Development of a Non-Premixed Ultra Micro Combustion Chamber

J. Trilla, P. Bécret*, J. Grossen*, W. Bosschaerts* and P. Hendrick***
**Royal Military Academy of Belgium, Applied Mechanics Department*
Avenue Renaissance 30, B-1000 Brussels, Belgium
***Université Libre de Bruxelles, Faculty of Applied Sciences*
CP165/41, avenue F.D. Roosevelt 50, 1050 Brussels, Belgium

Abstract
The increasing energy needs for portable consumer electronics such as cellular phones and laptop computers motivate the development of compact power sources, called PowerMEMS. Even if overall efficiencies of only a few percents are reached, the system weight and size could be reduced significantly by the use of fuel based systems comparing to the most performing batteries of today. Of those fuel based PowerMEMS, micro gas turbines are expected to offer the highest power density.

This paper presents the collaboration between two research groups, the RMA and FH Aachen for the development of an injection system prototype for a micro gas turbine combustion chamber using H_2 as a fuel. The aim of this study is the development of a combustion chamber for a micro gas turbine delivering around 1 kW. In this text, two different concepts are described and basically the CFD work is reported. The results are showing a first good agreement with FH Aachen experiences and promise an interesting on-coming work.

1. Introduction

Micro gas turbines have experienced a growing interest in the last decade due to the new manufacturing technologies from the semiconductor industry that enable the construction of gas turbines with diameters of a few millimetres or centimetres. The micro gas turbine potential for a large energy density namely makes them attractive for portable power units as well as for propulsion of small unmanned aircrafts. Both applications namely need a high performance of the power delivering system to reduce the weight and size of the overall system. Even with efficiencies in the order of a few percents, micro gas turbines offer a reduction in weight compared to both primary cells as well as rechargeable batteries (see ref. [1], [2], [3] & [4]).

Around the world, several groups are currently working on ultra micro gas turbines, following the example of MIT where the different components of the micro gas turbine have been designed, manufactured and tested. In Belgium, the PowerMEMS group launched such a project too. This project groups several universities and research institutes (KU Leuven, IMEC, VKI and RMA) and is aimed at the development of the different technologies required for replacing rechargeable batteries in a wide range of applications. Besides the fuel-based systems, power scavenging systems ranging from a few µW till the mW range are also pursued for the group. At a certain moment, for the Belgian PowerMEMS project, a relatively high mass flow rate was adopted (compared to other micro gas turbine projects). Besides the increase in power output, this also results in a slightly turbulent regime inside the combustion chamber. Later in this text, Figure 12 presents the layout of the global machine for the Belgian project.

Reducing the size of a gas turbine to a centimeters scale or less of course poses some new challenges which, on their turn, demand some new design methods. The design space for the combustion chamber, for instance, is significantly constrained by the need for a sufficiently high residence time to complete the combustion which prevents a simple scaling down of a classical combustion chamber from a large scale conventional gas turbine. This paper reports the method used by the Royal Military Academy (RMA) for the design of the combustion chamber for such an ultra micro gas turbine, with the emphasis on the numerical simulation aspects. A first section of the paper addresses an overview of two new injection systems at the micro scale that are being analyzed and tested for our final global machine. The second part of the paper then discusses the CFD results obtained for both concepts, the so-called regular and inverse micromix combustion chambers.

2. Hydrogen injection system design

The injector design and technology was a relatively new field at the RMA a few years ago while at FH Aachen university a huge experience on injection systems was available (see reference [16]). Systems as the micro injectors for an APU have been tested and built in their facilities. The reduction of one of the existing micro injection system was thus the first concept to analyze. This so-called "Regular Micromix" injector presented an axial air inlet with the hydrogen injected radially through a micro cavity. Just reducing to the micro scale presented a new challenge for the group. The mixing process, done upstream, is based on a cross-flow interaction between hydrogen jets and an axial air flow (the main flow). 60 half circular slots increase the air velocity in order to improve mixing. One hydrogen injection hole is placed in front of each air gap. After that, a version for an axial H_2 injection was considered too (the so-called "Inverse Micromix"). Some experience with both concepts was acquired in the past at FH Aachen.

