Investigation of combustion in miniaturised combustor for application to micro gas turbines

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Abstract

Assessing the feasibility of combustion in miniaturised combustors (volume less than 1 cm^3) is a key point for the development of micro gas turbines. This paper presents the results obtained with a first combustion chamber, with a hydrogen-air mixture, tested in a laboratory especially built for the study of micro-combustors. We obtained a stable combustion with a combustion power of between 100 W to 1200 W, in a range of air mass flow of between 0.1 to 0.5 g/s, an equivalence ratio of between 0.3 to 0.7. These results are based on the temperature measured by means of thermocouples and the optical diagnostic spontaneous Raman scattering technique.

NOMENCLATURE

h	Heat transfer coefficient (W/m²/K)
LHV	Lower Heating Value (J/kg)
$\dot{m}$	Mass flow (g/s)
P	Power (W)
S	Surface (m²)
t	Time (s)
T	Temperature (K)

Greek symbols:

ε	Emissivity
Φ	Equivalence ratio
η	Efficiency

Subscripts:

a	ambient
c	thermocouple (exhaust gas temperature)
ch	chemical
e	external surface of the combustor
g	hot gases
net	net power
th	thermal
w	wall

1. Introduction

To reduce the size and weight of power generation machines for autonomous devices, several alternative systems to the currently used heavy batteries are investigated worldwide. As micro gas turbines are expected to offer the highest power density, several research groups have launched programs to develop ultra micro gas turbines, following in the footsteps of the MIT group [1].

At ONERA, a research program is under development [2], with the support of the Ministry of Defence (DGA/UM AERO), in order to develop a demonstrator of the micro gas turbine engine type delivering 10 to 100 Watts of electrical power. The main application of this tiny engine is micro-drone propulsion (15 cm length and wingspan).

Due to the small volume of the device (about 6 cm^3), there are many problems to tackle; the manufacturing of the rotating and static parts, the gas journal and thrust bearings (rotating speed up to 1 million rpm), combustion in a small volume, the micro electromechanical converter…

Taking into account these physical and technological challenges led ONERA to develop and test some micro-combustors. The first one is a small cylinder, 20 mm diameter and 2.7 mm high, corresponding to a volume of 850 mm^3. It is fed with an air-hydrogen mixture (air mass flow of between 0.1 g/s to 0.5 g/s). A very stable combustion has been obtained for a large range of equivalence ratios (0.3 to 0.7). The wall temperature (measured by means of thermocouples and with a two-color infrared pyrometer) does not exceed 1350 K for an equivalence ratio of 0.7. Recording the temperature profile of the walls during transient sequences of heating or cooling and the exit gas temperature at the outlet of the micro-combustor (measured by means of a small thermocouple - 0.25 mm diameter) allow us to determine the overall efficiency of the micro combustor. The values obtained lie between 0.45 and 0.8, depending on the equivalence ratio (from 0.35 to up to 0.7) and the mass flow. In order to understand micro-combustion phenomena better, laser-based measurements (spontaneous Raman scattering) have been performed in addition to classical thermal measurements. The 3D numerical simulations are also carried out in order to compare with the experimental results. In the near future we are planning to test other combustor geometries especially in the non-premixed case.

2. Constraints for the micro combustors

Regardless of the final size expected for this micro gas turbine, scaling down a classical gas turbine combustion chamber obviously generates specific problems that have to be overcome [1], [2], [3], [4]. In fact, the low Reynolds number flow (laminar zone) induces a poor mixing in the chamber on the one hand, between fuel and air, and on the other hand between cold and hot gases. Moreover, the reduction of the size of the combustion chamber decreases the gas residence time which approaches the reaction time. In the same way, the external heat losses increase due to the high surface/volume ratio of the combustion chamber.

The potential performance of a micro gas turbine has been determined with the software called "Hot button" [2], [5]. The results of this software, developed at ONERA, pointed out the necessity to have a combustion power comprised of between 300 W to 1000 W in order to obtain, after electrical conversion [2], a net power equal to between 20 W and 100 W.

In the references [2], [6] and [7], some calculations of the minimum reaction time of the air/hydrogen mixture, in a perfectly stirred reactor, have been carried out and we obtained a value of around 0.1 ms (with 90 % for the chemical efficiency and 90 % for the thermal efficiency). From these values, it becomes possible to determine the minimum volume of the micro combustor, in order to have complete combustion.

