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TECHNICAL PAPER

Design and fabrication of microchannel test rig for ultra-micro wave rotors

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Abstract Wave rotor technology has shown a significant potential for performance improvement of thermodynamic cycles. The wave rotor is an unsteady flow machine that utilizes shock waves to transfer energy from a high energy fluid to a low energy fluid, increasing both the temperature and the pressure of the low energy fluid. At microscale, shock wave compression was shown analytically to have higher efficiency than compression by mechanical devices such as impellers or pistons. A second step in proving this superiority of shock wave compression is to design and test a microscale shock tube, which is a perfect model for one of the wave rotor channels. Last step is fabrication of a full wave rotor manufactured using traditional MEMS technology. The paper summarizes the conclusions of the analytical study, describes the details of fabrication of micro shock tube test rig and the design of the ultra-micro wave rotor (UμWR).

1 Introduction

Ultra micro gas turbines (μGT) is expected to be a next generation of power source for applications from propulsion to power generation, from aerospace industry to electronic industry. 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. The reason behind this, is the increased power density with decrease in specific dimensions, fact stated by the so called "cube square law" (Fréchette 2000). The output power is proportional to the mass flow rate of working fluid through the engine. While this 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. Thus, the power density, equal to power/volume ratio, will be proportional to the inverse of the characteristic length. Today, the Power MEMS community comprises research groups all over the world and many results were summarized by Epstein and Jacobson in their "informal survey" (Jacobson and Epstein 2003).

Although many of the initial problems and challenges of micro-turbomachinery were overcome, a problem is still to be solved: the efficiency of the overall thermodynamic process is low, making the system not yet feasible. This is due to physical effects that have more influence on the process at microscale compared to regular scale fluid dynamics: wall shear stresses and friction, viscous forces, usable strength of materials, and chemical reaction times. Also, the manufacturing processes are still constraining the design to an approximate 2D layered design, which is restricting the flow and affecting the mass flow rate.

The low efficiency (below 50%) of the turbo compression system in a microfabricated Brayton cycle device (Müller and Fréchette 2002) has been identified as a major problem for the feasible design space of the project. This is where the wave rotor technology is most welcomed providing a solution, which will increase the efficiency of the compression and/or increase the pressure boost of fresh air

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delivered to the combustion chamber, thus increasing the efficiency of combustion.

Used initially as a high pressure stage for a gas turbine locomotive engine (Seippel 1949), the wave rotor was commercialized only as a supercharging device for internal combustion engines (Doerfler 1975; Zehnder and Mayer 1984; Heisler 1995), but recently there is a stronger research effort on implementing wave rotors as topping units or pressure gain combustors for gas turbines (Welch et al. 1995; Paxson 2001; Akbari and Müller 2003). The wave rotor is a pressure exchanger that uses the concept of direct pressure transfer between fluids by waves. A basic wave rotor consists of a rotating drum with straight channels arranged around its axis. The drum lies between two stationary end plates, each of which has a few ports or manifolds controlling the fluid flow through the channels. Figure 1 presents a schematic axial wave rotor drum and its end plates.

The gap between the end plates and the channel assembly has to be relatively small to minimize leakage losses. In a typical configuration, the cycle starts with filling the channels with air coming from the compressor, through the low pressure air port (LPA). Through rotation, the channels open next to the gases coming from the combustion chamber at high pressure and temperature (HPG). Hence a shock wave is formed that compresses the air in the channel. This high pressure air (HPA) is then released to the combustion chamber, while the remaining gases, which are now pre-expanded to a lower pressure (LPG) are than scavenged towards the turbine. The periodic exposure of the channels to both fluids between which the pressure is exchanged, assures a channel wall temperature between the temperatures of both fluids, which gives the wave rotor an inherently self-cooling feature. Further, the velocity of the working fluid in the channels is about one-third of values within turbomachines. Therefore, the rotor channels are less prone to erosion damage than the blades of turbomachines and viscous loses are less severe.