Figure 1 presents and compares both ideas. At the left-hand side, the Regular Micromix is shown where mixing is done by penetration of hydrogen jets established by holes of 0.2 mm diameter in the air cross flow. While at the right-hand side, the Inverse Micromix uses axial hydrogen injection. The hydrogen is delivered through a porous plate characterized by holes of 3 micrometers diameter.

This collaboration was thus an interesting challenge for both groups; for the RMA the benefit of an experienced partner in testing combustion and for FH Aachen the work done in CFD simulations at the RMA that was useful to validate and further develop their concepts.

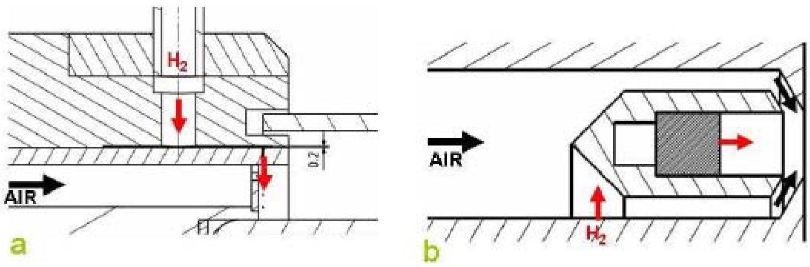

Figure 1: FH Aachen injection concepts to micro scale: regular (a) & inverse (b) micromix

3. CFD on the "Regular Micromix Injection system"

Integrating this concept to our global machine appeared to be not too complex because of its general combustor simplicity. However, the injection part had to be optimized to have a good mixing and to stabilize the flame as much as possible. CFD was then an interesting tool.

Figure 2 presents a global view of the combustor. At the left, the manufactured combustor is shown while at the right a 3D view of the CFD model is depicted. Dimensions of the combustion zone are presented. The air mass flow is coming axially while hydrogen is supplied around the combustor before being injected radially into the combustor (see red arrow). The simulations were thus focused on optimising the injection region.

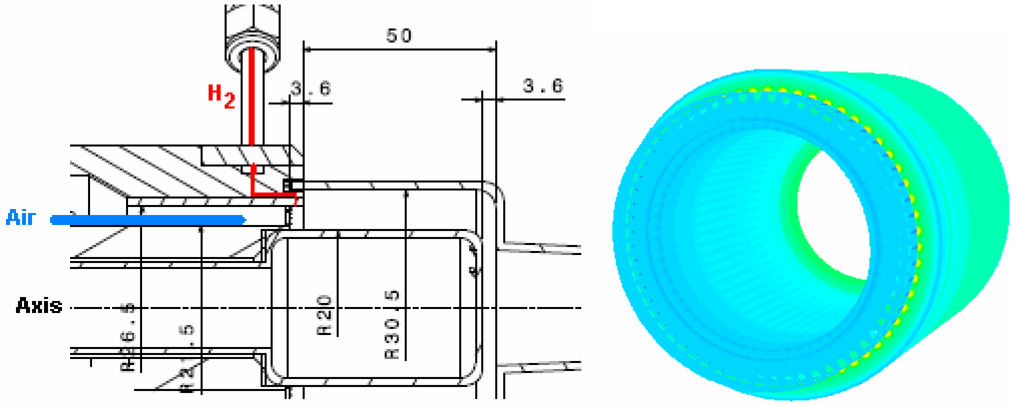

Figure 2: Global view of the combustion chamber with the regular concept (dimensions in mm)

The CFD work strategy was planned with the following steps. First, atmospheric pressure simulations have been done, with one injector modelled and then three injectors (to see the boundary condition influence). All the walls are represented and colored by temperature (K) in Figure 2. The 60 air injection holes are visible. In this simulation, the walls are not meshed but present a 2 mm virtual thickness.

The boundary conditions for the two lateral faces are periodic boundary conditions. So the finite volumes of the two lateral faces are mathematically neighbours. In other words what goes out from one side goes in at the other -linked- side. Walls are not meshed; just a virtual thickness of 2 mm is given. Heat transfer coefficient and emissivity are also given. In order to capture the mixing by cross-flow without having a too expensive computational cost, a refinement of the mesh has been used in the mixing zone. After a couple of iterations, to improve our results, velocity and temperature gradient based on mesh refinements have been used.