With this first chamber, in addition to the wall temperature and the exit gas temperature measurements with thermocouples, spontaneous Raman scattering technique has been used. This method allows us to evaluate the concentrations, the gas main species and the temperature at the outlet of the chamber. The objective is to obtain some complementary information on the chemical efficiency.

3. Experimental set up

A specific laboratory has been established at Palaiseau ONERA Center and a first micro-combustor has been tested [2]. This first combustor is presented on Figure 1. It has a very simple geometry: a cylinder of 20 mm diameter and 2.7 mm high. This volume of 850 mm^3 has been determined according to the nominal values for the combustion power (500 W), the mass flow rate (0.4 g/s) and the Damkhöler number (the ratio between the residence time and the characteristic chemical reaction time =10).

The air hydrogen mixture (premixing case) enters the combustor through a water cooled tube liner of 2 mm diameter. As shown on the picture, a porous cylinder is added just upstream of the inlet of the actual combustor to eliminate the possibility of flashback. A thin layer of zircon is deposited on the upper face of the micro combustor in order to reduce the conductive heat transfer towards the water cooled support. The combustion gases are radially squeezed through 24 holes of 0.5 mm diameter. For the ignition, we use an electric discharge between the end of a tungsten wire (0.2 mm diameter) and the wall of the micro combustor (in stainless steel). This igniter was built by the firm Thermocoax.

To measure the wall temperature of various zones, the combustor is equipped with 4 thermocouples (0.5 mm diameter for the sheath - type K). In addition an infrared two-color pyrometer (wavelengths of 1.52 and 1.64 µm) is used. The location of the thermocouples is presented on the Figure 1 (Tw1 to Tw4).

