# Development of a gas turbine with a 20 mm rotor: review and perspectives

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**Abstract**

This paper reviews the status of the Belgian powerMEMS turbine development. The technology developments for realizing a 20 mm diameter hydrogen-based gas turbine running at 500,000 rpm are presented. The overall layout is taking into account rotor dynamics and internal heat management. The system is relying on miniaturized air bearing technology designed for optimal performance at high running speeds. For the rotor construction, a three-dimensional micro manufacturing technology is being developed. The rotor geometry has been optimized taking into account the aerodynamic performance, the rotor heat management, material strength at elevated temperatures, and centrifugal load. For the hydrogen combustion system, several configurations have been simulated and compared with experimental results. The system also incorporates a recuperator that optimized in terms of geometry, performance, and manufacturability. Finally the design of a high-speed Switched Reluctance generator is discussed.

*Keywords: PowerMEMS, Microturbine, and Hydrogen*

## 1 - INTRODUCTION

In literature, two different turbine size ranges can be found: a "microscopic" range (MIT [1], Tohoku University [2], Onera [3], National University of Singapore [4]) and a "mesoscopic" range (Stanford [5], University of Tokyo [6], Tohoku University [7], ETH Zurich [8], Belgium [9]). The micro range uses silicon technology, enabling the production of very small components with high accuracy and aims at an electrical power output in the range of 1 to 10 W. Applications could be in small portable electronic devices, wireless sensors, or consumer electronics.

The micro gas turbine discussed here fits into the mesoscopic power segment aiming at an electrical power output of about 1 kW. All components had to be redesigned and new concepts had to be used. Major problems are the high rotational speed (> 500,000 rpm) and temperature (> 1200 K), and the efficiency of the components. The next sections give an overview of the whole project.

## 2 - GENERAL LAYOUT AND SENSORS

Figure 1 shows the general layout of the microturbine and generator. The system basically consists of a compressor, recuperator, combustion chamber, turbine and electrical generator. In total it has a diameter of around 95 mm and a length of 120 mm. The compressor and turbine impellers are 20 mm in diameter. The rotor takes only a small part of the total volume, in contrast to large gas turbines. This is typical for microturbines where the relative combustion chamber and recuperator size has to be increased to get sufficient time for combustion.

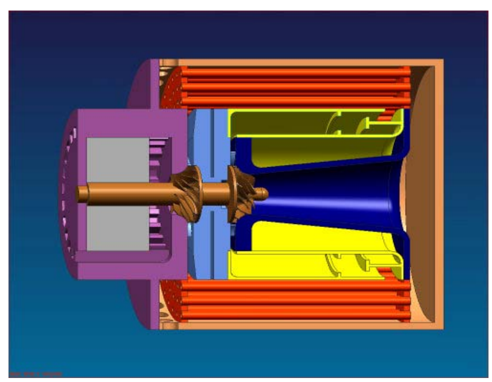

**Figure 1: General layout**

An annular design was chosen. The combustion chamber is enclosed on the outside by the recuperator and by the exhaust diffuser on the inside, which allows recycling heat losses from the combustion chamber. The generator is located on the left side, far from the hot parts. The inlet air is led through the generator stator for additional cooling. To extract more power, an exhaust diffuser is added to create a sub-ambient pressure at the turbine exit.

A single-shaft solution is preferred as any two-shaft solution results in an overall lower performance or major complications in the design [10]. The following rotor dynamic aspects were taken into account during microturbine design: air bearing fractional speed whirling resulting in subsynchronous shaft vibrations, magnetic forces in the generator causing supersynchronous vibrations, unbalance causing synchronous vibrations and other asymmetries in the system (bearings, generator, etc.) causing synchronous vibrations, including higher harmonics.

A stiff shaft suspended on air bearings has very low suspension eigenfrequencies and relatively high bending and torsion eigenfrequencies, which is desirable. However, the geometry of the single shaft solution is not ideal, as heavy masses are located at the ends while the compressor inlet introduces a low stiffness in the center. In the current design the suspension eigenfrequencies are a few 100 Hz. The first bending and torsion eigenfrequencies lie around 8.5 and 17.5 kHz respectively, the former coming close to the rotational frequency (8.3 kHz). Current rotor optimization aims to increase the first bending eigenfrequency.

