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IMPROVED μ-SCALE TURBINE EXPANDER FOR ENERGY RECOVERY

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ABSTRACT

Micro power converters for energy recovery are increasingly important for a number of future applications. The Austrian Institute of Technology (AIT) is presently developing an innovative μ-scale turbine expander for work recovery in transcritical CO_2 heat pumps. The main drawback of a lower COP (coefficient of performance) of transcritical CO_2 heat pumps compared to conventional heat pump systems can be compensated by utilizing the pressure difference between the high pressure and low pressure part of the pump for work recovery. Work recovery can be realized by substituting the expansion valve between the high and low pressure side by a Pelton turbine with specific two phase flow turbine blades. In order to increase the power output, the generator was integrated into the turbine to reduce the friction losses and hence increase the overall efficiency. An important aspect is that the generator is directly connected with the high pressure part of the turbine. One part of the project is the optimization of the turbine geometry via simulation tools. The paper will give an overview about our microturbine development as well as a comparison of the power output of each turbine generation. Furthermore the present paper discusses a concept that utilizes our microturbine together with a micro combustion module that enables a micro power generator with very high power-to-weight ratios based on green fuels.

1 INTRODUCTION

The Space Propulsion & Advanced Concepts department at the Austrian Institute of Technology has a long history in developing miniaturized Liquid-Metal-Ion-Sources (LMIS) for space applications, including the application of the ion source for active spacecraft potential control of satellites (ASPOC) as well as for a secondary ion mass spectrometer. Over the last 5 years, our activities expanded in a number of other micropropulsion areas such as μPPT thrusters for CubeSats or chemical micropropulsion including the development of micro mono-propellant and bi-propellant thrusters using green propellants e.g. hydrogen peroxide. In recent years, the development of micro power converters [1] (turbine and Stirling engines) as well as innovative gas storage solutions based on microspheres started to expand our activities towards novel micro power technologies. This paper will give an overview of our microturbine developments so far.

1.1 BACKGROUND μ-TURBINE DEVELOPMENT

A microturbine was developed to produce the power for the pumps of a rocket engine earlier in a previous project [2]. The successful testing of the microturbine triggered our interest towards micro power converters in general since they may be used to increase the overall energy efficiency for a number of applications including compression and absorption heat pumps, air conditioning units, thermal storage devices or even building elements. The first generation turbine was driven by the decomposed hydrogen peroxide of a bipropellant thruster. Two types of turbine blade diameter were investigated; one has a diameter of only 10 mm, whereas the other one has a diameter of 23 mm. The different diameters lead to different rotational speeds (230,000 rpm for the smaller rotor and 80,000 rpm for the larger rotor) and different manufacturing processes (Lithography, Electroplating, and Molding for the smaller rotor and mechanical manipulation of aluminum with a high speed milling machine for the larger rotor) [3]. Figure 1 shows the small turbine rotor (left) and the larger rotor (right). The turbine was coupled to an electrical generator for producing electrical power. Due to sealing problems, friction losses, stray fields of

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the coupling magnets and inefficient magnetic coupling between the turbine and the generator, a low power output was achieved.

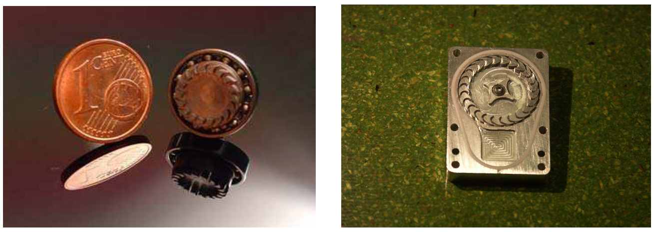

Figure 1. First generation turbine blades [2] [3].

The improvement of the power output was the driving force for the second generation turbine. Our experience and several lessons learned results in a complete new housing design. Figure 2 shows the turbine blade housing and the complete assembly with all new parts. The new design allowed higher power outputs at lower rotational speeds of 10,000 to 15,000 rpm with the same turbine blade (see Figure 2, right). The leakages were reduced by redesigning the gas inlet and outlet. The dynamic loads were reduced by using two bearings instead of one and hence a smoother run of the turbine was observed. The successful testing of the second generation turbine triggered our interest towards micro power converters for a number of applications. We identified CO_2 heat pumps as a first application for our microturbine converter, whereas several technological changes had to be taken to adapt our small high temperature/low pressure turbine system to a low temperature/high pressure turbine system. Furthermore the use of stronger magnetic couplings, slide bearings, a stronger generator and application oriented turbine blades were necessary to improve the performance of the 3rd generation turbine system [4]. The next chapters describe the theoretical background of energy recovery in CO_2 heat pumps and our 3rd generation turbine system followed by an improved 4th generation turbine system including first simulation results.

