} = \frac{7.44 \text{ cc}}{1000 \text{ cc/L}} \times \frac{\text{RPM}}{60 \text{ s/min}}$$

The exhaust flowrates are used here as a measure of the inlet flowrate, since there is only a small difference in mass flowrate due to the fuel added, and differences in volume arise due to the different chemical composition of the inlet and exhaust gases. Typically the molecular weight of exhaust products will be 5–15% less than for the inlet air, and the volume flowrate of the two streams are related to this at atmospheric pressure and temperature.

Figure 7 shows that the delivery ratio, is about 50% across the speed range of the engine. The Figure also shows that the ratio is lower at idle and mid throttle settings, but higher at WOT.

There are a number of factors contributing to this variation in delivery ratio with engine speed.

Firstly, the position of the carburettor inlet just behind the propeller means that it is facing forward. Therefore, air going into the engine is blown in by positive pressure. The pressure behind the propeller will increase as a function of speed and will therefore increase the relative flowrate into the engine.

Secondly, the engine is designed for maximum power. This means that the scavenging system is designed to work at optimum at high speed and wide open throttle. This is likely to contribute to the rise in the delivery ratio at higher speed.

Thirdly, the emissions measurements show that combustion improves at WOT operation and consideration of the combustion equations shows that this will lead to a lower volume flowrate of products than for incomplete combustion. This contradicts the measured trend, indicating that the first two factors are possibly of more significance than this latter.

In summary, the volume flowrate measurements show good correlation with engine speed, and are in the expected range conventional two-stroke engines [5]. The results therefore give confidence in the measurement technique used.

#### Measured fuel consumption

Measured fuel consumption data are plotted against power in Figure 8. When converted to efficiencies, these show a range from almost 0% at idle to nearly 20% for some of the WOT conditions. This maximum value is in good agreement with values from conventional two-stroke engines and gives confidence in the sensitivity of fuel flow measurement method [5].

The 'fish hook' characteristic of the WOT data is of interest in this figure, which when plotted as specific fuel consumption against power is clearly similar to the classic 'fish-hook' graph [6]. With maximum power operation at a condition on the rich side, the trend was for richer mixtures to give higher fuel flowrate and leaner mixtures giving lower fuel flowrate, although detailed measurements were not taken of the mixture strength at each operating point. This characteristic is seen in conventional engines [6], and gives added confidence to

