INVESTIGATION OF SCALING LAWS FOR COMBUSTION ENGINE PERFORMANCE

S. Brown, S. Menon, C.Hagen
Energy systems engineering, Oregon State University – Cascades, Bend, OR 97701

ABSTRACT

Thermal and fluid boundary layer effects paired with an increasing surface area to volume ratio for decreasing engine size results in non-linear scaling of key performance parameters for combustion engines. These effects are accentuated by chemical kinetics which assume significance for small scale engines given their high operating speeds. Different methods of quantifying these scaling laws have been attempted, resulting in different outcomes. Numerous studies in scaling laws were examined and compared as a first step in unifying the various methods and their results. The outcome of this unification may provide more complete scaling laws to design higher performance combustion engines, especially those small in size where scaling has significant effect on efficiency and power. Increased performance of small combustion engines gives vast possibility to further applications in fields such as aerospace, personal power and micro power generation.

1. INTRODUCTION

Miniature combustion based power sources have extensive applications in fields such as portable power generation and unmanned air vehicle (UAV) propulsion. Given their significantly higher energy density, considerable efforts have been made in the past decades to harness the chemical energy of hydrocarbon fuels using small scale combustion engines. These efforts have given rise to a variety of engines and combustors that may or may not resemble their conventional scale counterparts. Examples [1] of such devices include miniature Wankel engines, free piston engines, miniature internal combustion engines (ICE's), miniature gas turbine engines (GTE's), Swiss roll combustors, and micro-thrusters. However, miniaturization of combustion engines is fraught with difficulties due to material and thermo-physical challenges. These include increased frictional, thermal, and combustion losses, sealing and mass loss issues, ignition and fuel delivery problems, as well as material cracking due to high thermal and mechanical stresses. These challenges have precluded the successful development and commercialization of combustion engines at and below the millimeter scale. Combustion engines at the centimeter scale are still viable as evidenced by the plethora of ICE's built and operated for propulsion of small UAV's. However, the performance of these engines is nowhere close to that of conventional scale ICE's. Existing data on small ICE's show their performance to be about half that of conventional scale ICE's. This indicates that considerable room exists to improve upon current performance which can potentially result in increased range/endurance of applications that utilize these engines.

Identifying the potential for performance improvement of current engines requires an understanding of performance of existing engines, how it scales with size, and the reasons for the observed scaling. To this extent, we attempt to study scaling laws of combustion engine performance with engine size. First, we try to understand how fundamental parameters such as residence time, surface area to volume ratio, and Reynolds number scale with combustion engine size. These parameters are key in understanding the thermo-physical issues which tend to limit the performance of engines as they scale down in size. Next, we survey existing studies on scaling of combustion engine performance with engine size. In doing so we consider three major categories of combustion engines:

reciprocating ICE's, GTE's, and rocket engines (RE's). Key performance metrics and their scaling as identified by different studies are surveyed. Next, we focus our attention on ICE's and identify the major sources of energy losses. Finally, existing literature data on energy loss breakdown in ICE's is analyzed to identify any scale-relevant information. The breakdown of energy loss pathways is found to be significantly altered as ICE's scale down in size. This information is highly pertinent to our ongoing efforts to improve the existing performance of small ICE's. The main motivation is to develop efficient ICE's for UAV propulsion which is described in more detail in the final section of the paper. The proposed future plans for engine performance testing using a custom-built dynamometer, and measurement of component energy losses are also described.

2. THERMO-PHYSICAL EFFECTS

In this section, we examine the leading thermo-physical effects which have an impact on the performance of combustion engines particularly as they scale down in engine size.

2.1. RESIDENCE TIME

The residence time in an engine is defined as the time available for the combustion of a given amount of fuel. In a 2 or 4-stroke reciprocating ICE, this is the time corresponding to the power stroke and can be defined as follows:

$$\tau_r[s] = \frac{60}{N\ [RPM]}$$

where N is the engine speed.

For GTE's and RE's, an approximate combustor residence time can be estimated based on the volume of the combustor, mass flow rate and an approximate mixture density which can be estimated from the combustor inlet pressure and average combustor temperature [2].

$$\tau_r[s] = \frac{\rho_c\ \left[\frac{kg}{m^3}\right] V\ [m^3]}{\dot{m}\ [\frac{kg}{s}]}$$

For ICE's, operating engine speeds tend to increase as engine size decreases. This is generally due to the fact that smaller engines are able to produce less torque and they tend to deliver the required power output by spinning faster. Faster operating speeds results in lower residence times, making less time available for the fuel to burn. Figure 1 shows this trend [2, 3]. Also included in Fig. 1 are residence times obtained for some GTE's. Similar trends are observed for both types of engines.

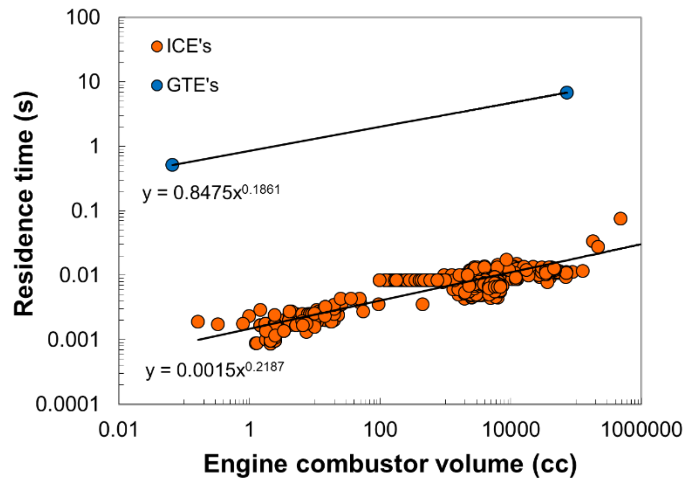

Figure 1: Residence time as a function of engine displacement [2, 3].

A decreased residence time can have a significant effect on the performance of combustion engines and can be related to the Damköhler number (Da). The Damköhler number is a dimensionless number representing the ratio of physical time to chemical time.

$$Da = \frac{\tau_r\ [s]}{\tau_c\ [s]}$$

where chemical time can be defined on the basis of flame thickness and flame speed as,

$$\tau_c[s] = \frac{l_f\ [m]}{S_l\ [\frac{m}{s}]}$$

The chemistry timescale depends on the particular fuel, mixture equivalence ratio, pressure and temperature. Decreasing residence time results in a decreased physical time, leading to a decreased Da since the chemical timescale does not change significantly. A lower Da implies less complete combustion, which in turn decreases overall engine performance and results in unburned fuel in the exhaust.