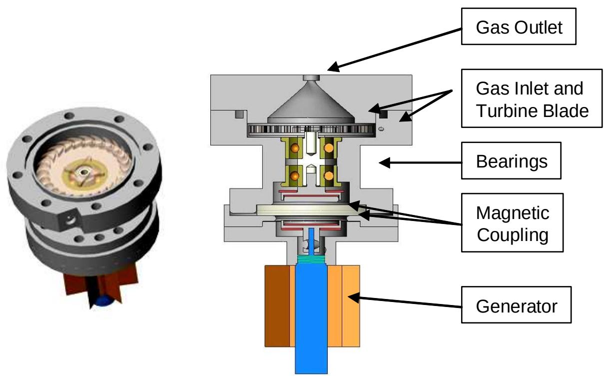

Figure 2. Second generation turbine blade housing and complete assembly (55 mm height and 35 mm diameter) [4].

1.2 ENERGY RECOVERY IN CO_2 HEAT PUMPS

The chosen application case for our microturbine is a transcritical CO_2 heat pump cycle for domestic applications like tap water heating or high temperature room heating for retrofitted buildings. The use of CO_2 as refrigerant could overcome the temperature limitations of retrofitted buildings (90/70 or 70/50°C flow/return temperature) and tap water heating systems (60°C), which are too high for conventional heat pumps. CO_2 is a natural refrigerant with negligible global warming potential and its coefficient of performance (COP) does not significantly decrease with increasing heat sink temperature. The main drawback of transcritical CO_2 heat pumps is the lower COP compared to conventional heat pumps, which originates from the nonisothermal heat rejection in the gas cooler. One option to negotiate this drawback is the use of microturbines for work recovery between the high pressure and low pressure part of the heat pump. A particularly suitable opportunity is the substitution of the expansion valve between the high and low pressure side by an expansion machine, whereas the pressure difference in case of CO_2 heat pumps is considerably larger (up to 90 bar) compared to conventional systems (e.g. 15 bar for R410A). Figure 3 shows the concept of such a small size two stage microturbine boosted CO_2 heat pump system; the microturbine could power the compressor of the second stage or produce electricity. It has been shown in a thermodynamic parametric study that the microturbine starts in the transcritical region of the working fluid and finishes in the liquid-vapor region. A power yield between 60 and 150 W could be converted into electricity via our microturbine in a 2 kW water heating system [5] [6] [7].

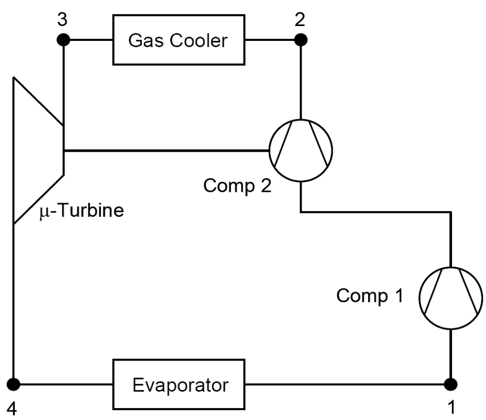

Figure 3. Microturbine boosted CO_2 heat pump system [7].

1.3 3RD GENERATION TURBINE EXPANDER

Previous work [7] described the design and calculations of the 3rd generation turbine expander in detail. Two types of turbine geometry were considered in association with the low flow rate of the working fluid in CO_2 heat pumps. The first type is the 90° inward radial turbine and the second type is a turbine based on the Pelton turbine, whereas the second solution seemed to be

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favorable because of the high pressure differences between inlet and outlet. In addition the low flow rate of working fluid (0.02 kg/s) favors the second option, too. One of the big challenges for the layout of the rotor and stator blades/nozzles was the fact that the working medium changes its state from liquid to wet steam during the expansion process. Therefore the final design based on the so-called “Turgo”-principle, which means a “half-Pelton” turbine. Figure 4 shows the turbine blades of the Pelton wheel with a rotor hub diameter of 25 mm. The turbine blades were made with a laser milling process. The calculated rotational speed was 43058 rpm and 50 blades, which ensures a constant torque since more than one blade channel is admitted at the same time by the nozzle exit jet.

