DESIGN AND CHARACTERIZATION OF A LIQUID-FUELED MICRO-COMBUSTOR

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ABSTRACT

As part of an effort to develop a microscale gas turbine engine, this paper presents the design and experimental characterization of a micro-combustor that catalytically burns JP8 fuel. Due to the high energy densities of hydrocarbon fuels, microscale heat engines based on them may enable compact power sources with specific energies higher than those of current battery systems. In addition, utilizing a commonly available logistics fuel would provide advantages for military applications. Thus, a microscale engine burning JP8 fuel is attractive as a portable power source.

A liquid-fueled micro-combustor with a combustion chamber volume of 1.4 cm$^3$ and an overall die size of 36.4 mm $\times$ 36.4 mm $\times$ 6.5 mm was designed, micro-fabricated, and experimentally characterized. Two configurations were tested and compared; one with the combustion chamber entirely filled with a catalyst, and the other with the combustion chamber partially filled with a catalyst. In the configuration filled with a catalyst, JP8 combustion was sustained at mass flow rates up to 0.1 g/sec, and an exit gas temperature of 780 K; an overall combustor efficiency of 19%, and a power density of 43 MW/m$^3$ were achieved. The primary limitation on increasing the mass flow rates and temperature further was structural failure of the device due to thermal stresses. With the partially-filled configuration, a mass flow rate of 0.2 g/sec, and a corresponding power density of 54 MW/m$^3$ were obtained. The exit gas temperature for the partially-filled configuration was as high as 720 K, and the maximum overall efficiency was over 22%. Although the reduced amount of catalyst led to incomplete combustion, smaller thermal losses resulted in an increase in the overall combustor efficiency and power density. A non-dimensional operating map was constructed based on the experiment, and it suggests that improving the thermal efficiency would be necessary to achieve higher efficiencies in the device.

NOMENCLATURE

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$Bi$ Biot number
$C_b$ bulk concentration [mol/m$^3$]
$C_p$ constant pressure specific heat of air [J/kgK]
$D_{ab}$ molecular diffusion coefficient [m$^2$/sec]
$h$ specific enthalpy [J/kg]
$h_f$ heating value of fuel [J/kg] or [J/mol]
$M$ molecular weight [g/mol]
$m$ mass flow rate [kg/sec]
$Nu$ Nusselt number
$P$ pressure [Pa] or [atm]
$Pe$ Peclet number
$q$ heat flow [W]
$R$ Gas constant of air [J/kgK]
$R$ radius [m]
$Sh_D$ Sherwood number based on diameter
$T$ temperature [K]
INTRODUCTION

There have been extensive efforts to develop a portable electric power source that can improve upon the performance of current battery technology. Because hydrocarbons have a specific energy of approximately 40 MJ/kg, whereas the best lithium-ion batteries have about 0.5 MJ/kg, a hydrocarbon-based device with a chemical-to-electric efficiency of only a few percent could have benefits over batteries [1]. Fuel-burning devices can also be refilled quickly, and one can easily and accurately check their current level of fill. Both solid-state heat-to-electricity converters [2, 3] and internal combustion engines [4–6] are being studied for the micro-power generation using combustion. Epstein et al. [7, 8] led an initiative to design and build a shirtbutton-sized gas turbine engine using silicon semiconductor micro-fabrication technology. This engine is about one hundredth the length scale of its conventional counterparts, thus one millionth the volume, and is referred to as a microengine [9]. Bench-top microengines are designed to produce about 10 W of electrical power or 0.1 N of thrust within a package about 1 cm³ in volume. The resulting power density would be on the order of 10 MW/m³. Like their larger counterparts, the microengine requires a high temperature combustion system to convert chemical energy stored in fuel into fluid thermal and kinetic energy.

Previous research at MIT made progress on the development of micro-combustor technology for this application. Waitz et al. [10] were the first to study combustion systems for microengines. In a flame tube experiment, they showed that a lean-burning hydrogen-air combustor was a feasible initial development strategy for micro-combustors. Mehra et al. [11, 12] and Spadaccini et al. [13] built hydrogen micro-combustors mimicking the microengine’s flow geometries and thermal boundary conditions. They did not include the rotating spool, which is complex to fabricate and not considered critical to the micro-combustor functionality. In the hydrogen devices, exit gas temperatures in excess of 1600 K, efficiencies over 85%, and a power density of 1400 MW/m³ were achieved.

