MINIATURIZATION LIMITS OF SMALL IC ENGINES

Shyam Menon and Christopher P. Cadou
Department of Aerospace Engineering,
University of Maryland at College Park, College Park, USA

Abstract: Considerable effort has been devoted in recent years to building miniature heat engines as battery replacements and prime-movers for micro-air vehicle propulsion. Simple thermodynamic analyses show that as a heat engine is miniaturized, it becomes less thermodynamically efficient. A critical length scale exists at which losses outstrip power production and cycle efficiency goes to zero. The objectives of this research are to identify a minimum practical length scale for two-stroke piston engines and investigate the processes responsible for setting this limit. The performance of 7 engines weighing 15g to 500g is studied using a specially designed dynamometer. Peak power outputs have been measured at 8-278W with peak efficiencies ranging from 3-9%. A scaling analysis similar to one established for conventional scale engines shows the minimum displacement for a 'practical' IC engine to be between 0.5 and 1 cc.

Keywords: Heat engines, miniaturization, scaling, MAV propulsion

INTRODUCTION

There is increasing demand for miniature power systems with applications ranging from micro-propulsion to human-portable power packs. Heat engines operating on liquid hydrocarbons appear to be a natural choice due to the superior energy and power densities of 'conventional' scale engines [1]. Miniature internal combustion (IC) engines have been utilized for propulsion in unmanned air vehicles (UAVs) and for stationary sources of electrical power [2]. However, in order to fully realize the potential range/endurance advantage of energy dense liquid hydrocarbon fuels over batteries, miniaturized engines need to achieve levels of efficiency that are comparable to conventional-scale engines (>10%). This becomes more difficult as size is reduced: The ratio of power production to power loss (due to heat transfer and friction) scales with surface to volume ratio which increases as the size of the engine is reduced [3]. Further, engine speed also tends to increase with decreasing size which means that efficiency loss due to incomplete combustion eventually also becomes an issue [4]. Taken together, one expects there to be a minimum size below which losses outstrip energy release and it becomes impossible to close a thermodynamic cycle – let alone implement it efficiently.

Peterson used a simple heat transfer analysis to show that the minimum size of a Stirling engine is approximately 1 mm for conventional manufacturing materials [5]. Apart from this, however, there appears to be relatively little work in the literature focused on the scaling of small engine performance with size. Previous work by the authors focused on performance data collected from a large number of small engine manufacturers [6]. Both two and four-stroke engines were considered. The results showed that engine power output obeyed a power-law scaling of the form $y=Ax^b$ over a remarkably wide range of sizes. This was consistent with the findings of Bonner [7] for larger engines. However, few reliable performance data were available for the smallest engines making it difficult to extrapolate to smaller scales. Earlier investigations by Heywood focused on understanding the effect of changing engine size and advances in technology on engine performance [8] suggest that other methods of correlating engine performance may work better. For example, plotting maximum torque against displacement volume appeared to correlate the performance of many different engines quite well but plotting maximum power normalized by mean piston speed versus piston area seemed to provide the best correlation. Previous work in our group used these methods to interpret data acquired using a specially built dynamometer [9] from four small model airplane engines [10].

The overall objective of this work is to improve our estimate of the minimum 'practical' size of a loop-scavenged, two-stroke piston engine and to improve our understanding of the physical processes underlying the observed scaling. This has been accomplished by improving the small engine dynamometer system and making additional measurements so that the scaling of thermal, mechanical, and chemical efficiency can also be determined.