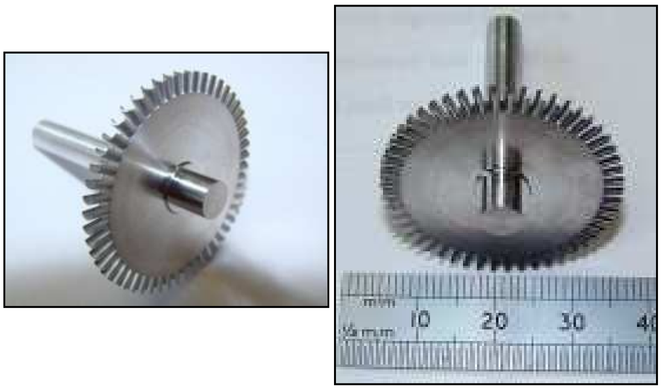

Figure 4. Pelton Wheel.

Figure 5 shows the design (left) and the prototype (right) of our 3rd generation turbine. The application of this system is as a throttle valve replacement in CO_2 heat pumps in combination with electrical power production. Please note that the first and second generation is designed for decomposed hydrogen peroxide at high temperatures (up to 200°C) and relative small pressures (up to 6 bar) whereas this turbine is for high pressures and low temperatures.

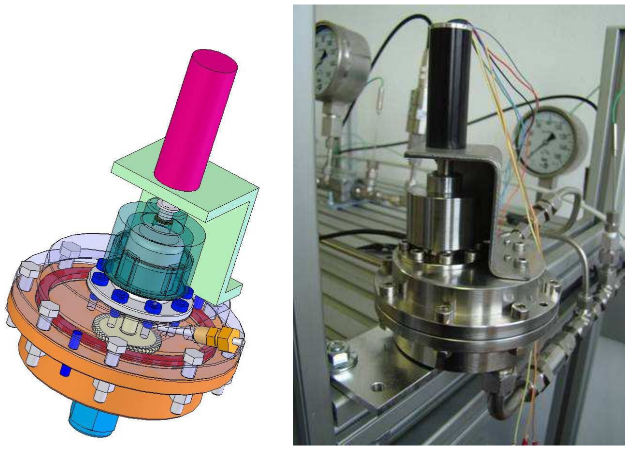

Figure 5. 3rd generation prototype of a microturbine for energy recovery (200 mm height and 100 mm diameter) [7].

The results of the dedicated testing of the turbine are shown in Figure 12 in comparison with the improved system. The calculated inner power of the turbine is 123.5 W at an efficiency of 0.56, which corresponds with the turbine output. The system consists of a 50 W generator, a magnetic coupling, the described turbine blade (Figure 4) and an injector. A maximal electrical power output of 52 Watts was reached with a starting pressure of 70 bar at 32,500 rpm in gas operation mode and 36 W at 23,000 rpm with a gas-water mixture. We used this gas-water mixture to simulate the gas-liquid medium change of the originate CO_2 heat pump. The lower power output of the gas-water mixture in comparison with the gas operation mode could be explained with higher friction losses generated by water. The low power output of the whole system in comparison with the theoretical calculations (52 W vs. 123 W) showed that this system had enormous internal losses and hence great potential for optimization [7].

1.4 IMPROVED TURBINE EXPANDER DESIGN

The identified improvements include the substitution of the needle cage and the generator with a full integrated power system without friction losses. In addition the 50 W generator was substituted by a 100 W generator and the electronic control system was adapted to the expected higher rotational speed and hence the higher power output. Figure 6 shows the design (left) and the prototype (right) of our 4th generation turbine with an integrated generator.