Hydrocarbon fuels such as ethene and propane were also tested in these devices, but the mass flow rate capabilities were significantly limited since the reaction time-scales of hydrocarbon fuels are approximately an order of magnitude longer than those of hydrogen. To broaden the operating range of the micro-combustor, Spadaccini et al. [14, 15] developed a catalytic micro-combustor. A platinum-coated, high porosity metal foam was placed inside the combustion chamber. The enhanced reaction kinetics of catalytic combustion increased the mass flow rate capabilities of the device; stable propane-air combustion was achieved at mass flow rates in excess of 0.35 g/sec. However, exit gas temperatures were somewhat low and limited to 1100 K, owing to lower thermal efficiencies. Nevertheless, the increased mass flow rate results in a combustor power density of 1200 MW/m³ burning propane fuel, which is a 8.5-fold increase over the non-catalytic propane-air combustion. Despite the progress on hydrogen and propane micro-combustors, the microengine would be more practical if it utilized a fuel that is easier to store and transport, such as JP8. Development of a reliable liquid-fueled combustion system suitable for integration with the microengine is the subject of this paper.

LIQUID-FUELED MICRO-COMBUSTOR CHALLENGES

Key design requirements for the microengine combustor include significant temperature rise, high efficiency, low pressure drop, structural integrity, reliable ignition, and flame stability. Because high power density of a gas turbine engine is realized by passing large mass flow rates through small cross-sectional areas, flow residence times in the combustor are inevitably short and may become similar or even less than the chemical reaction times that are invariant with size. This can lead to incomplete combustion, low efficiencies, and sometimes blowout of the flame. Moreover, due to enhanced heat transfer at microscale (smaller length scales result in higher surface area-to-volume ratios), the micro-combustor tends to lose a relatively large fraction of the flow enthalpy across the combustor walls. Thin walls and high thermal conductivity of silicon make the structure nearly isothermal, leading to poor thermal isolation of the combustor, exacerbating the heat loss problem. Non-adiabatic operation lowers combustor temperatures, and the low temperatures reduce chemical reaction rates, making the residence time issue more severe. Thus, fluid dynamics, chemical kinetics, and heat transfer are strongly coupled in a microscale combustor.

Using a liquid fuel poses additional challenges. It is known that the gas-phase reaction time is not significantly different for light and heavy hydrocarbons. Levebvre et al. [16] published an experimental report on ignition delays of various fuels, indicating that the spontaneous ignition delays of premixed propane and prevaporized/premixed JetA (a kerosene-based jet fuel similar to
JP8) are similar. Although the detailed chemistry of catalytic JP8 combustion is more complex than that for propane, we may assume that there will not be a significant difference in the catalytic reaction time-scales between propane and JP8. However, the diffusion time-scale, which is approximately ten-times longer than the reaction time-scale in the micro-combustor environment, is longer for JP8 fuel than for propane due to heavier molecules. The mixing time, which is usually longer than the diffusion time and the reaction time, is also longer for heavy hydrocarbon fuels.

Considering these aspects, a logical strategy for making the liquid-fueled micro-combustor as small as possible is to prevaporize and premix the fuel and air before entering the combustion chamber. To further reduce the combustion time-scale, catalytic combustion is also considered necessary.

**DESIGN AND FABRICATION**

In order for the micro-combustor to be compatible for integration with the microengine, it must have a geometry and a flow path that are similar to the microengine. Hence, the combustion chamber is in the shape of an annulus, allowing the flow to enter from the outer diameter, travel radially toward the inner diameter, and finally exit through the inner diameter. A schematic of the microengine flow path is shown in Figure 1. Operating parameters were also picked to be consistent with those of the microengine. Table 1 specifies the design operating conditions for the liquid-fueled micro-combustor.

A reduced-order design model was developed to estimate the time-scale of catalytic JP8 combustion. The model is valid for a slow-diffusing fuel, with its diffusion time-scale much longer than the reaction time-scale. Under this condition, the overall combustion time can be approximated as the diffusion time of fuel molecules. This approximation also eliminates the need for a surface kinetics model, which is not available for JP8 combustion. In this model, the combustor is assumed to be a simple circular tube, containing an internal flow that is steady, adiabatic, compressible (variable density), and viscous. The inner wall of the tube is treated as catalytic, with chemical reactions occurring only on the walls, and no gas-phase combustion. The combustion process is considered to be constant-pressure. The fuel is prevaporized and premixed with air before entering the combustion chamber. With these assumptions, the reacting flow problem becomes a mass transfer problem. The fuel concentration profile is zero at the wall and peaks at the center of the tube. This concentration gradient causes the fuel molecules to diffuse to the catalytic walls. Because the reaction rates are much faster than the diffusion rates, the fuel molecules are immediately consumed by chemical reactions. Using a mass transfer equation, the model computes the amount of fuel that diffuses to the wall and is subsequently oxidized. This fuel consumption can be traced along the tube, and a lengthwise profile of the fuel concentration can be obtained. Then, the axial location where the fuel concentration becomes 10% of the initial concentration can be found, and the time for the flow to reach this location can be considered as the overall time-scale of JP8 combustion. To calculate diffusion rates, JP8 fuel was approximated as C_{13}H_{23.4} with average molar weight of about 179 [18]. In the bulk stream, the fluid density and the specific heat were represented by those of air since the stoichiometric mixture has only 7% fuel by weight. Then, the mass transfer equation can be written as:

\[ \frac{dT C_b}{dt} = - \frac{S h_D D_{ab}}{R^2} (T C_b) \]

where \( T \) is the fluid temperature, \( C_b \) the cross-section-averaged concentration of fuel molecules, and \( R \) the radius of the reaction tube. The Sherwood number, \( S h_D \), is analogous to the Nusselt number in heat transfer, and the molecular diffusion coefficient, \( D_{ab} \), can be given by the Fuller correlation [19] for the corresponding temperature and pressure:

\[ D_{ab} = \frac{1.013 \times 10^{-7} T^{1.75} \sqrt{1/M_a + 1/M_b}}{P} \left( \frac{v_{ab}^{1/3} + v_b^{1/3}}{2} \right) \]
where

\[ T : \text{temperature [K]} \]

\[ P : \text{pressure [Pa]} \]

\[ M_a, M_b : \text{molecular weight of the species a and b} \]

\[ v_a, v_b : \text{diffusion volume of the species a and b} \]

Conservation of energy provides a relationship between temperature and concentration:

\[
\frac{dT}{dt} = \frac{-h_f}{\rho C_p} \frac{d(TC_b)}{dt} + \frac{dC_p}{dT} T^2 \frac{dT}{dt} \quad (3)
\]

where \( h_f \) is the heating value of JP8, \( \rho \) the fluid density, and \( C_p \) the constant pressure specific heat\(^2\).

Solving this set of coupled non-linear differential equations numerically with appropriate initial conditions and fluid properties, it was found that the fuel concentration falls below 10% of the initial concentration in approximately 2.5 ms. Figure 2 shows a typical model result. The characteristic diameter of our catalyst is less than 700 \( \mu \text{m} \), so the figure indicates that 2.5 ms residence time should be sufficient. Based on this result, the combustion chamber was sized to be 1.4 cm\(^3\) to ensure that the flow residence time is longer than 2.5 ms at a design flow rate of 0.3 g/sec and a pressure of 2 atm.

In conventional gas turbine engines, fuel is usually directly injected into the combustion chamber in the form of droplets. For micro-combustor applications, however, the fuel needs to be vaporized and mixed with air before entering the combustion chamber due to the short flow residence times available. Considering that the microengine has readily available hot surfaces, typically at a temperature higher than the final boiling point of JP8, a fuel vaporizer with 49 micro-channels (hydraulic diameter \( \approx 0.5 \text{ mm} \) and a length \( \approx 10 \text{ mm} \)) was designed. More details of the design process can be found in Peck [20]. This design benefits the overall engine cycle by recuperating heat lost to the structure while vaporizing the fuel.

Figure 3 shows exploded views of the liquid-fueled micro-combustor. The test rig consists of six layers that are either bonded or mechanically clamped. As described in the figure, air and fuel are supplied through the holes near the edge in Layer 2, go down along the channels in Layer 1, and enter the device through the holes on the opposite end of Layer 2. The air goes directly into the mixing chamber, and the fuel enters the vaporizer at the outer diameter. The fuel is vaporized in the micro-channels, and injected into the mixing chamber through a set of 100 \( \mu \text{m} \) injection holes. The fuel and air mix while flowing radially outward, and enter the combustion chamber through the inlet slots. The fuel and air mixture are catalytically combusted in the combustion chamber while flowing radially inward. Finally, the combustion product exits the device through the exit nozzle. All the layers are held together by spring-loaded clamps made of machinable glass ceramics. Table 2 lists key dimensions of the test rig.

