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Ultra-Micro Wave Rotor Investigations

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Abstract

Ultra Micro Gas Turbines (UμGT) are expected to be a next generation of power source for propulsion and power generation, from aerospace to electronic industry. Knowing that the efficiency of the conventional turbomachinery is small at microscale, especially the one of the compressor, utilizing a wave rotor to improve the performance of an UμGT appears to be a promising solution. Adding a wave rotor is much easier at micro scale than at macro scale since the wave rotor can easily be etched in silicon due to its common extruded 2D shape.
This work introduces some concepts of incorporating a wave rotor to an ultra-micro gas turbine and the advantages of wave rotors, topping gas turbines especially at microscale. Based on documented wave rotor efficiencies at larger scale, a gasdynamic model, and CFD models, the wave rotor compression efficiency at microfabrication scale could be estimated at about 70%.

Keywords: PowerMEMS, wave rotor, ultra micro gas turbine, pressure exchanger, efficiency

1 INTRODUCTION

Starting in 1995, with the MIT "Micro Gas Turbine" project, the mechanical engineering research world has explored the idea of "Power MEMS". Microfabricated turbomachinery like turbines, compressors, pumps, but also electric generators, heat exchangers, internal combustion engines and rocket engines have been on the focus list of researchers for the past 10 years [1].
The probably most investigated power sources are gas turbines with structures of micrometer size that have been referred to as *Ultra-Micro Gas Turbine (UμGT)* to distinguish them from small industry gas turbines of 1-250 kW that are often referred to as microturbines.
Due to their high power density, ultra-micro gas turbines (UμGT) are appropriate solutions for powering small unmanned air-vehicles (UAV) and electronical equipment associated with them, such as sensors, probes or cameras. A typical size of a microfabricated (on-the-chip) UμGT is 10mm×10mm×3mm with a power output between 1 and 100W. Also these microfabricated gas turbines are suitable for high-density, *distributed* power generation onboard larger aircrafts. Applied in batches they yield high redundancy and reduce the vulnerability of the system. The theoretic power density of turbomachinery increases while their size decreases, the reason is the so called cube square law: The output power is proportional to the mass flow rate of the working fluid that scales with the through-flow area, which is proportional to the square of the characteristic length. The mass or volume of the engine is proportional to the cube of the characteristic length. Hence Power/Volume is proportional to the inverse of the characteristic length [2].

The wave rotor is a pressure exchanger that uses pressure waves for direct energy transfer between fluids. A basic wave rotor consists of a rotating drum with straight channels arranged around its axis. The drum rotates between two end plates. Each of which has a few ports. The fluid flow through the channels is controlled by their intermittent exposure to the ports when rotating.

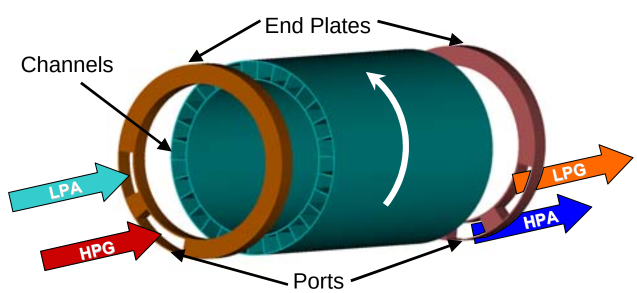

Figure 1. Axial wave rotor drum and end plates.

Figure 1 presents a schematic four-port axial wave rotor with end plates as it can be used for gas turbine topping (Fig. 2). In a through flow (TF) configuration, all flows travel in the same direction. In a reverse flow configuration (RF), each flow (gas or air) exits the same side at which it enters. Considering a TF wave rotor, it can be imagined that the channels are initially filled with air coming from the compressor through the low pressure air port (LPA/1). When they are exposed to the high pressure (high-temperature) gas coming from the combustion chamber (HPG/3), a shock wave is initiated that compresses the fresh air. This high pressure air (HPA/2) is provided to the combustion chamber, while the pre-expanded low pressure gas is scavenged to the turbine (LPG/4).

