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Clean Flat Flame Combustor for Ultra Micro Gas Turbine

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Abstract

Ultra micro gas turbine (UMGT) is a promising power source for small portable electronic and miniature mechanical devices, such as micro robots and micro aerial vehicles, because of its high power and energy densities. In order to utilize UMGT as a viable power source, the components of the UMGT must be developed because downscaling reveals many challenges that do not occur in conventional sized gas turbines. As the micro combustor is one of the key components of UMGT, it needs to be improved in order to achieve high combustion efficiency, wide flame stability and low pressure loss in a small volume. Flat flame combustion can be achieved using a porous or perforated plate as a flame holder. In this study, a sintered stainless steel plate, with an average pore size of 200μm and a thickness of 3 mm, was used as a flame holder, within a 46 mm diameter quartz walled combustor. CO and NO_X emissions were collected at different air to fuel ratios. This study shows that sintered stainless steel can be used as a flame holder providing very clean combustion with a combustion efficiency of 99% in a small scale. In addition, flame behavior with varying equivalence ratios and pressure loss values through the flame holder are presented.

Introduction

Portable small electronic and miniature devices such as notebooks, micro robots and micro air vehicles need more compact and efficient power supplies. Currently, batteries are used as a power supply for these devices. However, batteries are not compact constitute most of the volume and weight of these devices and also need a long time for recharging. Therefore, a continuous, light, high power density and efficient power source is essential. The combustion-based ultra micro gas turbine (UMGT) is one of the most promising micro power sources because of its high energy and power densities [2, 4]. UMGT with less than 10% overall efficiency still has a higher energy density than batteries.

The concept of UMGT was first developed by Epstein at the Massachusetts Institute of Technology's (MIT) Gas Turbine Laboratory using Micro-Electro-Mechanical Systems (MEMS) technology around 1995 [3]. This was followed by other UMGT research projects conducted around the world like the University of Tokyo's 'palm top' and 'finger top' UMGT projects [7], Belgian PowerMEMS project [9] and ONERA's DecaWATT project [8].

During the past twenty years of research, most research groups have chosen hydrogen as a fuel because of its high heating value, high burning velocity and leaner flame stability. However, hydrogen is not a good candidate for small portable devices because of its storage problems.

Up till now, only Ishikawajima-Harima Heavy Industries (IHI) has successfully achieved a working palm sized micro gas turbine with a power output of 400 watts. For smaller ranges of power output, there are still some challenges to be overcome. In spite of IHI's success, a methane fuelled ultra micro gas turbine has not yet been prototyped nor manufactured. Therefore, this research aims to be a step along the way in developing a UMGT using methane as a fuel.

The realization of UMGT as a viable power source requires the development of components since downscaling introduces new challenges for each of these components. Since micro combustor is one of the key components of UMGT, it has to be developed in order to realize the UMGT as a viable power source. It is not easy to achieve stable, high combustion efficiency, wide flame stability with less pollutants in small scale combustors because downsizing introduces new problems which do not occur in typical gas turbine combustors. Yuasa et al. specified the fundamental downscaling problems of micro combustors as smaller residence time for mixing and combustion, high heat loss, and high pressure loss [13]. It can be said that the two most important downscaling problems of combustors are smaller residence time and high heat loss [5, 13].

Although the flat flame burner method was first developed and applied to UMGT by Yuasa [11, 12], and also applied by Marbach and Agrawal [6] there is a lack of data showing the flame behaviour with different air to fuel ratios and combustion characteristics. Therefore, a new, simple and efficient flat flame combustor was developed in order to understand flat flame combustion at small scale. The objective of this paper is to evaluate flat flame combustion on a small scale combustor. The specific objectives are to show the pressure loss through the flame holder, to investigate the flame behaviour at varied air to fuel ratios, CO and NO_X emissions and combustion efficiency.

Experimental Set-up

A test rig, which enables the observation of both the flame shape and location, was developed in the Thermodynamic Laboratory of the University of Auckland.