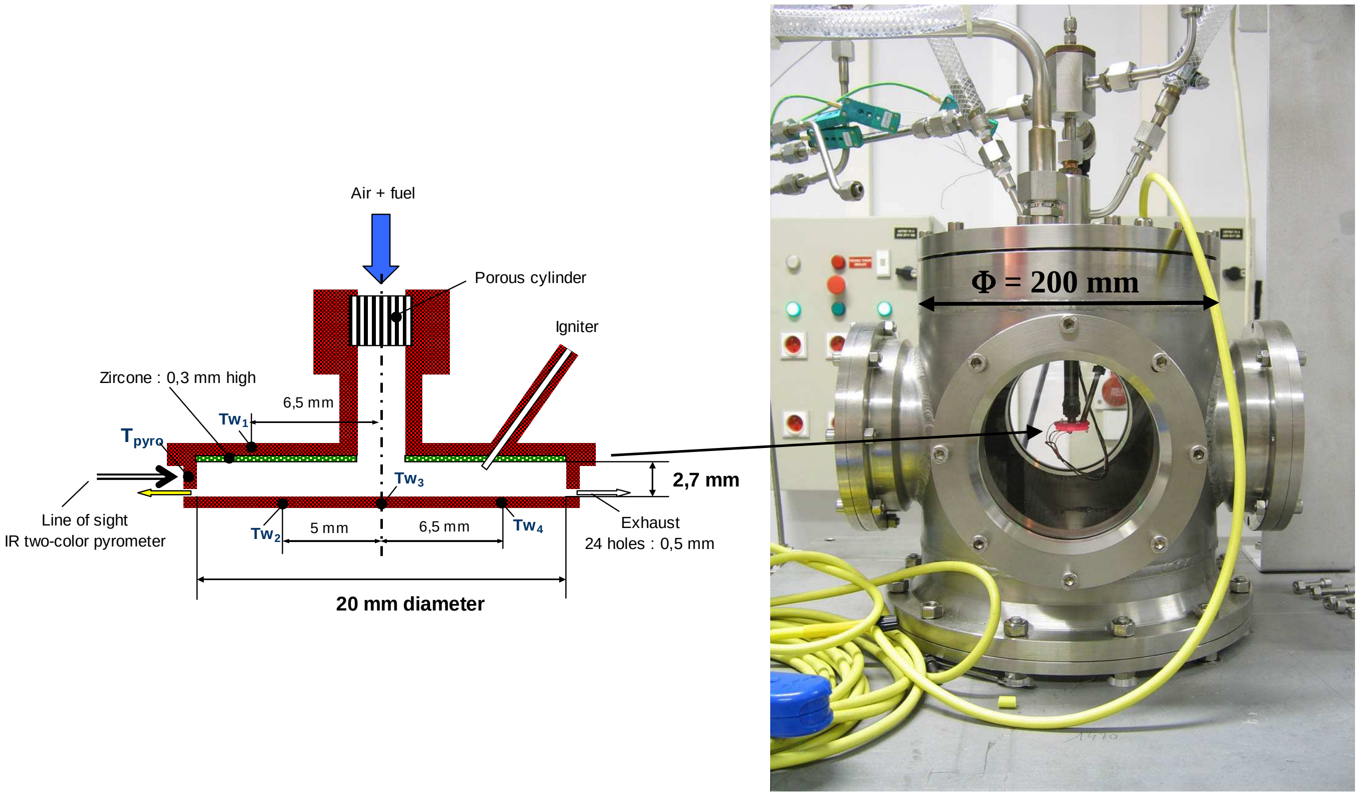

Figure 1: Cross-section of the first micro combustor and its position in the pressurized vessel.

For the tests, this micro combustor is placed in a pressurized vessel (Figure 1). The vessel is internally cooled by nitrogen and the mixture of nitrogen and combustion products is exhausted through an adjustable valve. Silica port-holes allow us to visualize the combustor. Optical measurements; infrared pyrometer, IR camera, spontaneous Raman scattering are also possible through these windows.

4. Thermal measurements

The experimental conditions are recapitulated hereafter: air mass flow rate 0.1 to 0.5 g/s and equivalence ratio 0.3 to 0.7; the inlet gas temperature is 300 K. The micro combustor in operation is presented on Figure 2. In this case, the air mass flow rate is 0.5 g/s and the equivalence ratio is 0.5.

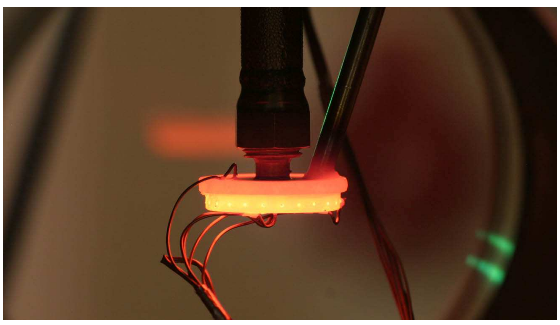

Figure 2: Firing micro combustor.

4.1 Steady state results

The mean wall temperatures of the micro-combustor, deduced from the thermocouples, are shown on Figure 3 for the range of mass flow rates and equivalence ratios. We can see that the mean wall temperature is directly connected to the equivalence ratio. The pressure in the combustion chamber is 2 bars.