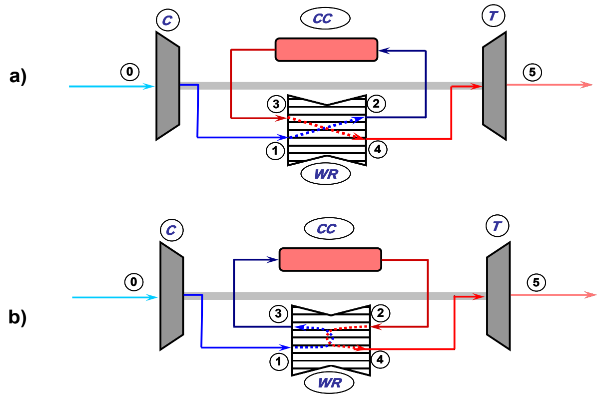

Figure 2. Schematic four-port wave rotor topping
a) Through-flow configuration;
b) Reverse-flow configuration (C – compressor, CC – combustion chamber, WR – wave rotor, T – turbine).

The power required to keep the wave rotor at tuned speed is negligible, since it only needs to overcome rotor windage and bearing friction. It can be made self-driven using some momentum of the flow. Further, the wave rotor is inherently self-cooling, since the channels are alternatively exposed to cold and hot fluid. Also in a regenerative way the wave rotor harvests some of the heat conducted away from the combustor by the structure, which is a severe problem for microfabricated gas turbines that also reduces the efficiency of the turbo compressor. Fluid velocities in the wave rotor are typically about one-third of that in the connected turbomachinery, reducing viscous loses.

Adding a wave rotor to a microfabricated gas turbine appears convenient, since the commonly extruded 2D shape of a wave rotor is ideal for microfabrication processes that are mainly two dimensional (etching, deposition, oxidation, bonding). Additional material and manufacturing steps can be kept to a minimum, producing the wave rotor on the same wafer and in the same processes as the core engine.

2 PROPOSED INITIAL DESIGNS OF A WAVE ROTOR TOPPING AN UμGT

Starting from a baseline engine similar to the one developed by the MIT research group, several wave-rotor-topped ultra-micro gas turbine configurations are proposed [3]. Adopting the four-port configuration, several cycles per revolution can be achieved with a multitude of four ports, reducing the rpm. Figure 3a and 3b show a wave rotor added at outer diameter of the disk formed by the compressor/turbine unit. A second possible design implies using additional wafers for a multi-layer rotor, as shown in Fig. 3c. The perfect axial alignment of the compressor/turbine unit with the wave rotor may pose a challenge. The shown design insolates the compressor better from the combustor heat, especially with the counter flow of the compressed air, where a regenerative effect appears again. The third design concept introduces a new idea in having multiple wave rotors arranged circumferentially around the compressor/turbine unit. The shown configuration in Fig. 3d implies self-driven wave rotors, which can be achieved by arranging the ports in proper angles, so that the impulse of the fluid streams can be utilized.