A mixing chamber is inserted at the bottom of the combustor to obtain homogeneous uniform premixed fuel-air. Fuel is supplied from a fuel cylinder, controlled and measured by a Sierra mass flow controller, where it enters the bottom of the mixing chamber. Air enters the mixing chamber through two pipes after being heated by two Omega T type air process heaters. On top of the mixing chamber, a machinable ceramic part is used as a base for the combustor, which helps to reduce the heat loss from the flame to the mixing chamber. A quartz tube is chosen as the combustor wall since it facilitates observation of the flame. The inner diameter of the first quartz tube is 46 mm with a 1.5 mm thickness. A photo of the flat flame combustor and mixing chamber is shown in figure 1. In the present test New Zealand natural gas was used as a fuel, due to the main constituent being methane. The molar gas composition of New Zealand natural gas in Auckland is listed in table 1.

A sintered stainless steel plate, R200, was used as a flame holder and was provided by Siperm Tridelta from Germany. A photo of the flame holder is shown in figure 1. The R200 flame holder has a 3 mm thickness and an average pore size of 200 μm. The porosity of the flame holder is in the range of 49~54%.

The experiments were performed under atmospheric pressure and room temperature. Pressure values were measured by a 2100 Meriam smart gauge pressure transducer and a Digitron manometer. The calibration of the transducers was performed by using a Betz manometer and a U-tube manometer. Pressure drop measurements were performed in the non-reacting flow case.

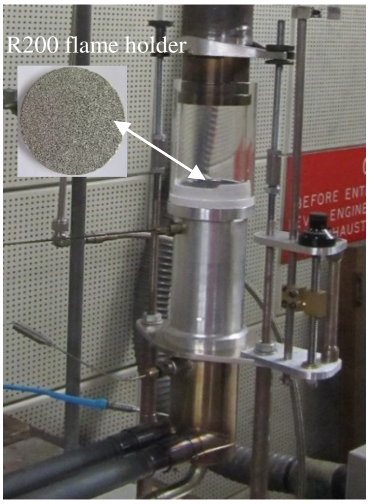

Figure 1. Flat flame combustor and mixing chambers

Gas components	% Mole fraction
Methane	82.0201
Ethane	7.3924
Propane	3.134
n-Butane	0.5891
I-Butane	0.5366
n-Pentane	0.0927
I-pentane	0.1244
Hexane	0.0551
Nitrogen	0.4251
Carbon dioxide	5.6306

Table 1. Molar gas composition of New Zealand natural gas in Auckland (July/2012)

For the measurement of CO_2 and CO, a Signal multi gas analyzer was used. For the measurement of O_2, a Signal 8000 series gas analyzer was employed. For the measurement of NO_X and unburned hydrocarbon (UHC), Signal 4000 series and Signal 3000 series gas analyzers were used, respectively.

Experimental Results and Discussion

Pressure Loss

One of the requirements of micro combustors for UMGT application is to keep the pressure loss to a minimum. Ideally the combustor pressure loss should be less than 5% of the operating combustor pressure [10, 12]. In flat flame combustors, most of the pressure loss occurs through the flame holders. Therefore, the measurement of pressure loss against incoming flow velocity was performed.

Since this flame holder is used for flat flame combustion, and one of the conditions for flat flame combustion is that the incoming flow velocity be less than the burning velocity, the pressure loss values were therefore measured up to a maximum incoming velocity of 2 m/s. This value was calculated by taking into consideration the preheating of the reactants, since the burning velocity S increases with the increase of the reactants temperature. Since the main composition of New Zealand natural gas is methane, the burning velocities of methane were considered in the calculations. The effect of the initial reactants temperature T_u on burning velocity for methane/air flames at atmospheric pressure was calculated by equation (1) provided by Andrews and Bradley [1].

$$S = 10 + 0.0003717T_u^{\,2} \quad 150\text{K} < T_u < 1000\text{K} \qquad (1)$$

Percentage of pressure loss to ambient pressure versus incoming flow velocity plots with different flame holders are shown in figure 2. From this figure, it can be concluded that sintered stainless steel R200 has a pressure loss of less than 2% throughout the whole range of incoming flow velocities. This indicates that R200 is a suitable candidate as a flame holder for a flat flame combustor.