The concept of adding a wave rotor to an ultra-micro gas turbine was addressed by several research groups from all over the world. With great experience gathered in the wave rotor field, Ribaud at ONERA was attracted by this idea and at begin studying the possibilities of incorporating a wave rotor to an ultra-micro gas turbine. A more extensive work was done by the University of Tokyo research group, directed by Nagashima (Okamoto and Nagashima 2003). Recently, Michigan State University in collaboration with the Warsaw University of Technology is intensively searching for a feasible method of topping a microfabricated gas turbine with a wave rotor. The new proposed design of wave rotors, which have the channels placed radially instead of axial with respect to the axis of rotation, appears to be the solution to the problem (Piechna et al. 2004).

Starting from a baseline engine similar to the one developed by the MIT research group, a radial wave rotor topped, ultra-micro gas turbine was proposed (Iancu et al. 2005). The wave rotor works in a four-port configuration, namely each cycle is completed once the wave rotor channels make contact at one end or the other with all four ports. The overall aspect of the wave rotor may include a larger number of ports depending on the number of cycles per revolution. The radial wave rotor (wave disc) will be incorporated in parallel with the combustor; schematics are shown in Fig. 2.

Unlike the axial wave rotor, the wave disc concept employs the flow in radial and circumferential directions. This can substantially improve the scavenging process by using centrifugal forces and, the channel shape along its length can be tailored in width and angle introducing additional degrees of freedom into the design.

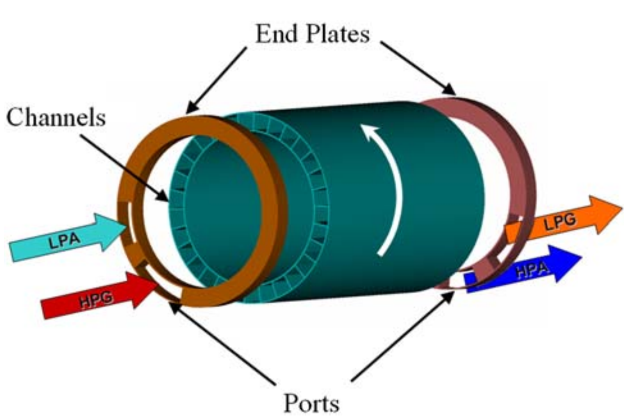

Fig. 1 Axial wave rotor drum and end plates, showing port notation

2 Theoretical investigation of a two-dimensional microchannel

Extant literature shows several investigations of compressible flow in microchannels. Some have focused on uncovering the characteristics of the flow (Xue and Chen 2003), others studied the behavior of compressible flow at microscale and the differences in relation to large scale (Papautsky et al. 2001). With all this, there is a lack of defined experimental results to evaluate the behavior of compressible flow in microchannels. This paper is proposing an experimental study of wave rotor microchannels, following results to be compared with previous analytical and numerical ones.

The implementation of a wave rotor at ultra-micro scale appears most effective if its compression efficiency is

