EFFICIENCY AND STABILITY
OF A MESO-SCALE COMBUSTOR AT 3 ATM

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Abstract
The performances of a cylindrical meso-scale swirl combustor having a volume of about 254 mm$^3$ and working at 3 atm have been experimentally investigated. The analysis has been carried out for different equivalence ratios. In these experimental conditions, information about stability and efficiency of the meso-combustor were derived. To this purpose Fourier Transform Infrared Spectroscopy measurements have been carried out at the exhaust of the combustor. The gas concentration results obtained with this analysis are then compared with measurements carried out with commercial gas analyzer.

Introduction
Advancements in microelectronics and miniaturization of mechanical systems like micro-satellite and unmanned aerial vehicles (UAV) have triggered the need for high performance small-scale power generation and propulsion as well for efficient high power-density energy sources. However, the absence of these sources has hindered the progress towards achieving a completely miniaturized system. From this point of view, systems based on combustion are very attractive due to the high energy density of hydrocarbon fuels (~40 MJ/Kg). Thus, development of high efficiency small size combustor is a first step towards the design of devices able to convert chemical energy into mechanical or electrical ones.

Meso-scale combustors have been extensively studied while operating at atmospheric pressure. These studies are essentially devoted to the investigation of the combustor performances also with the application of different diagnostic techniques [1-6]. At the same time, feasibility studies of devices (i.e. micro-turbine and compressor) aimed to convert the chemical energy into mechanical one has been undertaken and demonstrated [7, 8].

The aim of the present work is to investigate more realistic operating condition for a meso-combustor that should operate in a ultra-micro gas turbine. To this purpose, according to the work of Isomura et al [7], the meso-scale combustor performance is investigated at a relatively high, 3 atm, pressure condition.

Stability limits of a methane-air mixture were studied for a range of mass flow rates between 1 Nl/min and 6 Nl/min while chemical efficiency estimation of the combustion was focused on a total mass flow rate of 3 Nl/min and a range of equivalence ratio between 0.7 and 0.9.
Experimental Set-up and Procedure

The AISI 321 stainless steel non-premixed meso-scale whirl combustor studied in the present work (Fig. 1) has a parallelepiped shape with a width and height of 22 mm and a depth of 12 mm. The cylindrical combustion chamber, perpendicular to the squared face, has a diameter of 6 mm and a depth of 9 mm, corresponding to a total volume of 254 mm$^3$. For the optical access to the combustion chamber, two circular quartz windows with graphite sealing are used. Stainless steel pipes (1 mm ID) are used to feed fuel and oxidizer (air). The fuel injection is radial (at the top of the combustor in Fig. 1), while the air injection is tangential (on the right of the combustor) with respect to the combustion chamber, which provides a swirled flow. As it can be observed in the cut-out figure, while the injection holes are placed on the same plane at one extremity of the combustion chamber, the tangential exhaust hole (2 mm ID) is positioned on the opposite side.

The exhaust gas temperature is measured with an insulated N-type thermocouple (1 mm diameter) located at the exit port. As for the temperature of the combustor, a blind hole (2 mm depth) placed on one side allows to allocate a bare wire K-type thermocouple (1 mm diameter). Thermocouple signals are acquired by a 16 bit ADC boards.

![Figure 1. Sketch of the meso-scale combustor (left) and combustion chamber cut-out (right).](image)

In order to operate at 3 atm, the combustor is placed in a stainless steel pressurized chamber with quartz optical accesses. To achieve such condition the regulation of a N$_2$ flow and a needle valve aperture placed at the exhaust of the chamber is required. A digital pressure transducer is used to measure the pressure inside the chamber.

Fuel, oxidizer and N$_2$ flow rates are controlled by thermal mass flow meters (1% accuracy). The operating conditions under study are: total mass flow rate of 3 Nl/min and an equivalence ratio between 0.7 and 0.9.

For the analysis of the exhaust, the sampled gases are sent through an heated transfer line, equipped with a cut-off particulate filter, either to a Fourier transform infrared spectrometer (Nicolet 6700) or to a gas analyzer (see Fig. 2).
As for FT-IR measurements the exhaust gases are sent to a variable pathlength gas-cell (Gemini Mars series 6.4M, internal volume of 0.75 l). In order to prevent condensation, both the transfer line and the gas-cell are temperature controlled and maintained at 393 K.