Evaporation of fuel is also a concern with regard to residence time. Evaporation of a droplet of liquid fuel takes a finite time, and decreasing the residence time decreases the time available for fuel evaporation. If a fuel is not fully evaporated and subsequently burned before the end of a power stroke, then unburned fuel is thrown away as exhaust, polluting the environment while decreasing both engine power output and overall engine efficiency.

In some small ICE's fuel is actually used to cool the engine by absorbing heat from the metal parts. This is especially true for glow fuel engines which burn methanol fuel. Methanol has a high latent heat of vaporization and helps cool the engine at the expense of reduced overall efficiency.

2.2. Surface Area to Volume Ratio

The surface area to volume ratio is an important parameter in engines because it dictates many of the losses of the engine. As engine size decreases, the surface to volume ratio increases, which can be seen in Fig. 2 which shows data for a range of ICE's from miniature methanol based engines to large aircraft engines [3].

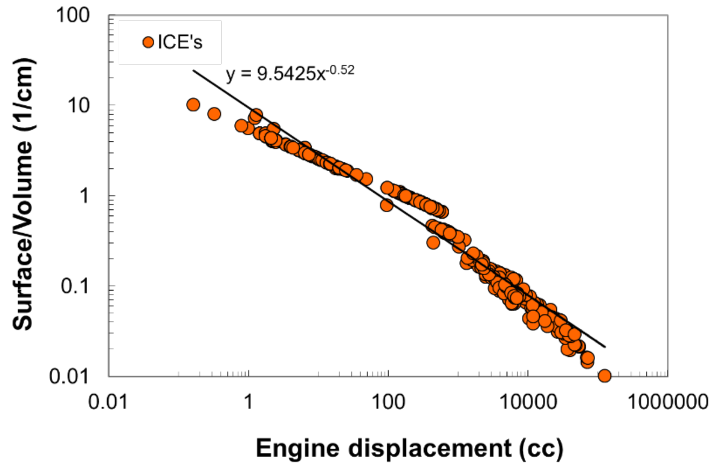

Figure 2: Surface area to volume ratio as a function of engine displacement [3].

Surface area to volume ratio has important implications for thermal losses. As engine size decreases, a higher percentage of the hot gases are in direct contact with the combustion chamber walls. This leads to an increase in thermal losses as a percentage of the total losses. Higher heat losses mean a less efficient engine with lower power output.

Similar to the plot in Fig. 2, maximum engine power output can be plotted as a function of surface area to volume ratio [4]. This is shown in Fig. 3 which shows that with smaller engines, a slight decrease in power (and likely engine volume) results in a significant increase in surface are to volume ratio.

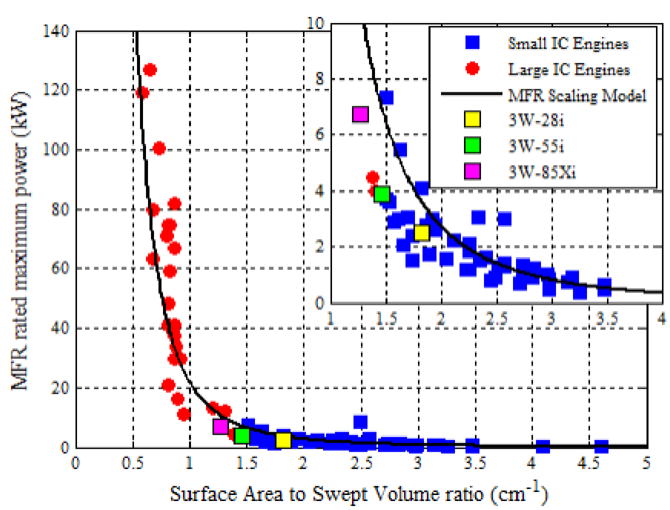

Figure 3: Maximum engine power output as rated by the manufacturer as a function of surface area to volume ratio [4].

Increasing surface area to volume ratio has implications for combustion losses in addition to thermal losses. This arises primarily due to thermal or radical quenching effects. Thermal quenching is the process of the flame front being quenched due to heat loss to the cylinder walls while radical quenching is a similar effect brought about by diffusion of excited state radicals to the cylinder walls. Thermal and radical quenching can have significant effects in small engines due to the higher surface area to volume ratio which results in a higher percentage of gas being in contact with the relatively cool (compared to combustion temperature) wall. Additionally, for extremely small engines there could be a size where the chamber is smaller than the flame thickness, resulting in quenching of the flame front and incomplete combustion.

Frictional losses are dependent directly on surface area and can be increasingly important as engine size decreases. Increasing engine speed for smaller engines can also have an important impact on frictional losses.

2.3. Reynolds Number

As engine size changes there is a change in Reynolds number (Re). In general, decreasing engine size results in decreased Re. This is primarily caused by the decreasing size of the intake valves and manifolds. Figure 4 shows Re for a range of ICE's plotted as a function of engine displacement. A horizontal line represents an Re of 4000 which forms the boundary for transition from laminar to turbulent flow in pipes. For the smallest ICE's, Reynolds numbers can become low enough that the flow transitions from turbulent to laminar [5]. This has implications on the mixing of the fuel and air, as turbulent flow provides far better mixing. An engine with poor mixing may have significantly decreased performance.

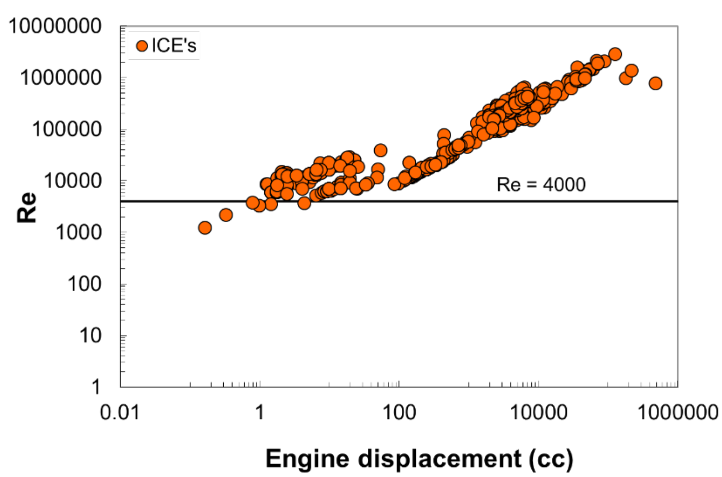

Figure 4: Estimated Reynolds number based on intake flow area as a function of engine displacement for various ICE's.

