Liquid-Fuel Combustion in Miniature Power and Propulsion Systems

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Abstract

Liquid hydrocarbon fuels have high mass and volume specific energies. Miniature devices capable of releasing this energy with high specific power face substantial challenges that include short residence times for evaporation, mixing, and heat release, as well as thermal management for reducing heat loss but also keeping temperatures within material limits. In response to these challenges, this paper describes two approaches for utilizing liquid fuels in miniature combustion systems. The first is a small reciprocating engine used for powering model airplanes. Our results show that the engine performance is seriously compromised by fuel evaporative cooling and high lubricant demands. The second is a liquid film combustor that evaporates the fuel from the combustor wall before it burns. In this configuration, the reaction is stabilized by a unique triple-flame structure.

Keywords: Portable power, Mini-engine, Mini-combustor

1 - INTRODUCTION

Liquid hydrocarbon fuels are capable of very high mass specific and volume specific storage of chemical energy. It is important to consider, therefore, the direct use of liquid fuels in portable power systems that are expected to operate for long periods at relatively high power because such fuels represent the most viable on-board energy storage option in such cases [1]. This paper summarizes the combustion performance of two centimeter-scale power devices that utilize liquid hydrocarbon fuels. One system is a commercially available 4-stroke reciprocating piston engine running on a mixture of methanol, nitromethane, and castor oil, and the second is a fuel film combustor that operates continuously. These devices are considered mesoscale systems and they are not intended for micropower applications but rather for situations where substantial power is needed in compact systems. The piston engine, for example, produces several hundred Watts of mechanical power and the film combustor can operate with thermal output that ranges up to a kiloWatt. Both of these devices have been studied at the University of California, Irvine for some time, and in this work we present the key operational aspects identified by the research.

2 - MINIATURE RECIPROCATING ENGINE

The O.S. Engines FS-30-S, shown in Figure 1, was chosen for study because it is a representative example of a modern mass-produced model engine. The engine is a single cylinder, 4.89 cc displacement four-stroke design, with single intake and exhaust valves driven by pushrods. A mixture of methanol, nitromethane, and castor oil (the latter nominally acting primarily as a lubricant) is used for fuel. The piston has a single piston ring. According to the manufacturer's specifications, the practical rpm range is 2,500—13,000, the weight of the engine is 278 grams, and the maximum power output is 0.5 brake horsepower (373 watts), which occurs at 10,000 rpm. Based on these specifications, the mass specific power is 1300 W/kg (neglecting the weight of the fuel). For testing, the engine is mounted on a custom-built dynamometer and, as shown in Figure 1, the cylinder head is instrumented with an in-cylinder pressure transducer and an optical fiber for detecting flame luminosity. Further details of the experimental apparatus are available in [2-4].

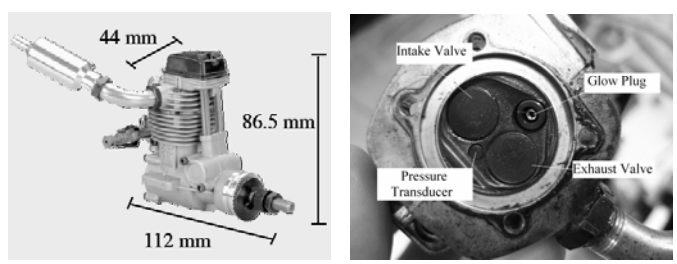

Figure 1. Miniature 4-stroke model airplane engine (left) and the engine head from the engine showing the location of the pressure transducer

The combustion process is initiated with a platinum wire glow plug coupled with the compression heating of the fuel/air mixture. We measure the peak specific power to be approximately 300 W/kg. Although this value is significantly higher than the 100 W/kg achieved by most electrochemical devices, the peak measured fuel conversion efficiency (9.3%) is low compared to full-size engines, and the value falls

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below 5% over much of the engine's operating range. The efficiency is even worse when considering the possibility that some of the lubricating castor oil might also be acting as a fuel. Cylinder pressure measurements show that friction and pumping losses are substantial. Energy lost through heat transfer to the cylinder walls, lack of sufficient residence time for combustion, and the effects of crevice volume are amplified at small scales because of high surface-area-to-volume ratios.

