MESOSCALE COMBUSTOR/EVAPORATOR DEVELOPMENT

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ABSTRACT

Battelle has developed a mesoscale combustor/evaporator that provides a lightweight and compact source of heating, cooling, or energy generation for both man-portable and stationary applications. The device uses microscale flow channels that increase the available surface area for heat transfer and reduce the fluid boundary layer. These characteristics in turn result in heat fluxes for hydrocarbon/air combustion in excess of 25 W/cm^2 and thermal efficiencies of 80 to 90%. Furthermore, high heat transfer rates allow for short channels and reduced pressure drops.

Recent development efforts have focused on obtaining low emissions and improving the combustor/evaporator fabrication process. By using spatially varying stoichiometry inside the combustor, catalyst coated microchannels, and increased coolant temperature, the combustor's CO and NO_x emissions were reduced to below California standards for hot water heaters and boilers. The fabrication process photochemically machines thin metal laminates and then uses diffusion bonding to form a monolithic component. This approach is capable of high fin aspect ratios and can be scaled up for mass production.

INTRODUCTION

Small-scale combustion of liquid fuels is becoming increasingly important for defense applications, particularly for man-portable energy systems. In the future, the individual soldier will require lightweight and compact sources of electric power and microclimate control. Man-portable applications for a compact combustor include

- man-portable power sources, such as compact Stirling cycle heat engines, liquid metal heat engines and direct energy conversion devices
- man-portable heating for cold climates
- man-portable cooling using the heat-actuated absorption cycle heat pump.

In addition to defense applications, there are important commercial applications for a small combustion system. Applications include distributed space conditioning of buildings, hot water heating, and distributed power generation (Wegeng et al. 1995; Ameel et al. 1996a,b; Wegeng et al. 1996a,b).

The energy system requires thermal energy in all of these cases. Fortunately, hydrocarbon fuels are a convenient and high-density energy source. When compared to advanced batteries, hydrocarbon fuels have an energy density (W/kg or W/m^3) a factor of 100 higher (Menjak et al. 1998).

Clearly, the key to using hydrocarbon fuels as a heat source is the availability of a lightweight and compact combustion system that both burns the hydrocarbon fuel and efficiently transfers the released thermal energy to a heat-transfer fluid. Recent developments in microchannel evaporative heat transfer offer the potential for making a very small integrated combustor/evaporator.

Research conducted on microchannel evaporation has demonstrated that evaporative heat transfer coefficients of between 10,000 and 30,000 W/(cm^2-K) can be obtained in microchannel evaporators with heat fluxes exceeding 100 W/cm^2 (Ravigurarajan et al. 1996). For this work, the microchannels reduce the flow channels to micron dimensions, which increases the surface area available for heat transfer and may reduce the thickness of the fluid boundary layer. Smaller boundary layers in turn would reduce heat-transfer resistance and increase heat removal fluxes over conventional heat exchangers (Gui and Scaringe 1995).

Battelle has recently developed a microchannel combustor/evaporator system that takes advantage of the energy density of these fuels and the heat-exchange efficiency of microchannels to produce a "palm-sized" combustor, capable of generating as much as a kilowatt of thermal power.

This article describes these mesoscale combustor development efforts. Three areas have been investigated and will be discussed: (1) the combustor thermal properties, including heat flux, thermal efficiency, and thermal response, (2) methods of improving the

emissions, and (3) fabrication approaches to provide a low-cost, high-volume process for manufacture.

EXPERIMENTAL DEVICE

A conceptual drawing of the combustor/evaporator is presented in Figure 1.

Air and clean fuel, such as natural gas, are introduced into the bottom of the combustor/evaporator. A sintered metal plate acts as the flameholder, and a ceramic insulated wire provides the spark for ignition. The gases burn in the combustion chamber 3 to 5 cm^3 in volume. The products of combustion turn 90° and enter the array of microchannels where they are cooled. They are then collected out the bottom of the combustor and analyzed. On the opposite side of the combustion chamber and combustor microchannels are the evaporator microchannels, separated by 0.16 cm of metal. Thermal energy is conducted from the combustor to the evaporator, where the thermal energy is used to heat or vaporize the working fluid. Water has been used for the working fluid in the demonstration, but ultimately, the evaporator will be used to heat a range of fluids, including refrigerants, for a heat-actuated man-portable cooling unit and liquid metal for a compact power generation unit.