2.4. Conservation of Momentum Equation

In a 2002 research paper by A. Carlos Fernandez-Pello [5], the fundamental conservation equations of momentum and energy are followed in order to examine the change in energy transfer given decreasing engine size. These equations show that as characteristic lengths and times decrease (which are both a consequence of decreasing engine size), viscous and diffusive transport effects which were previously neglected in larger engines become increasingly important, and eventually dominate conservation equations when engines decrease towards micro-electro-mechanical systems (MEMS) scale devices. These results allude to the fact that high efficiency in small engines cannot be achieved simply by scaling down larger engines. To do this would be to ignore the fact that the flow and combustion conditions in small engines are fundamentally different from those in large engines.

3. Scaling of Engine Performance

As engine size changes, the performance of the engine also changes. It is not only power that changes, but also normalized parameters such as efficiency. Measuring the performance of engines is the best way to qualitatively find where losses are originating and therefore can be used to increase the performance of those engines through experimental work. This section discusses metrics commonly used to quantify engine performance and how these scale with engine size for different types of engines.

3.1. Internal Combustion Engines

ICE's are the most widely studied of all engine types. This can be attributed to their significant role both in industrial and consumer products. Their scaling for each performance parameter is described in the following sub-sections.

3.1.1. Power

Power output of an engine is one of the most important parameters, as it fulfills the power requirement needed by the engine user. In the case of combustion engines, chemical energy of the fuel is converted into mechanical work. Significant losses within the energy conversion means that chemical energy is wasted and therefore the process is more expensive to the end user. For an ICE, power output (P) can be expressed in terms of torque (τ) and engine speed (N) as follows,

$$P\;[W] = \tau[N-m] * \omega\left[\frac{rad}{s}\right] = \tau[N-m] * \frac{2\pi N\;[RPM]}{60}$$

A larger combustion volume allows for more fuel to be burned at any given time, increasing the power of each power stroke and therefore the power output of the system as a whole. This implies that peak engine power output should increase with engine size. Figure 5 shows a plot of peak engine power vs. engine displacement for ICE's.

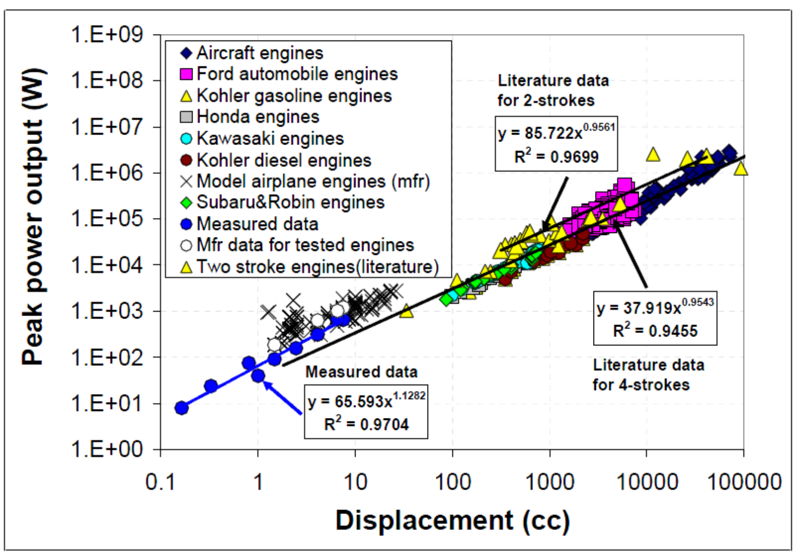

Figure 5: Peak engine power output as a function of engine displacement [3].

Figure 6 shows results from a scaling study by McMahon and Bonner [6] for maximum power output as a function of engine displacement for a wide range of ICE's.

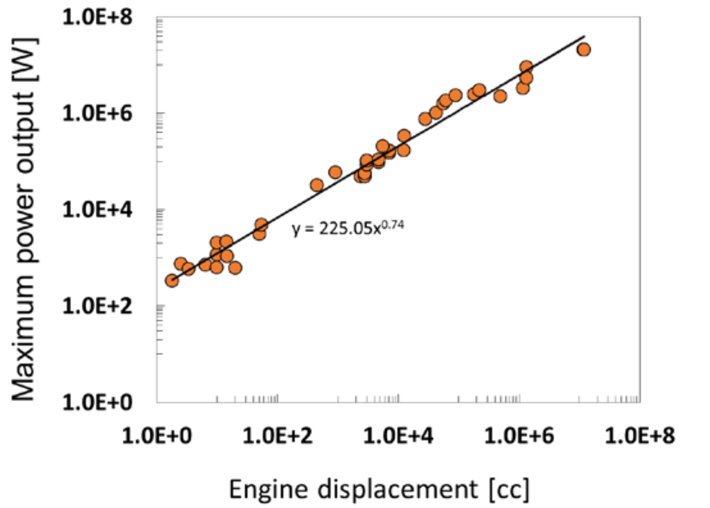

Figure 6: Maximum engine power output as a function of engine displacement [6].

Figure 7 shows results from a third source, Chon and Heywood [7], for maximum engine power output as a function of displacement. This plot shows results similar to those observed in Figures 4 and 5.

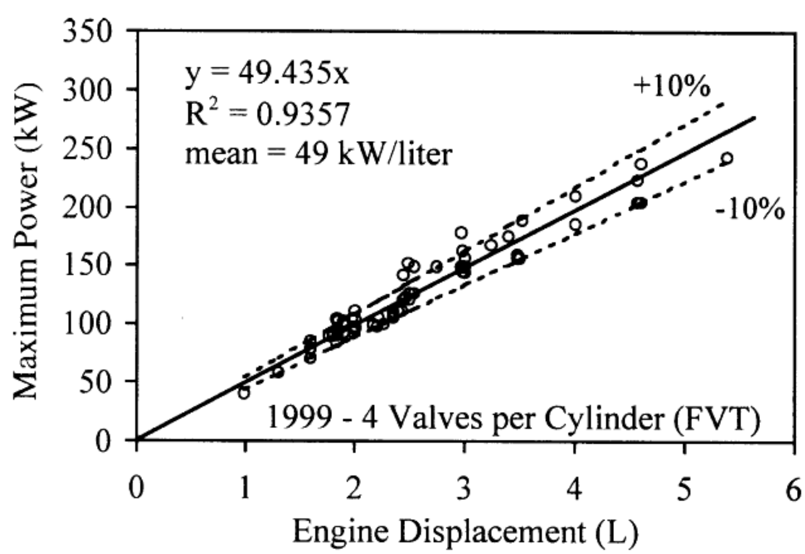

Figure 7: Maximum engine power output as a function of engine displacement for 4-stroke spark ignited engines [7].