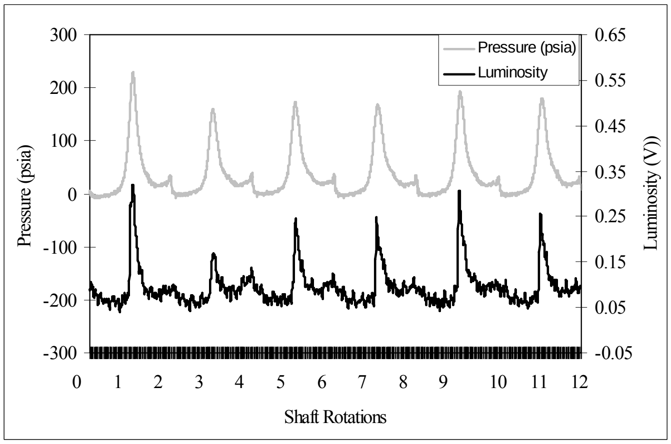

Figure 2. Pressure (upper trace) and luminosity (lower trace) inside the miniature piston engine cylinder during operation.

Figure 2 shows simultaneous traces of the pressure and the luminosity from inside the miniature combustion chamber during engine operation. The figure shows substantial cycle-to-cycle fluctuations in both measures. The luminosity varies more in percentage terms than does the pressure, but this is mainly because the combustion pressure is an increment on top of the motored compression pressure base whereas the luminosity has an essentially zero baseline value. The second combustion event in the figure shows a very weak luminosity signal, and a correspondingly low peak pressure, indicating a poor performing cycle that reduces engine efficiency. It is not obvious from the figure, but more detailed scrutiny of the luminosity data shows that the start of combustion (i.e., the ignition timing) is remarkably reproducible despite its reliance on compression heating and glow plug initiation.

Selecting a single pressure trace over 360 crank angle degrees allows the construction of the engine's indicator diagram, as shown in Fig. 3. The indicator diagram shows that there is substantial work required for pumping fuel and air into the engine and the exhaust out of it. Evidence of this latter work appears in the pressure trace where the smaller secondary pressure peak in each cycle relates to exhausting effort. Integrating the indicator diagram over the appropriate strokes shows that the pumping work is approximately 20% of the indicated work. The indicator work or power, when compared to the measured (or brake) value quantifies the frictional losses. In this engine, these losses are substantial, and for the condition shown in Fig. 3, the power required to overcome friction is 60% of the indicated power [3,4]. The high friction results from high rotational speeds, relatively

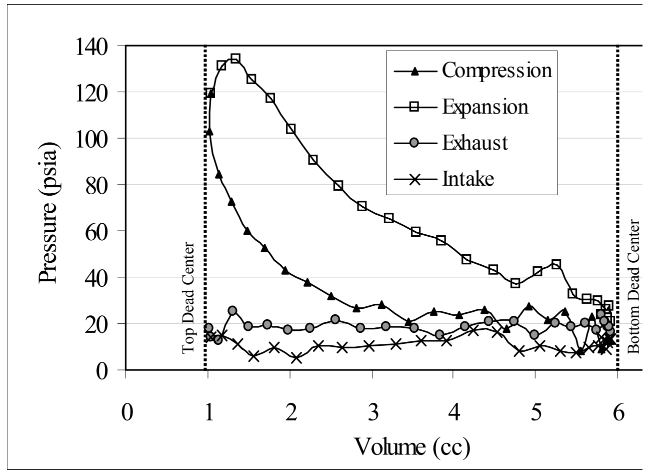

Figure 3. Indicator diagram for a single 4-stroke cyle of the miniature piston engine.

poor tolerances, and the simple lubrication strategy of bringing the lubricant in with the fuel. Future work will include more detailed analysis of the major sources of these frictional losses.