The liquid-fueled micro-combustor rig is a hybrid structure consisting of three different materials: silicon, sapphire, and SD-2 glass. The sapphire combustion chamber (Layer 5), exit tube, and SD-2 packaging glass (Layer 2) were fabricated with ultrasonic machining by Bullen Ultrasonics. The three silicon layers were micro-fabricated in the Micro Technology Laboratory (MTL) at MIT. The catalytic insert was fabricated from nickel foam (with approximately 90% porosity) that was cut into the shape of the combustion chamber in the MIT machine shop, and coated with platinum in MIT’s Technology Laboratory for

\(^2\)Values of \( C_p \) were evaluated as if the working fluid is pure air, which is in fact not the case. This assumption generally under-predicts \( C_p \) by about 15% compared to the more rigorously estimated \( C_p \) of the combustion reactants and products.
Table 2. KEY DIMENSIONS OF THE TEST RIG

| Group               | Parameter                          | Value                        |
|---------------------|------------------------------------|------------------------------|
| overall             | overall die size                   | $36.4 \text{ mm} \times 36.4 \text{ mm} \times 6.5 \text{ mm}$ |
|                     | packaging block (Layer 2)           | $36.4 \text{ mm} \times 70.0 \text{ mm}$ |
| combustion          | outer radius                       | 16.7 mm                      |
| chamber             | inner radius                       | 6.5 mm                       |
|                     | height                             | 2 mm                         |
| vaporizer           | number of channels                 | 49                           |
|                     | length of each channel             | 10 mm                        |
|                     | inlet hydraulic diameter           | 595 $\mu$m                   |
|                     | outlet hydraulic diameter          | 320 $\mu$m                   |
| fuel injection      | number of holes                    | 50                           |
| holes               | diameter of each hole              | 100 $\mu$m                   |

Advanced Materials and Structures (TELAMS) by dipping in platinic acid. Silicon micro-fabrication mainly involved photolithography with seven photomasks and Deep Reactive Ion Etching (DRIE) using a Surface Technology Systems (STS) Inductively Coupled Plasma (ICP) etcher. Silicon fusion bonding and silicon-to-glass anodic bonding were also used. Figure 4 shows images of the micro-fabricated vaporizer channels and the fuel injection holes.

**EXPERIMENTAL CHARACTERIZATION: FILLED CATALYST CONFIGURATION**

Catalytic combustion of JP8 was successfully stabilized in the device, and experimental data were collected under various equivalence ratios and mass flow rates. First, a configuration with the combustion chamber entirely filled with a catalyst was tested, and results are presented in this section.

To ignite catalytic combustion, the catalyst must first be activated [19]. It is known that platinum becomes activated for hydrocarbon combustion when it is heated to temperatures above 600 K. To achieve this level of preheating, hydrogen was burned in the device prior to switching to JP8. Using this procedure, catalytic JP8 combustion was sustained successfully in the micro-combustor test rig, as is evidenced by the glowing catalytic insert shown in Figure 5.
Temperature Response

The temperature response of catalytic JP8 combustion is plotted versus the total (air + fuel) mass flow rate in Figures 6 and 7. Temperature measurements are obtained by using 250 µm unsheathed type-K thermocouples. The exit gas temperature is measured at the exit nozzle, and the structural temperatures are measured around both the outer rim and the exit of the combustion chamber. The two structural temperature measurements differed by less than 10 K, which is within the 95%-confidence uncertainty range. As included in each figure, 95%-confidence uncertainty for the exit gas temperature measurements is ±32 K, and ±12 K for the structural temperature.

Figure 6 shows the exit gas temperature as a function of the equivalence ratio for each mass flow rate setting. Although measured data lie within the uncertainty bands of one another, a higher mass flow rate generally resulted in a higher temperature at the same equivalence ratio. Catalytic JP8 combustion was stabilized at equivalence ratios as low as 0.7 and as high as 1.4. Whereas there is normally a peak around the equivalence ratio of 1.0 for gas-phase combustion, no peak was observed in this experiment. This is because fuel conversion efficiency is low, and the combustion is limited by the diffusion of the fuel. The higher the concentration of fuel molecules, the higher the diffusion rate becomes, and more fuel can be burned, producing higher temperature.

Figure 7 shows the exit gas temperature and the structural temperature as functions of the mass flow rate. The structural temperature plotted is an average between the two structural temperature measurements. Stable combustion was shown at a mass flow rate as high as 0.1 g/sec (Figure 7), and the corresponding exit gas temperature was 780 K (φ = 1.1). In general, the temperatures increase with the mass flow rate, which indicates that the performance of the combustor is not limited by chemical efficiencies in this range, showing a potential to allow a higher mass flow rate. However, the design mass flow rate of 0.3 g/sec was not achieved because of a structure failure, which is believed to
be due to excessive thermal stresses in the sapphire. There is little difference between the exit gas temperatures and the structural temperatures, which is typical for catalytic combustion [19]. This is because the chemical reactions occur on the catalytic surfaces, and the heat is transferred to the bulk gas via convection (heat transfer by radiation becomes significant when the catalyst temperature exceeds 800 K). Due to the existence of short conduction paths with relatively small thermal resistance between the catalytic insert and the sapphire structure, the heat tends to readily flow from the catalyst to the structure, resulting in high structural temperatures.