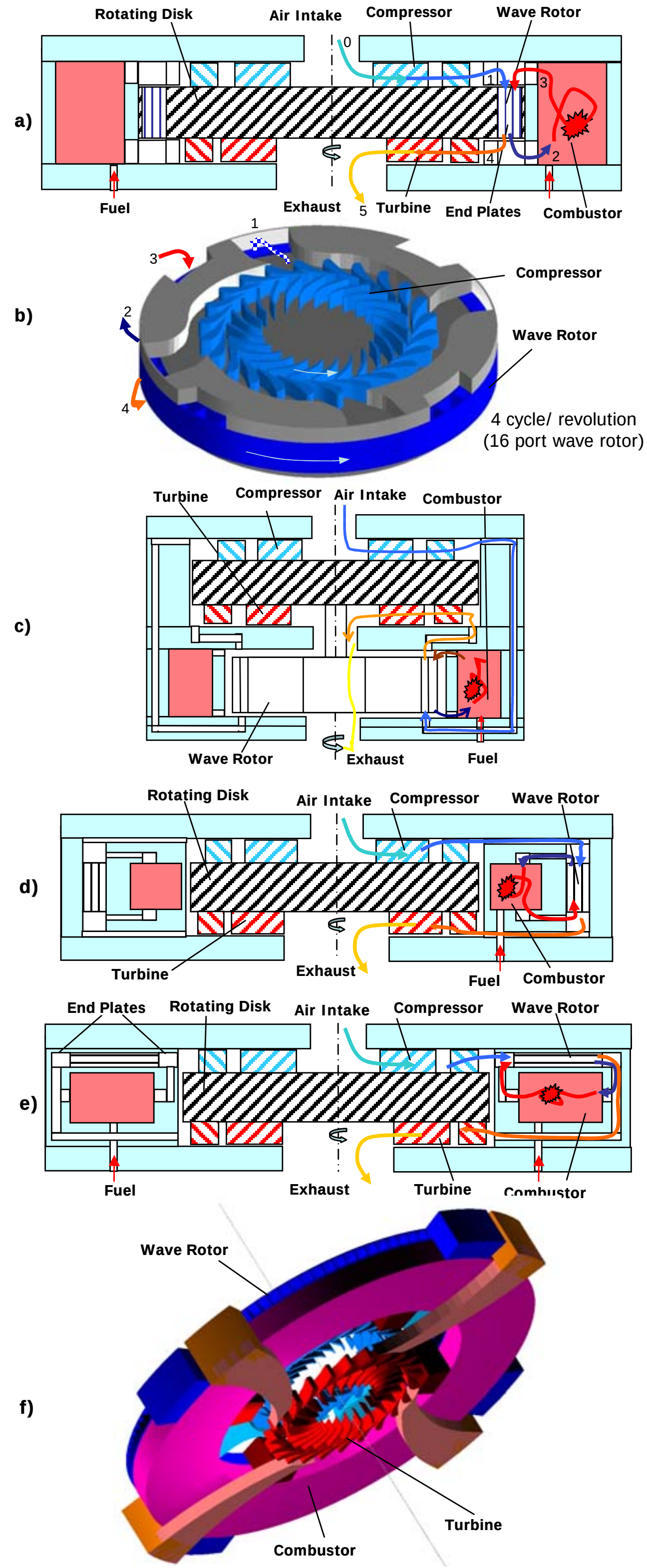

Figure 3. Conceptual designs of wave rotor topped UμGT: a) and b) "Classic" design, b) "Two-layer" design c) "External" design, e) and f) "Radial" design.

Another new and innovative idea is using a radial wave rotor [4] instead of the traditional axial wave rotor (Fig. 3e and 3f). It seems far more suitable for ultra-micro gas turbines. Its shape and overall surface to height ratio is even more ideal for microfabrication processes. Plus, the variable cross-sectional area has been proven to provide a more efficient shock wave compression [5]. The radial-flow wave (wave disc) concept employs the flow in radial and circumferential directions. This can substantially improve the scavenging process by using centrifugal forces.

3 PERFORMANCE CHARACTERISTICS OF ULTRA-MICRO WAVE ROTORS

At micro scale the effect of wave-rotor topping often differs from that at larger scales. At a large scale, mostly the goal is either to increase the cycle overall pressure and temperature ratio or to substitute the wave rotor for costly high pressure turbomachinery stages. The most significant performance gain has been found for engines with low compressor pressure ratio and high turbine inlet temperature [6,7]. At the ultra-micro scale, the optimum cycle pressure ratio is very small, e.g. around 2, due to the low component efficiencies [8]. Thus, mostly a single-stage centrifugal compressor can easily generate the low optimum overall pressure ratio and a further increase with the same efficiency actually decreases the desired performance. Therefore, the wave rotor integration is most effective if its compression and expansion efficiencies are greater than those of the turbomachinery components of the baseline engine. This enhances not only the overall compression and expansion efficiencies, but it also increases the optimum cycle pressure ratio. This additionally enhances the performance, while usually the pressure ratio of the spool compressor decreases. This in turn can additionally enhance the isentropic efficiency of the spool compressor, provided its polytropic efficiency (aerodynamic quality) stays the same.

