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Three technological bricks for a micro turbine concept for micro power generation

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Abstract
Research on three technological bricks applied to a microturbine, namely the microcombustion chamber, the gas bearings and the feasibility by MEMS technology have been conducted. A general concept was used as a guideline for the three topics. Concerning the combustion, first tests were carried out concerning the mixing in microchannels. A study of the combustion with 0D analysis focused on the influence of the heat losses and of the fuel/air mixing an finally 3D computations were also performed. Concerning the gas bearings, a concept suited to MEMS technology was chosen. Groove bearings as thrust bearings and tilting pads for journal bearings have been computed and will be soon tested at scale 5/1. Concerning the MEMS technology, process flow studies have begun and first microturbines have been satisfactory etched. The main concern for this issue is the etching of the gap for the tilting pads.

Keywords : PowerMEMS, microturbine, combustion, gas bearing

NOMENCLATURE

C : radial clearance of the bearing
Da : Damkholer number
m' : mass flow rate
Pa : ambient pressure
Pg : gas pressure
Re : Reynolds number
Tg : gas temperature
τ : residence time
μ : viscosity
R : shaft radius
V : volume
ω : angular speed

1 INTRODUCTION

Due to the increase in power requirements, many efforts have been done over the past decade to build a micro heat engine able to produce electricity in order to replace batteries in portable systems such as robots or computers for example. Among those systems, Onera decided to focus on the microturbine concept which seems very promising for microdrone propulsion. The first work was mostly dedicated to the energetic behaviour of such engine which led to better understand the key points to address from a energetic point of view to make this concept feasible [1]. The resulting concept is a 8 mm diameter turbine with the combustor located above it (figure 1).

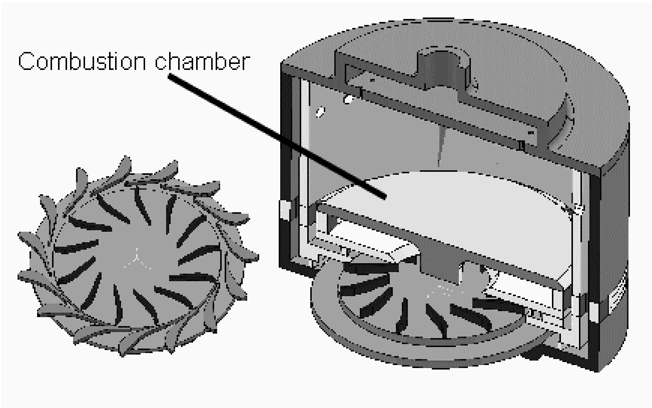

Figure 1 : proposed microturbine concept

The strategy is to separate the combustion chamber from the compressor/turbine. This allows to reduce the surface/volume ratio and then to decrease the heat losses. This also allows to benefit from a larger combustion chamber and then larger residence time that could help to increase the combustion efficiency. In addition, this also yeld to a cooler compressor compared to a annular design (MIT type) and finally this also simplify the combustion chamber machining by avoiding etched and then bonded silicon wafers.

As a first stage, it was decided to study and the design three technological bricks that could be suited to this concept :

- the microcombustion,
- the gas bearings,

- the microtechnology applied to this concept.

This paper presents the work realised on these three topics.

2 MICROCOMBUSTION

For the combustion chamber, there are three specific problems connected to its small scale:

- a small Reynolds number (thus laminar flow) causes a bad mixing between fuel and air,
- a small Damköhler number (residence time comparable to chemical reaction time),
- the level of external heat losses.

2.1 mixing studies

The mixing at low Reynolds was experimentally investigated in a channel of 1.3 mm in height. PLIF measurements were done on a N_2 injection with acetone as a tracer. The flow was cold and Reynolds number from 100 to 500 have been investigated for different fuel mass flow rates. A "turbulence" promoter was also investigated. The figures 2 to 4 show typical results obtained.