Based on the temperature data, the power density can be calculated as:

\[
P_{\text{fluid}} = \frac{\text{fluid power}}{\text{combustor volume}}
\]

(4)

Efficiency Breakdown

From the experimental measurements, the overall combustor efficiency can be calculated by dividing the enthalpy gain of the fluid by the maximum possible fuel power that may be released [21]:

\[
\eta_{\text{overall}} = \frac{(\dot{m}_a + \dot{m}_f)h_{\text{exit}} - \dot{m}_a h_{\text{inlet}}}{\dot{m}_f h_f}
\]

(5)

where \(\dot{m}_a\) and \(\dot{m}_f\) are the mass flow rates of air and fuel respectively, \(h_{\text{inlet}}\) and \(h_{\text{exit}}\) are the specific enthalpies at the inlet and the exit, and \(h_f\) the lower heating value of JP8. Using the structural temperature data and a 1-D heat transfer model, it can be estimated how much heat is lost through the device. Adding the heat loss to the enthalpy gain of the fluid gives the total amount of heat that has been released from the fuel. Dividing the total heat release by the maximum fuel power that could have been released yields chemical efficiency:

\[
\eta_{\text{chemical}} = \frac{(\dot{m}_a + \dot{m}_f)h_{\text{exit}} - \dot{m}_a h_{\text{inlet}} + q_{\text{loss}}}{\dot{m}_f h_f}
\]

(6)

Dividing the overall combustor efficiency by the chemical efficiency provides an estimate of how much heat is retained in the fluid as opposed to how much heat has been released from the fuel. This is defined as thermal efficiency:

\[
\eta_{\text{thermal}} = \frac{(\dot{m}_a + \dot{m}_f)h_{\text{exit}} - \dot{m}_a h_{\text{inlet}}}{[(\dot{m}_a + \dot{m}_f)h_{\text{exit}} - \dot{m}_a h_{\text{inlet}}] + q_{\text{loss}}}
\]

(7)

These efficiency components are plotted in Figure 8 for the equivalence ratio of 1.1. As seen in Figure 7 (a), the exit gas temperature keeps rising with the mass flow rate until the structural failure; more fluid power is generated as the mass flow rate goes up. Therefore, the overall combustor efficiency increases with the mass flow rate. In Figure 7 (b), likewise, higher mass flow rates lead to higher structural temperatures and thus more heat losses. Since the chemical efficiency is associated with the sum of fluid thermal power and heat loss, the chemical efficiency increases with the mass flow rate as well. This implies that the device is not chemically-limited in this mass flow rate range, showing that it could potentially be operated at higher mass flow rates if the structure bore the thermal load.
Non-Dimensional Operating Map

It is critical in catalytic combustion to ensure that the fuel-air mixture stays in the combustion chamber longer than it takes for the fuel molecules to diffuse through the concentration boundary layer and onto the catalytic surfaces, on which they react with oxygen. The Peclet number is a non-dimensional parameter defined as the ratio between the characteristic flow residence time and the characteristic diffusion time of fuel molecules:

$$\text{Pe} = \frac{\tau_{\text{residence}}}{\tau_{\text{diffusion}}}$$  \hspace{1cm} (8)

A large Peclet number indicates that the residence time-scale is sufficiently long compared to the fuel diffusion time. At low mass flow rates, large Peclet numbers are typical. As the flow rate is increased, however, the flow residence time becomes smaller; the Peclet number is reduced unless the fluid temperature increases appreciably to augment diffusion and reduce the diffusion time-scale.