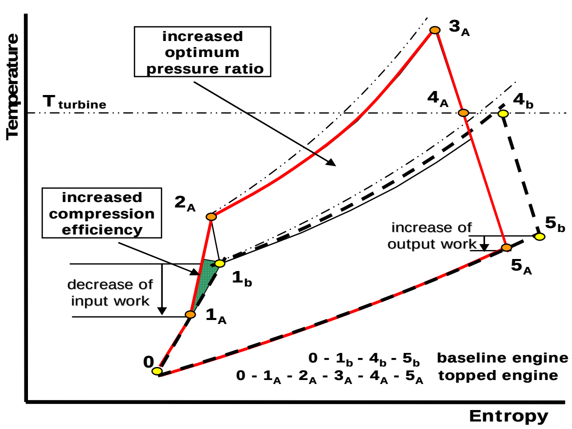

Figure 4. Temperature – Entropy diagram for ultra-micro gas turbines, with and without wave rotor.

The turbine inlet temperature may stay the same or can be lowered while the combustion takes place at a higher temperature. Mostly both the overall efficiency and specific power increase. External losses are leakage, windage, friction in the bearings of the rotor. All these loses also occur in turbomachinery, but rotational and internal flow speeds can be lower in a wave rotors.

An initial study on the efficiency of the compression process in a wave rotor channel has shown that values around 70% can be achieved at microscale [3]. This is more than around 50% for the baseline compressor [8]. For large scale wave rotors with a channel length of about 100-300mm the value of 83% is consistent throughout the literature [9]. For the smallest documented wave rotor with a channel length of 69mm [10], an isentropic compression efficiency of ≈79% can be found using the wave-rotor characteristic equation [7]. No values are available at smaller scale. However, the above results show no or only a small decrease in efficiency with reduced size, which encourages investigations at the ultra-micro scale.

Simple extrapolation of available wave rotor efficiencies versus the corresponding wave rotor channel length generates the straight trend line in Fig. 5a that predicts a >70% wave rotor efficiency at ultra-micro scale (about 1mm channel length). For comparison, the broken trend line shows efficiency values of compressors suitable for or corresponding to the reported wave rotors.

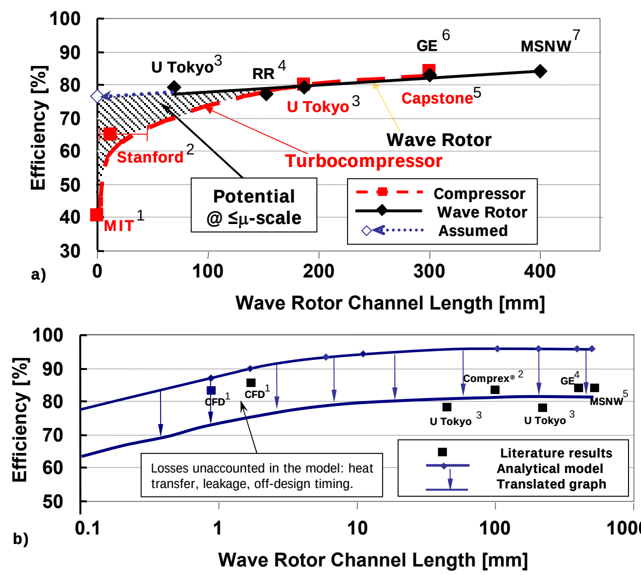

Figure 5. a) Efficiency trend of compression process: Solid line – wave rotor efficiency; Dashed line – compressor efficiency. References: 1[8], 2[11], 3[12], 4[13], 5[14], 6[15], 7[16].
b) Wave rotor compression efficiency as function of channel length for constant length/diameter ratio of 6.67. References: 1[17], 2[9], 3[10], 4[15], 5[18].