Design of the sensors required to operate the system is a challenge because of the small size and evident aggressive atmosphere linked with hydrogen combustion. The sensors must control the turbine by measuring a.o. pressure, temperature and rotational speed. MEMS sensors, e.g. a pressure sensor, are considered to be a viable solution, but are often limited in their operating conditions, in comparison to their macroscopic variants. Research is ongoing in the use of heat and chemical resistant materials (e.g. ceramics like silicon carbide, oxide or nitride) for the construction of such a MEMS pressure sensor.

## 3 - THERMODYNAMIC CYCLE AND EFFICIENCY

During the aerodynamic design of micro gas turbine components, it is questionable if the computational tools, used for large turbomachinery components, are still valid for the non adiabatic flows at very low Reynolds number flows in rotating channels with relatively large surfaces roughness. Special research is underway to verify the turbulence models at those particular conditions. A special facility has been built to measure directly the relative flow in a rotating channel at low Reynolds number by means of Particle Image Velocity. First measurements show that the traditional turbulence model fall short in accounting for the rotational effects [11].

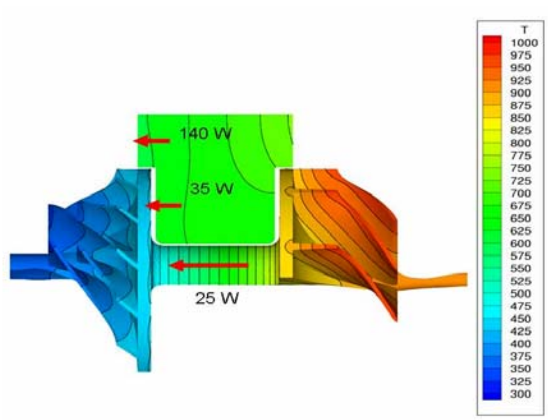


**Figure 2: Heat transfer inside a micro gas turbine (20 mm rotor OD, TiT = 1200 K, CiT = 293 K)**

Small dimensions lower the efficiency of the compressor and turbine. Manufacturing tolerances further limit the minimum clearances that can be achieved. Hence larger peripheral speeds are needed to achieve the required pressure ratio. Best efficiency is obtained with a more complex 3D impeller geometry. This not only complicates the manufacturing but also requires a careful design to achieve high performance and guarantee the mechanical integrity of the turbomachinery components. A multidisciplinary optimization technique is developed for this purpose [12]. The large heat transfer between the turbine and compressor has been evaluated by a combination of diabatic flow calculations and a Finite Element Analysis of the heat transfer in the solid impellers, housing and shaft. A systematic study has revealed that the internal heat transfer is function of the dimensions, geometrical shape and conductivity of the materials used (Figure 2). The impact on cycle performance turns out to be less than generally accepted [13].

## 4 - BEARINGS

Due to miniaturization the rotational speed required by the thermodynamic cycle, results in speeds of more than 500,000 rpm for rotor diameters around 20 mm. Focus of research is on hybrid and foil bearings. A rotordynamic modeling tool of a micro-turbine rotor supported on aerostatic bearings has been developed. The system allows an accurate prediction of critical speeds, imbalance response and stable operation range. First, an accurate and efficient modeling technique has been developed to obtain static and dynamic air bearing properties. These bearing coefficients serve as input for a rotordynamic model yielding damped natural frequencies, unbalance response and stability limits [14]. For experimental validation of this model coastdown measurements were used to identify the cylindrical and conical critical speed at different bearing supply pressures. Figure 3 shows that there is good agreement between simulated and measured mode frequencies (cylindrical and conical) at varying supply pressures.

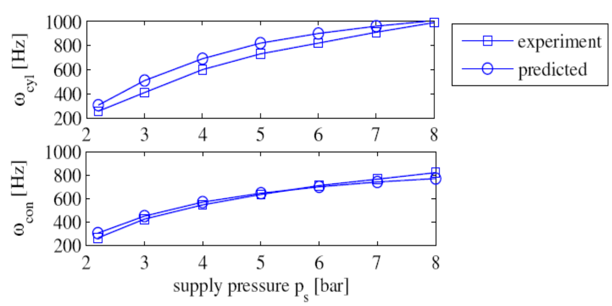


**Figure 3: Experimentally identified and predicted critical speeds.**

A second part of the work focuses on designing new foil bearing concepts, suitable for the small dimensions encountered here. Figure 4 shows the experimental setup used to test the different bearing designs [15]. It consists of a housing with nozzles and sensor interfaces in which different bearing modules can be inserted. In the picture shown, aerostatic thrust and journal bearing inserts are used for bearing the test shaft. The tested bearing is in the middle.