Figure 3 presents the comparison between contours of static temperature resulting of our simulation and the experimental test set-up built at FH Aachen. The results of the simulations present the temperature of the inner wall (with the corresponding colorbar on the left) and the high temperature region corresponding to the flames (colorbar on the right).

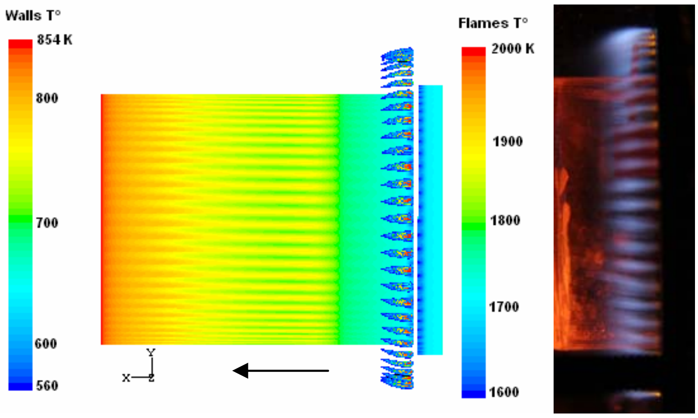

Figure 3: Comparison between simulations and experiment

The simulation gives a maximum inner wall temperature of 854 K. The shapes of the small flames are very similar between simulation and experiment. One flame is created in front of each hydrogen injector. Each flame is tilted towards the inner side of the combustor. Flame temperature reaches about 2000 K. The shape of the flame is presented on Figure 4. The 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 is at an inlet temperature of 690 K. The high flame temperature is reduced afterwards by mixing the hydrogen-air with the unburned air.

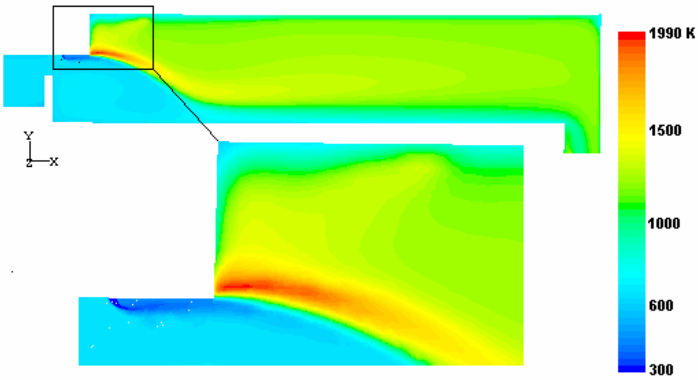

Figure 4: Middle plane of the combustor: static temperature contours (K)

An important check for a good injection system is the penetration jet. Figure 5 presents different cuts in the flow-field, allowing the visualization of the vortices due to the cross-flow, the left cut shows a reversed flow just after the hydrogen injection. This sector is characterized by a low total velocity. The small horseshoe vortex due to the boundary layer is visible just before the hydrogen jet. At the right side, the measure of the end of the penetration jet is taken : around 0.3 mm.

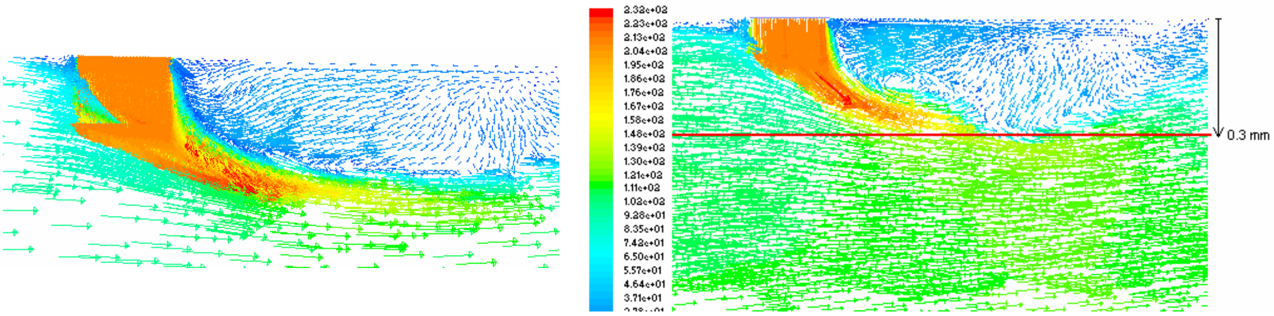

Figure 5: Middle plane: velocity vectors colored by velocity magnitude [m/s]