One of the interesting challenges of assessing the fuel/air equivalence ratio and the efficiency of the miniature engine is to determine how much of the castor oil burns. For example, assuming none of the castor oil burns leads to operating equivalence ratios near stoichiometric, but if all of the castor oil burns, the equivalence ratio approaches 2. Similarly, the engine thermal efficiency ranges from 5-9% depending on whether or not we include the energy content of the castor oil in the calculation. We are in the process of determining the fraction of castor oil burning by carbon-dating the CO_2 in the exhaust. The preliminary results suggest that approximately 30% of the castor oil burns as fuel.

3 - LIQUID FILM COMBUSTOR

The liquid film combustor is a novel design for a small-scale liquid-fueled combustion system, which takes advantage of volumetric reactions for quick energy release and a nonvolatile fuel that provides high specific energy. To make use of the high surface-to-volume ratios with decreasing size that generally increase heat loss, the film combustor injects

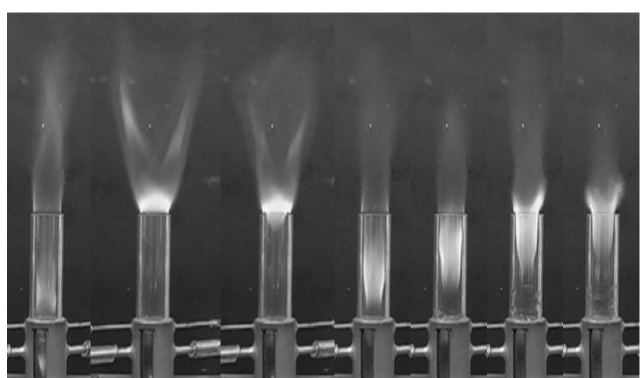

Figure 4. Images of the film combustor operating on heptane. Air flow rate increases left to right.

the fuel as a liquid film on the inner combustor surface, effectively reducing losses by redirecting heat towards film vaporization. This film is generated and stabilized in a tubular chamber by introducing swirling airflow. The novelty of this miniature film combustion concept is described in [5]. Several early investigations into the film combustor showed that a flame could be stabilized without recirculation or a physical flame holder as would be needed in a macroscale device [6,7]. The fuel tolerance and operational window in terms of air and fuel flow rates were fairly narrow, however, leading to further study in a transparent combustor. Quartz combustors did not hold the flame and so sapphire was used. Figure 4 shows a series of images of the sapphire liquid fuel film combustor operating on heptane as the airflow rate is increased from left to right. Initially, the airflow is insufficient to carry the fuel upward and so it pools at the bottom, producing a pool fire. At higher air flow rates, the flame jumps to the exit of the tube where the exiting rich mixture burns as a diffusion flame anchored to the rim. As the flow speed increases further, the flame begins to dip inside the tube as it seeks the evaporating fuel. The fourth image shows the optimal flow speed for this configuration, where the flame is now contained deeply within the combustor. As the flow increases in the next three images, the anchor point of the flame begins to move upward until it is blown out of the tube.