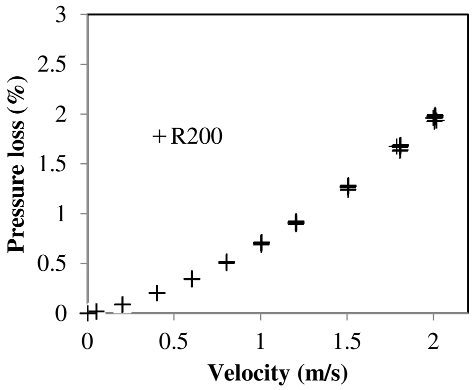

Figure 2. Percentage of pressure loss vs incoming velocity

The Flame Behaviour with Changing Air to Fuel Ratio

For UMGT applications, the main focus is only on the lean side of the stoichiometric air/fuel ratio. Therefore, in this paper the flame behaviour on the lean side of the stoichiometric is presented.

A flat flame occurs very close to the flame holder. The reactants are heated naturally from the flame holder which is in turn heated from the flame. The flame behaviour on the surface of the R200 flame holder was observed at a constant air mass flow rate of 0.38 g/s with equivalence ratios varying from 0.51 to 0.95.

At an equivalence ratio of 0.51, there was no stable flame. The flame was flickering and flapping like a butterfly, after which the flame eventually blew out from the combustor. The reactants were around 303 K, showing that there was no natural heating from the flame. As can be seen from the photo of the flame just before blow out in figure 3a, the flame was weak with a very light blue colour. When the equivalence ratio was increased to 0.54, the flame was still unstable, flickered a lot and lifted approximately 3 to 4 cm above the flame holder, as shown in figure 3b. Since the flame was far from the flame holder, the reactants were at room temperature.

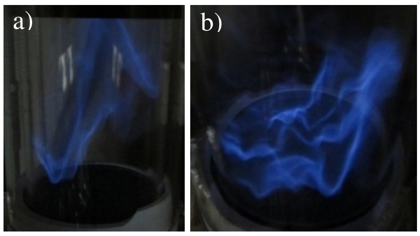

Figure 3. Flame photos at an air mass flow rate of 0.38 g/s and equivalence ratios of a) 0.51 and b) 0.54

In figure 4a a flame, which was photographed just after ignition, can be seen burning when the reactants were at room temperature, whilst keeping the air mass flow rate constant at 0.38 g/s, and an equivalence ratio of 0.62. Compared to the flame at an equivalence ratio of 0.54, the flame had a brighter blue colour and moved closer to the flame holder. However, the flame was still unstable and flickering. At this equivalence ratio, since the flame was closer to the flame holder, natural heating of the reactants from the flame was observed. The reactants were naturally heated up to 343 K and the flame at this reactants temperature is shown in figure 4b. With natural heating the bigger sized lifted conical flames started to settle down on the flame holder surface, apart from close to the quartz wall boundary.

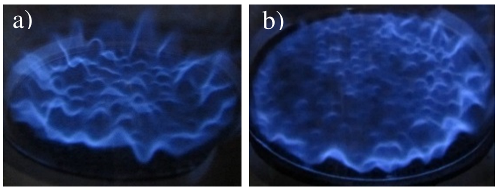

Figure 4. Flame photos at an air mass flow rate of 0.38 g/s and an equivalence ratio of 0.62, when the reactants are at a) room temperature, b) 343 K

A similar preheating effect was also observed at an equivalence ratio of 0.68 and is shown in figure 5. At this equivalence ratio, flames can be observed when the reactants were at room temperature in figure 5a, and when the reactants were naturally heated up to 360 K in figure 5b. When the reactants were naturally heated up to 360 K, the flame completely settled down on the flame holder surface except for near the combustor wall, where a few mm high lifted, flickering conical flames were observed.