The microchannels in the combustor and evaporator have dimensions from 50 to 200 microns across and 0.5 to 3 mm tall. Since the units contain hundreds of microchannels, each approximately 1 cm long, for a fixed total mass flow rate, the pressure drops are generally small (<1000 Pa). The overall dimensions of the unit studied for most of this work was 5 cm by 5 cm by 1.5 cm. The devices were constructed from aluminum, copper, and stainless steel.

During testing, the temperatures of the inlets and outlets of both the liquid and gaseous streams were measured as were the water and gas flow rates. Combustion products were cooled, the water was condensed, and the emissions were analyzed using a gas chromatograph and a chemiluminescent NO_x analyzer.

THERMAL PROPERTY STUDIES

The initial tests were performed to compare the combustor/evaporator thermal efficiency as a function of heat flux to the working fluid. The heat flux is defined as the quantity of heat imparted to the working fluid per unit surface area of the combustor profile. The combustion efficiency is defined as the ratio of the heat transferred to the working fluid relative to the heating value of the fuel. In this case, the heating value of the fuel is based on the combustion products containing only liquid water (higher heating value, HHV). By increasing the flow of fuel to the combustor, higher heat fluxes could be achieved and the thermal efficiency can be measured for these increased fluxes.

For these studies, methane and air were used in stoichiometric proportions as a premixed flame. The combustor had a surface area of 22 cm^2, and the working fluid was water entering the evaporator at ambient temperature and an 80 g/min flow rate. Results are shown in Figure 2. Based on our experimental results, air/methane combustors can attain heat fluxes of nearly 25 W/cm^2 while maintaining heat transfer efficiencies of >80%. Because of highly effective heat transfer from the combustion products in the microchannel heat exchanger, the temperatures of the gases exiting the combustor were very close to the temperature of the exiting working fluid.

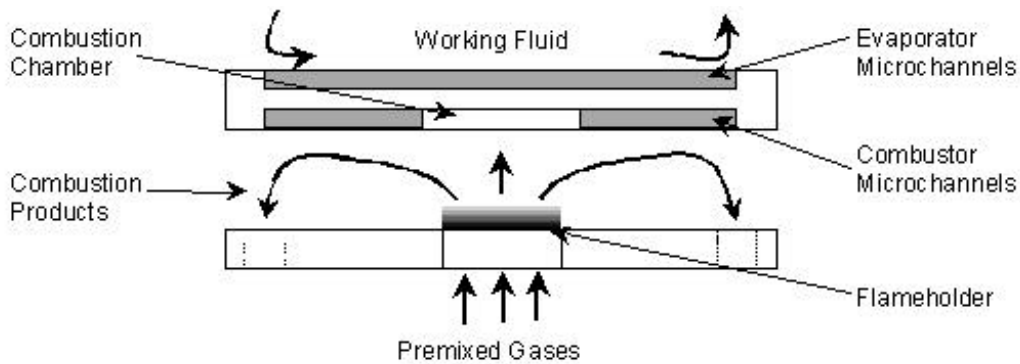

Figure 1. Exploded View of the Mesoscale Combustor/Evaporator

Figure 3 illustrates the distribution of the energy for one of the cases shown above. As can be seen, the majority of the heat energy goes into the working fluid. Significant but considerably smaller fractions of the heat loss are associated with incomplete combustion and uncondensed water. The incomplete combustion products include unburned methane, CO, and H_2 gases. The combustion products also contain a mixture of steam and liquid water. Because the results are based on the HHV, the maximum thermal efficiency when steam is the product rather than water is 90.1%. In the case of Figure 3, the maximum thermal efficiency using HHV was 92.5%. The heat losses associated with the temperature of the exhaust gases were not a significant fraction of the overall thermal inefficiency. These losses and the convection of heat from the metal surfaces were relatively small and remained so even at high methane flow rates.

