

# TESTING AND NUMERICAL STUDY OF A 10KW HYDROGEN MICRO COMBUSTOR

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**Abstract:** A comparison between experiments and numerical simulations of a 10kW hydrogen micro combustor is presented. Three steps are compared: mixing by hydrogen jet in an air cross-flow, general combustor flow field in cold flow and, finally, flame shape and temperature profile for the real scale combustor in reacting conditions.

**Key Words:** hydrogen, micro combustion, micro mixing, jet in cross-flow, “Regular Micromix” combustor.

## 1. MOTIVATION

Hydrogen micro combustion studies are pushed forward by the increasing request for small power generators or propulsion systems for small unmanned aerial vehicles (UAV), and by the stronger regulations in terms of pollutant emissions. However reducing the size of the combustor introduces new challenges to be overcome as the study of micro mixing, thermal losses or the relatively large size of the fuel supply.

The Royal Military School of Belgium (RMS) and Aachen University of Applied Sciences in Germany (ACUAS) work both on hydrogen combustion for micro gas turbine engines. In Belgium, the PowerMEMS [6] consortium groups several universities in order to design a micro gas turbine ( $\mu$ GT). This  $\mu$ GT integrates a heat exchanger and an electrical generator, and is using hydrogen as fuel. The RMS is in charge of the combustor development. At ACUAS, nearly 20 years of experience in hydrogen combustion research for gas turbines exists [4, 5], so a complementary collaboration has been set up coupling the experience in testing and the test facilities of ACUAS with numerical simulations at the RMS.

## 2. “REGULAR MICROMIX” INJECTOR

The current state of the ACUAS combustion chamber under development integrates the so-called “Regular Micromix” burning principle for

gaseous hydrogen originally designed by ACUAS for the use in small gas turbines like auxiliary power units in airplanes. The Regular Micromix concept is a non premixed diffusive burning principle. Each injector is composed of a fuel jet (hole of 0.2 mm diameter) penetrating radially into an axial cross flow of air which enters the combustor via a half circular inlet. A crown of 60 injectors creates the annular combustor which has an outer diameter of about 60 mm. Downstream of the hydrogen injector a step enlarges the chamber and permits the anchoring of the flame. The combustor is 20 mm long and has a radial inwards oriented outlet designed to match the radial turbine proposed for the micro gas turbine. A combustor slice corresponding to one injector is presented on Figure 1.

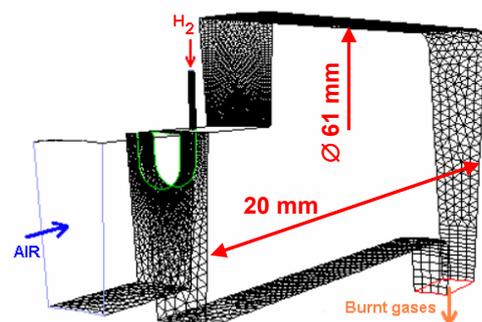


Figure 1 - Geometric description of one injector of the micro combustor

## 3. CROSS-FLOW MIXING STUDY

First, a comparison between numerical simulations and experiments will focus on the cold flow mixing. Three different distances

separating the air inlet and the hydrogen holes will be studied in order to get a better understanding of the interactions between the jet in cross-flow and the free shear layer. Experiments are done using an upscaled water analogy test facility where the visualizations of the jets in cross flow were made by milk injection at the hydrogen inlet for visualization of the injected jet. The geometry used for the numerical simulations was adapted to match the test set up: an axial outlet is considered. Simulations are run in cold flow. Figure 2 presents the comparison. Along the flow path, the mixing – decrease of hydrogen molar fraction – is visible. The jet stays in the air flow coming from the air injector and does not penetrate in the recirculation zone created by the air injector. There is no interaction between jet and free shear layer due to this recirculation. For this reason, the mixing process remains unchanged if the distance between air and hydrogen injectors is increased to 2 or 3 mm. This result is confirmed by the simulations and by the water analogy [7] testing in Figure 2.

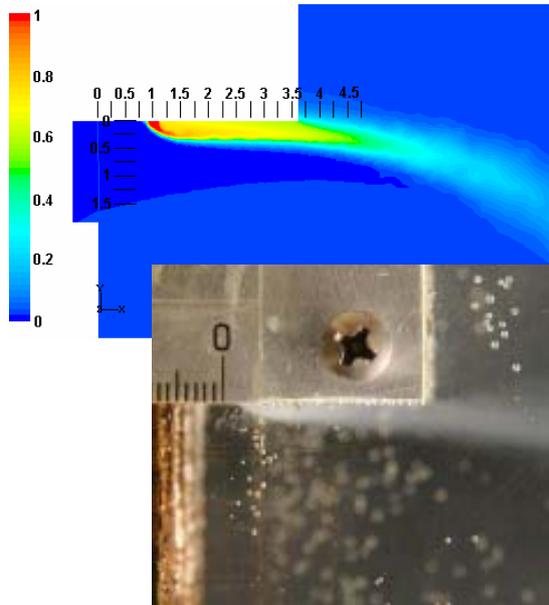


Figure 2 - Comparison between contours of hydrogen molar fraction and water analogy

Some vortex structures resulting from a jet in cross-flow are unsteady like the wake vortices. They cannot be resolved by the RANS approach but steady vortices are well captured. The most important for mixing, the contra rotating vortex pair, are for example captured. On Figure 3,

velocity vectors show the good mixing by entrainment of air into the hydrogen jet.

