DEVELOPMENT OF A HYDROGEN COMBUSTION CHAMBER FOR AN ULTRA MICRO GAS TURBINE

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Abstract: In the ongoing miniaturization, ultra micro gas turbines have experienced a growing interest around the world. High performance of the power unit and reduced weight and size of the overall system for the propulsion of small unmanned air vehicles as well as for portable power generation systems is required. In Belgium, the Flemish PowerMEMS Consortium groups several universities and research institutes developing an ultra micro gas turbine (µGT). This µGT integrates a heat exchanger and an electric generator, using hydrogen as a fuel. The Royal Military School of Belgium (RMS) and the Aachen University of Applied Sciences in Germany (ACUAS) work both together on hydrogen combustion for micro gas turbine engines. Detailed investigations on the burning characteristics for different chamber configurations were carried out for an optimization of the burner concept.

Key words: hydrogen, micro, powermems, combustion chamber, micromix

1. INTRODUCTION

Micro gas turbines have experienced a growing interest in the last decade due to new manufacturing technologies from the semiconductor industry that enable the construction of gas turbines with diameters of a few millimeters or centimeters. The micro gas turbine potential for a large energy density makes them attractive for portable power units as well as for propulsion of small unmanned aircraft. Both applications 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 (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 an ultra micro gas turbine have been designed, manufactured and tested. At the opposite of the MIT's 2-D design and ~17W of electrical power output, the powerMEMS group in Belgium launched a project to develop a more conventional 3-D design µGT in the 1 kW range. This project groups several universities and research institutes (KU Leuven, IMEC, VKI and RMS) and is aimed at the development of the different technologies 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. In this collaboration framework, two so-called micromix principles for diffusive hydrogen combustion have been developed, optimized and tested. Figure 1 illustrates both mixing concepts: the “Regular Micromix” (a) principle, where hydrogen is injected into an airstream, and the ”Inverse Micromix” (b**)** principle, where air is injected into a hydrogen atmosphere. The numerical results as well as the experimental results for both principles will be described here with a focus on the inverse concept.

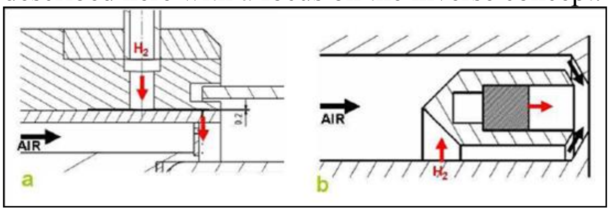

Fig. 1: Micromix concepts

Numerical investigations (CFD)

On the side of the simulations, a Reynolds Average Navier-Stokes (RANS) approach has been preferred. Fluent together with Chemkin were selected as CFD codes. A reduction of the computational costs has to be performed considering the large number of geometries to be tested. The turbulence model is a k-Omega Shear Stress Transport model (SST), which has been chosen considering the large presence of walls. Chemical reactions are calculated by a Chemkin scheme of 18 equations, containing 9 species (N_2, N, O_2, H_2, O, H, OH, H_2O and HO_2). A link between turbulence and chemical reactions is set up by the use of Eddy Dissipation Concept (EDC) where reactions take place in small turbulence scales.

2. REGULAR MICROMIX PRINCIPLE

2.1 Geometry description

The so called regular "micromix" diffusive burning principle of gaseous hydrogen is based on the fluid mechanical phenomenon of jets in crossflow. This well known mechanism is widely used in a great variety of industrial and aerospace applications like V/STOL aircraft, turbine blade cooling or dilution holes in gas turbine combustors. The air is entering the chamber through U-shaped holes in a guiding panel. At a specific distance downstream of the guiding panel, the hydrogen is injected via 0.2 mm diameter holes (one for each hole in the air guiding panel). In total there are sixty injection holes radially arranged over a diameter of 53 mm. After the injection zone, there is a Carnot diffuser like discontinuous enlargement bringing the outer diameter of the annular chamber to 60 mm whereas the inner diameter is kept at a constant value of 40 mm. This enlargement serves as a flame anchoring point (Fig.1.a).