To evaluate the Peclet number, the flow residence time-scale is first calculated with a density based on average temperature:

$$\tau_{\text{residence}} = \frac{\rho V}{\dot{m}} = \frac{PV}{\dot{m}RT}$$  \hspace{1cm} (9)

where $P$ is the combustor pressure, $V$ the combustor volume, $\dot{m}$ the total mass flow rate, $R$ the gas constant for air, and $T$ the average temperature in the combustion chamber. Upon using the average temperature and molecular diffusion coefficient, which is evaluated based on the average temperature, Equation (1) integrates to:

$$C_b(t) = e^{-\frac{Sh_D \bar{D}_{ab}}{R^2 t}}$$  \hspace{1cm} (10)

Since the diffusion time-scale is defined as the time that fuel concentration becomes 10% of the initial concentration:

$$e^{-\frac{Sh_D \bar{D}_{ab}}{R^2 \tau_{\text{diffusion}}}} = 0.1$$  \hspace{1cm} (11)

Thus,

$$\tau_{\text{diffusion}} = -\frac{R^2 \ln(0.1)}{Sh_D \bar{D}_{ab}}$$  \hspace{1cm} (12)

Substituting $\bar{D}_{ab}$ with the Fuller correlation (Equation (2)):

$$\tau_{\text{diffusion}} = \left(\frac{2.30 R^2 (\frac{1}{v_a} + \frac{1}{v_b})^2}{1.013 \times 10^{-2} Sh_D \sqrt{1/M_a + 1/M_b}}\right) \frac{P}{T^{1.75}}$$  \hspace{1cm} (13)

Using the temperature and the mass flow rate measurements for each experimental data point, corresponding Peclet numbers can be computed by dividing Equation (9) by (13):

$$\text{Pe} = \frac{\left(1.013 \times 10^{-2} V Sh_D \sqrt{1/M_a + 1/M_b}\right) T^{0.75}}{2.30 R^2 (\frac{1}{v_a} + \frac{1}{v_b})^2} \frac{T}{\dot{m}}$$  \hspace{1cm} (14)

Using Equation (14), Peclet numbers are evaluated based on the measured $T$ and $\dot{m}$, and plotted versus the total mass flow rate in Figure 9. As stated earlier, the Peclet number decreases with the mass flow rate mainly due to the reduction in the flow residence time. Its dependency on temperature is weak relative to mass flow rate, and consequently, the Peclet number is only a weak function of equivalence ratio in the liquid-fueled micro-combustor.

The chemical efficiency and the thermal efficiency can also be plotted as functions of the Peclet number as in Figure 10. Although there are broad uncertainty bands, Figure 10 displays a few general trends. First, increasing Peclet numbers generally result in decreasing thermal efficiencies. This is because high Peclet numbers represent low mass flow rates (Figure 9), and the thermal efficiencies have a tendency to increase with the mass flow rate as shown in Figure 8. The impact of the Peclet number on chemical efficiencies is unclear in this plot. However,
it can be said that low Peclet numbers do not significantly reduce the chemical efficiency, which suggests that the device is not chemically-limited in this mass flow rate range, i.e., the device has enough catalyst in the combustion chamber.

Second, chemical efficiencies decrease as the equivalence ratio is increased, whereas thermal efficiencies are not influenced by the equivalence ratio. This is likely because the thermal efficiency is most strongly associated with the heat transfer characteristics of the device. Other parameters that may impact the efficiencies, e.g., catalyst geometry, fuel diffusion characteristics, pressure, temperature, and mass flow rate, are lumped in the Peclet number. Figure 11 diagrammically explains how the relevant parameters can be grouped into non-dimensional parameters. In brief, the chemical efficiency is a function of the Peclet number and the equivalence ratio, and the thermal efficiency is a function of the Peclet number and the thermal boundary conditions (fluid-structure interaction characteristics) of the specific device.

The experiment-based Peclet numbers are mapped out on a non-dimensional space in Figure 12. The vertical axis represents the chemical efficiency, and the horizontal axis represents the thermal efficiency. The product of the two is the overall efficiency, which is also shown in the figure. All the experimental data are plotted in the chemical efficiency-thermal efficiency plane, and each data point has a corresponding Peclet number although the exact value is not marked in the plot for the sake of legibility. Instead, shown in Figure 12 are the lines of constant Peclet numbers, which were generated by fitting the experiment-based Peclet numbers with the least squares method.

\[ Pe = \frac{a}{\eta_{\text{thermal}}} + \frac{b}{\eta_{\text{chemical}}} \]

The average error\(^5\) of the least square fitting was 12.4%. Because the thermal efficiency depends on the thermal boundary conditions, the non-dimensional operating map (Figure 12) is device-specific. However, unless the thermal boundary conditions are drastically different, this map can also be used as a design tool to predict the performance of catalytic micro-combustors over a range of combustor volumes. For example, once design parameters such as mass flow rate, equivalence ratio, and exit gas temperature are specified, the required overall efficiency can be computed using Equation (5). For a catalytic combustor, it is known that the structural temperature is similar to or slightly lower than the exit gas temperature, so the structural temperature can be estimated.

\[ Err = \frac{1}{n} \sum_{k=1}^{n} \left( \frac{Pe_k}{a/\eta_{\text{thermal},k} + b/\eta_{\text{chemical},k}} - 1 \right)^2 \]

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\(^4\)After inspecting the trend of the Peclet number distribution, a form of the Peclet number was used, then coefficients \(a\) and \(b\) were determined by the least square method. The map shows regions of both interpolation and extrapolation.