The response of the coolant-water exit temperature to an increase in methane flow rate is presented in Figure 4. In this case, the methane flow rate data have been re-basedlined to unity, and the temperature rise data have been offset to a zero initial state. In this form, the data can be fit to an exponential curve, which is the expected response to a step function increase in heat rate:

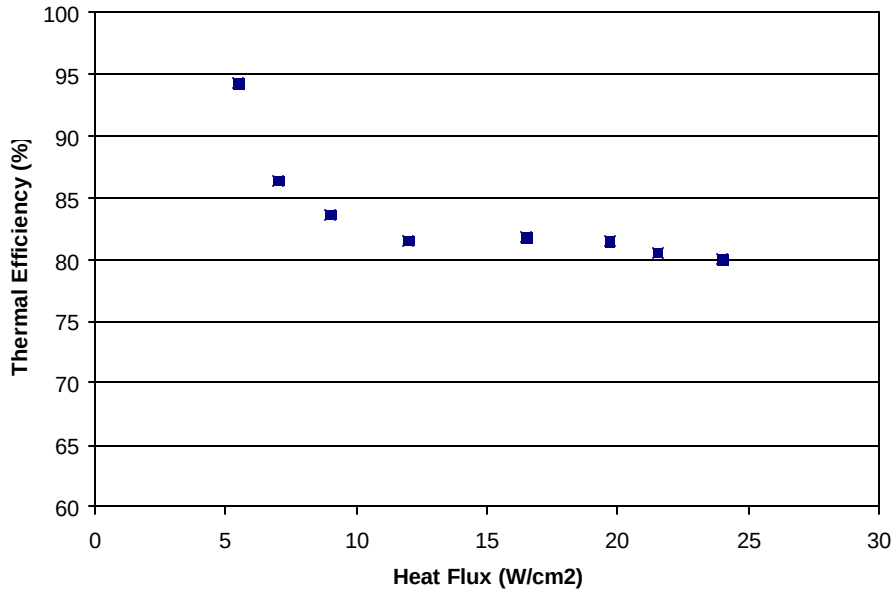

Figure 2. Thermal Efficiency as a Function of Heat Flux for the Microchannel Combustor

$$\frac{\Delta T}{\Delta T_{t=\infty}} = 1 - e^{-t/\tau}$$

The response times for an aluminum combustor that was tested range from 0.4 to 0.65 minutes for the methane increases studied. The response times for a similarly designed copper combustor appear to be slightly longer, ranging from 0.6 to 0.7 minutes. For both combustors, the temperature reaches 90 to 95% of the new equilibrium value within the first 2 or 3 minutes of the step change. Additional discussion of the thermal properties of the microchannel combustor is presented in Drost et al. (1997).

EMISSIONS IMPROVEMENTS

In addition to small size and high efficiency, a commercially successful device must meet current and projected air pollution emissions requirements. Reducing emissions, particularly unburned hydrocarbons, can improve efficiency and further reduce the weight of the system for military applications. The difficulty is that the thermal NO_x formation reaction is promoted by high temperatures and long residence times. Similarly, CO oxidation to CO_2 is also promoted by high temperature and long residence times. Thus, temperature and residence time must be carefully controlled to minimize NO_x formation and maximize CO oxidation. Preliminary measurements of NO_x emissions for the current air/methane microchannel combustor range from 3 to 26 ppm. The target for NO_x is 25 ppm or less was met in most cases. However, the original design of the air/methane combustor produces significant amounts of partially burned hydrocarbons with the exhaust gases containing up to 0.5% CO and H_2. The low concentrations of NO_x and high concentrations of CO indicate that the combustion gases are quenched very quickly after ignition. The challenge was to reduce the level of unburned hydrocarbons and CO to an acceptable level, while maintaining the high heat flux, efficiency and low NO_x emissions associated with the current design.

Three approaches were attempted to reduce the CO emissions. First, insulation was applied to the combustion zone to inhibit heat transfer and raise combustion temperature. Second, catalyst was placed inside the combustor to assist in lower temperature CO oxidation to CO_2. Third, the excess air in the fuel/air mixture was increased, which in turn increases the amount of oxygen available to react with CO and unburned hydrocarbons.