3.1.2. Efficiency

The efficiency of an ICE defines the faction of fuel energy converted to usable work. The equation below can be used to calculate efficiency.

$$\eta\ (\%) = \frac{Work\ out\ [W]}{Chemical\ energy\ in\ [W]} * 100 = \frac{P\ [W]}{\dot{m}_f \left[\frac{kg}{s}\right] * Q_R \left[\frac{J}{kg}\right]} * 100$$

A maximum efficiency of 100% is not achievable because the useful energy (exergy) is less than the total chemical energy, given an environment operating above absolute zero temperature. A second law exergy efficiency can be used to more accurately portray the efficiency of the system. The high amount of heat, friction, and chemical losses in reciprocating engines, especially as size decreases, makes reaching high efficiencies unrealistic.

Thermo-physical effects as outlined in Section 2 lead to a decreasing overall efficiency of ICE's with engine size. The combined effects of increasing surface to volume ratio, reduced residence time, and kinetics all contribute to reduce overall efficiency for smaller ICE's that essentially use the same design as their larger counterparts. The significant decrease in engine efficiency with engine size decrease is demonstrated in Fig. 8 where overall efficiency at peak operating power is plotted as a function of engine displacement.

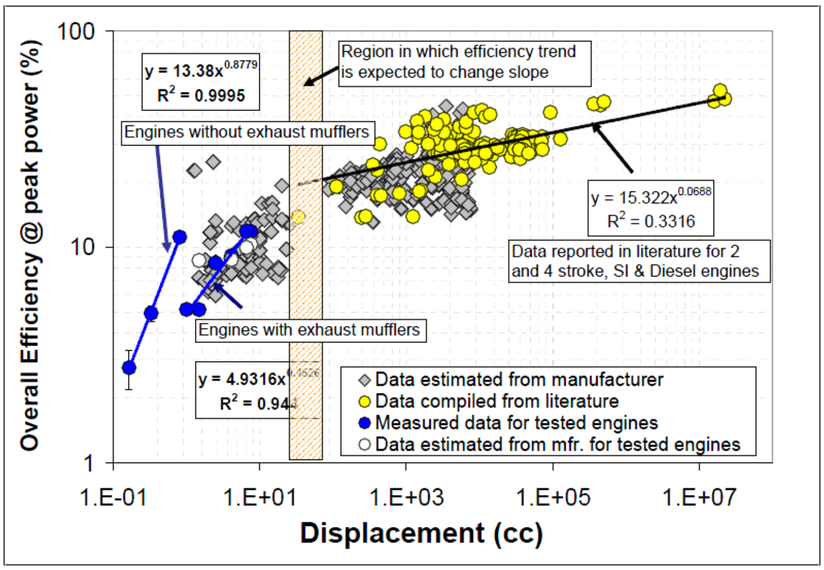

Figure 8: Overall efficiency as a function of engine displacement for various ICE's [3].

With overall efficiencies of small (<100cc) engines dropping into the single digits, it is hoped there is room for considerable improvement to increase power output and reduce fuel consumption. These improvements translate directly into increased range/endurance of unmanned air vehicles and other applications utilizing small ICE's.

3.1.3. Brake Specific Fuel Consumption (BSFC)

BSFC can be used to compare engines of all types and sizes. It is defined as the fuel consumption per power output of an engine. This is a direct function of efficiency, as the more fuel that is burned for a certain power output, the higher the brake specific fuel consumption. This parameter is defined in the equation below,

$$BSFC\ [\frac{g}{kW-hr}] = \frac{Mass\ flow\ rate\ of\ fuel\ [\frac{g}{hr}]}{Engine\ power\ output\ [kW]}$$

Creating an equivalent amount of power using a small engine takes a significantly higher amount of fuel than a large engine, which results in poor system efficiency. This is shown in Fig. 9 where SFC at peak power is plotted for various ICE's as a function of engine displacement. Some of the smaller ICE's require 10 or more times the amount of fuel used by larger ICE's to create an equivalent amount of power.

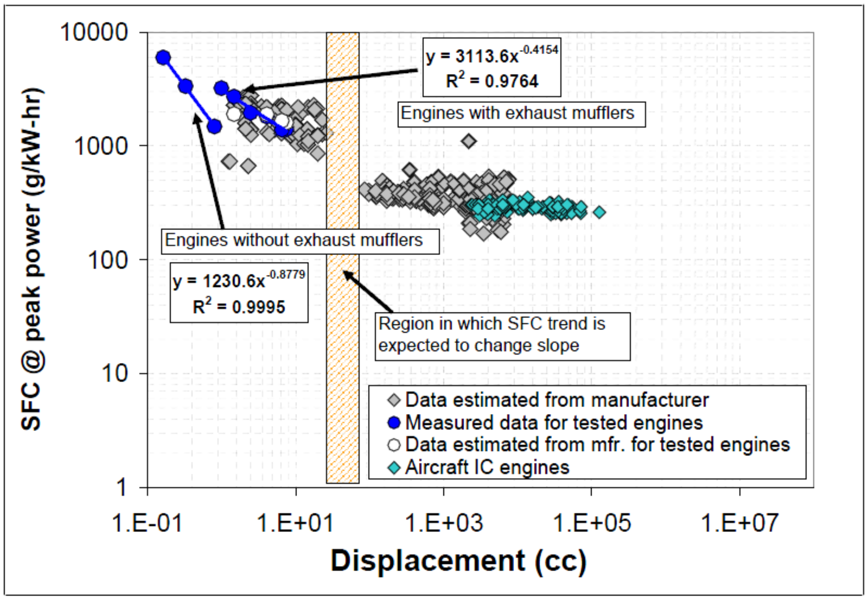

Figure 9: BSFC as a function of engine displacement for various ICE's [3].

A significant increase in the performance of small ICE's means decreasing their BSFC levels to under 1000 g/kW-hr, closer to the more reasonable value of 400 for larger ICE's.

3.1.4. Brake Mean Effective Pressure

BMEP is another normalized parameter that can be used for comparing engines of different sizes and designs. It is defined as the work done by the engine per volume of engine displacement and represents how well the cylinder volume is utilized to produce power. The parameter is defined as the following equation.

$$BMEP\ [Pa] = \frac{Work\ per\ engine\ cycle\ [J]}{Engine\ displacement\ [m^3]} = \frac{P\ [W] * n_R}{V_d\ [m^3] * N[RPM]}$$

where n_R is 2 for 4-stroke cycles and 1 for 2-stroke cycles. Figure 10 shows the scaling of BMEP as a function of engine displacement. As can be seen in Fig. 9, BMEP of smaller engines is significantly lower than that of larger engines.