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with reasonable accuracy. Then, assuming a proper value for the surface area, the total heat loss can be estimated using a simplified heat transfer model like the one introduced in Peck [20]. Then, the overall efficiency can be broken-down into the thermal and chemical components, and the operating point can be located on the non-dimensional operating map, allowing the designer to read the corresponding Peclet number. Using this Peclet number, as well as the desired mass flow rate and exit gas temperature, the combustor volume can then be determined from Equation (14).

**PARTIALLY-FILLED CATALYST CONFIGURATION**

Although the use of a catalytic insert extends mass-flow-rate capability, exit gas temperatures tend to be lower than for gas-phase combustion. Moreover, the exit gas temperature requirement of 1300 K is so close to platinum’s melting point that the structural integrity of the catalytic insert becomes an issue for the catalytic micro-combustor. Therefore, catalytically-anchored gas-phase combustion, or hybrid combustion, was explored [15]. This concept has been adopted in some conventional gas turbine combustors, especially in ground-based power generators, due to advantages in ignition, stability, and emissions [22–26]. Because the flammability limit of hydrocarbon fuels is rather narrow around the stoichiometric equivalence ratio, conventional gas-phase combustors have a fuel-rich primary zone followed by a diluted secondary zone, which cools the combustion products with dilution air to a safe operating temperature for the turbine. Due to elevated combustion temperatures, the primary zone produces NOx emissions. Catalytic combustors, on the other hand, can reduce NOx emissions by burning uniform lean fuel-air mixtures at lower temperatures. Unlike conventional applications, however, the concept of catalytically-anchored gas-phase combustion was proposed for the liquid-fueled micro-combustor to achieve both high reaction rates and high exit gas temperature without jeopardizing the catalyst. To test this configuration, only the front two-thirds of the combustor volume, instead of the entire combustor, were filled with a catalytic insert.

**Temperature Response**

With the combustion chamber only partially-filled with catalyst, JP8 combustion was stabilized in the device at a mass flow rate as high as 0.2 g/sec, at which point the combustion blew out. Figure 13 shows the temperature response from the experiment. Unlike the filled catalytic combustor results, there is
a fairly large discrepancy between the exit gas temperature and the structural temperature, suggesting that this configuration can provide better thermal isolation of the combustion chamber, and thus higher thermal efficiencies. The efficiency breakdown will be discussed in the next section. The maximum exit gas temperature obtained was 723 K ($\dot{m} = 0.07$ g/sec), and due to the extended mass flow rate, the maximum power density was 54 MW/m$^3$ ($\dot{m} = 0.2$ g/sec), the best achieved in the device. However, the operational requirement of 1300 K was still not met. It appears that the combustion process did not transition to gas-phase combustion even though the fuel-air mixture was at a temperature higher than the gas-phase autoignition temperature (typically 520 K at 1 atm). This inhibition of gas-phase ignition has been reported by other researchers, including Dupont [27] and Griffiths [28]. Using methane, Dupont et al. found that heterogeneous catalytic combustion prevailed up to 1400 K. The inhibition of gas-phase ignition was attributed to the depletion of fuel species in the gas. Griffiths et al. explained the inhibition to be also associated with water vapor desorbed from the catalytic surfaces. The large amount of water vapor prevents favorable conditions for gas-phase ignition by catalyzing reaction paths that consume the free radicals H and CH$_3$, and form more stable species such as HO$_2$ and C$_2$H$_6$.

Efficiency Breakdown

Figure 14 shows the overall, chemical, and thermal efficiencies as functions of the mass flow rate for an equivalence ratio of 0.9. The large difference between the exit gas temperature and the structural temperature, as noted in the previous section, results in enhanced thermal efficiency. Since conductive heat transfer from the catalytic insert to the structure is reduced due to smaller contact area, heat can be retained in the fluid better. However, due to inhibition of gas-phase ignition, the non-catalytic portion of the combustion chamber cannot be actively used, which results in the reduction of the effective volume of the combustor. Therefore, the performance of the combustor is chemically-limited at high mass flow rates, i.e., the chemical efficiency declines with the mass flow rate, and eventually the reactions are blown out. This will be discussed in more detail using non-dimensional parameters in the next section.