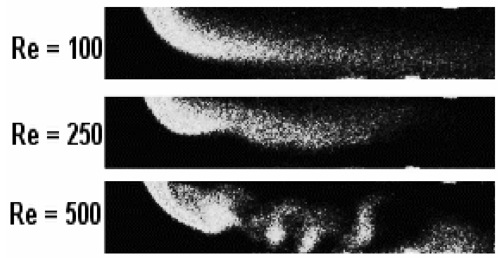

Figure 2 : Images for three Reynolds numbers

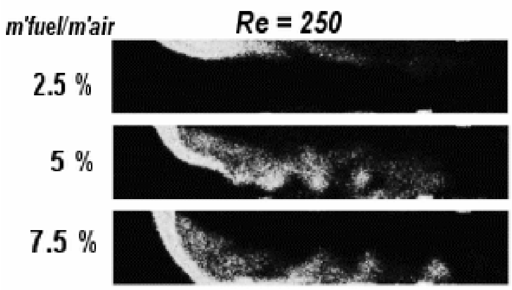

Figure 3 : Images three mass flow rates (Re = 250)

From those results, it can be clearly identified that despite the low Reynolds numbers, some turbulence structures appear with growing Reynolds due to the increase of the main flow speed. It can also be seen that the increase in mass fuel flow rate can have a dramatic effect which can lead to move from a fuel hardly penetrating the flow to the fuel mostly located on the opposite wall. Concerning the backward facing step, the comparison between fig. 2 and 5 shows that it really enhances the mixing, even for Re=250 and above.

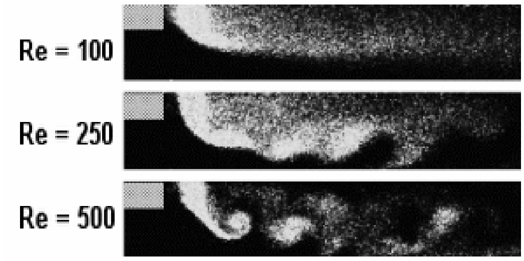

Figure 4 : Images for three Reynolds numbers and a step

2.2 Combustion studies

As a first step 0D computations were made to estimate the needed reaction time for the combustion and for various fuels. This approach was undertaken with Perfectly Stirred Reactor (PRS) and Partially Stirred Reactor [2]. With the PSR model, the extinction limits were computed for different fuels (methane and hydrogen) as well as different inlet temperatures or equivalence ratio and also heat losses (fig. 4). This can give a good estimate of the minimum residence time needed for the combustor.

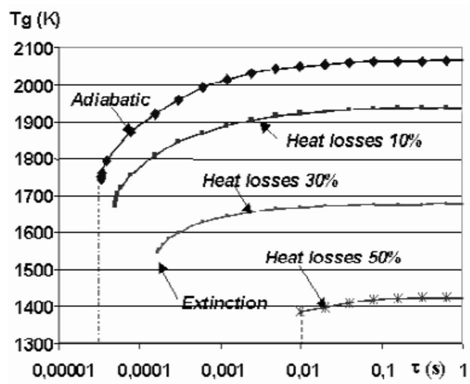

Figure 4 : Gas temperature versus residence time for different levels of heat losses (CH_4)

With the PaSR model, the influence of the micro mixing time on the needed residence time was studied. Compared to the PSR it was found than the residence time can be changed by several order of magnitude when the mixing is slower (fig. 5). From these studies, it was found out that for 30 % of heat losses , a reasonable mixing time of 10^{-4} s and Da = 1, a minimum volume of 600 mm^3 was necessary for pure methane. This value can decrease by an order of magnitude for pure hydrogen. The volume is estimated with : $V_{\min} = m' \tau r T_g / P_g$

In parallel, 3D computations were also performed. The figure 6 shows typical results obtained for a combustion chamber that could be applied to the design presented in figure 1. The code used is the CEDRE code developed by Onera. In this code will be implemented a micro mixing model which was developed within the frame of the 0D studies.

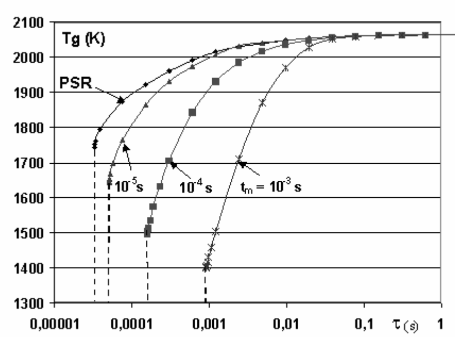

Figure 5 : Gas temperature versus residence time for different mixing time scales (CH_4 without heat loss)

