

# Preliminary development of a hydrocarbon-fueled catalytic micro-combustor<sup>☆</sup>

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## Abstract

This paper reports development of a hydrocarbon-fueled micro-combustion system for a micro-scale gas turbine engine for power generation and micro-propulsion applications. A three-wafer catalytic combustor was fabricated and tested. Efficiencies in excess of 40% were achieved for ethylene–air and propane–air combustion. A fabrication process for a six-wafer catalytic combustor was developed and this device was successfully constructed.

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## 1. Introduction

MIT's Gas Turbine Laboratory and Microsystems Technology Laboratories have been developing a micro-gas turbine engine capable of producing 10–50 W of power in a volume less than 1 cm<sup>3</sup> while consuming 7 g of fuel per hour [1]. Applications include power generation, propulsion systems for small air vehicles, and a variety of blowers, compressors, and heat pumps. Power densities for these devices are estimated to be an order of magnitude greater than those for current battery technology.

As part of this program, several micro-fabricated, silicon, gas phase combustion systems have been designed, fabricated, packaged, and tested [2–4]. The development of the micro-engine combustion system has been pursued through a combined program of experiments, numerical simulations, and analysis. With hydrogen fuel, these systems reached gas temperatures exceeding 1800 K, combustor efficiencies greater than 90%, and power densities above 1100 MW/m<sup>3</sup>, well within the requirements of a micro-gas turbine thermodynamic cycle.

However, for hydrocarbon fuels such as propane, the power densities drop to approximately one-tenth of that for hydrogen. These fuels are more challenging to micro-combustor development due to 5–50-fold increase in reaction time when compared to hydrogen. However, they are required for practical devices due to their increased energy density, availability, and ease of storage. This has motivated the current study of catalytic combustors as a means of developing a high efficiency, high power density, hydrocarbon-fueled micro-combustor.

## 2. Challenges and concept

The functional requirements of a micro-combustor are similar to those of a conventional gas turbine combustor. These include the efficient conversion of chemical energy to fluid thermal and kinetic energy with low total pressure loss, reliable ignition, and wide flammability limits. However, the obstacles to satisfying these requirements are different for a micro-scale device. As first described by Waitz [5] a micro-scale combustor is more highly constrained by inadequate residence time for complete combustion and high rates of heat transfer from the combustor. Micro-combustor development also faces unique challenges due to material and thermodynamic cycle constraints.

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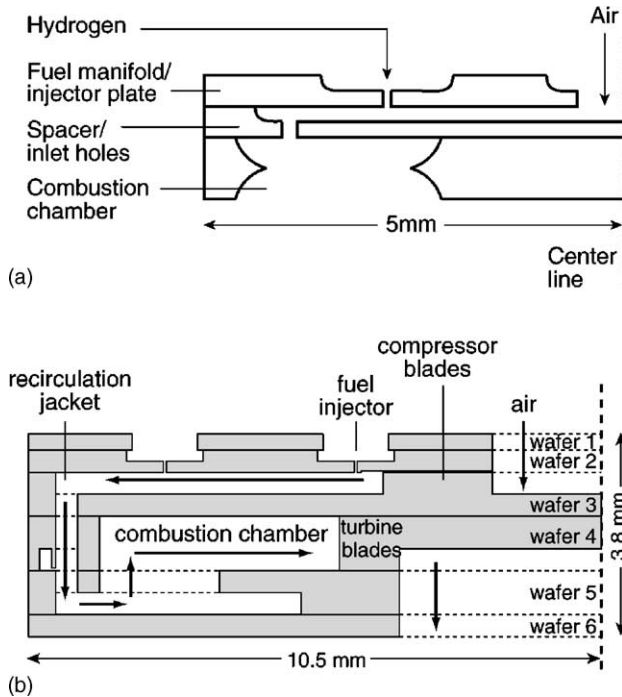


Fig. 1. Schematic of combustors used for catalytic tests: (a) three-wafer combustor, (b) six-wafer combustor.