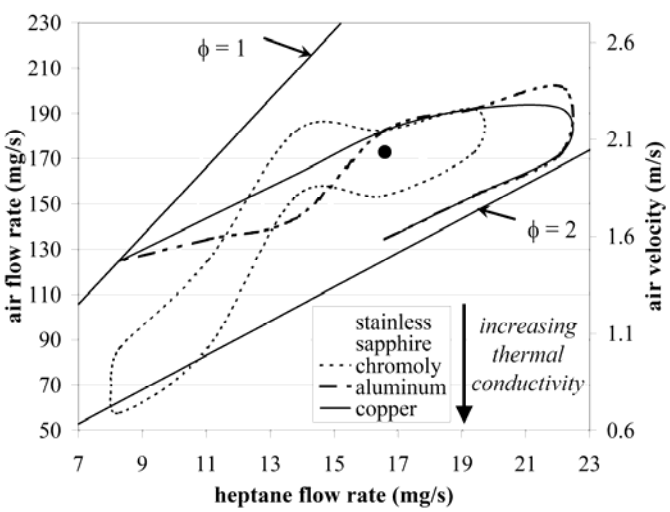

Figure 5. Fuel flow rates and air flow rate operating regimes for combustors constructed of materials with various thermal conductivity.

The qualitative investigation of flame behavior, and the fact that the flame could not be stabilized in a quartz chamber suggested that wall heat transfer plays a role in the film combustor. It appeared that heat transfer from the flame to the wall, then down the wall into the liquid fuel film, helped provide the necessary fuel evaporation rate to sustain the flame. To investigate this phenomenon, five combustors of different materials were tested. As shown in Fig. 5, and as expected, the higher the thermal conductivity of the wall material, the wider the operating limits of the combustor. In this case, stable operation was defined as flames with the appearance of the 4th and 5th images in Fig. 4 above. Similarly, wider operating limits were obtained with more volatile fuel (hexane) and narrower limits were observed with less volatile fuel (octane) [8].

In order to identify the structure of the flame, and to help explain the mechanism by which it stabilizes inside the chamber, chemiluminescence images of the excited state OH*, CH* and C_2* radicals were collected. In order to remove the line-of-sight ambiguity from these images, an Abel transform was performed. As shown in Figure 6, the Abel transform provides the radial distribution of the radical species. The figure highlights the fact that the flame is hollow, with a cylindrical flame sheet anchored midway to the center near the base of the flame and then approaching very close to the wall further downstream. It is this downstream portion of the flame that transfers the majority of the heat into the wall where it conducts upstream in order to aid in evaporating the liquid film.

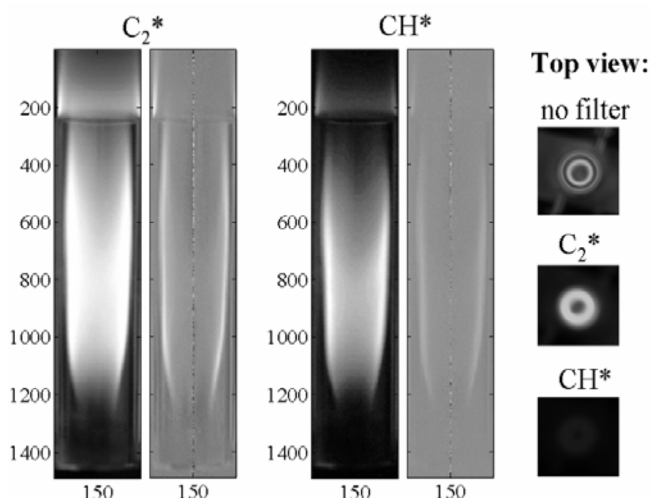

Figure 6. Chemiluminscence images of the film combustor. The image to the left is the normal camera image and the one to the right is the Abel transformed version. The three round images are top views confirming the hollow core of the film flame.

The leftmost C2 image in Fig. 6 suggests that there are two flames. The inner flame is anchored near the base and is fed directly from the evaporating fuel film. A secondary flame sits at the tube rim and burns excess fuel leaving the chamber with ambient air. We have run this combustor in a pure nitrogen environment and suppressed this external flame without perturbing the inner one. As seen in Fig. 5 we do not obtain stable operation at stoichiometric or lean conditions, so the inner flame operates overall rich. Because the fuel is evaporating from the wall near the inner flame base, and because there is a swirling flow within the chamber, it is likely that there is a radial fuel concentration gradient, with low (or perhaps even zero) concentration on the axis and high concentration (essentially saturated conditions) near the wall.