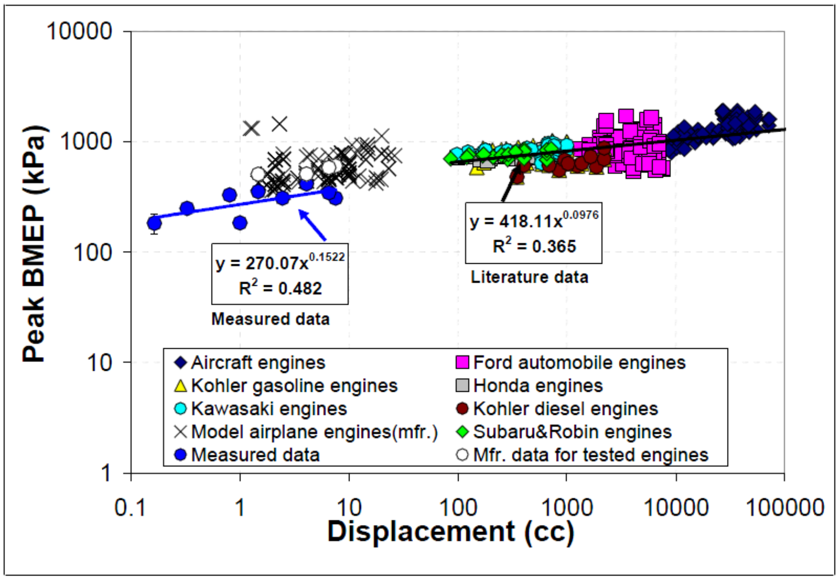

Figure 10: BMEP as a function of engine displacement for various ICE's [3].

This means that smaller engines are not utilizing their combustion volume efficiently. By increasing the BMEP a power increase of tenfold or more could be seen in small ICE's comparable to those of larger ICE's.

3.2. Gas Turbines

Gas turbines, though fundamentally different than reciprocating engines given their steady state flow conditions, can be evaluated much in the same way as their reciprocating counterparts. However, it is difficult to quantify engine size, as the design of a turbine is more dependent on the flow conditions of the turbine, turbine blade size, etc. The three parameters evaluated here are power, overall efficiency and "heat rate" which is comparable to BSFC. The data points presented below are obtained from various engine manufacturers. These are primarily for industrial turbines having a wide range of power outputs.

3.2.1. Efficiency

Much like ICE's, gas turbines appear to have an increased efficiency with increased engine power. GTE's from four different manufacturers [8-11] built to deliver stationary power were surveyed and their overall efficiency plotted against turbine maximum power output. This is shown in Fig. 11 along with additional literature data obtained for GTE's [12-13]. The literature data includes aero-derivative and stationary GTE's.

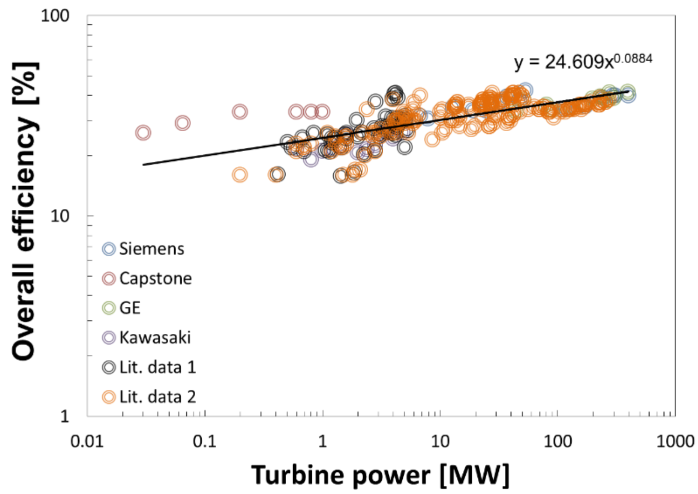

Figure 11: Overall efficiency as a function of power output for various gas turbine engines [8-13].

3.2.2. Heat Rate

The heat rate, which is measured in kJ/kW-hr, is comparable to BSFC. Instead of a measure of fuel flow rate per unit power output, heat rate measures a total amount of energy into the system for a given amount of energy out of the system. Figure 12 shows a graph of heat rate verses turbine power output.

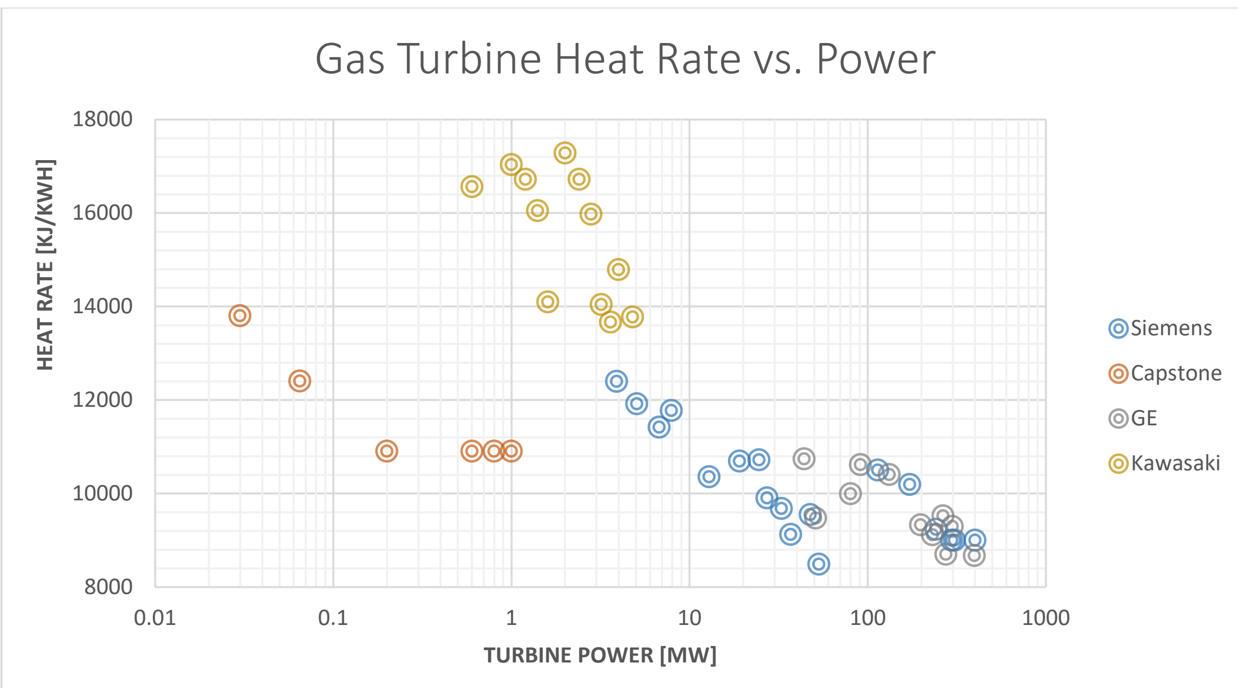

Figure 12: Heat rate as a function of power output for various gas turbines [8-11].