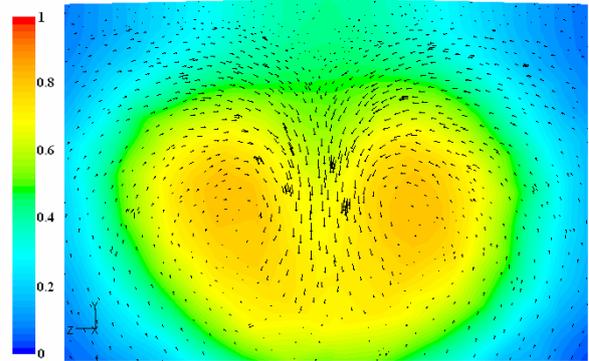


Figure 3 - Contours of molar fraction of hydrogen and velocity vectors.

(Plane perpendicular to the axial flow at 5 diameters of the  $H_2$  injection center)

#### 4. COMBUSTION CHAMBER FLOW FIELD STUDY

Secondly, the global and cold flow field will be investigated. The water analogy test facility reproduces the combustor with a step, an inner sided outlet and a 20 mm length. Figure 4 compares the path lines issued from the numerical simulation to the visualization using soap in the air flow [7]. Three recirculation zones are present. A first one just behind the air injector creates the free shear layer. The second, the smallest, is located behind the step enlarging the combustion chamber. This zone stabilizes the flame. Finally, there is a recirculation zone in the upper right corner of the chamber.

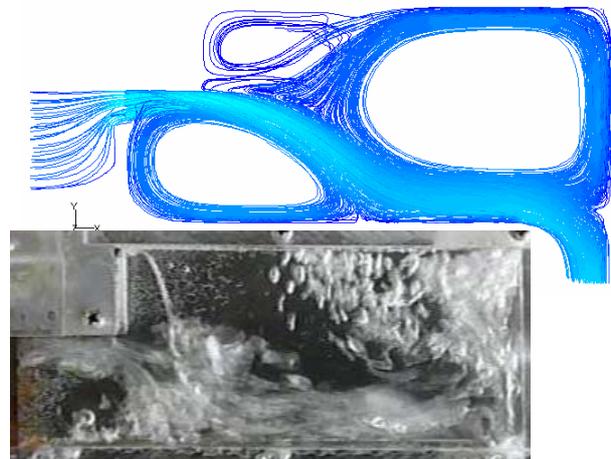


Figure 4 – Comparison between path-lines issued from the air inlet & water analogy

## 5. COMBUSTION TEST & HOT FLOW SIMULATIONS

Finally, the reacting flow is investigated for the chamber's design point ( $\lambda=6$ ; 6.7 g/s air;  $T_{inlet}=690$  K). Here flame shape, outlet temperature and species will be compared. Figure 5 presents the flame shape and the contours of static temperature. The test runs with an operating pressure of 1 atm. The flame attachment point is located at the external corner of the so called "step". This step creates a recirculation zone at low velocity. The dark blue zone is due to the hydrogen injected at 300 K. Air has an inlet temperature of 690 K. The high flame temperature is reduced afterwards by mixing with the third recirculation zone. Maximum temperature is 1620 K. Walls near the flame attachment point do not see a too high temperature. Hydrogen is preheated by the walls.

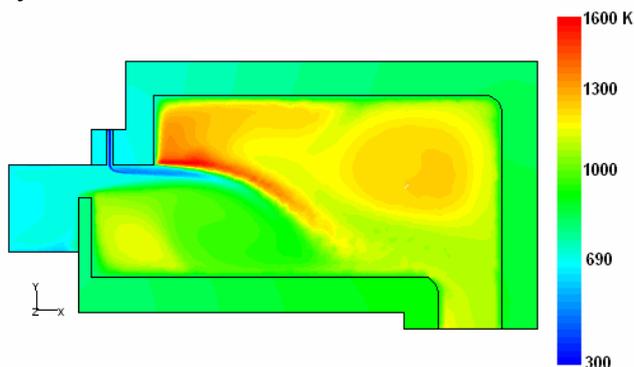


Figure 5 - Middle plane: contours of static temperature (K).

Mass weighted average of the static temperature at the outlet section equals 1100 K. Experimental temperature given by exhaust gas analysis for adiabatic conditions is 1136 K. With a stainless steel chamber, three thermocouples in the axial direction (at 2.7, 9.45 and 16.2 mm from the external step) are placed in the external wall. One measurement is taken at the outlet section also in the external wall. The injector studied by the numerical simulation is the one at 12 o'clock position.

A difference of about 60 K is observed between simulations and experiment but this difference is about constant for each measurement point.