A mathematical model was created that includes the entropy production by a normal shock that runs through the channel, the wall friction generated by the gas flowing through the channel, and the entry losses due to the porting [19]. Only heat transfer, leakage and off-design conditions are neglected. The model has been applied to compressible air flow in the channels with Reynolds numbers in the range of

500 to 1500 and friction factors have been adopted as developed and experimentally verified for gas flow in silicon microchannels by Ying-Tao and his research group [20]. The upper continuous line in Fig. 5b represents results of the analytical one dimensional model. Using a FLUENT CFD model, data points for two channel lengths of 1mm and 2mm were calculated. The literature results initially presented in Fig. 5a generate the lower curve in Fig. 5b. The analytical model over predicts the efficiency by approximately 10…15%. This difference is attributed to external losses not considered in the model. Hence, a real compression efficiency of 65…70% can be predicted for microscale ultra-micro wave rotors with channel lengths in the order of 1mm. According to the here employed model that is applicable for all wave rotor sizes, shorter wave rotor channels with larger diameter let expect a higher compression efficiency of the wave rotor. Also higher gas temperatures yield higher efficiencies.

Using the model that results in a variable wave rotor efficiency, the in Fig. 5 shown design space of wave-rotor-topped UμGT can be generated, using only points optimized for specific work or optimized for thermal efficiency [17]. The underlying procedure for cycle calculation and optimization is documented in [21,22].

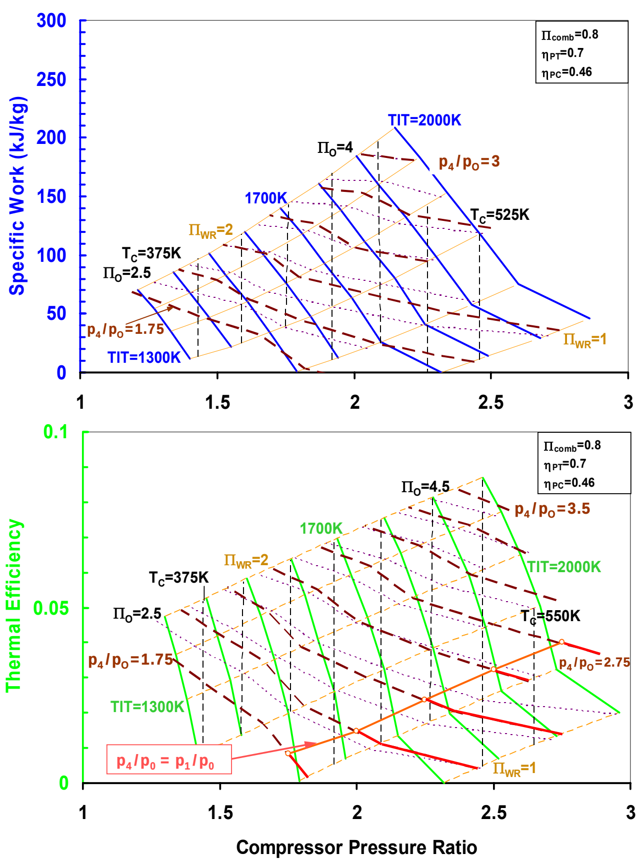

Figure 6. Design points for wave-rotor-topped UμGT optimized for specific work (top) and thermal efficiency (bottom). Π_{comb}-combustor pressure loss ratio, η_{TP}-polytropic turbine efficiency, η_{PC}-polytropic compressor efficiency, Π_{WR}-wave rotor overall pressure ratio

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