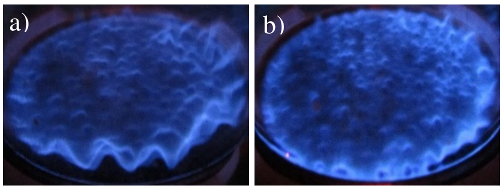

Figure 5. Flame photos at an air mass flow rate of 0.38 g/s and an equivalence ratio of 0.68, when the reactants are at a) room temperature, b) 360 K

When the equivalence ratio was increased to 0.75, a blue flat flame consisting of tiny distinctive conical flames was observed except at the quartz wall boundary. At the quartz wall, a few mm high lifted larger conical flames were present. The flame holder was slightly red indicating that the flame occurred very close to the flame holder. Due to this, the reactants were naturally heated up to 393 K. There were red spots on the flame holder surface and the graphite sealant, which can be seen in figure 6.

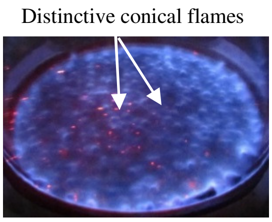

Figure 6. Flame photo at an air mass flow rate of 0.38 g/s and equivalence ratio of 0.75

Further increase in the equivalence ratio, results in a red flame holder, showing that the flame holder temperature increased due to both the closeness of the flame to the flame holder and the high heat release because of the higher fuel flow rate. Figure 7a shows a photo of a blue flat flame sitting on a very red flame holder, which was taken at an equivalence ratio of 0.95. In this case, the reactants were naturally heated up to around 430 K. In addition to the flat flame, a big cone shaped, slightly red glow which extended along the combustor tube was also observed, as can be seen in figure 7b.

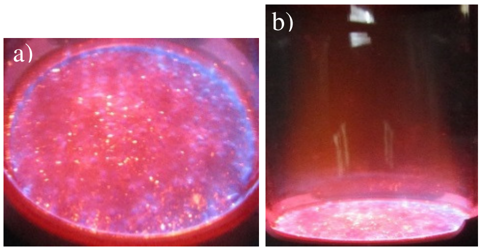

Figure 7. Flame photos at an air mass flow rate of 0.38 g/s and equivalence ratio of 0.95 a) closer view from top, b) side view

Thus, at low equivalence ratios when the flame is lifted and unstable, flat flames can be achieved by preheating the reactants.

Exhaust Emissions

Nitrogen oxides (NO_X), CO and UHC are the main sources of pollution from combustion. Therefore, the measurement of emissions becomes important. Since in this study the equivalence ratios were calculated from the exhaust emissions, O_2, CO, CO_2, NO_X and UHC compositions were collected. Therefore, in addition to the pollutant emissions, O_2 and CO_2 concentrations are presented.

Figure 8 presents the exhaust gas composition data in mole fractions as a function of equivalence ratio at an air mass flow rate of 0.38 g/s. As can be seen from Figure 8, at the lean side of the stoichiometric, as the equivalence ratio decreased, O_2 concentrations increased and reached up to a value of 10.83 % mole fraction at an equivalence ratio of 0.51. On the contrary, CO_2 concentrations decreased, and a mole fraction of 6.1 % was measured at an equivalence ratio of 0.51. At all equivalence ratios, CO concentrations were zero. The NO_X emissions at an air mass flow rate of 0.38 g/s over a range of equivalence ratios are presented in figure 9.

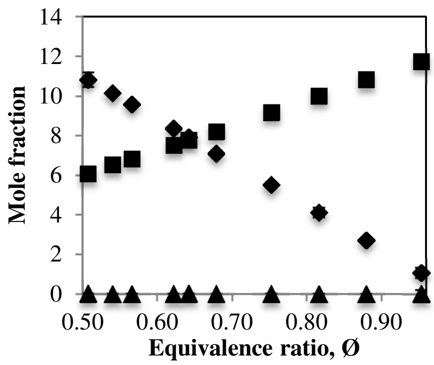

Figure 8. CO_2 (square), O_2 (diamond) and CO (triangle) emissions of natural gas at an air mass flow rate of 0.38 g/s with varying equivalence ratio