2.2 Experimental results

To start testing, the first test chamber scheduled with the regular micromix concept had the singularity of having external walls in quartz glass in order to have visual access to the combustion zone during testing. Different chamber geometries regarding chamber volume and shape were tested thoroughly under ambient pressure with cold and preheated entrance air. The results of these investigations lead to an optimized chamber variant from which a stainless steel model was fabricated. For the validation with the numerical simulations, axial as well as radial thermocouple measuring points were incorporated in the chamber wall [10]. With this prototype chamber, a full test campaign under pressurized conditions resembling all parameters of the µGT was successfully accomplished. All the results showed a very stable and efficient burning at this small scale and produced a complete mapping of the regular micromix combustion chamber. As a next step, a final prototype with focus on the µGT integration was set up but has not yet been tested ([5], [6] and [9]).

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2.3 Numerical investigations (CFD)

A six degrees slice of the total combustion chamber was computed. One hydrogen injector and one air hole are modeled in this geometry. The boundary conditions for the lateral faces of the slice are periodic. So the finite volumes of the two lateral faces are mathematically neighbors. For more accuracy, the walls have been meshed as well. Heat transfer coefficient, emissivity and outside temperature are also imposed on the external surface. The simulation gives a maximum inner wall temperature of 854 K. The shapes of the small flames are very similar between simulations and experiments. One flame is created in front of each hydrogen injector. Each flame is tilted radially towards the inner side of the combustor. Flame temperature reaches about 2000K. Further details on this investigation can be found in references [5] & [6].

3. INVERSE MICROMIX PRINCIPLE

3.1 Geometry description

The "Inverse Micromix" injector uses a low speed axial hydrogen injection and a radial air injection. Hydrogen is distributed through a porous block which serves as a natural barrier against flash back. Air is distributed along the injector and redirected radially towards the chamber center. The recirculation zones created in this area improve mixing (Fig.1.b). The possibility to create a mixing and a combustion zone exists.

3.2 Numerical investigations (CFD)

This injector geometry presents a perfect axial symmetry. No three dimensional effects are expected, so a two dimensional study was started, providing simpler geometries and more simple 2D calculations. The first geometry examined used exactly the injector presented on Fig. 2 followed by a rectangular chamber. The volume of the chamber is calculated using the minimum residence time of the reactants.

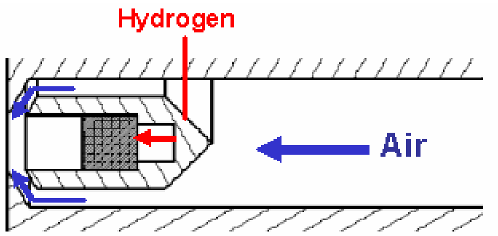

Fig. 2: "Inverse Micromix" injector: working principle

First trials with a typical annular combustor using this injection system gave a too high temperature, of about 2300 K peak in the combustion zone. These temperatures are far too high for the wall material, being a normal grade stainless steel. Moreover, hot walls will create larger heat losses.

Injection optimization & axial by-pass concept

To reduce wall temperatures, a new concept was introduced: the axial by-pass. The idea is to combine a traditional air by-pass with cooling air going along the walls. A richer region will be created in the combustor center allowing a larger range of overall equivalence ratios. As the by-pass air flows along the walls, it maintains the flame in the center and creates a thermal protective layer for the walls. For doing that, a deviation plate is introduced. It is located just downstream of the hydrogen injector. The plate separates the air flow into two parts; the by-pass flow which continues axially along the combustor walls and the mixing flow which is deviated by the deviation plate towards the center of the chamber where the hydrogen is injected. The external geometry outlines are driven by the space available in the global micro gas turbine, limiting the maximum 2D dimensions of the combustion chamber to a rectangle of 55 mm long and 10 mm high. The outlet is radially oriented towards the machine axis. A 5 mm long free space upstream of the hydrogen injector acts as the air inlet. Combustor wall thickness is 1 mm. As the first simulations showed the high potential of this design in terms of controlling wall temperatures and increased operating range, a parametric study on the geometrical design was started. The aim of this investigation was to determine which dimensional parameters are essential in controlling the combustor behavior.