EXPERIMENT

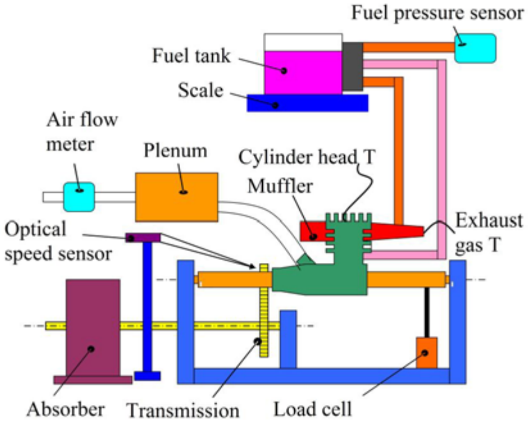

Fig. 1: Dynamometer layout with gear transmission.

Figure 1 is a schematic diagram of the dynamometer system developed specially to handle the challenges posed by small engines. These include high operating speeds, low torque, low air and fuel flow rates, unsteady air flow rates, and large 1/rev disturbances. The principal measurements made are torque, speed, fuel flow rate, air flow rate, cylinder head temperature, and exhaust gas temperature. These are used to compute power, overall efficiency (specific fuel consumption), and volumetric efficiency. A feedback control system is used to adjust the engine load so as to maintain constant speed. A separate motoring setup (Figure 2) is used to measure frictional losses. Nusselt number correlations measured in a separate heat transfer experiment [11] are used to estimate thermal losses from the cylinder head. A detailed description of the setup, the test procedure, data collection and analysis has been previously reported [9]. The inertia of the large hysteresis brakes and gears in this setup do not permit smaller engines to accelerate to their normal operating speed. For these engines, a direct drive setup is utilized that eliminates gears and uses smaller brakes mounted in-line with the engine shaft using flexible adaptors. Each engine is operated across a range of speeds and mixture settings to measure the entire operating map. The peak power and efficiency are computed for each engine in order to establish scaling relationships.

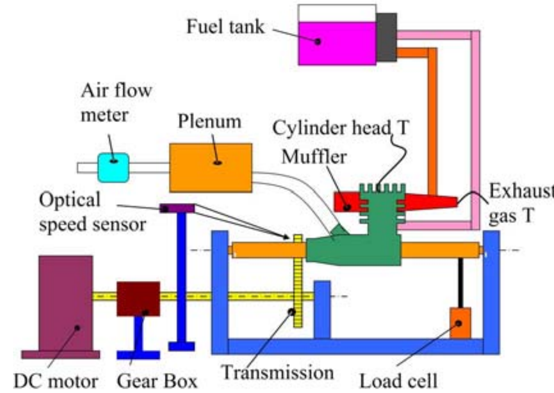

Fig. 2: Dynamometer layout for motoring tests.

The power output of the engine (P) is given by:

$$P = \Gamma \omega \quad (1)$$

where Γ is the torque and ω is the engine speed. The overall efficiency (or fuel conversion efficiency) of the engine is given by:

$$\eta_o = P / \dot{m}_f Q_r \quad (2)$$

where Q_r is the heating value of the fuel and $\dot{m}_f$ is the fuel mass flow rate. A variety of factors contribute to the overall efficiency. These are identified by writing the overall efficiency as the product of mechanical, thermal, chemical, and volumetric efficiencies:

$$\eta_{overall} = \eta_{mechical} \eta_{thermal} \eta_{chemical} \eta_{volumetric} \quad (3)$$

The thermal efficiency is given by:

$$\eta_{thermal} = \frac{P_{fuel} - Q_{env}}{P_{fuel}} = \frac{P_{fuel} - Q_{conv} - Q_{exh}}{P_{fuel}} \quad (4)$$

where P_{fuel} is the total available power in the fuel ($\dot{m}_f Q_r$) and Q_{env} is the heat loss to the environment. Q_{env} is the sum of $Q_{conv,}$ the convective heat losses from the engine cylinder head and Q_{exh}, the heat lost in the exhaust gas. The convective loss is determined using the following Nusselt number correlation developed from heat transfer measurements on miniature engine cylinder head [11]:

$$Nu = 1.24 \, \mathrm{Re}^{0.618} \, \mathrm{Pr}^{1/3} \quad (5)$$

In this expression, Re is the flow Reynolds number based on the cylinder head diameter and Pr is the Prandtl number for air. The heat lost in the exhaust gas is calculated from the air flow and exhaust gas temperature measurements. The mechanical efficiency is given by:

$$\eta_{mech} = \frac{P_{fuel} - Q_{env} - P_{mech}}{P_{fuel} - Q_{env}} \quad (6)$$