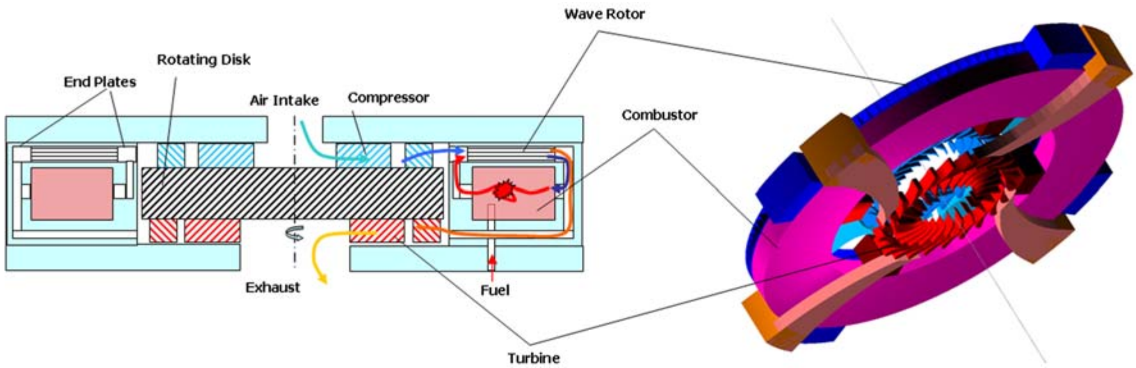

Fig. 2 Conceptual design of microfabricated µGT—"Radial" design

greater than that of the baseline spool compressor. Whereas the latter ranges low around 50% at ultra-micro scale, compared to about 70–90% at large scale, the compression efficiency of wave rotors has been found to be in the range of 70–86% (Iancu and Müller 2006). This may be considered as matching the efficiency of large-scale compressors or turbines and about 50% more than that achieved with ultra-micro scale compressors. Theoretical and numerical results encourage the idea that at microscale, compression by shock waves may be more efficient than by conventional centrifugal compressors, thus making the ultra-micro wave rotor a feasible idea for enhancing (upgrading) µGT.

A one-dimensional model was used to evaluate the efficiency of the compression process inside a microchannel. The process is similar with the one happening inside a shock tube. The difference is the process initialization time. If in a shock tube experiment, the process starts by breaking a membrane, here the process starts with one of the channel ends coming in contact with a high pressure fluid. The process is based on the gas dynamics of normal shock waves for one-dimensional flow as described by Anderson (2003). The model assumes air as a working fluid modeled as an ideal gas, and a friction coefficient along th channel to be a variable function of gasdynamic conditions. The theoretical results were compared to numerical one obtained using a CFD commercial code, in which the process was simulated using the same assumptions as in t theoretical case. The tube is initially filled with low pressure gas, followed by opening one end to a high pressur enclosure. Adiabatic conditions were chosen after an initia study of the impact of heat transfer to and from the walls of the cells. An extensive analysis was performed, studying the influence of several key factors on the efficiency of th compression process. The conclusions by Iancu and Müller (2006) suggest that high pressure gas temperature, lengt width ratio and shock strength are the most importan parameters. Entry velocity was kept constant for this analysis.

Further, it can be seen in the CFD results that for the initial part of the process, the pressure drop is confined over a short distance (between stations 2 and 3 in Fig. 3). As the shock wave travels further from the left to the right, the pressure gradient dissipates more and more continuously over a longer range. Instead of a well-defined shock wave, it then can be seen as a set of compression waves distributed over more than a half of the length of the channel (Fig. 3 below). Time scale has been normalized, $t = 1$ being the duration of pressure wave travel through the channel.

This effect has already been noted by Brouillette in his experiments with microscale shock tubes (Brouillette 2003), and it originates from the stronger influence of the viscous forces at low Reynolds numbers. In the density contour plot (Fig. 4), the existence of the boundary layer can be seen clearly, behind the shock wave as soon as it has traveled about 20% of the channel length.

Keeping a constant $L/D_H = 6.67$, a scale influence on the efficiency of the shock wave compression process was investigated, where L and D_H are the channel length and

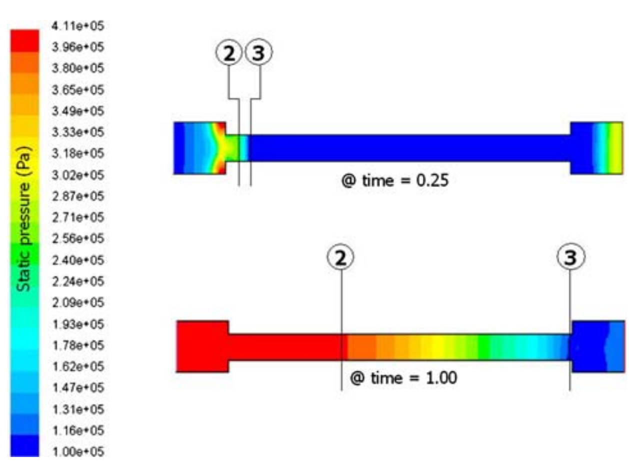

Fig. 3 Static pressure inside a microchannel at two different time steps. Flow and pressure wave moving from left to right. Results obtained using CFD code FLUENT 6.1