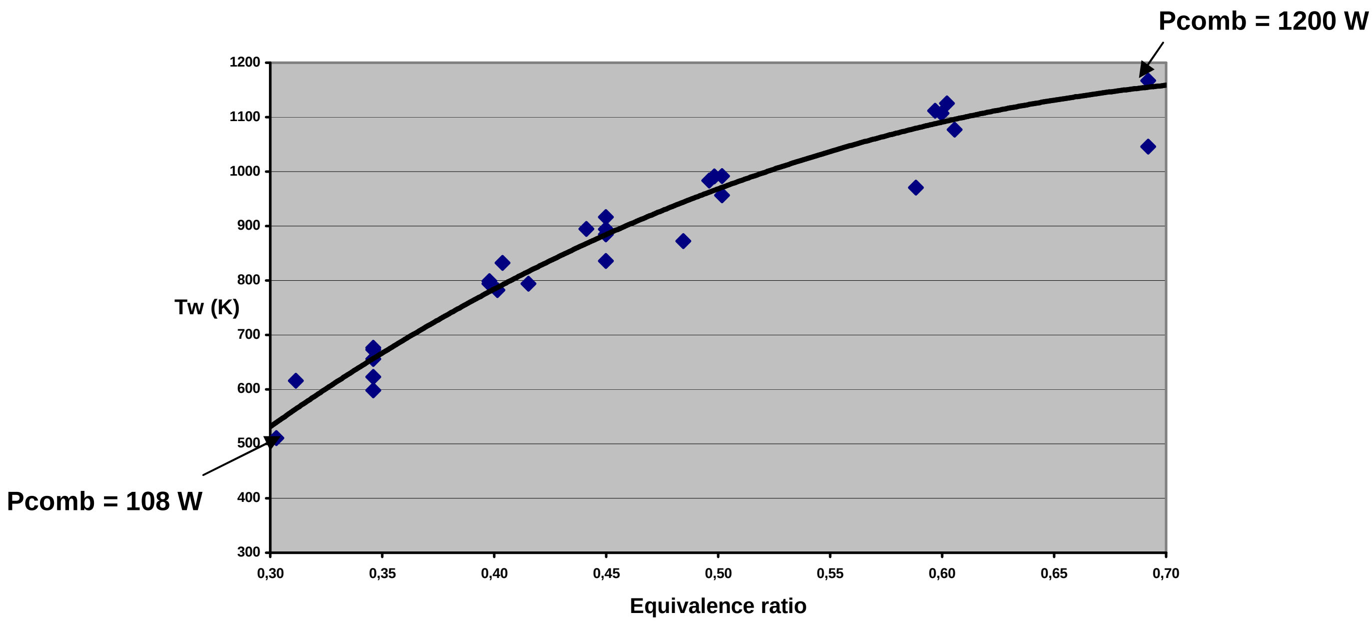

Figure 3: Mean wall temperature for the range of operating conditions.

4.2 Evaluation of the combustor efficiency

The combustion power (P_{comb}), calculated by the equation:

$$P_{comb} = \dot{m}_{H_2} \cdot LHV_{H_2}$$

is comprised of between 108 W and 1200 W (Figure 3). The combustion power of around 500 W mandatory for ONERA's micro gas turbine engine [5] is obtained and the required level is in the middle of the experimental range presented on Figure 3. The wall temperature, for an equivalence ratio less than 0.7, is below the temperature limit of stainless steel (X8CrNi25-21/AISI310S).

To calculate the thermal efficiency of the micro combustor, an evaluation of the heat losses is required. These losses are calculated as follows:

$$P_{th} = h_e S_e (T_w - T_a) + \varepsilon \sigma S_e (T_w^4 - T_a^4)$$

The two unknown factors, the external heat transfer coefficient around the combustor (h_e) and the emissivity (ε) of the wall, can be determined using a method based on the wall temperature transients [8], after cutting the air and hydrogen mass flows supplying the combustor. From these results, for several experimental conditions, an external heat transfer coefficient of about 60 W/m²/K and an emissivity of around 0.8 are inferred. The emissivity deduced from the two-color infrared pyrometer is also nearly 0.8. With these values, it is now possible to calculate the heat losses.

The combustion net power can be calculated with the equations [3]:

$$P_{net} = P_{comb} - P_{th} - P_{ch} = \eta_{overall} P_{comb} = \eta_{ch} \eta_{th} P_{comb}$$

where P_{ch} (chemical losses) are due to the mass flow of fuel which is not burnt. Consequently, the overall efficiency of the micro combustor can be written as follows:

$$\eta_{overall} = \eta_{ch} \eta_{th} = 1 - \frac{P_{th}}{P_{comb}} - \frac{P_{ch}}{P_{comb}} = \frac{P_{net}}{P_{comb}}$$

The chemical and the thermal efficiencies are written as:

$$\eta_{ch} = \frac{P_{comb} - P_{ch}}{P_{comb}} \qquad \eta_{th} = \frac{P_{net}}{P_{comb} - P_{ch}} = \frac{P_{net}}{\eta_{ch} P_{comb}}$$

To obtain the overall efficiency of the micro combustor, and consequently the chemical efficiency, it is necessary to determine the exit gas temperature [3], [9]. For this, we have used a small thermocouple, 0.25 mm diameter, which is located in front of the exhaust hole, at 1 mm from this exit, as presented on Figure 4 (left). The results obtained for the nominal air mass flow rate 0.4 g/s are also presented on Figure 4 (right). On this figure, the adiabatic gas temperature is drawn in red. The exit gas temperature measured with the thermocouple (in green on Figure 4) must be corrected in order to eliminate the radiative losses and the conductive losses in the wires of the thermocouple. Concerning the radiative transfer, a screen is placed around the thermocouple (see Figure 4) in order to reduce this loss. The temperature of the screen is measured with the pyrometer. The values obtained for T_c are represented in black. From the results obtained in the case of the perfectly stirred reactor [6], [7], we can calculate the different efficiencies (Figure 5).