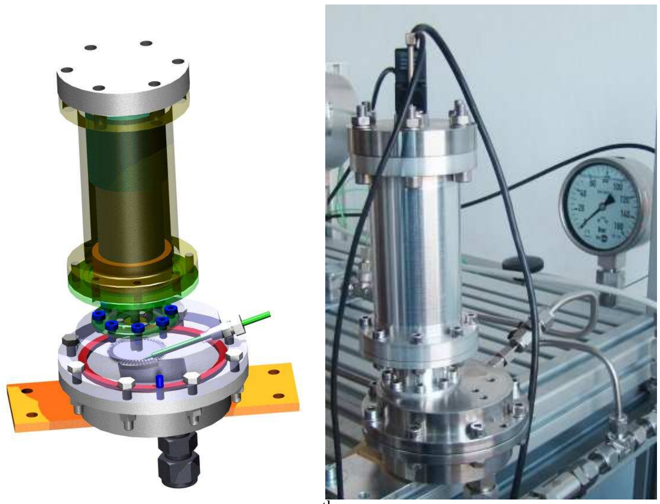

Figure 6. Improved 4th generation prototype.

1.5 TURBINE STAGE SIMULATIONS

In order to get an insight of the crucial parameters of the parts of the turbine, interacting with the fluid, a frozen rotor simulation has been done, using ANSYS CFX. Because the geometry of the blade is of great relevance for the performance, an approximative model of one blade has been analyzed under the assumption, that water will be used as the working fluid. This is of course a strong simplification of the physics, since in

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reality; the working fluid will be a two phase system. Nevertheless the simulation can be seen as a "worst case" scenario concerning the mechanical stress of the blade, since the acting force on the blade will become a maximum. As shown in Figure 7, using a standard set of boundary condition (in this case, 60 bar on inlet to 1 bar at outlet), the velocity of the water raises up to about 125 m/s at the upper edge of the blade. This is a non negligible factor for the design of the blade.

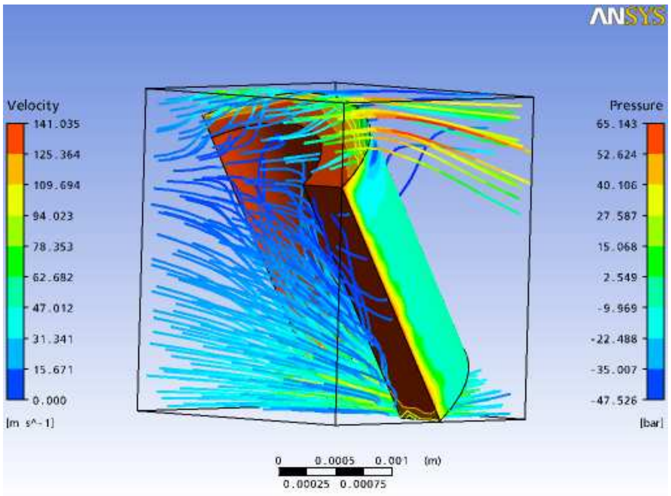

Figure 7. Dynamic fluid simulation of a turbine blade.

Considering the actual design, where the angle of the inlet is about 10°, a nearly homogeneous pressure on the inner wall of the blade can be reached. In order to reduce the complexity of the simulation, only the isothermal case has been considered, since the thermal influence on the fluid - rotor interaction is negligible. To analyze the behavior of the whole fluid - rotor system, a simulation of the whole wheel has been done (see Figure 8).

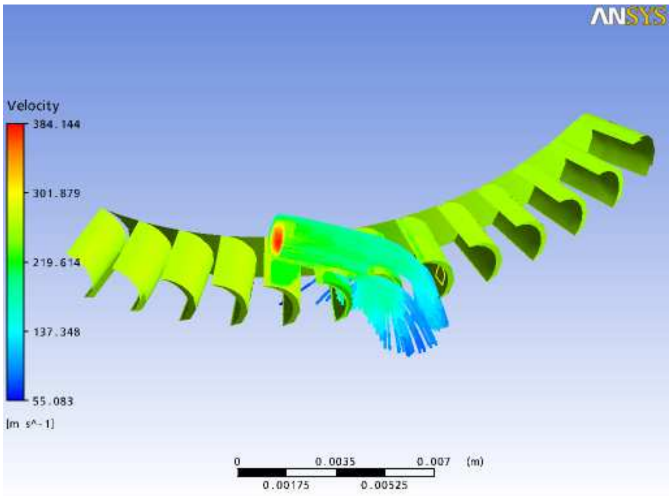

Figure 8. Rotor system simulation.