Based on combustion modeling, within approximately 3 milliseconds from initiation of the initial combustion process, the combustion gases are cooled as they impinge on the upper surface of the combustion chamber. This quenching of the combustion radicals is believed to be a significant cause of the increase in CO emissions. To allow the temperature to remain high longer inside the combustion chamber, the aluminum surfaces of the combustor could be coated

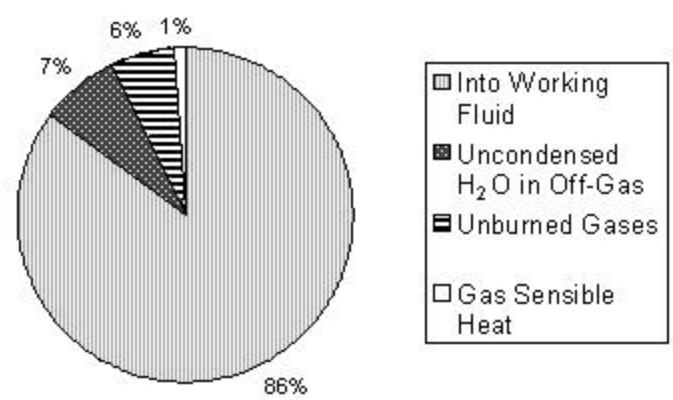

Figure 3. Distribution of Heat Energy from the Combustor at Stoichiometric Conditions

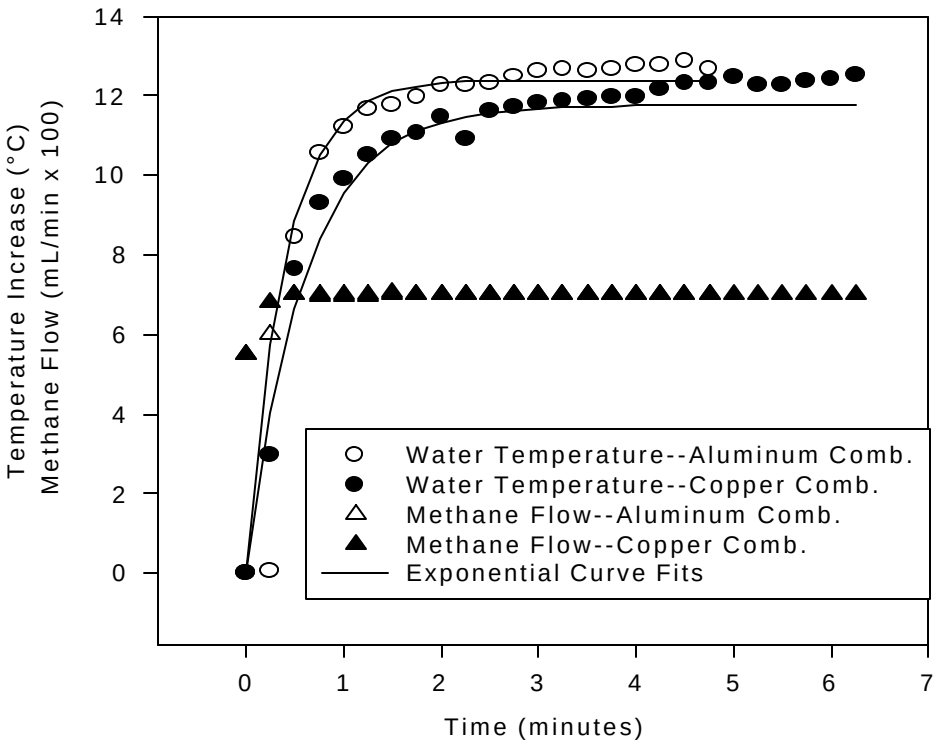

Figure 4. Thermal Response of the Microchannel Combustors to a Step Change in Methane Flow

with ceramic insulation. While this approach does reduce the area of heat transfer to the cooling water, based on the modeling of the microchannels done previously, there is sufficient heat transfer occurring down the microchannels that heat transfer is not required in the combustor (Drost et al. 1997).