P_{mech} is the frictional power loss which is determined from measurements of torque and speed made during motoring experiments. The volumetric efficiency is given by:

$$\eta_{vol} = Q/VN \qquad (7)$$

Q is the volume flow rate of air through the engine, V is the engine displacement, and N is the engine speed in Hz. The chemical efficiency is given by:

$$\eta_{chem} = \dot{m}_{fuel\ burned} / \dot{m}_{fuel} \qquad (8)$$

Unfortunately, we have no direct measurement of the mass of fuel burned. Therefore, the chemical efficiency must be inferred from other efficiencies and equation 3. Finally, the efficiency of an engine is also reported in terms of the brake specific fuel consumption (BSFC in g/kW-Hr or lb/HpHr) which is given by:

$$BSFC = \dot{m}_f / P \qquad (9)$$

RESULTS

Figure 3 shows a typical data set produced using the small engine dynamometer. While the measurements are reasonably comprehensive, only peak values are used when investigating performance scaling. Figures 4 and 5 show how power output and overall efficiency scale with engine size. As a reference, performance measurements from a few larger-scale engines are also presented. While both small and large engines appear to follow a power law scaling, the scaling laws themselves appear to be different and the smaller engines appear to be much more sensitive to changes in size than the larger ones.

Figure 6, which shows how the various efficiencies scale with engine size, explains this trend: In general, the thermal, mechanical, and chemical efficiencies all decrease with engine size. The behavior of the volumetric efficiency is more complex as it decreases and then increases for the two smallest engines. In the case of the smallest engines, this is probably due to the fact that the smallest engines do not have mufflers. Therefore, it appears that one simple method for improving engine performance is to remove the muffler – albeit with the penalty of increased operating noise.

Finally, figure 7 uses Heywood's scaling method to infer the minimum engine size from the performance measurements. Power laws are fit to plots of normalized power vs. piston speed and total power losses for each engine tested. The point at which these two curves cross is the extrapolated point of thermodynamic break-even and represents the minimum possible IC engine size predicted by our measurements. This turns out to be 3 mm and is consistent with Peterson's prediction for Stirling engines and Leach's theoretical prediction of a critical length scale ~ 1mm for the idealized problem of a pre-mixed flame propagating in a channel [12].

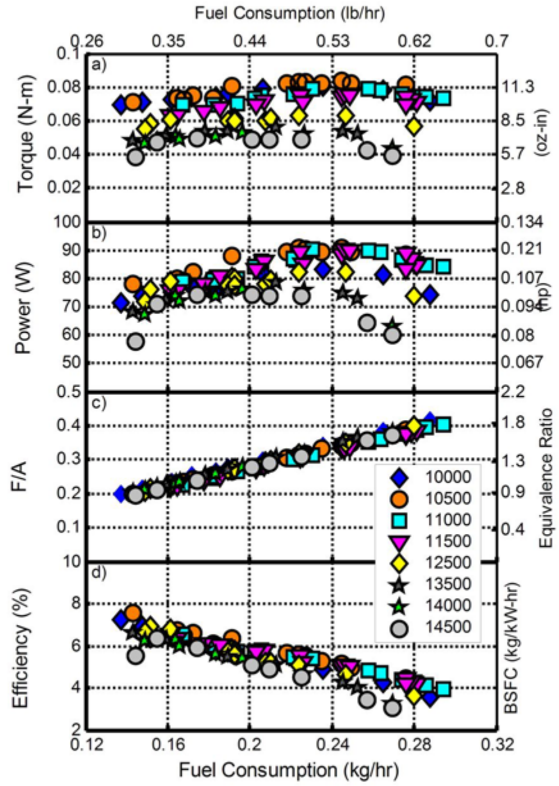

Fig. 3: Performance map for the Hornet engine.

