Integrated Microchannel Combustor/Evaporator Development

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ABSTRACT

Results are presented from recent development efforts toward a high-efficiency, microchannel combustor/evaporator. Two areas were studied: combustion efficiency and approaches to reducing CO emissions. Using this combustor, higher heating value (HHV) thermal efficiencies up to 91% were achieved. Furthermore, heat fluxes to the water coolant were as high as 21 W/cm^2 of combustor surface area. Six approaches to CO emissions reduction were evaluated both individually and in combination. Their effectiveness can be ranked as follows, in order of decreasing effect: fuel lean conditions, expanded combustor, catalyst on surfaces of combustion chamber, preheat feed gases, insulate combustion chamber, and plasma pretreat gases. Using these techniques in combination, the CO emissions could be reduced from >16,000 to <1000 ppm while keeping the NO$_x$ emissions <20 ppm.

The U.S. Department of Defense is investigating ways to improve the “soldier system.” A soldier of the future may require lightweight and compact sources of electric power and microclimate control. If such is the case, thermal energy could drive the electrical generation and provide the heating or cooling. Combustion of hydrocarbon fuels produces high-density thermal energy. These fuels have an energy density (W/kg or W/m^3) a factor of 100 greater than the most advanced batteries.

Battelle has developed a microchannel combustor/evaporator through the funding of the Defense Advanced Research Projects Agency (DARPA). The objective of this project was to characterize this combustor/heat exchanger in terms of combustion efficiency and emissions and find ways to further improve its performance.

A drawing of the Battelle combustor is presented in Figure 1. The overall dimensions of the unit studied are 5 cm by 5 cm by 1.5 cm. The entire unit is constructed of 7000 series aluminum alloy. Premixed air and natural gas are introduced into the combustion chamber where they are ignited with a spark. The flame holder is a 2 micron sintered metal plate. During operation, the flame sits approximately 2 mm from its surface. After burning, the gases impinge on the top of the combustor wall, separate into two horizontal streams, and enter the heat exchanger microchannels. The combustion products are cooled in an array of microchannels. There are approximately 200 microchannels, and each are 2 mm tall, 15.8 mm long, and 0.25 mm in width. While the lower side of the top plate has the

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gas-side microchannels, the upper side of this same plate has microchannels for the cooling water. These extend across both the combustion and microchannel regions. The flowing water cools the gases passing through the microchannels following combustion. The heat flux was based on the amount of heat transferred to the water per unit combustor surface area.

The first phase of this work evaluated combustion efficiency and heat flux at three methane flow rates: 400, 700, and 950 sccm. At each flow rate, four equivalence ratios (actual fuel to air ratio normalized to the stoichiometric fuel to air ratio) each in turn were investigated (0.9, 0.95, 1.0, 1.1) by adjusting the flow of air. 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 condensed, and the emissions analyzed using a gas chromatograph and a chemiluminescent NO_x analyzer (See Figure 2).

During the second phase of this work, several methods of reducing emissions were investigated experimentally. The purpose of these tests was to provide a screening study of options for further study. The techniques were by no means optimized. All the tests were performed at the same methane (550 sccm) and coolant water (80 g/min) flow rate. These emission control strategies were compared to the stoichiometric base case, both individually and in combination.

RESULTS OF THE COMBUSTION EFFICIENCY STUDY

The combustion efficiency is defined as the ratio of the heat transferred to the water 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). Therefore, if the water of combustion remains as a vapor (as it did in most cases), the highest efficiency attainable is 91%. HHV combustion efficiency data are presented as a function of stoichiometry and methane flow rate in Figure 3. Combustion efficiencies for the microcombustor range from 74 to 90%. The highest efficiencies are generally associated with lower methane flow rates and equivalence ratios of 0.9 to 0.95. Maximum heat fluxes to the cooling water for 400, 700, and 950 sccm methane flows were 10.1, 16.7, and 21.0 W/cm^2 of combustor area, respectively.

Figure 4 provides a distribution of the energy efficiency losses as a function of stoichiometry. The first bar in each group represents the total chemical energy added based on combustion at the HHV. The second bar in each group represents the energy going to heat the cooling water. The next four bars represent the inefficiencies. The first represent the uncondensed water in the gases exiting the system (based on the partial pressure of water at the gas exit temperature). The second inefficiency represents the sensible heat in the non-condensible exhaust gases. The third loss is the result of unreacted fuel being exhausted from the combustor (unburned CH_4, CO, H_2). The final loss is the estimated energy lost to the environment. It is not measured directly, but is obtained by an energy balance on the system. As the equivalence ratio increases, the quantity of unburned gases increases, resulting in a decrease in the energy going to the cooling water. The other losses are relatively constant, with the exception of convective losses which may be as high as 20 Watts. Any additional variation in the loss term could indicate error in the cooling water, condensed water, unburned gas, or sensible heat energies.

RESULTS OF EMISSIONS CONTROL STUDY

The results of the combustion efficiency tests showed that unburned gases generated during combustion need to be reduced, not only to improve thermal efficiency, but also to minimize air toxic emissions such as NO_x and CO. Typical results for the combustor at stoichiometric conditions are compared to the stringent Southern California small boiler emission limits [1] in Table 1. These results indicate that we have successfully limited the emissions of NO_x gases, but that the combustor exceeds current emission limits for CO.