There it can be seen, that the maximum momentum transfer lies within three blades and the force acting on each blade becomes a maximum at the center of the inner wall (which of course leads to an optimal momentum transfer in tangential direction). Different inlet angles have been analyzed and in our case, an inlet angle of 10° leads to optimal working conditions, also under the consideration of a two component working fluid.

1.6 EXPERIMENTAL RESULTS

The testing facility was specially designed for testing the turbine system with a mixture of water and nitrogen, due to easy handling compared to liquid CO_2. The pressurized water was mixed with pressurized nitrogen in a mixing nozzle, whereas the mass flow rate can be controlled manually with the pressure regulator and a needle valve for nitrogen and via the water pump for water. Data acquisition (various pressures, mass flow rates, temperatures, the rotating speed, and the power output) is conducted via a specially developed PC-based controls program using commercially available software. Figure 9 shows a power output test just with fluid medium. The maximum power output (T5) of 11 W was achieved at maximum water flow. This is more than twice of the last generation turbine (4 W). Our test showed that the generator could work in complete liquid medium without any limitations. Just the stainless steel bearings showed minor wear and tear. They will be substitute by suitable ceramic bearings. As before mentioned the turbine was designed in order to operate in a gas pocket. This test should demonstrate that through to high fluid medium ratio (in this case maximum) the friction losses become high and lead to much lower power output. It also shows that the integration of the more powerful generator have a high impact on the power output. Marginal power output was observed below water flows of about 1 l/min.

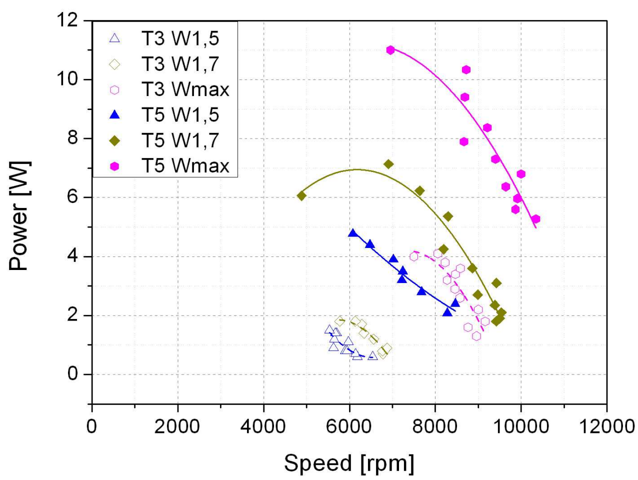

Figure 9. Power output in water operation modes for the 3rd and the 4th generation turbine.

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Figure 10 shows the power output in gas-water operation mode. The maximum power output of nearly 80 W was achieved with a low water flow of 0.5 l/min and 70 bar gas pressure at 32,500 rpm. The power output for a higher water flow of about 1 l/min is approx. 10% lower than for 0.5 l/min.

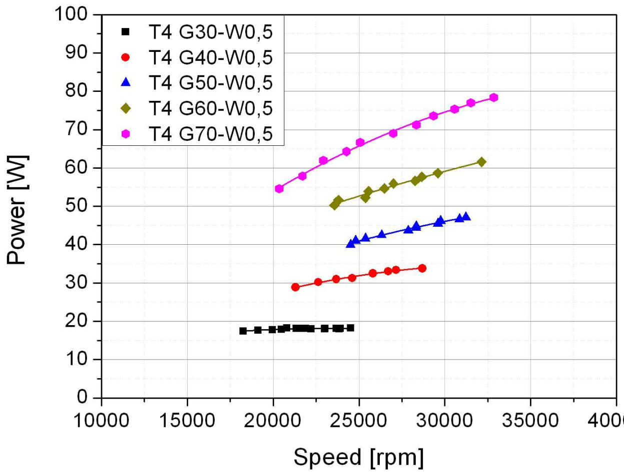

Figure 10. Power output in gas-water operation modes.

A matter of interest is also the behavior of the turbine in term of different mixing proportion of gas and water. Figure 11 show this for gas entry pressures of 50 bar and three different water-flow value 0.5; 1 and 1.5 [ln/min] for the 3rd and the 4th generation turbine. These tests verify our improvements of the 4th generation turbine. The power output is more than twice of the last generation turbine.