Complete and efficient combustion is limited by time scale constraints in a micro-scale device. Bulk residence time in the combustion chamber must be greater than the chemical reaction time of the fuel–air mixture for combustion to be completed. To ensure that this occurs, a designer of a micro-combustor can either increase the flow residence time or decrease the chemical reaction time. The characteristic combustor residence time is given by the bulk flow through the combustor volume

$$\tau_{\text{residence}} \approx \frac{\text{volume}}{\text{volumetric flow rate}} = \frac{VP}{\dot{m}RT} \quad (1)$$

where  $V$  is the volume,  $P$  the pressure,  $\dot{m}$  the mass flow,  $T$  the temperature, and  $R$  the gas constant. Residence time can be

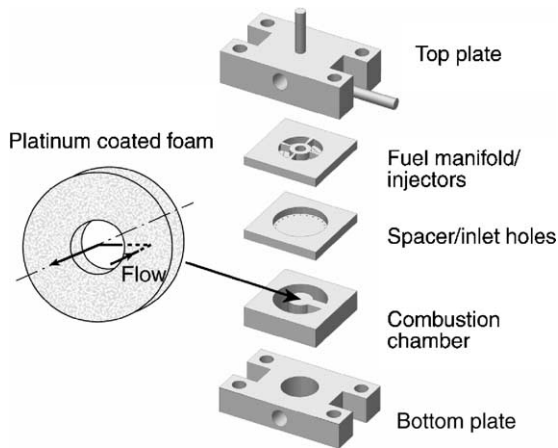
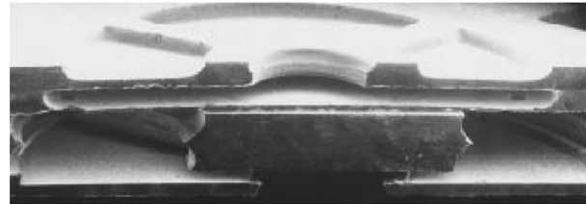


Fig. 2. Exploded view of three-wafer combustor, catalytic insert, and invar plates for packaging.

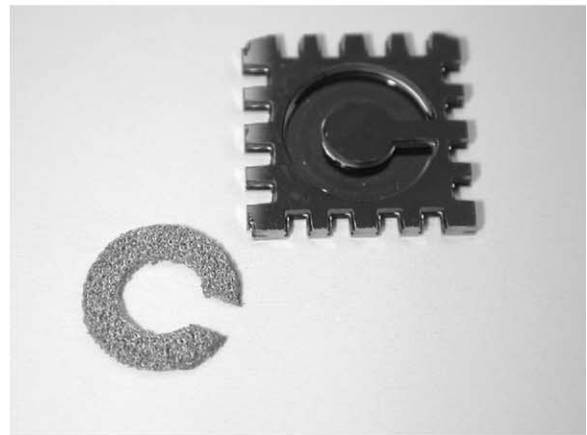
increased by increasing the size of the chamber, reducing the mass flow rate, or increasing the operating pressure. A chemical reaction time can be approximated by an Arrhenius type expression

$$\tau_{\text{reaction}} \approx \frac{[\text{fuel}]_0}{A[\text{fuel}]^a[\text{O}_2]^b e^{-E_a/RT_0}} \quad (2)$$

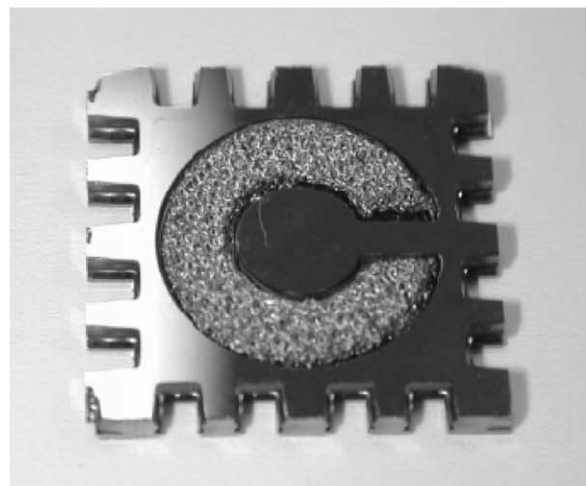
$E_a$  is the activation energy while  $A$ ,  $a$ , and  $b$  are empirically determined. Reaction time is primarily a function of fuel properties and the mixture temperature and pressure.