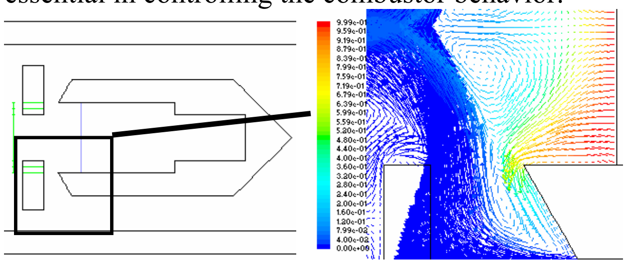

Fig. 3: Injection system with deviation plates

The first parameter being investigated is the deviation plate's height. This parameter has a direct impact on the by-pass ratio: large plates, reducing the distance between the deviation plates and the walls, resulting in a relative small by-pass flow and a relative increase of the mixing air flow. A second parameter to optimize is the distance between the hydrogen injector and the deviation plates. A too small distance, reducing the section available for the mixing flow, reduces the air mass flow useful for mixing and changes the by-pass ratio. An oblique injector wall is used to limit the recirculation zone due to stall of the mixing air. A recirculation zone is still present and with a too large injection section, hydrogen can enter in this zone, creating a flame attachment point in front of the deviation plate, exposing it to very high flame temperatures. Next, the influence of large deviation plates, keeping this time the distance between the deviation plate and the wall constant, was also investigated. The idea was to improve mixing by reducing the central section where the air and hydrogen pass through. But, as it can be seen on Fig. 3, the lower mixing air flow enters vertically in the mixing zone where it interacts with the upper air injector without influencing the mixing.

Combustor outlet optimization

Up to now, the optimization only concerned the injection zone, but the outlet has also to be improved, especially for turbine requirements. A mean temperature of 1200 K and a low pattern factor are required for the turbine inlet. Figure 4 presents with path lines colored by static temperature the two problems encountered at the outlet. First a too high temperature peak, higher than 1600 K, and secondly a recirculation zone reducing the effective outlet section.

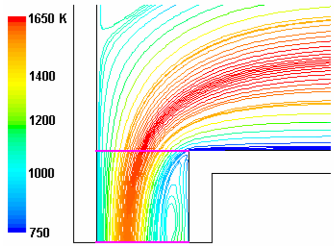

Fig. 4: Outlet peak temperature and recirculation zone: Pathlines colored by static temperature (K)

To reduce the temperature peak, a better mixing between main air and by-pass air has to be realized. For doing that a flow contraction is realized by adding a deflection block on the bottom wall. This reduces the cross section and increases flow trajectory.

Static temperature profile on Figure 5 shows the final design. Inlets temperatures are 300 K for hydrogen and 690 K for air. Maximum temperature, about 1850 K, is well located in combustor center. Wall temperatures are also reasonable: 870 K for the external walls and 920 K for the two deviation plates. By-pass air stays well along the walls and at the end of the chamber is partially mixed due to the contraction.

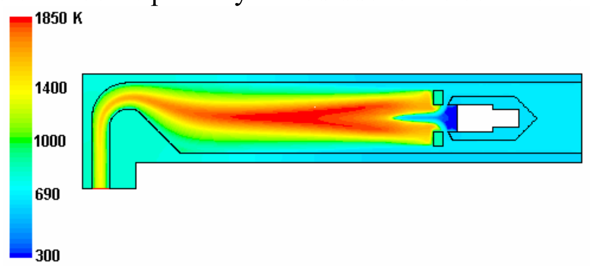

Fig. 5: Static temperature on the optimized geometry

A mass weighted average outlet temperature equal to 1219 K and a maximum temperature of 1400 K at the exit of the combustor gives a pattern factor of 0.34 which is acceptable for the ceramic turbine.