Because heat rate is the inversely proportional to efficiency, we can see that fuel required for a certain energy output is lower for the larger turbines, just as the fuel required for a certain power output is lower for larger ICE's. Heat rate and BSFC values are popularly used in industry since they relate to fuel price and hence economics of power generation.

3.3. ROCKET ENGINES

Efficiency of rocket engines is measured in specific impulse (I_{SP}), which is a measure of how much weight of fuel is required (in newtons) for a given impulse (newton-seconds). It can be expressed as,

$$I_{sp}[s] = \frac{I\ [N-s]}{m\ [kg] * g_o[\frac{m}{s^2}]}$$

where I is the impulse in N-s, m is the propellant mass in kg and g_o is the acceleration due to gravity in m/s^2. Sample values of I_{SP} are 242 s for the solid rocket boosters used on the space shuttle and 452 s for a liquid-fueled cryogenic rocket engine used as the space shuttle main engine.

While the I_{SP} value depends highly on the fuel choice of the system, it is observed that at the scale of the rocket is reduced considerably, energy loss mechanisms start to impact the I_{SP} value. Solid fuel rockets are the simplest systems but have the lowest I_{SP}. Liquid bipropellant engines are far more complicated given fuel tanks, high pressure valves and plumbing, and fuel storage, but have a much higher I_{SP}. Liquid monopropellant engines generally fall somewhere in between the two in terms of I_{SP}. Adding complexity to rocket engine systems also adds unwanted weight and a level of uncertainty in the system as a whole.

The thermo-physical issues related to fluid dynamics, heat transfer, and combustion affect miniaturization of chemical rocket engines similar to ICE's and GTE's. Lower Re and Peclet number (Pe) result in viscous and diffusive processes playing a more significant role [14]. Specific impulses are expected to be lower due to reduced combustion chamber temperatures resulting from increased heat loss and higher viscous losses. The lower residence time due to smaller length scales also pose a problem in ensuring complete mixing and combustion of the fuel-air mixture for liquid rockets. Given these effects, it is not surprising to see the I_{SP} starting to decrease with decreasing nozzle diameter in the graph in Fig. 13. The data in Fig. 13 were obtained primarily for scale model rockets [15] and some chemical micro thrusters [16].

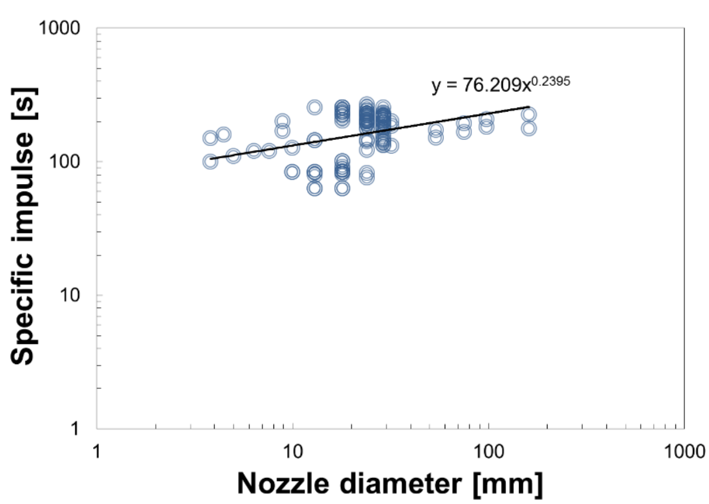

Figure 13: Specific impulse as a function of rocket nozzle diameter for a variety of chemical rockets [15-16].

4. ENERGY LOSSES IN ICE'S

In this section, we first identify and then analyze the energy loss sources in ICE's. Five major sources of energy losses can be identified for ICE's. Each of these sources corresponds to a specific portion of overall losses, although these portions change with changes in engine size. Overall efficiency can be calculated using the following equation. Efficiency parameters corresponding to the sources of energy loss can also be identified and will be mentioned in the sections below.

4.1. INTAKE LOSSES

The efficiency of an ICE intake during the air induction process can be expressed in terms of a parameter called the volumetric efficiency. A similar parameter used for 2-stroke engines is referred to as delivery ratio. Inefficiencies during the intake process result in the actual mass flow into the engine being less than the ideal mass flow rate. The difference can be expressed as intake losses. Volumetric efficiency for a 4-stroke ICE can be expressed as [17],

$$\eta_v\ [\%] = \frac{2 * \dot{m}_a \left[\frac{kg}{s}\right]}{\rho_a \left[\frac{kg}{m^3}\right] * V_d[m^3] * N[RPM]} * 100$$

where ρ_a is the ambient air density. In a 2-stroke ICE, induction is performed through a process called scavenging where the incoming fresh fuel-air mixture is used to displace burned exhaust gases from the engine cylinder. The induction process is characterized using a parameter called delivery ratio which can be expressed as [17],

$$DR\ [\%] = \frac{mass\ of\ delivered\ mixture\ per\ cycle\ [kg]}{reference\ mass\ [kg]} * 100$$

where the reference mass is defined as the product of the engine displacement with ambient air (or mixture) density.

4.2. COMBUSTION LOSSES

Combustion losses can be defined as the energy lost due to incomplete conversion of fuel chemical energy during the combustion process. Unburned fuel in the exhaust represents losses due to incomplete combustion. Combustion losses can increase considerably in 2-stroke engines due to short-circuiting. This occurs when fresh fuel-air mixture leaves through the exhaust port during the scavenging process without being burnt. Smaller residence time also leads to combustion losses since the exhaust port opens before the mixture is completely burnt. Larger engines have longer residence times which can result in lower combustion losses. Further in 4-stroke engines, the chances of short-circuiting are eliminated since there is no scavenging process during air induction.

4.3. MECHANICAL LOSSES

Mechanical losses are related to frictional losses in the engine. These can arise from fluid friction or mechanical rubbing friction such as at the piston-cylinder interface. Frictional losses are affected by engine operating speed as well as surface to volume ratio, both of which tend to increase with decreasing engine size.