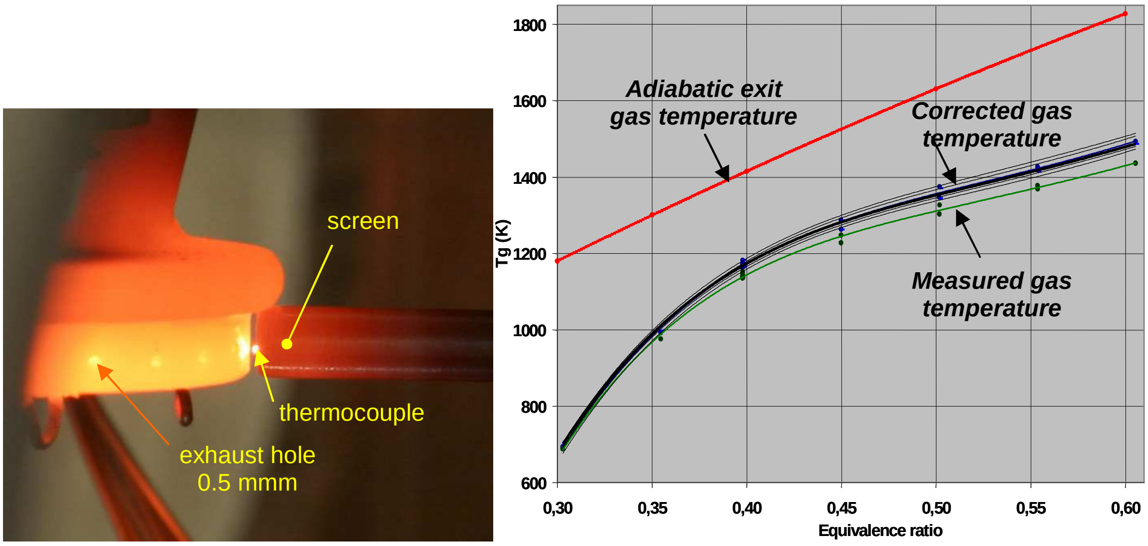

Figure 4: Exit gas temperature measured by thermocouple (0.25 mm diameter) - Mass flow rate 0.4 g/s.

We observe that the overall efficiency is nearly constant, around 0.8, for a range of equivalence ratio between 0.4 and 0.6. The thermal efficiency decreases slowly (its value clearly depends on the wall temperature) and on the contrary, the chemical efficiency increases sharply for an equivalence ratio of between 0.3 and 0.4.
The residence time of the flow in the micro combustor for the nominal mass flow rate, 0.4 g/s°, is close to 1 ms.

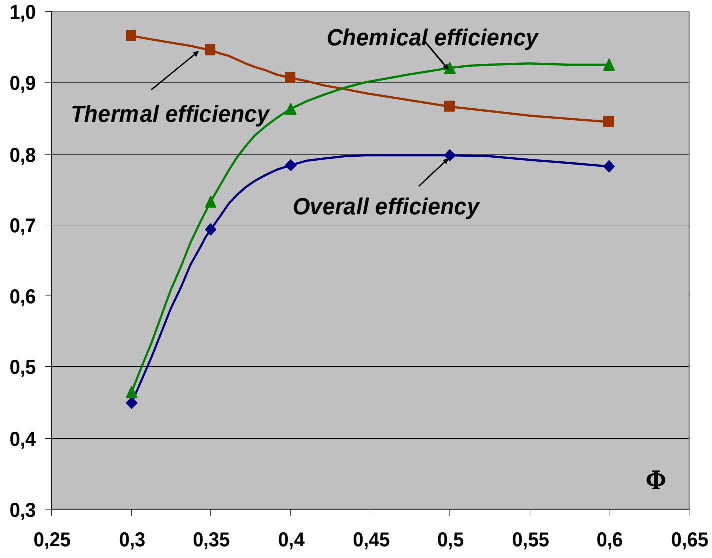

Figure 5: Overall, thermal and chemical efficiencies versus equivalence ratio - Air mass flow rate: 0.4 g/s.