During an initial screening study, a thin sheet of alumina ceramic was inserted on the upper surface of the combustion chamber. The CO emissions for fuel-lean conditions decreased from 3200 to 1000 ppm. The thermal efficiency actually increased from 83 to 85%. NO_x emissions remained below 25 ppm.

Catalysts can be used to convert CO to CO_2 and to combust residual amounts of hydrocarbons in the products of combustion. In an initial screening study, platinum catalyst was applied on an alumina substrate on the upper surface of the combustor. This approach also showed some promise as it reduced CO emissions at stoichiometric conditions from 12,100 to 4500 ppm CO. The surface area can be increased, and, in turn, the CO emissions reduced if, instead, the catalyst is coated on the surface of the microchannels. Typically, catalysts are more active at higher temperature. Because of the high heat fluxes in the microchannels, there is concern that the temperatures could drop below the ignition point before catalytic combustion could reduce the CO and H_2 concentrations to acceptable levels. For subsequent tests, both the microchannels and the upper surface of the combustor were coated with Pt catalyst.

Increasing the amount of air in the fuel/air mixture increases the amount of oxygen available to react with CO and unburned hydrocarbons. However, increased excess air also increases the velocity of the fuel and air mixture in the combustion zone and tends to blow out the flame, stopping combustion (equivalence ratios <0.8).

To solve this problem, a modified Hencken burner was developed that allows spatially variable stoichiometry across the surface of the combustor. This modified Hencken burner reduces emissions and improves flame stability by providing regions with fuel-lean mixtures while preventing flame blow-out by having other regions at a near-stoichiometric mixture of fuel and air.

To evaluate this approach, a test piece was developed that had a flame zone of the same dimensions as previous combustors, but allowed for individual control of stoichiometry in five regions on the burner. The burner surface was divided lengthwise, with each zone being 0.32 cm wide. The mixture of methane and gas could be independently controlled in each zone of the combustor. In conjunction with these tests, the microchannels were coated with catalyst to further reduce the CO emissions. Tests were then performed with the Hencken burner test article with catalyst in the microchannels. The results of these tests are presented in Figure 5. Using a fuel-lean mixture (equivalence ratio = 0.9) and catalyst in the microchannels reduced the CO emissions from slightly less than 4500 ppm to a value less than 1500 ppm. By including variable stoichiometry described previously with this test article, the CO emissions were further reduced to 1100 ppm. The ideal configuration for the Hencken burner was a

fuel-lean region in the center of the burner (at an equivalence ratio of 0.73) and near stoichiometric on the edges (equivalence ratio of 0.95). Overall, the equivalence ratio of this case was still at 0.9.