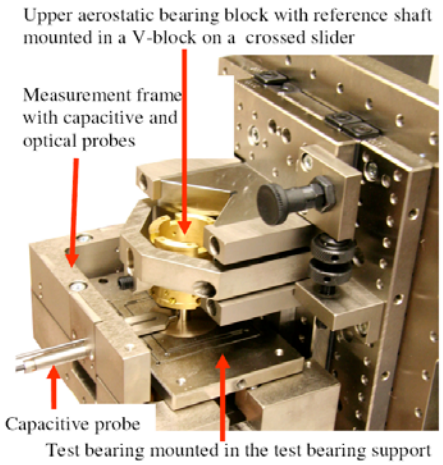


**Figure 4: Test set-up for foil bearings**

## 5 - COMPRESSOR AND TURBINE

The efficiency of every component is critical for the overall gas turbine performance (especially compressor and turbine, requiring an efficiency of at least 60-70%). One way to reduce the impact of losses on performance is by increasing the mass flow. The mass flow of the current design is therefore fixed at 20 g/s for an impeller diameter of 20 mm and a pressure ratio of three. A computerized design system based on a Genetic Algorithm, an Artificial Neural Network and a 3D Navier Stokes solver has been used to optimize the 3D compressor and turbine geometry. The main challenge regarding fabrication are the three-dimensional impellers for both compressor and turbine. For a first prototype, we opted to use a metal compressor and a ceramic turbine. The compressor forms a monolithic metal part with the shaft and has been machined on a Kern MMP 5-axis micromilling machine. Figure 6 shows a polymer test part.

**Figure 5: Micromilled 20 mm diameter compressor**

The production of the turbine impeller is more difficult because a Si3N4-TiN ceramic composite (Kersit 601 from Saint-Gobain) is used. Machining on a SARIX SX-100 micro-EDM machine is currently investigated. A pure silicon nitride coating will be applied by plasma-enhanced CVD. A reliable connection between the two parts is also under study.

## 6 - COMBUSTION CHAMBER

Although the functional requirements of a micro combustor are quite similar to those of a conventional gas turbine engine, miniaturization poses many new obstacles to be overcome: a much shorter residence time, higher surface area-to-volume ratio, low Reynolds number regime, and materials [16,17]. Hydrogen is an ideal primary energy source for this application. Compared to hydrocarbons, hydrogen has a greater heating value, a more rapid rate of vaporization, a faster diffusion velocity, a shorter reaction time and a significantly higher flame speed. So, it was certainly the first fuel to be investigated. The development of this combustion system has been focused on different aspects: mixing, addition of air dilution and integration in the global machine.

As a preliminary design [10], for the micro turbine under consideration, a fluid flow speed around 20 m/s was adopted resulting in an annular combustion chamber length of 50 mm and a height of 15 mm. Some plates were added to create extra recirculation zones and to increase the residence time of the mixture inside the combustor (Figure 6). The first T-shaped plate is added for fuel injection and mixing while the second small plate is added to stabilize and to anchor the flame. Furthermore to increase the performance of the combustion chamber a configuration with dilution is selected. Part of the air bypasses the flame and is injected downstream at both the external and internal diameter. In this way, both the stability and the efficiency of the chamber are increased. The by-pass air also cools the walls and in this way reduces the heat losses. Figure 6 shows the steps followed in this research.