5. Species concentrations and temperature measurements using Rayleigh and Raman scattering technique

1D imaging Rayleigh and Raman scattering has been applied for measuring temperature and the concentration of the major species (N_2, O_2, H_20, H_2) at the outlet of a fired micro-combustor operating with a H_2/air mixture (Figure 6 - left). A frequency-tripled output of an Nd:YAG laser at 355 nm, with a pulse energy of 70 mJ and 10 Hz repetition rate is focused 2 mm beside the micro-combustor, in an exhaust gases stream.

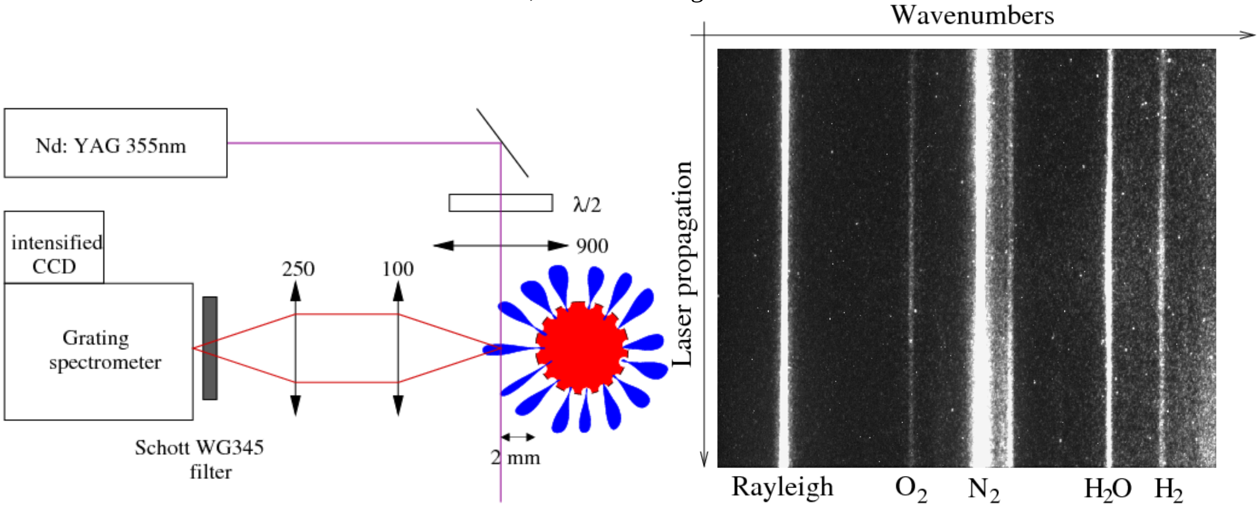

Figure 6: Experimental set-up and spatial profile of Raman and Rayleigh signals across the jet of burnt gases for an air mass flow rate of 0.1g/s and equivalence ratio of 0.35.

A half waveplate is mounted in front of the focussing lens, either to select Raman and Rayleigh signals, or background noise (blackbody radiation, species fluorescence, etc..). The scattered signal is collected by a first lens and then focused by a second lens onto the entrance slit of a grating spectrometer (Spex270M) connected to an intensified CCD camera (576 x 384 pixels). A high-pass Schott filter (WG345) is used to set Rayleigh and Raman signals to the same amplitude. This optical set-up allows us to record the spatial profile of Rayleigh and Raman signals along the laser beam, over a distance of 4 mm across the jet of burnt gases. Analysis of these experimental data allows us to determine the expansion of the jet together with the diffusion of the different species in the surrounding atmosphere (N_2) and to quantify the combustion efficiency of the micro-combustor. Typical signal evolution is shown in figure 6 (right) for an accumulation of 2000 single shots.

Temperature information is obtained from the dependence of the Rayleigh scattering upon density number and species Rayleigh cross sections. Species concentrations are measured by analysing the shape of the Raman spectrum of the different species. This method requires calibration curves for different temperatures and for each species. This calibration was performed in a flat flame operating with a H_2/air mixture, for various equivalence ratios.