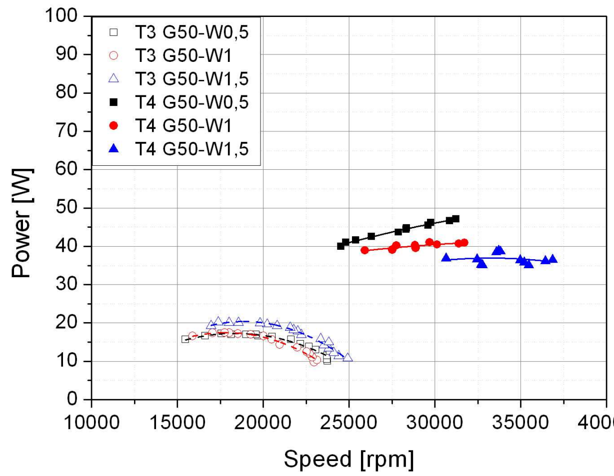

Figure 11. Power output at constant gas pressure and different water-flow values for the 3rd and the 4th generation turbine.

Figure 12 shows the gas tests. A maximum power output of 100 W was achieved at 70 bar and 28,000 rpm. This is more than twice of the last generation turbine, too. The 100 W are 80 % of the calculated maximum power output. Improvements for gas operation mode are rarely possible by using a more efficient generator. The selected generator has a maximum rotational speed of 27,000 rpm, we over boost the generator up to 15% (32,000 rpm) to achieve the higher power outputs. This was temporarily possible but not suitable for long-term operation. Major difficulties were monitored in the power requirements. The electric potential of the generator achieved maximum values of approximately 100 V at 100 W power output compared to a maximum voltage of 48 V as denoted from the manufacturer. This seemed to be the maximum over boost value for the generator and hence the power output. The gas-water flow from Figure 12 is significantly lower than the gas flow in gas operation mode. This could be explained with higher friction losses at the bearings and inside the generator.

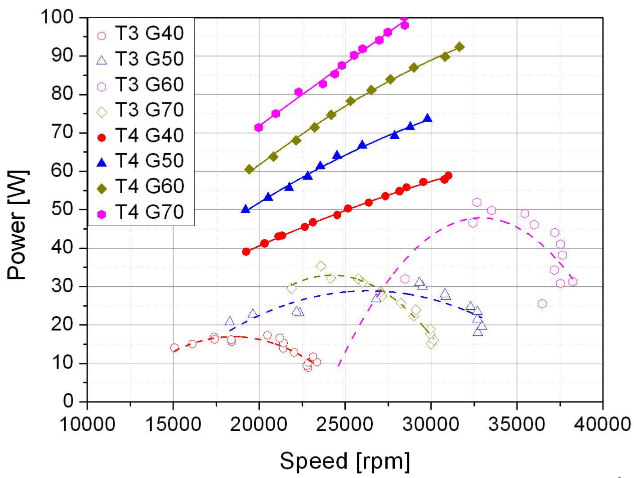

Figure 12. Power output in gas operation modes for the 3rd and the 4th generation turbine.

The comparison of two different gases (CO_2, N_2) as working medium is shown in Figure 13. Both curves become more and more similar with increased engine speed.

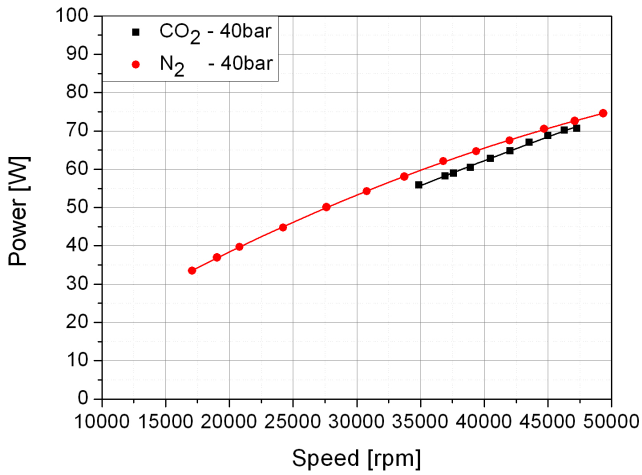

Figure 13. Power output for CO_2 and N_2

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The difference of the power output at 35,000 rpm is 6.3 percent and is decreasing to a value of 2.2 percent at a speed of ~47,500 rpm. In case of this experiment, the limitation factor was the maximum allowed engine speed of the generator. It is therefore the challenge for the next improvements to decrease the internal losses of the system in gas-water operation mode by design changes and to test a new generator with higher rpm's. One important tool for this task seems to be the simulation as described in section 1.5. As a matter of fact the extension of the simulation to a two-phase case may lead to additional difficulties not only in terms of computational power but also in the studies and assumptions according to the physical behavior of the system.