(a)



(b)



(c)

Fig. 3. Three-wafer combustor and catalytic insert with an inner and outer diameter of 5 and 10 mm, respectively. (a) SEM cross-section of three-wafer micro-combustor, (b) catalyst support prior to inserting into combustion chamber, (c) catalyst support inside combustion chamber.

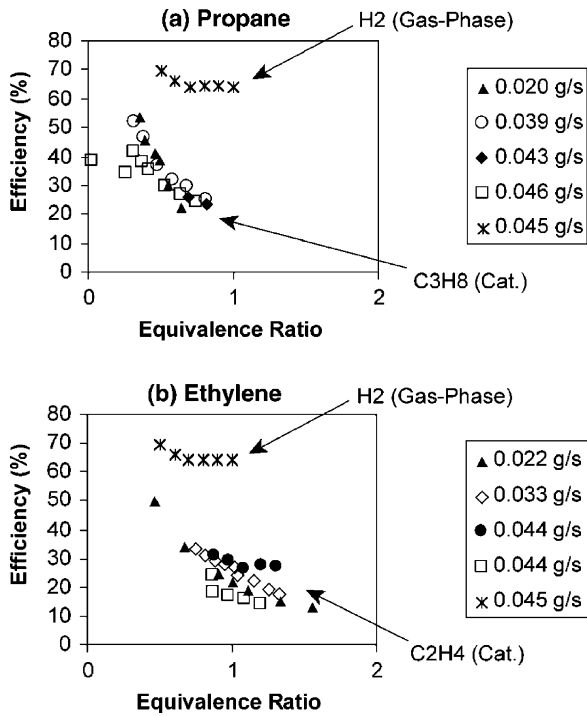


Fig. 4. Three-wafer catalytic combustor efficiency. (a) Propane, (b) ethylene.

Since the high power density requirements mandate high mass flow rates through small chamber volumes, the mass flow rate per unit volume cannot be reduced without compromising device power density. Hence, there is a basic tradeoff between power density and flow residence time

$$\text{Power density} \propto \frac{\dot{m}_f \text{LHV}}{V} \propto \frac{\dot{m}}{V} \frac{\rho}{\tau_{\text{reaction}}} \quad (3)$$



Fig. 5. Catalytic pieces being inserted into six-wafer combustor during fabrication.

where LHV is the lower heating value of the fuel and  $\rho$  the fluid density. For a given operating pressure (and thus density), and assuming residence time is equal to reaction time, reducing the chemical reaction time and thus required residence time is the only means of ensuring complete combustion without compromising the high power density of the device. As we move toward the development of a hydrocarbon-fueled combustor, this becomes a significant concern. The rate of a hydrocarbon–air reaction is typically 5–50 times slower than that of a hydrogen–air reaction. For constant mass flow rate and volume, this leads to a corresponding decrease in power density.