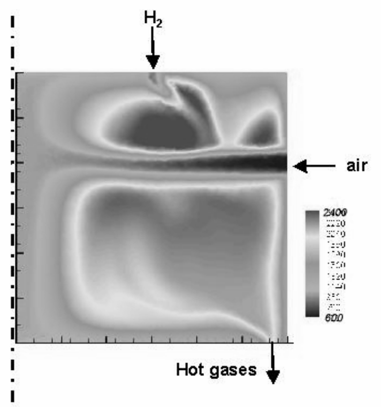

Figure 6 : computed temperature field

3 GAS BEARINGS

At the rotating speed of 1 million rpm it is clear that the gas bearings are mandatory. In order to avoid having an external air supply we decided to focus on hydrodynamic gas bearings. The journal bearings are constituted by tilting pads located at the periphery of the turbine whereas the thrust bearings are groove bearings. The tilting pad location is mainly imposed by microtechnology machining concerns. Indeed, it would have been simpler for the gas bearings behaviour to be located on a shaft, at smaller radius and then lower tangential speed but this implies difficulty for the micromachining process. The aim of the investigations is to develop a reliable theoretical model of the dynamic tilting pad gas bearings with a length/diameter ratio < 0.1. The method of calculation of the non-linear response to any excitation takes into account factors such as the pivot design, the friction in the supports and the mass of the pads. The target of the non-linear dynamic analysis of the titling pad gas bearing is to take into account the current forces occurring in the gas film for any excitation and to investigate the trajectory of the journal motion under such operating conditions. Such a formulation of the problem requires a simultaneous integration of the equations of motion for each titling pad and the bearing journal with the equations of pressure in the gas film of each titling pad. As a first step, it has been chosen to study those gas bearings at larger scale because it makes the machining and the measurements easier. As a result, a scale 5/1 model has been designed and built by the Lodz University according to Onera and SilMach needs (figure 8). The aim of the test that will be performed on this model is to assess the feasibility of the external tilting pad bearings at very high speed, to validate the stability, to evaluate the friction loss and finally to also evaluate the air leakage through the thrust bearings. Different height of tilting pads will also be tested. For the tests at scale 5, the compressibility factor $\Lambda = 6\mu\omega R^2/p_a C^2$ will be the same as the one for the scale 1.

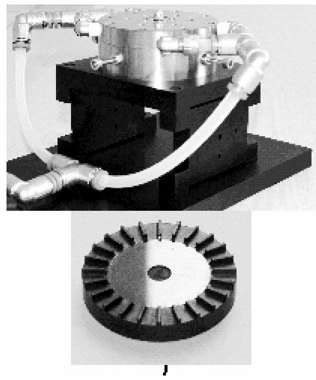

Figure7 – High speed gas bearing test rig

The test rig is achieved and the tests have begun in july 2005. A rotational speed of 40 000 rpm has yet been achieved for preliminary tests and the speed will be increased gradually to reach 235 m/s in periphery. In Fig. 8, examples of the calculation and experimental results corresponding to the chosen design of the tilting pad gas bearing in scale 5 excited by the synchronous rotating force (unbalance due to the fabrication imperfections) are shown.

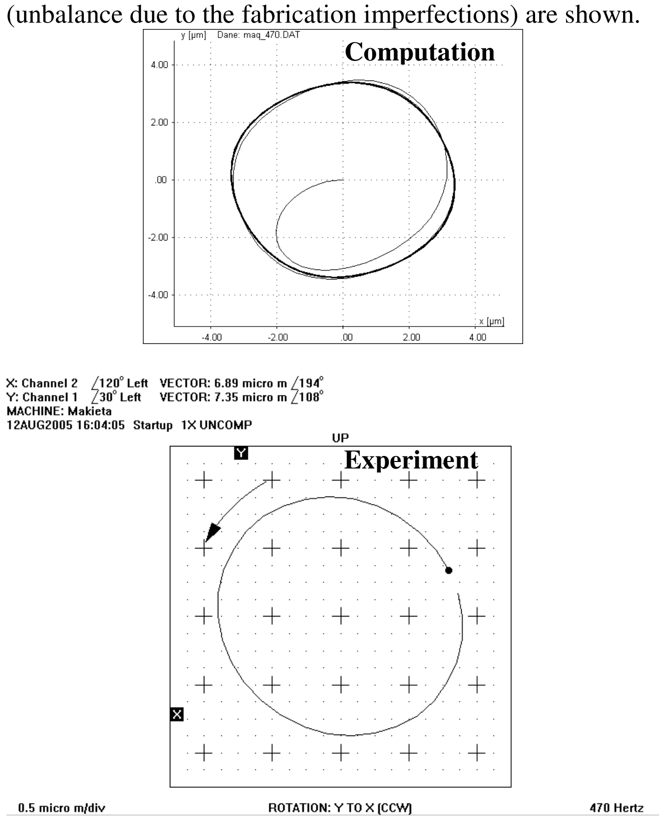

Figure 8 : Nonlinear orbit calculation vs. experimentation for gas bearing scale 5 model.