1.7 GREEN FUEL MICRO POWER GENERATOR

Another application for this converter is a high power refillable energy cell based on H_2O_2 microcombustion. Hydrogen peroxide (H_2O_2) is a non toxic liquid. It can be used as fuel or as an oxidizer. If hydrogen peroxide comes in contact with a suitable catalyst, it starts to decompose into water and oxygen. Due to the exothermic nature of the reaction, one obtains a relatively hot mixture of water steam and oxygen. The final temperature of the decomposed hydrogen peroxide depends mainly on its concentration (70-100%) and the efficiency of the catalyst. Initial tests have been done with hydrogen peroxide in concentration of 80 % by weight to verify the general operability of the catalysts followed by test with hydrogen peroxide in a concentration of 87.5 % shows an example of the decomposition temperature obtained for one of the mullite based catalysts. The theoretical decomposition temperatures of 80 % and 87.5 % hydrogen peroxide are 480°C and 670°C respectively. The influence of the system temperature can be simply investigated by preheating the system with a small flow of hydrogen peroxide to heat the system up. After stopping and reinitiating the flow, the decomposition temperature rises much faster than in the case of a cold start. This is shown in Figure 14 with the graph no. 1 and no. 3. While the graph no. 3 results from a cold start, the graph no. 1 is obtained with a system already at 100 °C. The preheated system has a temperature gradient in the transition phase of 25 °C/s while for the cold start it is only 10 °C/s [8] [9].

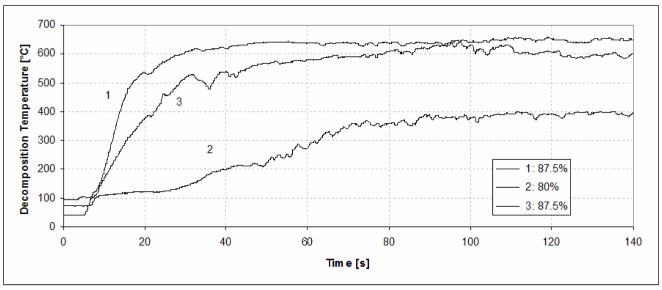

Figure 14. Decomposition temperatures for different initial system temperatures and hydrogen peroxide concentrations [8].

Figure 14 shows that AIT's catalytic hydrogen decomposition has the capability to produce enough hydrogen vapor at short times. Such a green power generator system could have additional features such as its immediate refill capability within 10 seconds, the supply of internal heat e.g. for high altitude UAV's and the supply with clean water. The basic components for such a generator are shown in Figure 15. A first generation breadboard micro power generator with an optimized turbine and thermal design focusing on terrestrial and probably dual-use applications is currently under development.

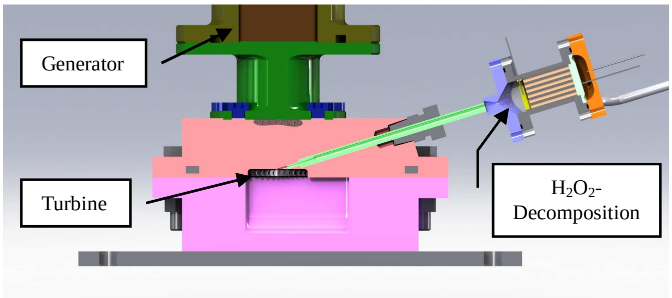

Figure 15. Green fuel micro power generator

2 DISCUSSION

The design of an improved laboratory model microturbine for energy recovery in CO_2 heat pumps has been presented. The main component of the system, the turbine blade, and its performance has been evaluated by simulations. First results of the tests and efficiency values are available and showed 100% higher power output compared to the 3rd generation turbine. Investigating the influence of operational parameters such as the mass flow rate and system pressure, a significant improvement of the rotational speed and hence the power output should be obtained especially in gas-water mode. Additionally, an advanced version of the turbine system for decomposed hydrogen peroxide is in preparation.

ACKNOWLEDGMENTS

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