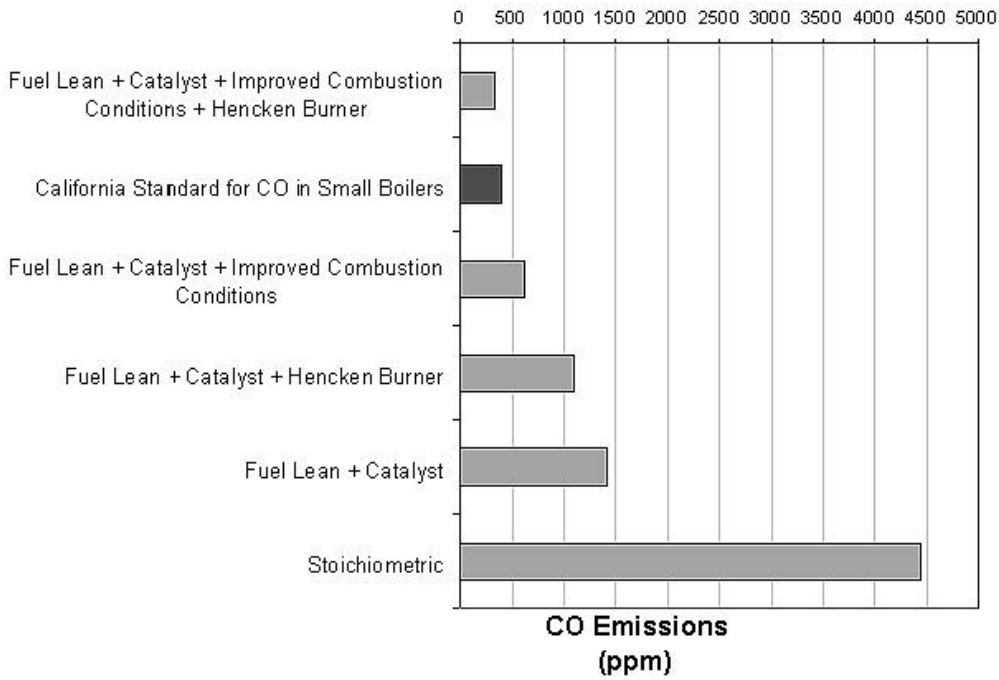

Figure 5. Impact of CO Emission Control Strategies on CO Emissions

CO emissions reduction improved significantly by combining the use of the variable stoichiometric Hencken burner with catalyst in the microchannels. However, the CO emissions were still found to be above the California limit for small boilers of 400 ppm CO.[1] As a proxy for increasing insulation, we increased the temperature of the cooling water to approximately 100°C. This decreased the CO concentration to 332 ppm. The higher water temperatures allowed the combustion chamber wall temperature to increase. Increasing insulation in the combustion zone should have the same impact on CO concentration as increasing the temperature of the cooling water. These modifications allowed us to attain low CO emissions, while the NO_x emissions also remained low. For all tests performed at fuel-lean conditions, the NO_x concentration was less than 10 ppm.

LOW COST FABRICATION

The early combustors were fabricated from two pieces of aluminum, steel, or copper using conventional machining techniques. The microchannels were either cut with a slitting saw or etched with electro-discharge machining. The two pieces were then assembled using RTV or metal gaskets. An improved method of manufacture was needed to reduce the fabrication cost, eliminate the need for sealing, and provide a means of mass production. A new lamination process was developed that was used to fabricate the combustors (Matson et al. 1998). This process shows promise for being mass production amenable and low cost. The microchannels are sealed during lamination, eliminating the problems of leaks. Finally, high aspect ratios are possible.

The lamination process consisted of the following steps:

1. Design of laminate sections
2. Fabrication of laminate sections by photochemical machining
3. Assembly of the laminates
4. Clamping of the laminates
5. Diffusion bonding of the laminates to form a monolithic component.

The laminates formed the individual flow channels, fin sections, and headers. The channel design depended on the channel geometry and aspect ratio required. For the combustor, the laminates were machined from 120-micron-thick copper. This process incorporated a photolithography step with chemical etching of thin metals. The choice of laminate material depended on the application. Metals were used for heat exchangers because of their high thermal conductivity, but ceramics and plastics could also be laminated. Figure 6 shows the shape of the two laminates used to assemble the combustor. A total of 375 laminates was used, 187 fin sections, and 188 spacer units. The spacer sections (Figure 6a) have copper etched away to allow gases to flow through the combustion chamber and gas-side microchannels and to allow liquid to flow through the liquid-side microchannels. The fin section (Figure 6b) has copper etched away to create a continuous combustion chamber and continuous headers, but copper remains over the microchannels to create the fins. The laminates were manufactured

[1] This CO emission requirement actually applies to a burner many orders of magnitude larger than the microchannel combustor studied here. It does, however, provide a stringent target for CO emissions.