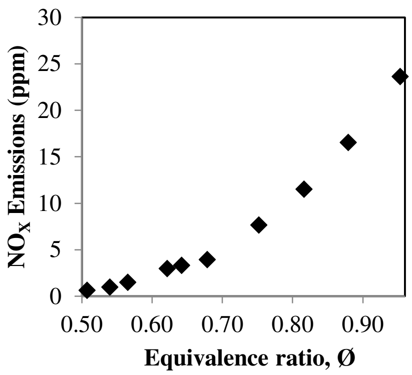

Figure 9. Effect of equivalence ratio on NO_X emissions of natural gas at an air mass flow rate of 0.38 g/s

NO_X emissions increased with increasing equivalence ratio on the lean side of the stoichiometric and reached its maximum value at equivalence ratio of 0.95, which was 24 ppm. UHC emissions were very low and within the inherent noise level of the gas analyser. This shows that complete combustion occurred within the 46 mm diameter quartz walled flat flame combustor.

Combustion Efficiency

At the lean side of the stoichiometric, more than 99% combustion efficiency was achieved at all equivalence ratios with the 46 mm diameter quartz walled flat flame combustor, utilizing New Zealand natural gas at an air mass flow rate of 0.38 g/s. This shows almost complete combustion occurred in this combustor.

The combustion efficiency using New Zealand natural gas as a fuel was calculated using the equation (2), where $\tilde{x}_i$ is the mole fraction of species i (i= CO, unburned hydrocarbon or H_2). The Q_{HV_i} are the lower heating values of these species, while the M_i are the molecular mass. The subscripts f and a denote fuel and air, while b indicates burned gas. For New Zealand natural gas, the combustion reaction is given in equation (3), while the molecular mass of the burned gas was calculated using equation (4). Heating values of 10.11 MJ/kg for CO, 120 MJ/kg for H_2, and 42.87 MJ/kg for both unburned hydrocarbon and fuel were used in the calculations.

$$\eta_{comb} = \left[1 - \left(\frac{\dot{m}_f + \dot{m}_{air}}{\dot{m}_f}\right)\left(\frac{\tilde{x}_{CO} Q_{HV_{CO}} M_{CO} + \tilde{x}_{UHC} Q_{HV_{UHC}} M_{UHC} + \tilde{x}_{H_2} Q_{HV_{H_2}} M_{H_2}}{Q_{HV_f} M_b}\right)\right] \times 100 \quad (2)$$

$$C_{1.177564}H_{4.121402}O_{0.112612} + \frac{2.151609}{\emptyset}(O_2 + 3.773N_2) = n_p(\tilde{x}_{C_3H_8}C_3H_8 + \tilde{x}_{CO}CO + \tilde{x}_{CO_2}CO_2 + \tilde{x}_{O_2}O_2 + \tilde{x}_{N_2}N_2 + \tilde{x}_{NO}NO + \tilde{x}_{H_2O}H_2O + \tilde{x}_{H_2}H_2) \quad (3)$$

$$M_b = \frac{\tilde{x}_{C_3H_8}M_{C_3H_8} + \tilde{x}_{CO}M_{CO} + \tilde{x}_{CO_2}M_{CO_2} + \tilde{x}_{O_2}M_{O_2} + \tilde{x}_{N_2}M_{N_2} + \tilde{x}_{NO}M_{NO} + \tilde{x}_{H_2O}M_{H_2O} + \tilde{x}_{H_2}M_{H_2}}{\tilde{x}_{C_3H_8} + \tilde{x}_{CO} + \tilde{x}_{CO_2} + \tilde{x}_{O_2} + \tilde{x}_{N_2} + \tilde{x}_{NO} + \tilde{x}_{H_2O} + \tilde{x}_{H_2}} \quad (4)$$

Conclusions

As a part of developing the micro combustor for UMGT applications, flat flame combustion was investigated within a 46 mm quartz walled flat flame combustor. The flame behaviour and stabilization of flat flame were investigated on a sintered stainless steel flame holder. In addition, pressure drop values through this flame holder were measured. The exhaust emissions showed that the flat flame combustor provides very clean combustion. Furthermore, over 99% combustion efficiency was achieved at all equivalence ratios showing almost complete combustion occurred in this combustor.

Acknowledgments

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