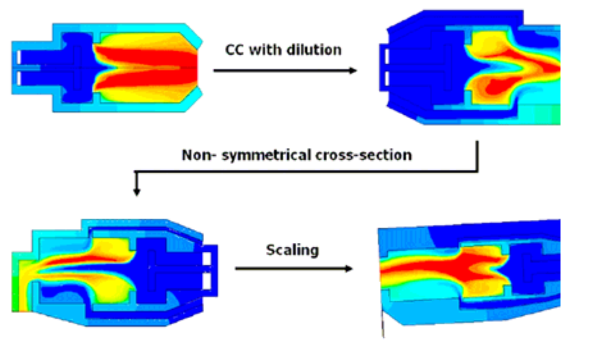


**Figure 6: Combustion chamber design**

## 7 - RECUPERATOR

The main challenge is to find a recuperator design with low pressure drops in the channels in combination with high heat exchanger effectiveness, taking into account geometrical constraints of system integration and manufacturing limits. In conventionally sized recuperators, complex, well-designed fin configurations are used in order to improve the gas-air heat transfer. In order to avoid these costly and difficult to fabricate configurations, alternative recuperator designs based on micro channels are proposed for micro-scale applications.

At present, no adequate micro recuperators have been tested in combination with a micro gas turbine. MIT already proposed a micro recuperator design in 2001, which was tested independently [18]. General design requirements for micro recuperators were proposed in 2004 [19]. The main conclusion of this research was that pressure drops are preferably located at the cold side of the recuperator. Therefore, the hot channels should be larger than the cold ones. Further, small heat exchangers generally suffer from performance deterioration due to streamwise heat conduction through the solid material. Therefore, an optimization based on cycle efficiency as a cost function on one hand and a detailed flow and heat transfer recuperator model on the other is performed to determine the optimal heat exchanger configuration. The recuperator under development is a counter-flow micro-channel heat exchanger, consisting of 6 cube-like blocks arranged in an annular shape around the gas turbine. Each block consists of alternating hot and cold plate layers with micro channels. Two configurations are studied numerically with an inverse pressure drop model in combination with a heat transfer model that accounts for axial heat conduction in the walls: one with the channels located in axial direction and one with the channels located in radial direction. In this case, the micro gas turbine radial design seems to be favorable for very small or high outer diameter values of the recuperator, whereas an axial design for intermediate values is preferred.

For a recuperator with length of 67 mm, ID of 60 mm and OD of 90 mm, a heat exchanger effectiveness of 87 % is achieved for pressure drops at hot and cold side of respectively 7.4 kPa and 11.1 kPa. This results in a total cycle efficiency of 34 %. The internals of this design consist of 7620 and 9816 hot and cold side microchannels with a hydraulic diameter of 381 μm and 289 μm.

## 8 - GENERATOR

The electrical machine is integrated onto the shaft of the turbine. There are 2 major operational modes: startup motor to speed up the turbine and secondly generator mode in case of steady-state regime. Two radial-flux machines are currently under investigation: a permanent magnet synchronous machine (PMSM) and a switched reluctance machine (SRM 6/4 configuration). In contrast to normal designs with speeds of about 10,000 rpm and operation temperatures up to 350 K, this machine will operate at speeds up to 500,000 rpm and at elevated temperatures ranging from 470 to 570 K.

The high speed results in large mechanical stresses so the geometry of the rotor is reduced to simple shapes: for the PMSM this is a round shape and for the SRM small saliencies are used. Another result of the high speed is the high operating frequency, e.g. for the SRM this is 33.3 kHz (single pulse driven). The high frequency introduces skin effect in windings and eddy currents in the magnetic rotor material. Therefore, the SRM rotor is laminated and in both machines litze-wire is used for the windings.

Continuous cooling is necessary for the PMSM since permanent magnets lose their properties around 400 K. Therefore the inlet air is passed through the cooling channels in the generator for additional cooling. Because of the higher resistivity of copper with elevated temperatures, the losses in the windings will be higher as well. As such, speed and temperature interact as well. With respect to the temperature, the SRM has a surplus over the PMSM since it does not depend on sensitive permanent magnets.

To start the turbine, the electrical machine needs an external energy source to create a magnetic field inside the machine. In generator mode the PMSM can operate without such energy supply but the SRM still needs an energy source to build up the magnetic field. After the startup this source can be removed, as the machine then becomes self-supporting.

## 9 - CONCLUSION

De development of a 20 mm diameter miniature gas turbine is underway. The small dimensions have implications on the efficiency of the components, the required design tools, their manufacturability and the integration of the assembly. The high thermal and centrifugal loads represent an additional design challenge. The first prototype components, design software and related test set-ups are currently available within the Belgian powerMEMS project.

## ACKNOWLEDGEMENTS

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