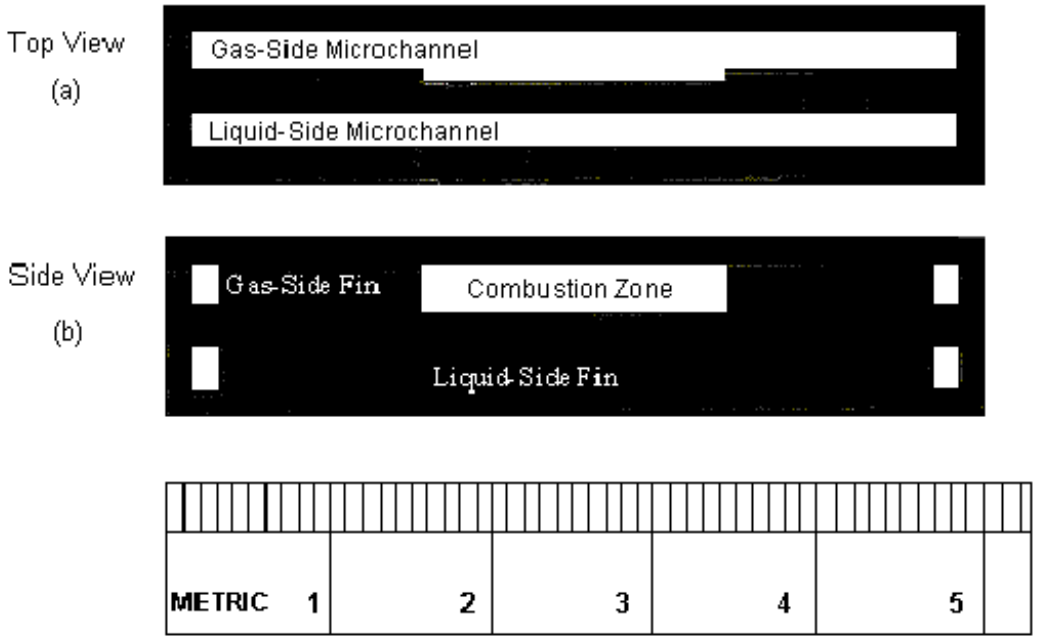

Figure 6. Individual Laminate Sections Used to Develop the Laminate Fabricated Combustor

by photochemical etching. The resultant laminates were free of burrs, defects, and stress. This process is capable of manufacturing thousands of laminates at low cost. The cost per laminate decreases as the number manufactured increases.

The fin and spacer sections were alternated during lamination to create the microchannels. Lamination started with a fin section, then a spacer section, and so on until all 375 sections were used. Lamination terminated with a fin section. This formed a 187-channel heat exchanger. Each strip was registered against the previous one with a fiducial on each side using a simple alignment jig. An end cap was attached to each side of this laminated structure. Fittings could be attached to the inlet and outlet in each end cap for attachment to gas or fluid lines. The aspect ratios of the upper and lower microchannels were 25:1 and 20:1, respectively.

The laminated units were assembled in a stainless steel clamp. The laminates were bonded together into a monolithic structure by a diffusion bonding process. Bonding process conditions depended on the metal used. For copper, the laminates were bonded using a pressure of 8,000 psi at 600°C. Allowances were made for a 4% compression of the copper so that the final dimensions matched those of the top plate. Inlet and outlet fittings were soldered onto the completed component.

The cost for four microchannel heat exchangers was $1300, or $325 per part. This was the lowest cost of any fabrication technique evaluated. If millions of laminations could be made on a production-line basis, it is conceivable that this cost could be cut by an order of magnitude.

Both the machined aluminum combustor and the "low cost" copper laminated microchannel combustor/evaporators were tested to determine thermal performance. These two combustors were compared in terms of thermal efficiency, emissions, and gas and liquid-side pressure drop. The tests varied the fuel flow rates between 400 and 950 mL/min (260 to 630 Watts theoretical), water coolant flow rates of 20 to 120 mL/min, and equivalence ratios of 0.9 to 1.1. The performance results show that the machined aluminum and the laminated copper microchannel combustor/evaporator have nearly identical performance. This demonstrates that it is possible to use a significantly lower cost fabrication process without compromising the performance of the device.

SUMMARY/FUTURE WORK

Based on the results of the research performed here, producing a mesoscale combustor/evaporator with high thermal efficiency is technically feasible. Using simple passive emission reduction strategies, both CO and NO_x emissions can be reduced sufficiently for commercial applications. Using the laminate process, potentially low cost/high volume fabrication of these combustors is possible.

Future work will focus on investigating the fundamental limits of micro-scale combustion using both gas-phase and catalyst-based combustion. This work will focus on liquid fuels as opposed to the gaseous fuels studied here.

ACKNOWLEDGMENTS

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