Device Comparison

As discussed in the previous section, the partially-filled catalytic combustor has relatively higher exit gas temperatures and lower structural temperatures. Figure 15 depicts these trends. This result is attributed to different components of the efficiencies that are presented in Figure 16. As seen in Figure 16, the
filled catalytic device has lower overall efficiencies even though it has higher chemical efficiencies. This is due to much lower thermal efficiencies. In other words, the filled catalytic device has more catalyst in it, so it can combust more fuel. However, due to the presence of a large contact area between the catalyst and the sapphire structure, it loses more heat, and the overall efficiency is reduced.

Figure 17 presents these results from an alternate perspective. It shows the chemical efficiencies of the filled catalytic device and the partially-filled device for the equivalence ratio of 0.9. Besides the two solid curves for each device, a new curve was generated, and is shown in a broken line. This additional curve plots the chemical efficiency of the partially-filled device versus Peclet number, but the Peclet number was recalculated based on a volume that is occupied by the catalyst (1 cm$^3$), not the entire combustion chamber (1.4 cm$^3$). Then, the new curve fits quite well with the filled device. This indicates that the reduction of the catalyst caused the effective combustor volume to decrease.

The two devices can also be analyzed on the non-dimensional operating map. In Figure 18, two data points are presented: one representing the filled catalytic combustor and the other representing the partially-filled one. They are both for a mass flow rate of 0.08 g/sec and an equivalence ratio of 0.9. With these same operating conditions, the Peclet number (based on the actual catalyst volume) for the partially-filled device is smaller due to a shorter residence time-scale. And because there is less catalyst, the chemical efficiency is also reduced for the partially-filled device. However, the increased thermal efficiency overcomes the reduction in the chemical efficiency, and the overall efficiency becomes higher compared with the filled device.

**CONCLUSION**

A liquid-fueled micro-combustor was designed, fabricated, and experimentally characterized as a part of the MIT micro-engine research program. It was demonstrated that a liquid-fueled combustion system may be feasible for microscale engines although further development is required. With the combustion chamber entirely filled with a catalyst, JP8 combustion was sustained stably at mass flow rates up to 0.1 g/sec, at which point the structure failed due to thermal stresses. An exit gas temperature of 780 K and an overall combustor efficiency of 19% were achieved.

The combustor was also tested with just two thirds of the volume filled with a catalyst, expecting that this configuration
could provide extended mass flow rate capabilities like a catalytic combustor as well as high exit gas temperatures like a gas-phase combustor. However, gas-phase ignition could not be achieved in the partially-filled combustion chamber. We believe that the catalytic combustion likely inhibited gas-phase ignition. Instead, the performance resembled a catalytic combustor with two thirds of the original volume. Therefore, the performance was limited mainly by insufficient flow residence time at high mass flow rates. This configuration resulted in a maximum mass flow rate of 0.2 g/sec and a corresponding exit gas temperature of 640 K, leading to the best power density realized in the device, 54 MW/m$^3$.

Figure 19 shows the non-dimensional operating map for the data obtained from both the filled and partially-filled devices. It shows that the filled device has relatively higher chemical efficiencies due to larger catalytic surfaces, whereas the partially-filled device provides better thermal efficiencies. This implies that it is possible to achieve the operational requirements without increasing the combustor volume if the filled device has better thermal isolation. One of the ways to do this would be including a recirculation jacket like the propane micro-combustor of Spadaccini [15]. The recirculation jacket is a wrap-around flow path thermally-isolating the combustion chamber. Minimizing the contact area between the catalyst and the combustor structure by suspending the catalytic insert on a seat is a possible option as well. Finally, the ability to micromachine materials with higher temperature capabilities would be a significant benefit.

The current work focused on maximizing power density rather than achieving high efficiency. Catalytic combustion was a good option for this objective. To make the micro-engine more practical, however, a high-efficiency liquid-fueled micro-combustor must ultimately be pursued. Since the required exit gas temperature is rather low compared to the adiabatic flame temperature of stoichiometric JP8 combustion, the high-efficiency combustor should be operated at low overall equivalence ratios. To efficiently burn JP8 fuel at low equivalence ratios, the combustor must be either a dual-zone combustor or a multistage catalytic-homogeneous hybrid combustor. Both of these options would require larger combustor volume. Comparing these two combustor designs and optimizing between high power density and efficiency will require further research efforts.

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