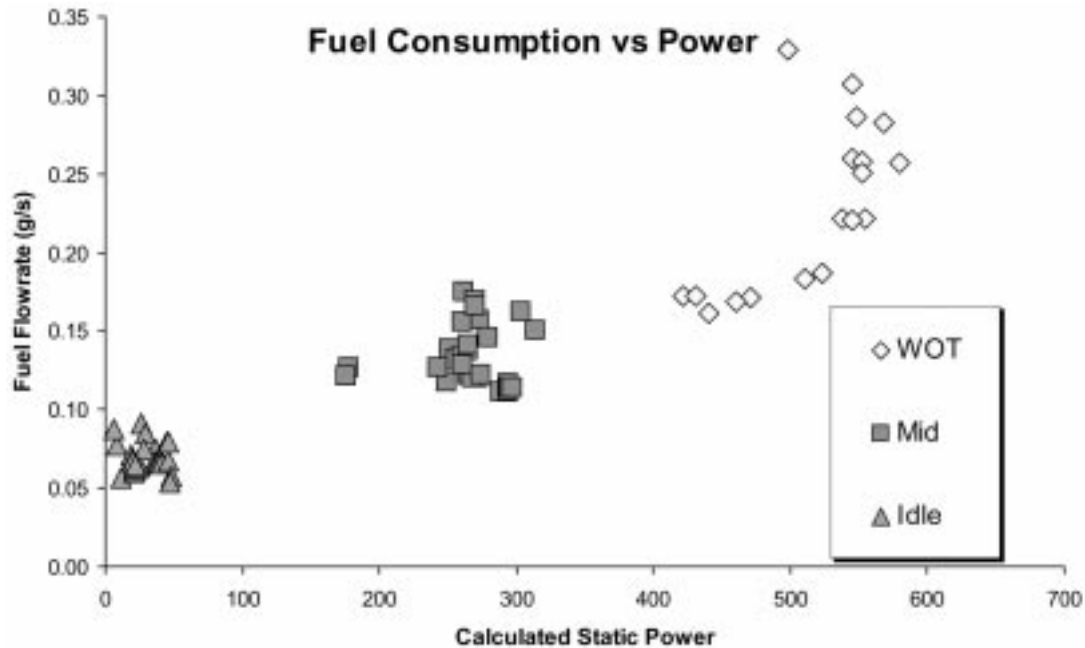


Fig. 8. Measured fuel flowrate versus power.

the ability of the small scale measurement system developed in this project.

### CONCLUSIONS

A small engine dynamometer was built to use with model aircraft engines, together with associated systems for the measurement of fuel flowrate, exhaust gas composition and exhaust gas flowrate.

Measurements made using these systems show good agreement with data from full sized engines

and therefore give confidence in the ability of this small scale measurement arrangement. The system is suitable for use in a wide range of experiments and projects related to internal combustion engine performance at a much lower cost than similar experiments on full-sized engines.

*Acknowledgements*—We are greatly indebted to, and thank, Alan Eaton, Thermodynamics Laboratory Technician, for construction of the dynamometer and for help with experimental measurements. RRR also wishes to thank the University of Melbourne, Department of Mechanical and Manufacturing Engineering, for facilities while on sabbatical leave to afford time to write up this work.

### REFERENCES

1. Tower Hobbies, *Tower Hobbies 1998 Catalog*, p. 210 (1998).
2. Gierke, *2-Stroke Glow Engines for RC Aircraft*, Vol. 1. Air Age Inc., Wilton, Connecticut (1994).
3. R. von Mises, *Theory of Flight*, Ch. XI. Dover Publications Inc., New York (1959).
4. R. J. Boucher, *The Electric Motor Handbook*, Ch 4. AstroFlight Inc., Marina Del Rey, California.
5. J. B. Heywood and E. Sher, *The Two-Stroke Cycle Engine—Its Development, Operation and Design*, Ch. 3. Taylor and Francis, PA (1999).
6. R. Stone, *Introduction to Internal Combustion Engines*, 2nd edition. MacMillan Press Ltd, London (1992).

**Gordon Otte** finished his Bachelor's Degree in Mechanical Engineering at the University of Auckland in 1998 with 1st Class Honours. He has since commenced his Masters Degree in engineering at the same institution, investigating current gas turbine power cycles for electrical power generation. He studied in Durban, South Africa, before immigrating to New Zealand in 1994, has a keen interest in the thermodynamics of power-producing devices.

**Keri Moyle** began a Ph.D. in Mechanical Engineering at the University of Auckland, New Zealand after graduating BE(Mech) with 1st Class Honours in 1998. Her interest in engineering began during secondary school education at Avondale College. Her PhD

topic involves flow in deforming elastic vessels in the human body, with a long term view to analyse and improve cardiac surgical theory and techniques using Magnetic Resonance Imaging and computational fluid dynamics.

**Robert Raine** is an Associate Professor in the Department of Mechanical Engineering at the University of Auckland, New Zealand. His degrees (B.Sc.(Eng), Ph.D.) are from the University of Southampton. His teaching interests are in thermodynamics, design and internal combustion engines. Research interests cover many aspects of internal combustion engines including the use of alternative fuels, combustion processes and exhaust emissions. He is Director of the Energy and Fuels Research Unit based in the Department of Mechanical Engineering.

**John Robertson** is a senior lecturer in Chemistry at Auckland University of Technology. He has a Ph.D. from the University of Auckland and has worked in research and contract laboratories in Canada and New Zealand for 10 years. A boyhood interest in radio controlled models was re-kindled some four years ago. This project started when, after numerous observations of erratic model engine performance based on 'bad fuel' he found virtually nothing in the academic or model literature on fuel composition and erratic performance.