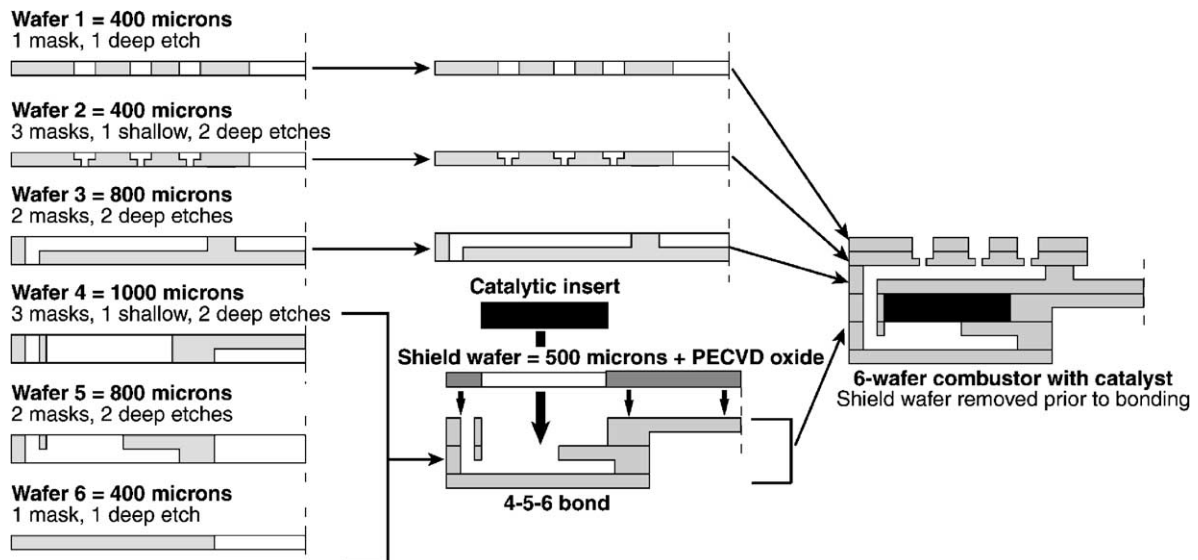


Fig. 6. Fabrication, assembly, and bonding process for six-wafer catalytic combustor.

For practical devices, hydrocarbon fuels such as propane and ethylene will be required. Spadaccini et al. [6] have shown that, with these fuels, power densities decreased by approximately a factor of 10. This was primarily due to the increase in reaction time.

To utilize these hydrocarbon fuels efficiently without increasing combustor volume or temperature, chemical conversion rates must be increased significantly. Catalysts act to decrease reaction times by lowering the activation energy associated with the reaction, thereby increasing reaction rate. To achieve this, we have been pursuing the development of catalytic combustion systems where platinum is plated onto a nickel foam substrate. To ensure a high degree of chemical conversion, the catalyst and its substrate must fill most of the combustor volume. However, to satisfy the gas turbine thermodynamic cycle, the combustor pressure loss should not exceed 5%.

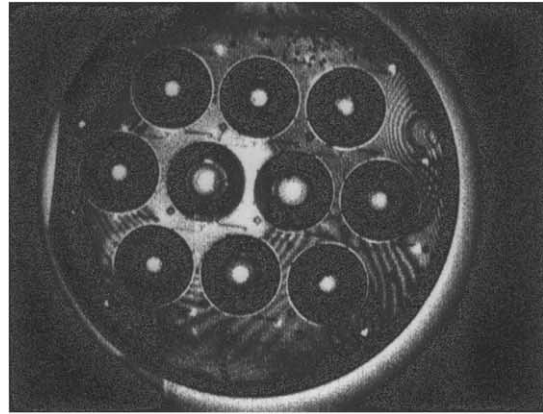
### 3. Fabrication and test results

Initial feasibility tests were carried out on the three-wafer level combustor shown in Fig. 1a. Nickel foam was selected as a convenient catalyst support material and was conventionally machined to fit in the combustion chamber. An electron-beam deposition process was used to coat the substrate with platinum, which serves as the active catalytic surface. The combustor's packaging scheme consists of placing the silicon between two conventionally machined invar plates. As a result, inserting catalyst material into the combustion chamber can be done outside of the clean room environment. Fig. 2 shows an exploded view of the three-wafer combustor, the surrounding invar plates, and the catalytic insert. Fig. 3 shows a photograph of the nickel foam support as it is fit into a three-wafer device.

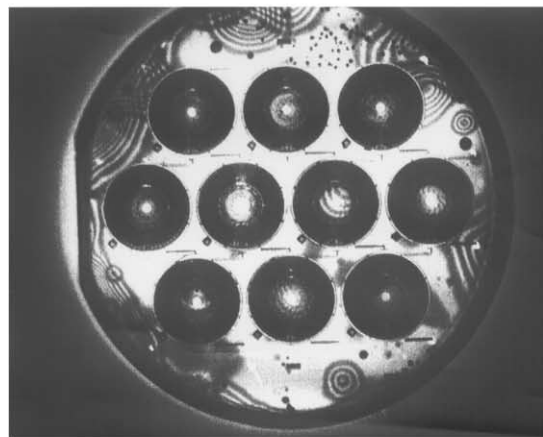
Previous gas-phase experiments with the three-wafer combustor showed that hydrocarbon combustion could not be sustained in the device due to insufficient residence time and significant heat loss from the structure. With the catalytic foam piece, combustion of both propane and ethylene was achieved. Fig. 4 shows the overall combustor efficiencies achieved for both fuels in this device over a range of mixture ratios. Efficiencies in excess of 40% were attained in both cases. This experiment represents the first stable hydrocarbon combustion in this device. In addition, it is important to note that hydrocarbon combustion was stabilized at the same mass flow rate as gas-phase hydrogen–air combustion. This resulted in power densities approximately half of that obtained with hydrogen rather than the 5–50-fold decrease expected for hydrocarbon–air reactions, indicating that there is significant catalysis occurring.