This kind of gradient is consistent with the conditions necessary for creating a triple flame.

The concept of the triple flame was first introduced by Phillips in 1965 [9], although he referred to the new flame type as a layer flame rather than a triple, tribrachial, or edge flame. Methane gas was introduced into the tops layers of a partially enclosed channel and air entered the channel from an open base. Phillips observed that flames would propagate along the interface between the buoyant methane and air layers, and was able to identify the triple flame structure as a premixed flame behind which excess unburned fuel from one edge and excess air from the opposite edge combined to burn in a diffusion flame. One important characteristic of triple flames is that the flow velocity upstream of the stabilization point decreases to approximately the laminar flame speed. This local deceleration of the flow permits a flame to stabilize itself in a velocity field that is overall faster than the stoichiometric laminar burning speed. Furthermore, Kim et al. [10] demonstrated that there must exist a large concentration gradient to maximize the reaction of the diffusion flame since the flame propagation speed is more strongly affected by the reaction rate of the diffusion flame than by the premixed flame. Based on these earlier findings and those observed in the liquid-fuel-film combustor, we have developed the schematic understanding of how the flame can stabilize itself within the chamber shown in Fig. 7. The heat conducted from the flame through the walls evaporates enough fuel to supply the reaction. The swirling air flow and wall evaporation produces a radial fuel concentration gradient so that a triple flame point is created at the point where the axial air flow matches the local flame speed. Further details of this work can be found in [11].

Although the wall film combustor is remarkably stable considering that it does not use swirl driven recirculation nor bluff-body flame holders, it does not burn all of the incoming fuel within the chamber. Future work will examine improved internal turbulence generation and fuel/air mixing to overcome this issue.

4 - SUMMARY

There remains an important need for portable power devices that can operate for long duration (~10 hours) at relatively high power (~100 W). Such devices will almost certainly carry liquid fuels. This paper describes two combustion devices that are designed specifically with these applications in mind. The miniature 4-stroke engine operates reliably and produces high power. Its efficiency is low, however, due in part to poor combustion control, but more seriously to high frictional losses. The fuel film combustor is a novel device that takes advantage of the increasing chamber surface areas at small scales and stabilizes an internal flame using a triple flame structure that relies on an important thermal coupling between the flame and the chamber walls. Its current design does not, however, allow sufficient fuel/air mixing for complete internal combustion. Both of these combustion systems will be studied further to achieve improvements.

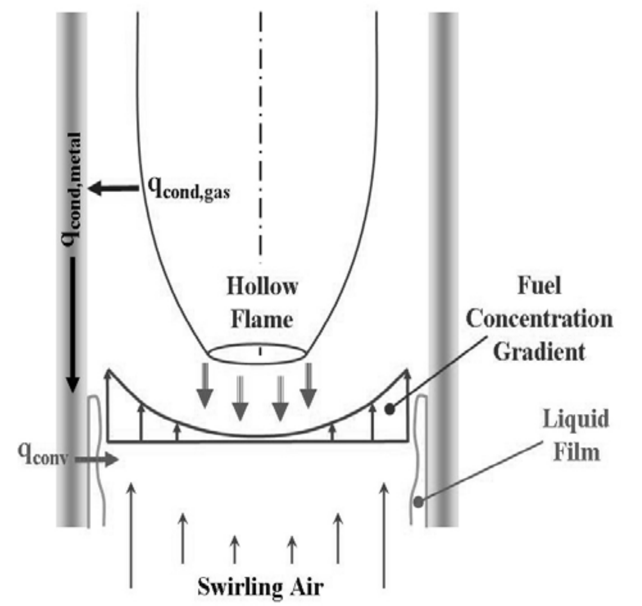

Figure 7. Cartoon showing how heat conducted from the flame through the combustor body vaporizes the fuel and creates a stable triple flame ignition site.

ACKNOWLEDGMENTS

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