3.3 Planar prototype

In order to validate the working principle of this injector type, a planar prototype of the Inverse concept was created. In this prototype the by-pass air will be omitted. As the combustor walls will not be insulated and tests will only be done at atmospheric pressure – and thus with a reduced air and hydrogen mass flow – the temperature of the walls will stay within the materials thermal limits. As there is not a turbine at the outlet of this CC, an open ended combustor design was chosen for the tests. The bump to ameliorate the temperature profile was not incorporated and the flow leaves the combustion zone in a free axial direction. It must be clear that this prototype is only used to verify the mixing capabilities of the concept.

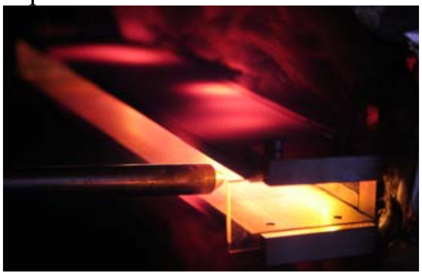

Fig. 6: Planar prototype in operation

3.4 Annular prototype

The next step was designing an annular combustion chamber using this same Inverse Micromix principle, taking into account the limited volume for the actual combustor. By means of 3D axi-symmetric CFD calculations, the geometrical parameters have been optimized as discussed above; the geometry of the combustion chamber to build is known. The material used for the construction of this prototype test burner remains the high temperature resistant INOX AISI 310. For this design, the slots in the deviation plates for cooling the walls with by-pass air will be included. This is necessary since this combustor will be thermally insulated during testing in order to get the testing conditions as close as possible to the real operating conditions of the overall mGT. Figure 7 shows the complete annular test chamber before testing without the outer wall.

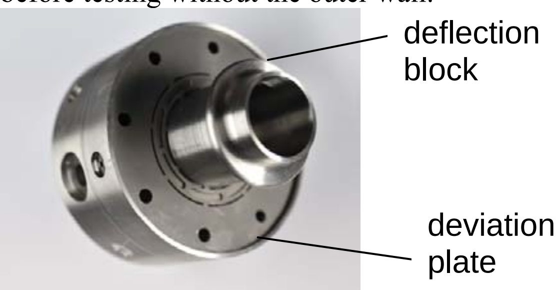

Fig. 7: Annular test chamber without outer wall

Atmospheric tests confirmed the confidence that was obtained during the planar prototype tests. At an air mass flow rate of 6,7 g/s, a very easy and safe ignition could be realized followed by a very stable combustion at and around λ= 6. Although the results of these first tests were very promising, it would be too soon to report about this campaign already in depth in this paper. The results have to be studied thoroughly and the complete program has to be carried out before further reporting can take place.

4. CONCLUSIONS

For the realization of a micro gas turbine, stable combustion in small volumes is mandatory. At the Royal Military School of Belgium, a research of 56 months on hydrogen micro combustion has been successfully carried out. This text describes the experimental results together with the CFD calculations of the two main concepts that were analyzed for the full size combustion chamber to be integrated in the micro gas turbine and qualitatively shows an acceptable correspondence with the first set of tests. On one hand, the Regular Micromix concept based on the jet in a crossflow mechanism was successfully downscaled for the use in a micro scale gas turbine. Different geometry variants of a miniaturized hydrogen prototype burner were tested on a new test rig for micro scale combustion chambers. At ambient pressure conditions, three different chamber geometries have been studied. All chambers showed successful ignition and a burning stability range up to λ=6. And on the other hand, the Inverse Micromix principle has also been proved. The planar prototype served first to validate the porous media and the mixing concept applied. Later on, with the gained experience in manufacturing and designing, the annular combustion test chamber has been built. Basic atmospheric tests confirmed the confidence that was obtained during the planar prototype tests. The possibility to create a mixing zone and a combustion zone exists. Both concepts present thus a valid solution for the ultra micro gas turbine under development.

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