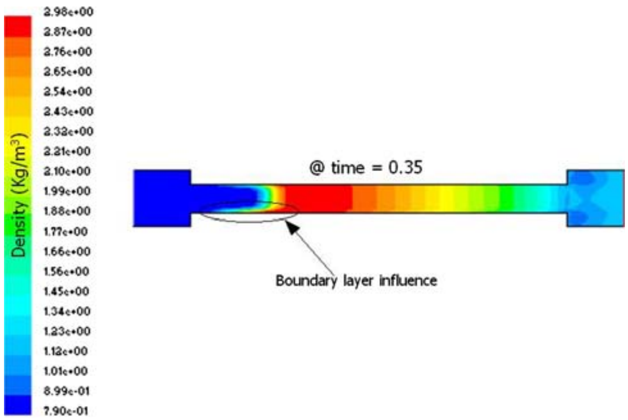

Fig. 4 Density contours inside a microchannel. Flow moving from left to right. Results have been obtained using CFD code FLUENT 6.1

diameter, respectively. The upper continuous line in Fig. 5 presents this effect based on the analytical one-dimensional model (Iancu and Müller 2006). Two sets of data points are shown along with this graph. Using the CFD model, the efÞciencies of compression process for two cell lengths were calculated (for 1 and 2 mm). Also, efÞciency values found in literature are added to the graph. It is observed that the analytical 1D model over predicts the efÞciency of the compression process mainly because it represents only the gasdynamic process inside the wave rotor cells, while the literature results present the efÞciencies of wave rotor systems as a whole. It can be concluded that the analytical model over predicts the efÞciency by approximately 10Ð15%. This difference is attributed to additional losses not considered in the analytical model. These are mainly due to leakage between the channel ends and the end

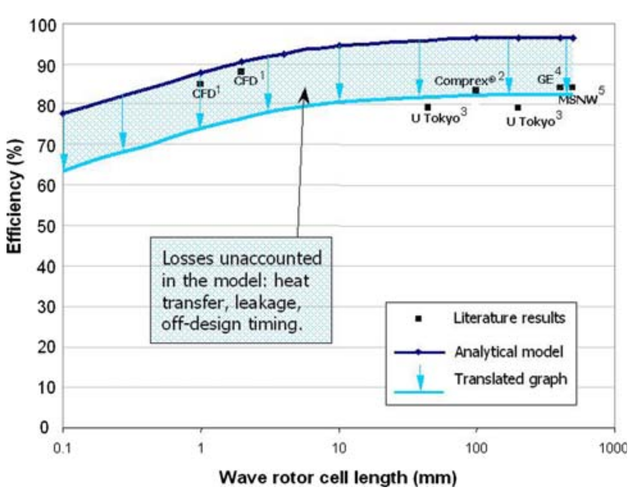

Fig. 5 Wave rotor compression efÞciency as function of channel length for constant length/diameter ratio of 6.67. References: *1* CFD model, *2* (Zehnder and Mayer 1984), *3* (Okamoto et al. 2003), *4* (Mathur 1985), *5* (Taussig 1984)

plates, but also some due to heat transfer and slight off-design operation. Accounting for these losses additionally to the results of the analytical model, a real compression efÞciency of 65Ð70% can be predicted for microscale ultra-micro wave rotors with channel lengths in the order of 1 mm.