In the literature, from the reference [12], a calculation for the maximal jet penetration was obtained. As a first calculation, the CFD results presented a relatively good agreement with the reference (see equation (1)).

$$Y_{\max} = 1.15 d_j \left(\frac{\rho_j U_j^2}{\rho_g U_g^2} \right)^{0.5} \sin\theta = 0.255 mm \tag{1}$$

The boundary conditions at both sides were also understudied. Two options were checked: symmetric BC & periodicity. Figure shows the Z velocity vectors on the lateral boundaries. At first sight, these vectors can look strange because what goes in does not go out at the opposite boundary; the linked vectors go both inside (and outside). This result seems unphysical. The only way to satisfy the physics is that the linked vectors compensate themselves. Checking the velocity magnitude, it can be seen that it is our case. That gives us the conclusion that these periodic planes are equivalent to symmetry planes. The influence of one injector is compensated by the influence of the neighbour one.

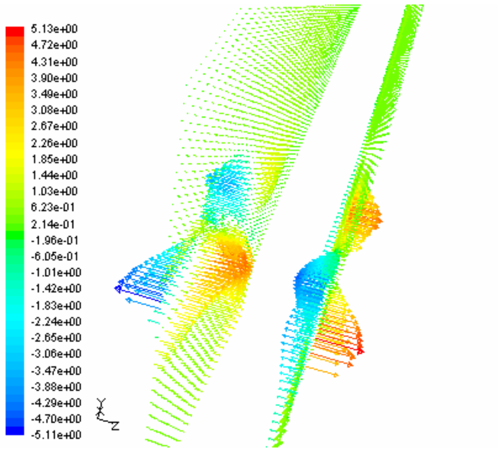

Figure 6: Periodic planes: vectors of Z velocity colored by Z velocity magnitude

These non-zero Z velocities on the lateral boundary-planes were verified with a 3 injectors-simulation in order to detect the possible interactions. The interactions between different hydrogen injectors were also investigated. Figure 7 plots the perpendicular cut 9 mm behind the hydrogen injector. From the static temperature profile, three identical flames are not anymore present. The central flame is smaller and less stretched than the two external ones. This shape can be explained by looking to the velocity vectors on the right side of the plot. Indeed, the external flames have larger Y and Z velocity magnitudes than the central flame.

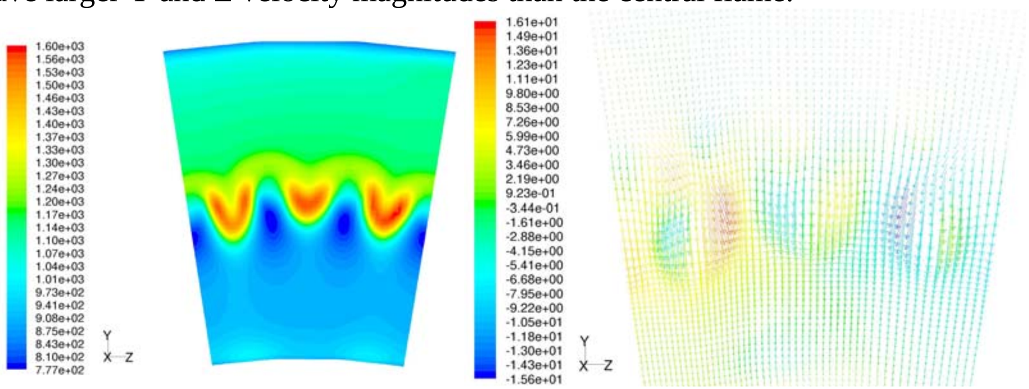

Figure 7: Y-Z plan 9 mm after injection: contours of static temperature (K) & vectors of velocity magnitude

At the moment, different new configurations on this concept are being simulated by CFD and will be tested in an early future. The position of the injector as well as the kind of recirculations desired to improve mixing are parameters to be checked first through CFD simulations. The intention of this collaboration is the result of a final co-joint injection system to be used for the Belgian PowerMEMS prototype. However, not only this option is considered. The inverse micromix concept appeared to be much more integrable to our design status. The research done with this second configuration is described in the next paragraph.