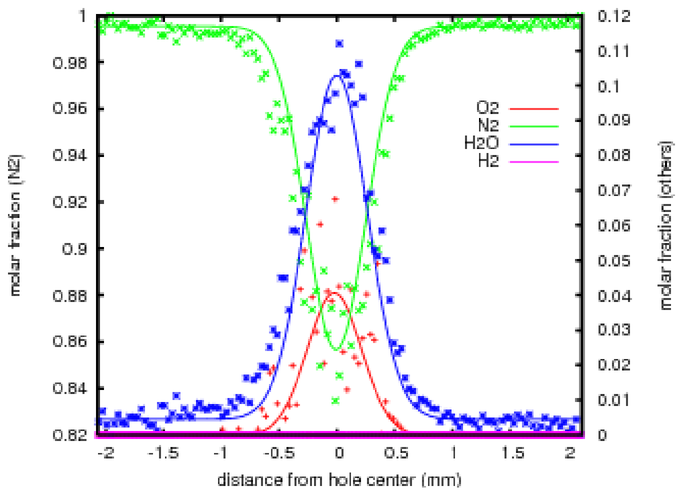

Figure 7: Radial profiles of molar fractions in the burnt gases jet (air mass flow rate: 0.1 g/s, Φ=0.4).

The main difficulty for optical measurements at the outlet of the micro-combustor comes from the blackbody radiation of the chamber which dramatically increases with equivalence ratio and air mass flow rate. This radiation interferes with Raman signals and may become prominent when the temperature of the combustor increases. This makes it difficult to properly quantify Raman signals for large equivalence ratio and air mass flow rate.
The first series of measurements were performed with an air mass flow rate of 0.1 g/s and equivalence ratio of between 0.3 and 0.7 (Figure 7).
The width of the burnt gases jet at half the profile height can be evaluated as 1 mm while the diameter of the outlet hole is 0.5 mm, which confirms jet expansion and diffusion of species in the surroundings of the jet. Combustion processes in the chamber can be estimated as complete and, therefore, combustion efficiency is close to 1 (0.92 with the thermocouple – Figure 5). Indeed, the ratio between oxygen and water molar fractions is very close to that obtained with numerical simulations of complete combustion, and no hydrogen residuals can be found in most cases. A summary of 0.1 g/s air flow measurements can be found in Figure 8.

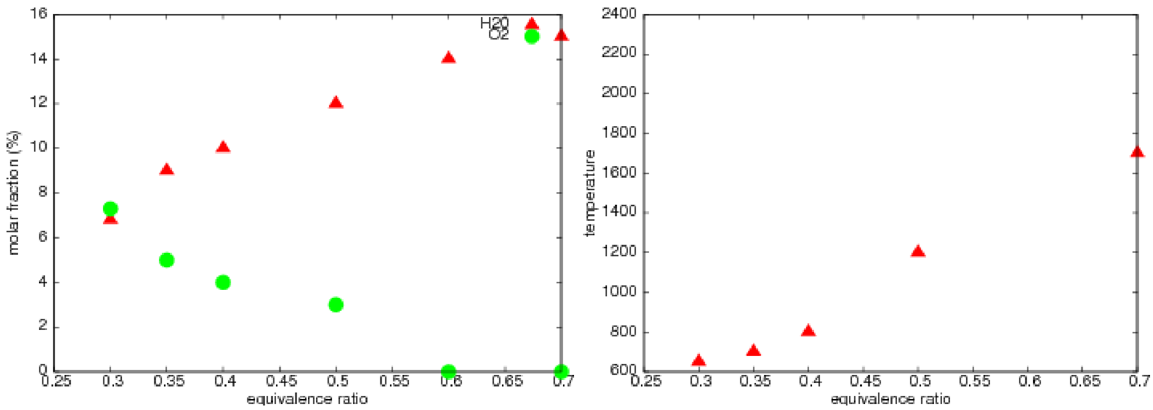

Figure 8: Molar fractions and temperature *vs.* E.R. for 0.1 g/s air mass flow rate.