For each condition an IR spectrum results from the average over 64 acquisitions, with a resolution of 0.5 cm\(^{-1}\), and the background subtraction, this last obtained with N\(_2\) flow. CH\(_4\), CO\(_2\) and CO concentrations in the exhaust gases are evaluated by applying a previous calibration.

As for the gas analyzer measurements, a non-dispersive infrared (NDIR) analyzer is used to measure CO and CO\(_2\) concentration, while an analyzer based on the paramagnetic technique is used for O\(_2\) concentration. The total unburned hydrocarbons are measured with a system based on a FID (flame ionization detector).

From the exhaust gas concentrations, measured with both the FT-IR and the gas analyzer, the chemical efficiency \(\eta_c\) is estimated according to the following relationship:

\[
\eta_c = \frac{[CO_2]}{[CO_2] + [CO] + [UHC]}
\]

Based on measurement accuracy and calibration errors, the estimated accuracy of the efficiency is about 8\% for gas analyzer measurements, and 12\% for FT-IR measurements.

**Results and discussion**

Stability limits are investigated by using the same procedure described in [9]. Lean and rich stability limits were respectively defined as the minimum and the maximum global equivalence ratio before flame blow-out.
In Fig. 3 are reported the results for methane-air combustion. The lean limit is determined to be slightly dependent upon mass flow rate while the rich limit is resulted to be greater than $\Phi = 1.4$ for the conditions studied.

![Figure 3](image3.png)

**Figure 3.** Rich and lean stability limits for a CH$_4$/air mixture - 3 atm.

In Fig. 4 is shown a typical FT-IR spectrum corresponding to a working condition of $\Phi = 0.7$ equivalence ratio and a total mass flow rate of 3 Nl/min. The carbon containing species with the largest concentration are CO$_2$, CO and CH$_4$.

![Figure 4](image4.png)

**Figure 4.** Example of a typical FT-IR spectrum (3 Nl/min; $\Phi = 0.7$).

Quantitative analysis is performed by using the FT-IR proprietary software (TQ-Analyst®) and considering the specific spectral regions of the species under study reported in Table 1.

**Table 1.** Gas species, spectral regions and analysis limits of FT-IR detection.

<table>
<thead>
<tr>
<th>Species</th>
<th>Spectral evaluation range [cm$^{-1}$]</th>
<th>Analysis limits [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>2130 – 2141</td>
<td>218 – 9844</td>
</tr>
<tr>
<td>CO (&lt;100 ppm)</td>
<td>2052 - 2136</td>
<td>3 – 101</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>745 – 765</td>
<td>4342 – 195400</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>2900 - 2930</td>
<td>11 – 501</td>
</tr>
<tr>
<td>CH$_4$ (&gt;500 ppm)</td>
<td>2850 - 2900</td>
<td>449 - 20200</td>
</tr>
</tbody>
</table>
Concentration results are shown in Fig. 5 for CO, CO$_2$ and CH$_4$ (open symbols, normalized to $\Phi = 0.7$), respectively. In the same figure the results of the exhaust gas concentrations obtained with the gas analyzer are overlapped for comparison (closed symbols). The agreement between the two sets of measurements is satisfactory for CO and CH$_4$. The carbon dioxide absolute concentration from FTIR measurements resulted slightly higher than the ones derived with gas analyzer, nevertheless the same trend is observed for the two sets of measurements. It is important to underline that with gas analyzer the total unburned hydrocarbon is detected, and such measurement is here compared with the unburned methane measured with FTIR spectroscopy. This assumption seems to be reasonable since the contribution of other unburned gas species, as derived from FTIR measurements, can be considered negligible.

***Figure 5.*** CO (left), CO$_2$ (center) and CH$_4$ (right) normalized concentrations for the range of equivalence ratio studied.

The chemical efficiency is estimated according to (1) and reported in Fig. 6. A good agreement between the two sets of measurements is obtained.

***Figure 6.*** Chemical efficiency estimated with gas analyzer and FT-IR measurements.

A quite high values of the chemical efficiency, higher than 95%, are obtained for almost all the equivalence ratios here investigated, resulting from both a low UHC level and a CO$_2$/CO ratio in excess of 15/20.
Conclusions
The stability of a meso-scale combustor operating at 3 atm pressure has been experimentally investigated. Chemical efficiency estimation has been evaluated using both gas analyzer and FT-IR analysis. Results showed reasonable agreement between the two sets of measurements. As further work, it could be interesting the investigation with different operative conditions: a different fuel (propane) and pre-heated air.

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References
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