3 Manufacturing of microchannels

The Þrst problem that arises when experimental investigations in MEMS are considered is cost. Fabrication costs are high, and this is one of the reasons the research is progressing with a slow pace. Another reason is that diagnostics and measurement at microscale are difÞcult, expensive and often destructive. An alternate and viable solution to experiment is numerical investigation. Either using specialized in-house codes or the newly developed CFD commercial codes, the research process time is tremendously decreased. Numerical analyses are faster and more affordable than experimental ones. The experiment often is still necessary after the numerical model has been thoroughly veriÞed. In the Þeld of microscale shock waves simulated by available commercial codes, the literature is not too vast. Although the wave rotor is based on a relatively simple engineering idea, its simulation is rather difÞcult to achieve. Shock waves behave differently at microscale than at macro scale. For a given Mach number the resulting particle velocity is lower, but the pressure is higher (Brouillette 2003). The diffusive transport phenomena can no longer be neglected at micro scale, and viscous stresses at the boundaries tend to deform the shock wave front. Also, the heat conduction to the wall prevents the ßow from remaining adiabatic. At a small scale the pressure rise across the shock increases with the decrease in the $Re \cdot D_H/4L$ factor for a constant Mach number, where Re is the Reynolds number.

A single channel experiment has been developed to investigate the wave phenomenon inside a single wave rotor cell. The channel has square cross-section with a 360 μm side length and 3 mm length. To be able to obtain more information, the channel was replicated at different scales on the same design matrix. Although the depth of the channel was maintained at 360 μm, the width and length was varied to 90 750, 180· 1,500, 360· 3,000 and 720 · 6,000 μm^2.

The process ßow used in fabrication of the single channel test rig is described in Fig. 6. The process uses both a silicon and a glass wafer. The fabrication process began with a Si wafer with thickness of 500 μm. Ten micrometers thick photoresist (AZ9260) was spin coated on the Si wafer with a spin speed of 2,000 resolutions per minute (rpm). Karl Suss MA-6 mask aligner was used to

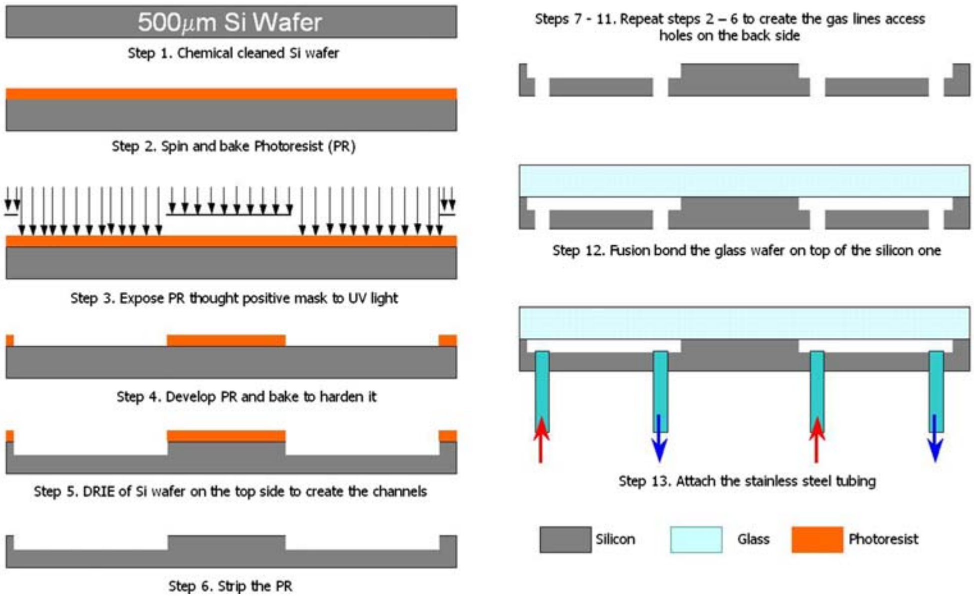

Fig. 6 Process ßow for microfabrication of single channel test rig

pattern the photoresist as the mask for deep reactive ion etching (DRIE). As shown in Fig. 6, the front of the wafer was DRIE etched to deÞne the channels and cavities with etching depth of 360 µm. The backside of the wafer was etched about 140 µm to create the access holes to front cavities for the tubing. The etch rate is about 3.8 µm per minute.