With larger air mass flow rates comes the problem of blackbody radiation interfering with Raman signals. Therefore, measurements performed with air mass flow rates of 0.4 and 0.5 g/s were restricted to a low equivalence ratio (i.e. $\Phi < 0.5$). As can be seen in Figure 9, there are hydrogen residuals with a typical molar fraction of around 1 % for $\Phi \sim 0.35$. This indicates that combustion is incomplete for this operating condition and combustion efficiency is reduced compared to the cases with lower air mass flow rate. Such results can explain the oscillations observed for the temperature of the combustor walls with this operating condition. Indeed, it is possible that this incomplete combustion leads to instabilities in the chamber and, therefore, to variations of heat transfer to the walls. No hydrogen residuals were observed for a larger equivalence ratio.

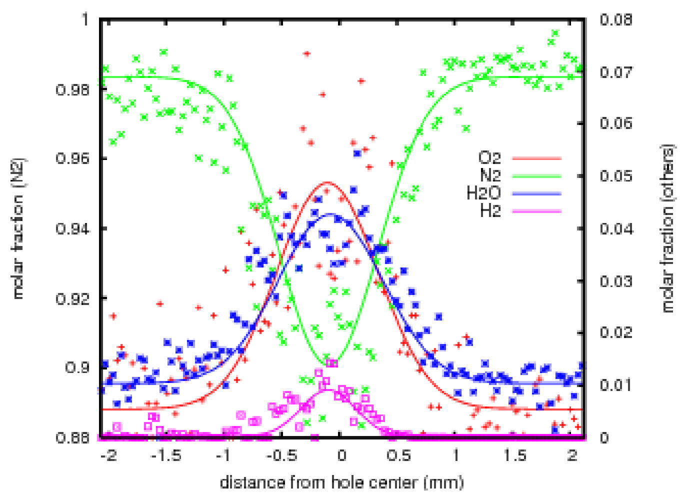

Figure 9: Radial profiles of molar fractions in the burnt gases jet (air mass flow rate: 0.4 g/s, Φ=0.35).

The chemical efficiency is about 0.87 in this case. This value is greater than those obtained with the thermocouple measurement for the exit gas temperature (0.72 – Figure 5).

6. Concluding remarks

For the development of a micro gas turbine engine, stable combustion is mandatory. The experimentations conducted with a first simple geometry micro combustor, in the case of air/hydrogen premixture, are satisfactory. We have obtained the net power of between 150 W and 950 W (which is necessary to provide a net power of 20 W to 100 W of electrical power with a micro gas turbine engine). The combustion is very stable for a large range of air mass flow rates (0.1 g/s to 0.5 g/s) and equivalence ratios (0.3 to 0.7).

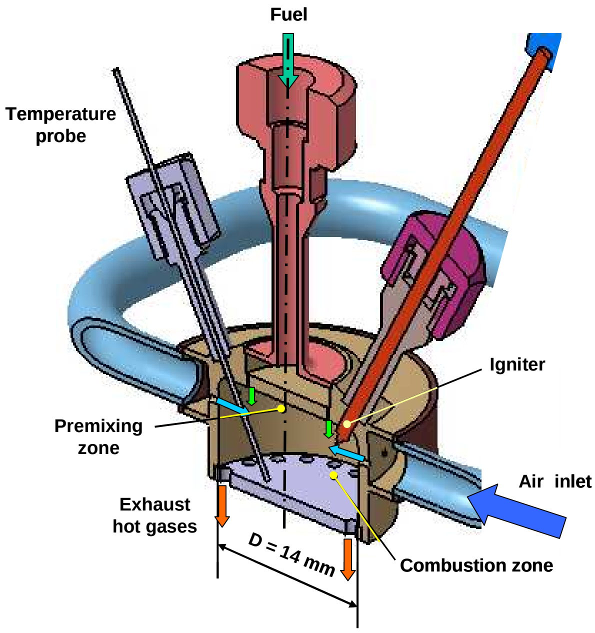

Figure 10: Second micro-combustor – Non-premixed case.

The tests will continue with the spontaneous Raman scattering technique with an air/hydrogen mixture and also with a propane/air mixture.
In the near future, we will test other combustion chambers, the second one is a non-premixed air/fuel chamber (Figure 10) and the third one is a two-stage combustion chamber, directly linked to the new architecture of a micro gas turbine engine (ONERA patent – see paper number 394 -EUCASS 2007).

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