Development of Hydrocarbon-Fueled Silicon Combustors for Micro Gas Turbine Engines

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Recent advances in the field of silicon micro-fabrication techniques and silicon-based Microelectromechanical Systems (MEMS) have led to the possibility of a new generation of micro heat engines for power generation and micro air-vehicle propulsion applications. The design for a silicon-based, micro gas turbine generator capable of producing 10-50 Watts of power in a volume less than 1 cm^3 while consuming 7 grams of fuel per hour has been developed. This represents a ten-fold increase in power density over the best available batteries.

An engine of this type will require a high temperature combustion system to convert chemical energy into kinetic and thermal energy. To accomplish this, a unique set of challenges must be overcome:

1. Shorter residence time for mixing and combustion.
2. Heat loss due to high surface area-to-volume ratio.
3. Material and structural constraints of silicon.
4. Rudimentary 3-D geometry due to limits of micro-fabrication techniques.
5. Micro-engine thermodynamic cycle constraints.

All of the above impact the design and development of a suitable micro-combustion system.

The baseline device is comprised of all the non-rotating functional components of the micro gas turbine engine. The device measures 2.1 x 2.1 x 0.38 cm, and is aligned-fusion bonded from 6 silicon wafers. Figures 35 and 36 show a schematic and a SEM of this micro-combustion system. Fabricated largely through Deep Reactive Ion Etching (DRIE), the structure required anisotropic dry etching through a total thickness of 3,800 mm. Complete with a set of fuel plenums, fuel injector holes, pressure ports, and compressor and turbine static airfoils, the design of the six-wafer structure required a multi-disciplinary approach that accounted for all the chemical, structural, and fluidic interactions as well as engine system considerations.

For the propulsion and power generation applications of interest, the principal figure of merit is power density. The baseline device achieved power densities in excess of 1100 MW/m^3 with hydrogen-air combustion. This corresponds to exit gas temperatures over 1700 K and combustor efficiencies greater than 95%. These power densities are three to four times larger than those produced by a conventional gas turbine combustor . Hydrocarbon fuels, such as ethylene and propane, have been burned in this device at lower power densities, 500 MW/m^3 and 150 MW/m^3 respectively.

In an attempt to achieve higher power densities and efficiencies using hydrocarbon fuels, a staged combustor has been developed. This dual-zone micro-combustor is a simple modification to the six-wafer geometry, but represents a significant change in combustion strategy. A series of holes through the inner wall have been created connecting the upper cooling jacket to the combustion chamber, thus some of the inlet air will be diverted from passing into the combustor inlet. Air that bypasses the combustor inlet is then introduced in the middle of the combustion chamber to reduce the temperature of the hot combustion products to the desired turbine inlet temperature of 1600 K. This diversion increases the local equivalence ratio of the fuel-air mixture entering the combustion chamber to near stoichiometric levels, increasing the temperature and thus, the kinetic rate. With this device, a 100% increase in power density was achieved for the same operating conditions as the baseline device. Data from both the dual-zone and the baseline combustors has been used to develop a non-dimensional operating space, which can be used as a design tool for gas phase combustors.

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A combustor which utilizes heterogeneous catalysis to improve hydrocarbon-air reaction rates, has also been identified as a means of increasing power density. Initial tests with platinum coated nickel foam implanted into previously fabricated three-wafer combustors, were successful. Where hydrocarbon-air combustion could not previously be stabilized, ethylene and propane were both burned at approximately the power density of hydrogen-air combustion in the same device. As a result, a six-wafer device with platinum implanted inside the combustion chamber has been fabricated and is currently being tested.

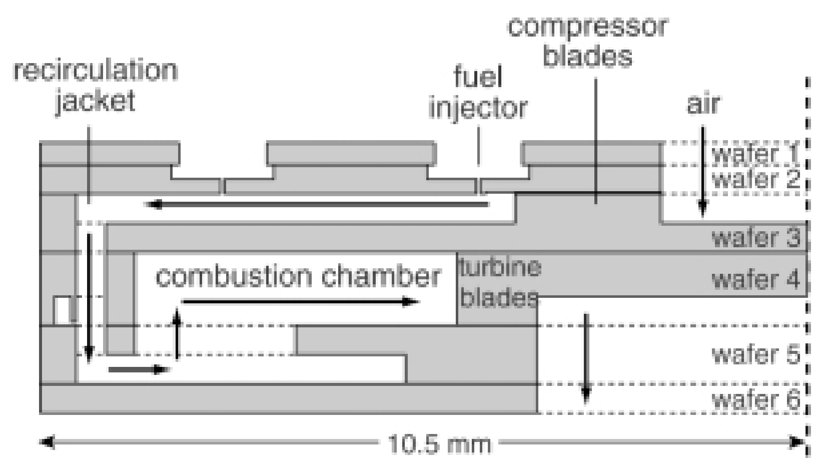

Fig. 35: Schematic of six-wafer combustion system.

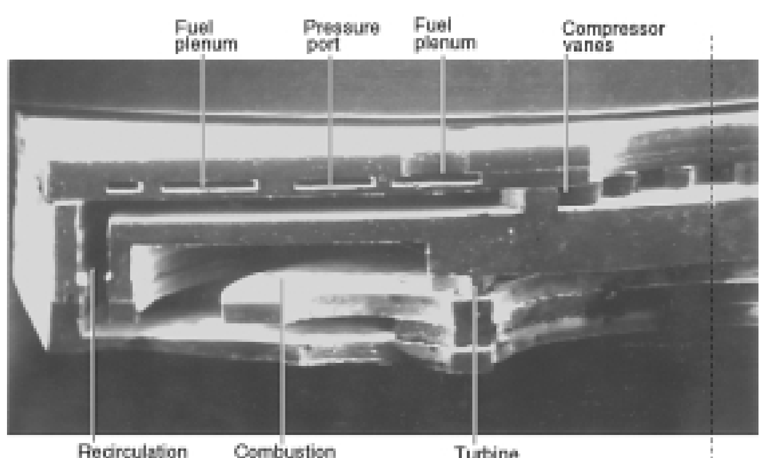

Fig. 36: SEM cross-section of six-wafer combustion system.