Table 1: Typical Emission Results Compared to California Standards

	NO_x (ppm)	CO (ppm)
Typical Stoichiometric Combustor Results	19	16600
California South Coast Area Small Boiler Emissions Limits	<30	<400

The formation of thermal NO_x is a relatively slow reaction. Therefore, long residence times at high temperatures promote its formation [2]. The low concentrations of NO_x in the microchannel combustor indicate that the flame temperatures are quenched very quickly after combustion. However, high concentrations of CO are formed as a result of this quenching because the reaction from CO to CO_2 is also relatively slow.

Several methods of reducing the CO while maintaining low NO_x emissions were investigated experimentally. These can be divided into three categories: preprocessing, combustion modification, and post combustion oxidation.

Preprocessing

PNNL has developed and demonstrated a microchannel plasma reactor where an intense electric field is generated in a microchannel. The resulting microchannel plasma reactor can be used to crack methane and generate hydrogen before it is burned. Hydrogen is highly reactive and it can be used as "kindling" to react with intermediate combustion products to reduce CO. For this study, testing was performed using simulated ~20% methane conversion to ethylene and hydrogen before combustion.

A simpler preprocessing technique that also increases the reaction kinetics is to preheat the gases before combustion. Heat from the combustion process can be used to preheat the gases before ignition. For this study, the gases were preheated electrically to 300°C before combustion. CO emission results were then compared to the base case.

Combustion Modification

Three approaches to reduce emissions inside the combustion chamber were attempted: burning a fuel-lean mixture, enlarging the volume of combustor, and insulating the combustor walls. A fuel-lean mixture increases the amount of oxygen available to react with CO and unburned hydrocarbons. An equivalence ratio of 0.8 was investigated during this study. By enlarging the combustion chamber, the CO has longer to react before being quenched by the cold wall. The combustion chamber height was increased from 0.63 to 2 cm. Higher temperatures inside the combustion chamber will also prevent the quenching of the CO reaction. The aluminum walls were coated with a ceramic insulating material, reducing gas heat transfer until the gases flow through the microchannels.

Post Combustion Modification

Catalysts can be used to convert CO to CO_2 and to burn residual amounts of hydrocarbons in the products of combustion. Typically, catalysts are more active at higher temperatures; therefore, there may be an advantage in combining gas-phase combustion in the combustion zone with catalytic combustion. Platinum catalyst was applied to the walls of the combustion zone on an alumina substrate. The platinum was reduced with H_2 gas before combustion.

The results of the tests described above are shown in Figure 5. A fuel-lean flame reduced emissions and improved efficiency significantly better than other alternatives. With an equivalence ratio of 0.8, the CO was decreased to 20% of its stoichiometric value (3165 ppm). Similarly, the NO_x was decreased to 40% of its stoichiometric value (7.5 ppm). The thermal efficiency increased slightly from 80 to 83%.

The expanded combustor is the second most effective in reducing CO emissions. CO emissions decreased to 30% of the standard combustor value at stoichiometric (5095 ppm) and 1% when combined with a lean fuel mixture (164 ppm). However, the thermal efficiency decreased from 80% to approximately 50%. Instead of heating the coolant, heat was lost to the surroundings, and the product gases as the combustor became very hot (>200°C as compared to 60°C for a standard combustor). Furthermore, the NO_x emissions increased to approximately 30 ppm. Therefore, this technique will not be pursued further.

Combustion chamber insulation, catalyst addition, plasma pre-reaction, and preheat all reduced the emissions to some degree without negatively impacting the efficiency. Their combined effects improved emissions even further. The approaches that reduced the emission levels to below 1000 ppm included 1) fuel lean + insulation, 2) fuel lean + insulation + plasma, and 3) fuel lean + insulation + preheat + plasma. The NO_x emissions remained below 10 ppm in all these tests. The catalyst (stoichiometric + insulation + catalyst) used at stoichiometric conditions appears to provide significant CO reduction when compared to the case without catalyst (stoichiometric + insulation). However, a similar test at fuel lean conditions showed no improvement using a catalyst. In the fuel-lean case, the catalyst may have lost its activity. Further testing is underway to determine if this is the case.

None of the above techniques reached CO emissions that were below the California limit of 400 ppm, however, they are to be considered only screening tests. They will need to be optimized further to decrease the CO emissions below these very stringent limits.

SUMMARY AND RECOMMENDATIONS

Battelle developed a combustor/evaporator that heats water using methane combustion. The combustor was studied over a range of stoichiometries and gas and water flow rates. For these tests, the HHV thermal efficiency ranged from 74 to 90%, with the highest efficiencies at low methane flow rates and equivalence ratios. Heat transfer rates of between 8.5 and 21 W/cm^2 were achieved over the range of conditions. While the NO_x emission levels were within required

California limits, the CO emissions were excessively high. Six techniques for minimizing the CO emissions were studied and compared to the stoichiometric base-case. A fuel-lean flame provided the largest improvement in CO emissions, followed by a larger combustion chamber. Plasma preprocessing, feed preheating, combustor insulation, and catalysis further reduced the CO emissions to below 1000 ppm.

Future studies will focus on further reducing CO emissions to below the Southern California limits of 400 ppm. This will be done by optimizing the conditions used in the above CO reduction techniques. Furthermore, future work will use computer modeling to develop an improved combustor design that allows for high combustion efficiency at high thermal fluxes.

LITERATURE CITED

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