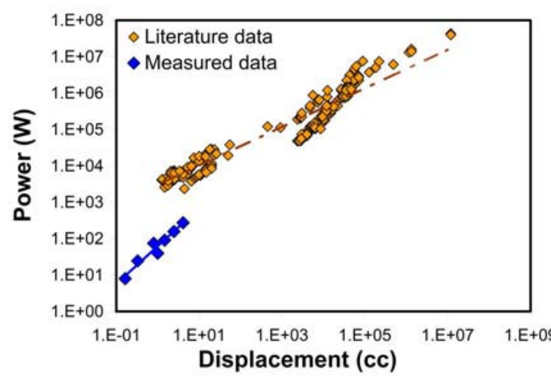

Fig. 4: Scaling of power with engine displacement.

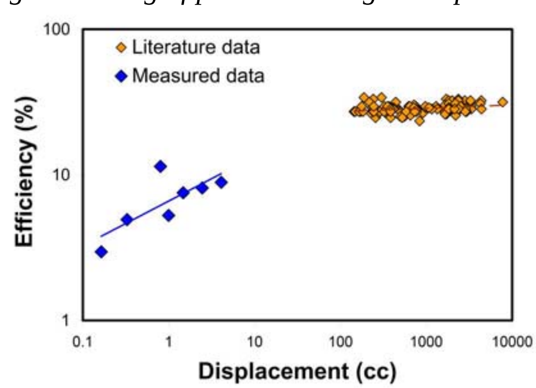

Fig. 5: Scaling of efficiency with engine displacement.

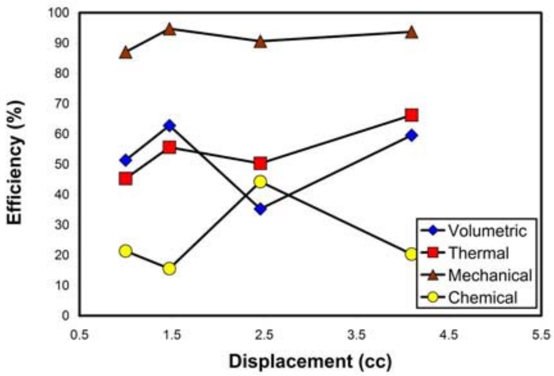

Fig. 6: Scaling of component efficiencies.

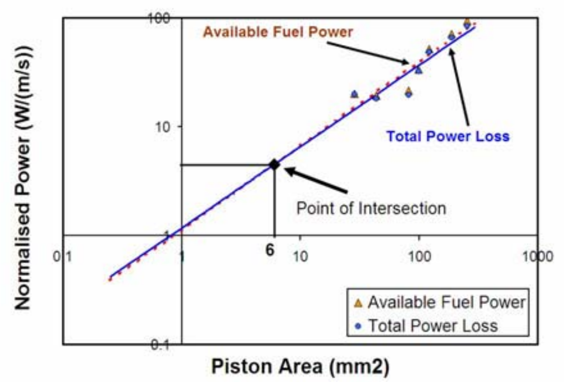

Fig. 7: Estimation of minimum length scale.

CONCLUSIONS

Comprehensive performance measurements have been made on a set of small loop-scavenged two-stroke IC engines ranging in size from 248 to 15 grams. Overall thermodynamic efficiency decreases substantially with decreasing engine size from 9% for the largest engine to 3% for the smallest engine. Extrapolating engine performance and losses to smaller scales indicates that the minimum possible displacement of a loop-scavenged two-stroke engine is approximately 27 mm^3 which corresponds to a piston diameter of approximately 3 mm.

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