4. CFD on the "Inverse Micromix Injection system"

As a first approach, the introduction of such an injector into an annular combustor was planned. The combustor chosen was an annular chamber with a step. The injector was located just before this step, leaving small gaps and angles to optimize. The good point of this design was the presence of a porous block to inject the hydrogen to avoid flashback. In the right picture on Figure 8 this concept is shown and also the different parameters to play with. The angle between the vertical direction and the injector, the entry gap and the discharge opening are the main geometrical parameters to define.

To start with, a parametrical study of all these geometrical parameters was carried out at the RMA. This parametric study was done to understand the effect of each design parameter in our design. The evolution of those simulations was always updated and validated by FH Aachen, mainly to know whether it was manufacturable or not. Despite the fact that in terms of mixing, some geometries were acceptable, an important issue appeared: the high wall temperatures achieved. With an equivalence ratio (The equivalence ratio means the fuel to air ratio divided by the fuel to air ratio in stoichometric conditions) of about 0.165, the average temperature at the outlet is about 1200 K, as required by the cycle analysis (with the current conditions of 20 g/s & 3 bar). New techniques to cool down these walls were thus needed. As it was done in the past in our previous design, the addition of dilution air was analyzed first.

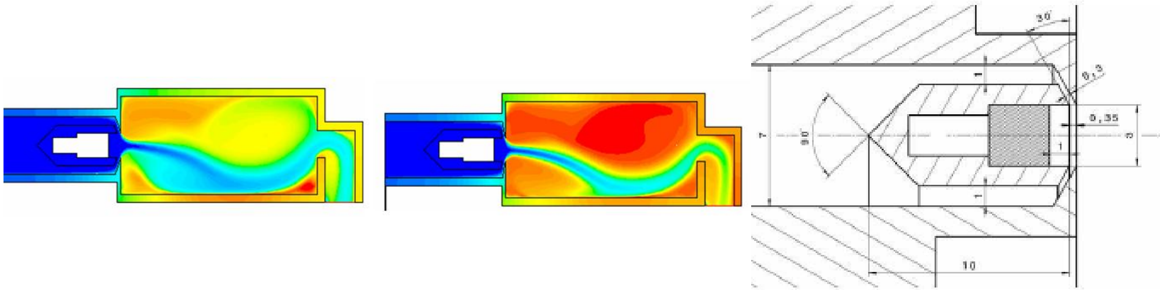

Figure 8: Two cases simulated (temperature profile) & geometrical detail on the inverse micromix concept

The temperature profiles indicate the high values achieved at the solid walls. These two geometries differ on the entry gap of the air : on the left side the 0.4 mm case and on the right the 0.5 mm one. The bigger the gap, the lower the air acceleration.

The too high wall temperatures were really a problem for our application. The integration into the overall gas turbine and the addition of the dilution was namely adding complexity. However, considering the dilution air as a fraction of the main flow (20 g/s), an axial by-pass air was considered. In the next paragraph this new design with dilution is described.

5. The integration into the micro gas turbine

In the development of this new design, the use of the total available space and the introduction of axial by pass air were the important points. Figure 9 presents this new design, a simple annular combustor with the Inverse Micromix injector (FH Aachen concept) and a kind of plate to split the air and also to serve as flame holder. The optimization of the different geometrical parameters was an interesting CFD work to do.

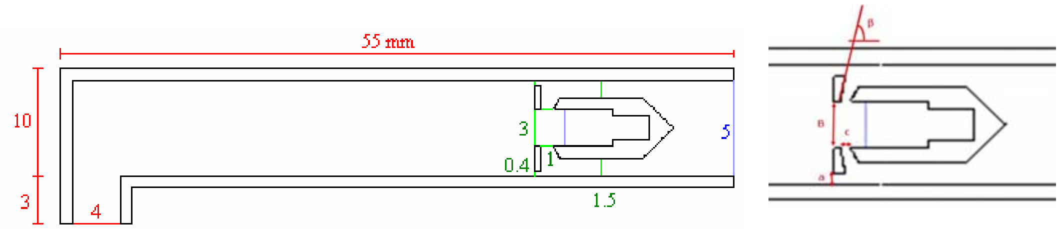

Figure 9: Axial by pass air combustor to use the inverse micromix injector

At the same time, at FH Aachen as a first step in the testing process, the development of a planar prototype of the Inverse Micromix concept was achieved. The geometries studied in this section are for the planar prototype. A two dimensional analysis was done. The combustion chamber's limits are fixed by the available place (55 mm length & 10 mm radial height). The injection system is composed by a 30° inclination injector and two rectangular deviation plates allocated to separate the flow between mixture and by-pass air. Rectangular deviation's plates are chosen because they incline 90° from the axial direction air mixing flow. It creates a radial air injection. The two air flow impact together producing a good mixing. An optimization process was carried out by the RMA by analyzing those parameters:

-By-pass channels & deviation's walls optimization
-Uniformization of outlet temperature distribution
-Optimum distance between deviation walls and injector
-Reduction of 'air-H2' section

Some differences rise between 2D and 2D axi-symmetric simulations. For the same 2D sketch, real surface is not the same. For 2D axis, an annular surface is considered and for 2D, a planar design with 1 m depth is taken into account. Enforce mass flow boundary condition would not produce the same velocity profile. For 2D study, mass flow conditions have to be recalculated. As the sketch in 2D and 2D axi will be the same, we impose the same air velocity at the inlet and the same equivalence ratio. Another difference that will influence mass flow is operating pressure. As 2D axis simulates the annular combustor after the compressor, operating pressure is 3 atm. And in 2D simulate the planar prototype running at 1 atm. All simulations run with inlet's temperatures of 600 K. Equivalence ratio is chosen at 0.1652 and air inlet velocity magnitude at 9.0568 m/s. It gives following mass flow: for air 0.04263 kg/s and for hydrogen 0.00020677 kg/s.

In the optimization process, the mixing zone appeared to be critical as well as important. Again, the gap and the discharge opening were parameters to check. The results of the investigation are depicted on Figure 10.

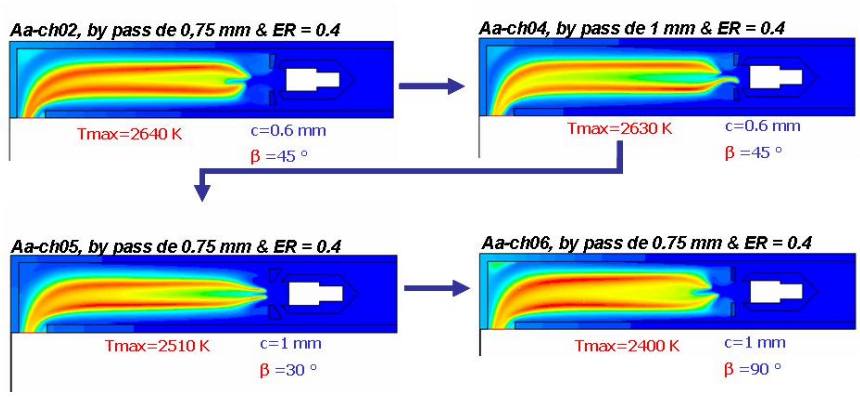

Figure 10: Temperature profiles of some geometries modeled in the optimization process

Another important issue for our final design and its integration into the global machine is the interferences with the two components that we have before and after the combustion chamber: the heat exchanger and the turbine (inlet stators). The inlet conditions were therefore checked. Until now, no exact conditions were known at our inlet. Approximately, the air temperature at the exit of the compressor is about 420 K, and then in the heat exchanger, it is heated up by 150 to 200 K. So an inlet temperature of about 600 K is reasonable to take into account.

Finally, concerning the interaction with the turbine, the temperature distribution is the main requirement from the turbo machinery point of view. 1200 K exhaust gas temperature as uniform as possible is the only need to deliver the expected power. A more uniform distribution is really necessary as well as an optimization of the by-pass air ratio. Indeed a too high temperature was reached in the middle of the outlet section. The axial air by-pass, cooling walls, leads to low walls temperatures. Hot exhaust gases hold the center. So a large temperature variation along the outlet section is obtained. The outlet section is taken to 4 mm width. A 3 mm high vertical pipe is added after the combustor in order to better understand the flow in the turbine inlet.