	<i>Experiment</i>	<i>FLUENT</i>	<i>delta</i>
<i>T1 axial</i>	807 K	750 K	57 K
<i>T2 axial</i>	872 K	812 K	60 K
<i>T3 axial</i>	905 K	842 K	63 K
<i>T outlet</i>	967 K	904 K	63 K

Table 1 - Comparison of wall temperatures between experiment and FLUENT-simulation



Figure 6 - Combustion test in the quartz chamber at design point  $\lambda=6$  and air mass flow of 6.7 g/s

Figure 6 is a picture of the combustion test. The injector studied by the numerical simulations is the upper injector. The luminous bar is the igniter. The inner side quartz wall is clearly visible. This figure has to be compared with Figure 7 that presents the flame shape with OH species contours. A good agreement is reached, the flame is anchored to the external step and directed inwards as in the experiment. One small flame is present for each injector and the different flames do not mix together.

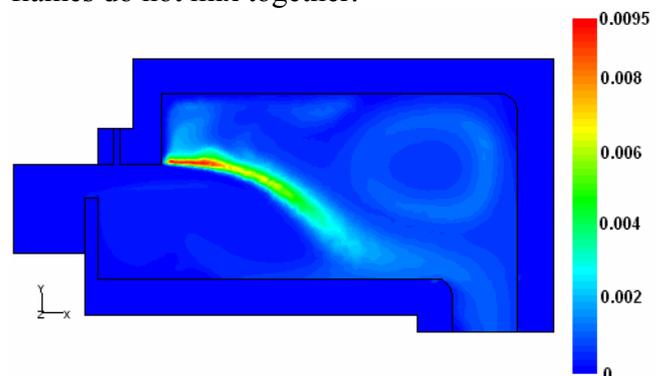


Figure 7 - Middle plane: contours of OH molar fraction.

Walls temperatures stay in an acceptable range; below 1030 K. External boundary conditions are

given by heat transfer coefficient, emissivity and external temperature. For meshed walls no great temperature difference is noticeable between inner and external sides. The hottest point is at the combustor exit. Zooming to the hydrogen injection region, the cooling effect of hydrogen on the wall can be seen. Figure 8 presents plots of static temperature at the chamber outlet for constant angular coordinate ( $-1^\circ$ ,  $0^\circ$ ,  $1^\circ$ ,  $2^\circ$  &  $3^\circ$ ). The chamber outlet is defined before the small convergent pipe representing the turbine stator vanes. The same shape is observed at  $-1^\circ$  and  $+1^\circ$  of the  $6^\circ$  slice of combustor. Along this radial direction, a temperature maximum is present at the hydrogen injection location.

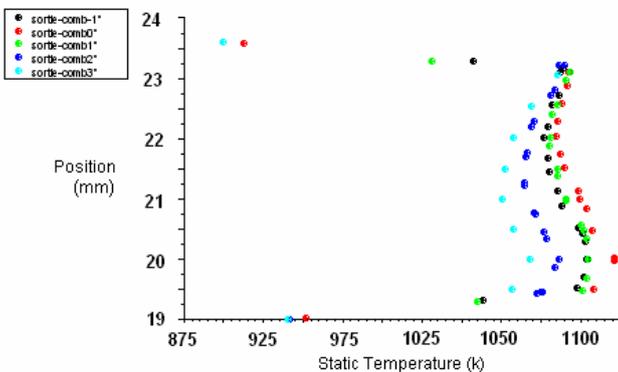


Figure 8 - Static temperature profiles at outlet, cut @  $-1^\circ$ ,  $0^\circ$ ,  $1^\circ$ ,  $2^\circ$  and  $3^\circ$

## 6. CONCLUSIONS

The efficient collaboration coupling the test experience at ACUAS and the numerical simulations at RMS allowed adapting and characterizing the “Regular Micromix” injector to the PowerMEMS micro combustion chamber. The 10 kW of thermal power is produced by a crown of 60 injectors.

The problem is divided into three steps. First the hydrogen-air mixing is investigated. Numerical simulations are compared to a water analogy test where mixing is visualized by milk injection. A good agreement between both results is reached. The interaction of a hydrogen jet with an air cross flow creates several vortices. Contra rotating vortices enhanced well the mixing process. The second step is the comparison of the main flow field. Water analogy is adapted to a 20 mm chamber length. Soap injection in the water analogy allows a good visualization of the

recirculation zones and offers a good agreement with the numerical simulations. Reacting flow investigations are done on the combustion chamber test rig with two different test set-ups. The quartz chamber allows flame visualization and shows a good agreement with the contours of OH species given by numerical simulations. The stainless steel chamber equipped with thermocouples delivers the wall temperature data. Besides the study of flow phenomena in cold and hot flow, combustion simulations show a good agreement. The absolute level of combustion chamber outlet temperatures is matched quite well, too. Also the wall temperature variations are caught by the numerical simulation and show good agreement against the experimental results.

So the “micromix” diffusive burning principle was successfully scaled down for the potential use in a  $\mu$ GT by experimental means. Also the underlying flow phenomena for the combustion chamber design were investigated and generally understood by experimental results, flow visualization and numerical studies.

Further work will focus on pressurized tests (3 bars) by experimental as well as numerical means.

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