After the DRIE etch, the front of the Si wafer was bonded with a glass wafer using anodic bonding to seal the channels. The glass wafer will allow optical measurement of the shock waves inside the channels. Karl Suss SB-6 bonder was used for the anodic bonding with the parameters listed in Table 1. After the bonding, dicing saw (Micro Automation 1006) was used to cut the sample into 15 · 15 mm dies for testing.

Table 1 Parameters for the anodic wafer bonding

Temperature	350°C
Force	307 N
Voltage	Ð1,000 V
Current	1Ð10 mA
Time	7.5 min

Figure 7 presents images of a fabricated micro-channels die. On the front side, the channels and the ßow plenums can be observed. The quality of the geometry resulted from the microfabrication technique is impressive, allowing for clear view of the smallest channel (90 µm in width). On the back side, the access holes for the ßow pipes are precisely etched. Also, on the back side in the top-right corner, the alignment marks could be seen. The details of fabricated micro-channels can be seen in the scanning electron microscope (SEM) pictures. Figure 8 shows the top view of four channels. In Fig. 9a and c it can be observed that the walls are not smooth, but show vertical wrinkles in the side walls of the channel. This feature might affect the boundary layer of the ßow through the channels, although the wrinkles are only a few microns in height. In Fig. 9b a

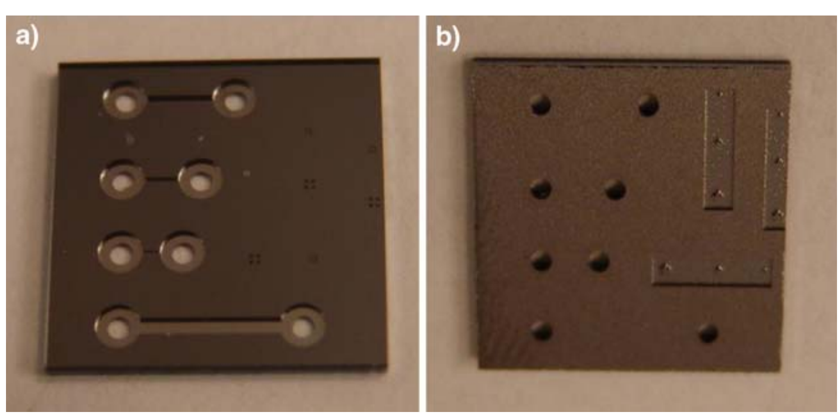

Fig. 7 Silicon microchannels. a Single die, front view. b Single die, back view

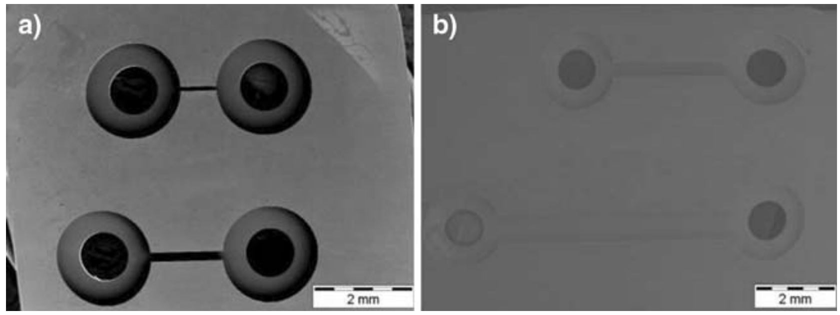

Fig. 8 Different size channels visualized with SEM: a 90 and 180 μm wide channels; b 360 and 720 μm wide channels