In Fig.9 an example of calculation results corresponding to the final microfabricated bearing working at 1 million rpm

and expected conditions of dynamic and static load are shown.
The final machine with its compressor and turbine will have to withstand axial thrust and acceleration. For this purpose, groove bearings were chosen because they can also be easily etched on a silicon wafer. The scale 1 thrust bearing have been computed and a clearance of 10µm was chosen to withstand the axial load. In addition, the flow rate in the groove bearings which is an external leakage from the system point of view was also estimated around 2.7 10^{-6} kg/s which hardly represents 0.7 % of the total flow rate.

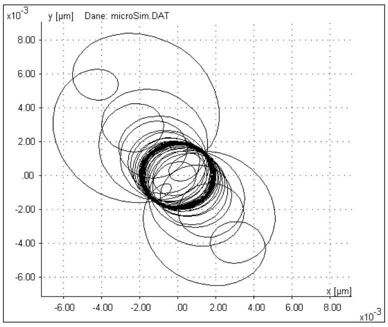

Figure 9 Nonlinear orbit calculation for 1 million rpm micro gas bearing

4 MICROTECHNOLOGY

It is worth to recall at this stage that the studied global concept allows separating the combustion chamber from the turbine/compressor part. Until now, we consider building the combustion chamber with classical means and the turbine module with MEMS technology.
As a first stage it has been decided to address the issue of demonstrating a turbine at scale 1 (8mm in diameter) turning at 1 million rpm and fabricated with MEMS technology. This model has to include the turbine, the stator but also the gas bearings. For the last issue, a close look has been given to simplify as far as possible the concept which led to have only a three wafers design for the turbine equipped with the bearings. A first turbine set was etched by SilMach (figure 9 and 10). The tilting pads will be implemented on this scale 1 model. The blade height is here only 220 µm instead of the 400 µm for the complete system since there is no power needed to drive the compressor.

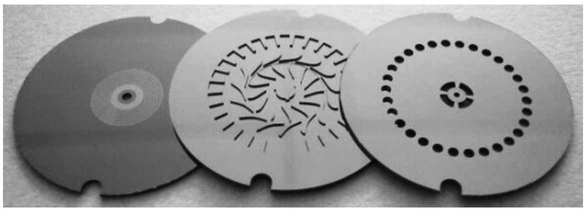
Figure 9- three wafers micro-turbine

The wafer one needed 4 masks to be etched and the two others 3. 73 process steps are necessary. The problem of the depth etched relative to the opening rate of the mask was addressed as well as the differences between a turbine etched at the centre of the wafer and another etched at the periphery.

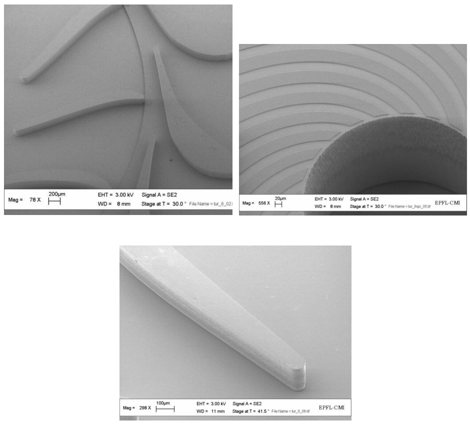
figure 10 – details of the turbine and groove bearing

It was found that the depth of the etching was relatively uniform for one turbine but that the turbine etched at the periphery was etched deeper that the central one. One other main concern link to this problem is the etching of the rotor/tilting pad gap which is only 4 µm for the nomnal speed of 1 10^6 rpm. This is a very demanding constraint link to the tilting pad technology and the process to obtain it is currently being investigated.

5 CONCLUSION

Based on a global concept, the combustion chamber, the tilting pad and the turbine/bearing etching have been studied. For the combustion, the first results obtained on the heat losses as well as the mixing of the fuel/air have influence helped us to define the combustion chamber volume which should be around 600 mm^3 for hydrocarbon fuels. 3D computation of such a chamber have been done and showed that the combustion could be stabilized and satisfactory. In parallel to this numerical work tests were done on the micromixing and combustion tests will be soon carried out.
Concerning the gas bearings, a concept suited to MEMS technology was defined and computed and showed that the stability should be achieved at 1 10^6 rpm for the microturbine. Tests have begun on a scale 5 model to have a experimental validation of this computation and also to determine the friction an the leakage of the bearings. In parallel, the MEMS process flow was investigated and the first microturbines were etched.

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6 REFERENCES

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