4.4. THERMAL LOSSES

Thermal efficiency combine energy losses due to heat transfer out of the engine through the engine walls and high temperature combustion gases exiting though the exhaust (sensible heat loss). Hot exhaust gases can be potentially used for regenerative power generation or turbocharging in systems with that capability, though this is rarely seen in small ICE's.

4.5. Blow-by Losses

Blow-by is the term used to describe gases that pass by piston rings into the crank case. This results in a reduced amount of fresh charge available to burn inside the engine cylinder resulting in a lower power output. These losses can be especially high for very small ICE's (<10 cc) which typically do not have any piston rings and depend on piston-cylinder clearances for adequate sealing.

4.6. Overall Efficiency

The overall efficiency of an engine can be expressed in terms of component efficiencies that characterize the energy losses described above. Accordingly power output from an ICE can be expressed as,

$$\dot{W}_{out}[W] = \frac{\eta_o\,[\%]}{100} * \rho_a[\frac{kg}{m^3}] * V_d[m^3] * \frac{N\,[RPM]}{60} * \left(\frac{F}{A}\right) * Q_R[\frac{J}{kg}]$$

Where the overall efficiency η_o can be expressed as,

$$\eta_o = \eta_v * \eta_{combustion} * \eta_{mechanical} * \eta_{thermal} * \eta_{blow-by}$$

5. Scaling of Energy Losses in ICE's

Three separate studies done on different ranges of engine sizes to quantify energy losses in ICE's are reviewed in this work as detailed in the following sub-sections.

5.1. Miniature glow-fueled ICE's

The first, by Menon [18], is on several miniature methanol-fueled ICE's engines having displacement volumes between 0.16 and 7.5 cc. Energy losses that were characterized include those due to intake, mechanical friction, heat transfer, incomplete combustion, and sensible exhaust. No blow-by losses were measured in the study. Figure 14 shows results of the study for the smallest and largest engine investigated and correspond to engine data at the operating point of peak efficiency. Energy losses due to different mechanisms are expressed as a percentage of the total energy lost.

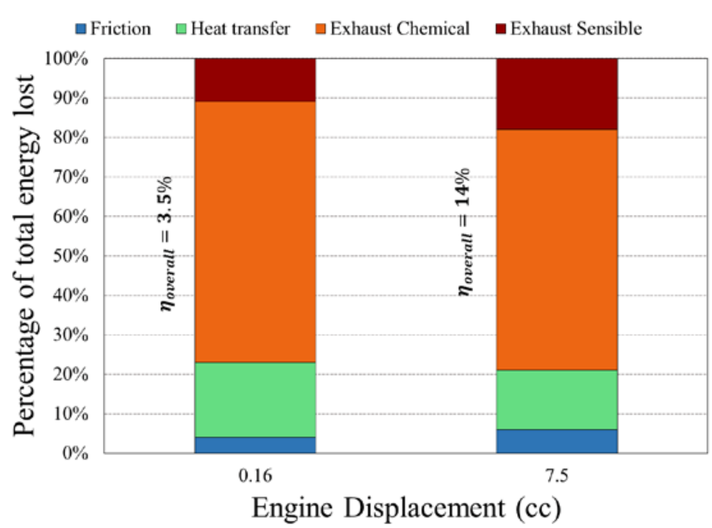

Figure 14: Engine energy loss map for miniature glow-fueled ICE's [18].

As can be seen above, the majority of the losses comes from unburned fuel being discarded into the exhaust. There is also significant heat transfer which contributes to engine losses, while frictional effects and sensible heat loss in the exhaust are not as pronounced.

5.2. SMALL SINGLE-CYLINDER GASOLINE FUELED ICE'S

In the second study from the Air Force Research Laboratory (AFRL) [4], the different energy losses in three small single cylinder spark ignited gasoline engines (28cc – 55cc) meant for unmanned air vehicle (UAV) propulsion were measured. Figure 15 shows results from this study.

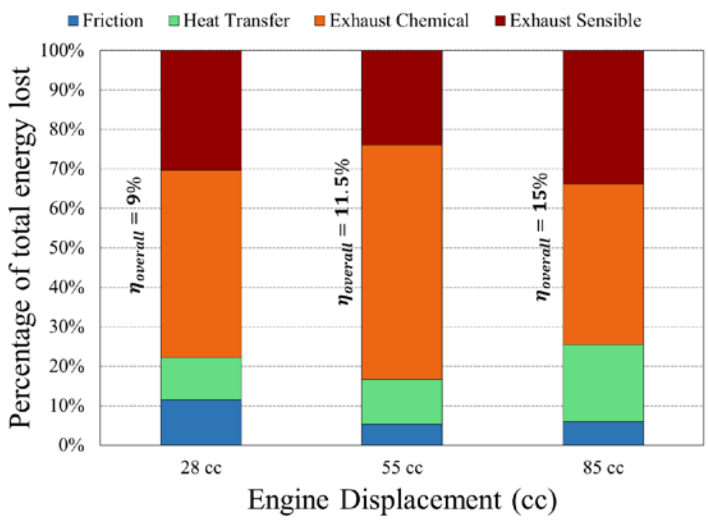

Figure 15: Engine energy loss map for single cylinder spark ignited gasoline ICE's for UAV's [4].

There are other losses that were not measured, since in the data presented in the publication for energy losses and power output do not sum up to 100% leaving about 20-30% of energy losses unaccounted for. Further two key assumptions were made in this study. One is that 20% of fuel energy is lost in short-circuiting, and the other that 5% of the fuel energy is lost due to incomplete combustion. This implies that the study assumed 25% of fuel chemical energy to be unavailable. Regardless, Fig.15 helps to visualize the sources of energy loss in small ICE's that are of very similar design and make as the majority of the engines used currently in small to medium sized UAV's. Mechanical losses make up the smallest portion, though they do increase as engine size decreases. Heat exhaust makes up approximately 15% of the total losses and does not change significantly with changing engine size. Chemical exhaust, or unburned fuel, makes up the most significant portion of losses. In order to have the most impact on increasing the overall efficiency of these size engines, designers must focus on combustion efficiency over all other losses.

5.3. CONVENTIONAL SIZED AUTOMOTIVE ICE'S

The final study is from data presented in Heywood [17], and focuses on automobile engines. These engines, likely in the 1500-4000 cc range, have a significantly different loss signature than the smaller engines considered previously as seen in the results plotted in Fig. 16.