A six-wafer level combustion system compatible with current micro-engine designs is shown in Fig. 1b. This system includes improved thermal management to retain heat in the device and a larger combustion chamber. For this device,

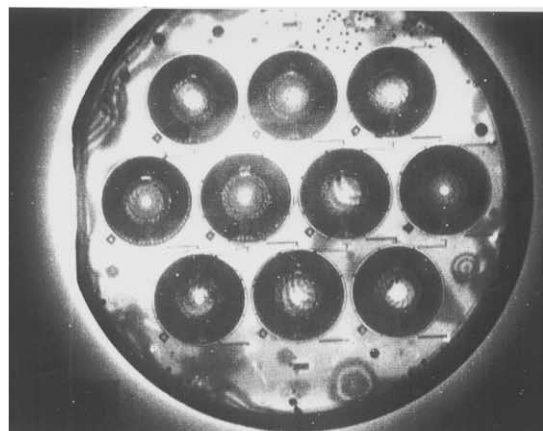
the platinum-coated nickel foam inserts must be placed into the existing design during the fabrication process in the clean room environment. This poses several challenges due to cleanliness of the inserts, particulate contamination of bonding surfaces, and damage to bonding surfaces via mishandling.



(a)



(b)



(c)

Fig. 7. Infra red images of the six-wafer stack with catalytic inserts: (a) after initial contact, (b) after cold press and prior to thermal-press, (c) after final anneal.

Platinum was deposited onto the nickel foam substrate by dipping the foam into a solution containing platinum acid. This was done to obtain better coverage and penetration of platinum onto the catalyst support. The inserts were then ultrasonically cleaned to remove large particles and debris. To protect the bonding surfaces from the inserts, a “shield wafer” was fabricated. This wafer was etched through with the shape of the inserts and silicon dioxide was deposited on its surface via plasma-enhanced chemical vapor deposition (PECVD). The fourth, fifth, and sixth wafer levels were fusion bonded prior to inserting the catalyst. The shield wafer was then aligned and contacted with these three levels. While in contact, the catalytic pieces were placed into the bonded 4–5–6 wafer stack through the shield wafer. Finally, the protective shield wafer was carefully removed. The PECVD oxide prevented the shield wafer from adhering to the 4–5–6 stack. Insertion of the catalytic pieces can be seen in Fig. 5.

Wafer levels one, two, and three were fusion-bonded forming another three-wafer stack. The final bonding of the two three-wafer stacks was unsuccessful due to the thick, stiff nature of the wafers. Small amount of bow in either bonding surface also was problematic. As a result, a new bonding sequence was developed. Rather than bonding two thick three-wafer stacks together, the level three-wafer was individually contacted to the 4–5–6 stack with the catalytic piece. This was followed by individually contacting and bonding the level two and one wafers. As a result, wafer bonding on the final build produced good bond quality over most of the wafer. This assembly/bonding process is shown in Fig. 6.

Fig. 7a shows an infra red image of the six-wafer stack immediately after contact. A small, well-contacted region can be seen in the center of the wafers. After several hours of room temperature pressing at 4 atm and 500 °C thermal pressing, the bond front propagated radially outward, resulting in 70% device yield. An infra red image after the room temperature press and prior to the thermal press is shown in Fig. 7b, while the final bonded stack is shown in Fig. 7c.

#### 4. Concluding remarks

Three-wafer combustors were fitted with platinum-coated nickel foam inserts and used as an initial catalytic combustor test-bed. Both ethylene–air and propane–air reactions were sustained at overall efficiencies in excess of 40% when previously it was not possible to burn hydrocarbon fuels in this device. This resulted in power densities approximately half of that obtained with hydrogen rather than the 5–50-fold decrease expected for hydrocarbon–air reactions.

A method for fabricating a six-wafer combustor fitted with platinum-coated nickel foam has been developed. Fabrication of these devices was completed. Pressure/mass flow characteristics and chemical and overall efficiency will be measured, and the operating space of the catalytic device will be mapped.

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#### Biographies

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