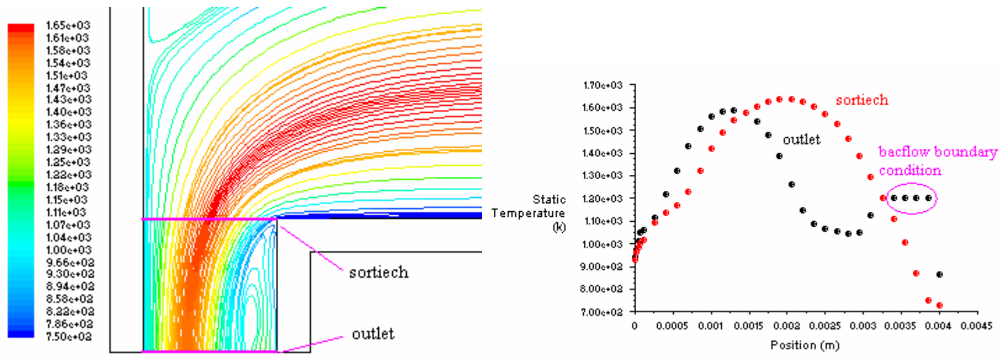

Figure 11: Particles trajectories colored by static temperature (K) & temperature distributions

Particles trajectories show a recirculation zone in outlet pipe due to the stall of the flow from the inner wall. This recirculation zone creates a smaller available section and gives bad information on the outlet average temperature. Certainly backflow temperature in the boundary conditions is defined. Mean temperature cannot be calculated at the outlet, a better result will thus be obtained at the section called ‘sortiech’, before the recirculation zone. To calculate a mean temperature, taking into account non uniform velocity profile, the mass-weighted average of static temperature will be used. Mass-weighted average is defined as:

$$\frac{\sum_{i=1}^{n} \phi_i \rho_i \left|\vec{v}_i . \vec{A}_i\right|}{\sum_{i=1}^{n} \rho_i \left|\vec{v}_i . \vec{A}_i\right|} \tag{2}$$

Static temperature average at the outlet of the combustor (in section called sortiech) equals 1314.5 K. Temperatures profile gives a maximum temperature of about 1650 K, so difference of 350 K. Figure 12 plots the integration of such a geometry with the global machine status. The next step of this research should be a detailed analysis of the final connections between the different components. These "connectors" will influence of course the geometries themselves. Nevertheless, the optimization of the mixing region has been achieved through CFD and the ongoing tests will confirm our expectative.

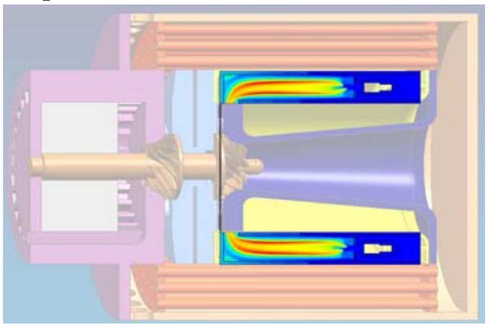

Figure 12: General powerMEMS micro gas turbine layout

6. Conclusions

For the realization of a micro gas turbine, stable combustion in small volumes is mandatory. At the Royal Military Academy of Belgian, a partner in the Flemish PowerMEMS consortium, a research group is actively developing this type of energy source. At the same time, at FH Aachen, the development of injection systems and the use of H_2 as a fuel have been usual topics of work. A cooperation between both institutes has thus been set up to group their expertise. This collaboration is manifested here through a set of experiments conducted at FH Aachen on a miniaturized combustion chamber and calculations realized at the RMA with Fluent®.

This text describes the CFD calculations with the two main concepts that were analyzed, and qualitatively shows an acceptable correspondence with the first set of tests. The cooperation will thus be extended to refine the comparison for these results. In terms of simulations, the final optimization of a combustion chamber with one of these concepts is pursued. The Regular micromix, as well as the Inverse concept, are still two valuable options for our final micro CC design. In the coming weeks, the planar prototype for the inverse configuration will be tested as a first stage to an annular prototype integrable to our current micro gas turbine.

Concerning the regular micromix, a new miniaturized combustion chamber with an architecture feasible for the current micro gas turbine will also be tested soon. Besides the wall temperatures measurements, some optical techniques to measure species are being analyzed. This approach will allow an estimation of the chemical efficiency which, multiplied with thermal efficiency, yields the overall efficiency of the micro combustion chamber. The numerical efforts will also be continued at the RMA with the commercial Fluent® software.

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