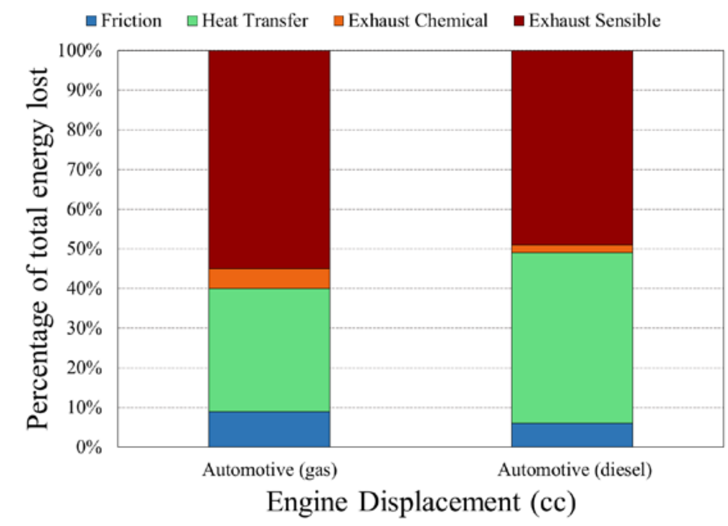

Figure 16: Engine energy loss map for conventional sized automotive gasoline and diesel engines [17].

In these larger engines, the amount of unburned fuel has been minimized. Because this loss portion is so low, we see the effects of the other losses as being more pronounced. The majority of losses comes from sensible heat loss out of the exhaust and heat transfer out of the engine. In order to minimize these losses in the future, waste heat recapture must be implemented into these engine systems.

Testing engines in this way and recording the loss percentages can give valuable insight to where losses are coming from in small ICE's. Once the losses are pinpointed, it becomes far easier to focus research on reducing the most significant source of efficiency loss.

6. Small Scale Propulsion Work

The authors are developing a small engine testing facility which includes a motoring dynamometer. This dynamometer and facility will be used to address some of the key problems covered previously. The initial focus is on small, 2-stroke engines for UAVs with a goal of building and testing long range vertical take-off lift (VTOL) fixed wing aircraft. Drive train research in this testing facility will allow for significant improvement on today's hybrid systems in UAV's. Preliminary data for a small ICE was obtained on a propeller test stand [19]. Figure 17 is a rendering of the motoring gimbal-mounted dynamometer design option for our laboratory.

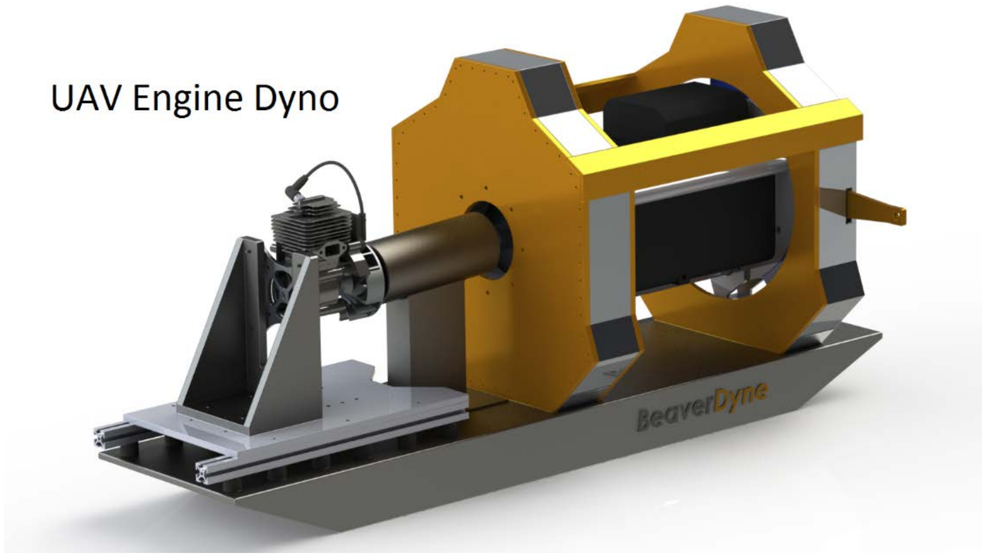

Figure 17: Rendering of the authors' small engine dynamometer.

Similar to the work done at AFRL, data on energy losses will be gathered with the aim of increasing the performance of small ICE's. The size range of ICE's to be tested in this facility will be between 15-30 cc displacement. Gathering this data will require a suite of sensors and various tests. Gathering data on friction losses is as simple as motoring the engine at its full range of speeds to find the frictional power draw. Thermal energy losses due to heat transfer and sensible energy in the exhaust will be measured using thermocouples placed at key locations on the engine and in the exhaust. Exhaust gas volumetric flow rate will also be required, and will be measured with a flow meter. Exhaust gas composition will be analyzed using a 5-gas Horiba Mexa 584-L emissions analyzer. Overall efficiency can be measured using the power output as measured by the dynamometer compared to the fuel input measured by a flow meter. Adding a cylinder pressure transducer and thermocouple to the engine head will also give important data such as combustion pressures/temperatures. This data can provide insight into combustion losses and pre-combustion blow-by given a predicted TDC pressure with a known compression ratio, equivalence ratio, intake temperature, and intake pressure of the fuel.

The future work done at our laboratory will provide valuable data on existing small ICE's and experimental data and results that can point to ways to increase small engine performance.

7. Conclusions

The scaling of key parameters involved in thermo-physical issues relating to engine size such as residence time, surface area to volume ratio, and Reynolds number was examined for different types of combustion engines. As combustion engines are scaled down, residence time decreases, surface area to volume ratio increases, and Reynolds number decreases. These effects result in increasing energy losses with decreasing engine size through pathways such as combustion losses, thermal losses, and frictional losses. These effects are evidenced in various scaling laws investigated in this work including those for: power, efficiency and BMEP for internal combustion engines; power and heat rate for gas turbine engines and; specific impulse for rocket engines. Scaling down the engine size tends to degrade performance in all three types of combustion engines. These observations are consistent with previous work on micro-combustion devices.

Three different studies from literature were examined to understand the relative size of energy loss pathways in internal combustion engines. These studies present a stark distinction between the energy loss pathways in conventional scale engines and those in miniature engines. While sensible energy loss in exhaust and energy loss due to heat transfer dominate in conventional scale engines, energy loss due to incomplete combustion dominates in miniature scale engines. This points to the fact that building efficient combustion engines at small scales cannot be simply accomplished by scaling down their conventional scale counterparts. These findings also point to a pressing need to understand the true nature of combustion and related processes in miniature scale engines including fuel-air mixing, ignition, flame propagation, heat release, and heat loss phenomena. Only through a thorough understanding of these processes can attempts be made to reduce combustion losses, and improve on existing performance of small combustion engines.

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