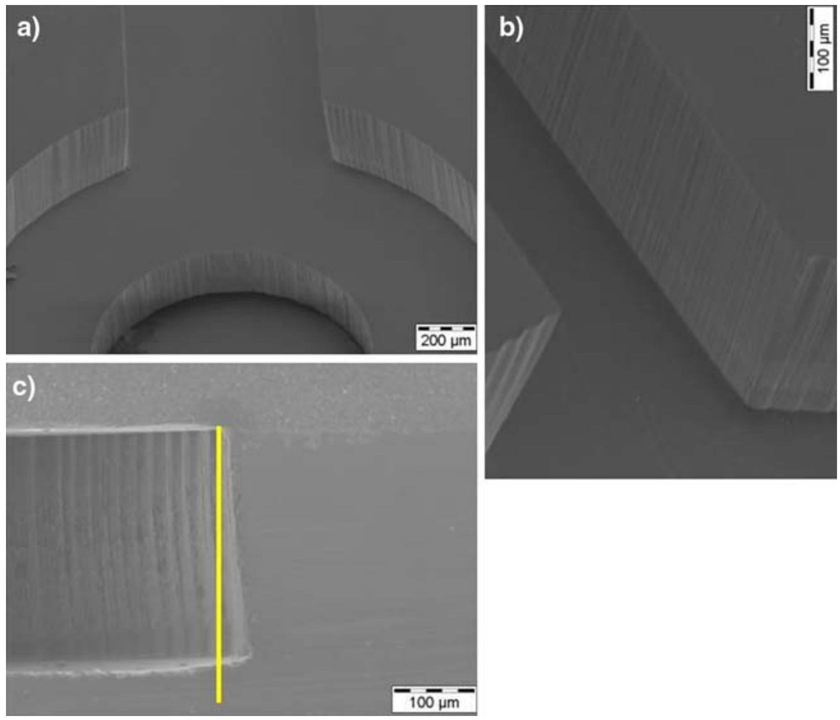

Fig. 9 Details of microfabrication of the silicon channel

different aspect is noticed, that the walls are under-etched. The lateral walls are deviated from the vertical with approximately 20 μm on the bottom (i.e. an angle of 3°), thus transforming the cross-sectional shape of the channels from rectangular to trapezoidal. Although this will not affect the microchannel measurements or the wave rotor performance, this aspect plays an important role for some of the turbomachinery components.

A great achievement of this fabrication process is the quality of the bonded structure. In Fig. 10 the bond between silicon and glass wafers is highlighted and it can be noticed that the bond is almost indistinguishable.

When examining the die under an optical microscope (Olympus BH2 with a SPOT Camera by Diagnostic Instruments Inc.), it can be seen that the geometry is accurate enough, errors varying from 1.3 to 22% (Fig. 11). Since the silicon is not transparent, reßection had to be used for visualizing the die instead of transmittance, and the walls generated some light interference, thus the walls look blurry. Using optical measurement for the channelsÕ width a part of the error is generated due to the light reßection interference. Figure 11 shows optically measured dimensions and the light reßection interference effects.

Last step of the manufacturing part was to create a bracket for handling the silicon die (chip). The bracket was created on the same system as the chip itself, based on a layer structure (Fig. 12a). A 1 mm thick aluminum plate was the middle layer (Fig. 12b) that holds the die from moving sideways. Two Plexiglas plates (5 mm thick) restrain the chip from the top to bottom. The Plexiglas was used for its transparent property, which allows for ßow visualization equipment to be used. Further more, the bottom Plexiglas plate had a set of 2 mm wide holes to allow the 1 mm (outer diameter) ßow pipes to be connected to the chip. The whole assembly is fastened with four bolts, one in each corner.

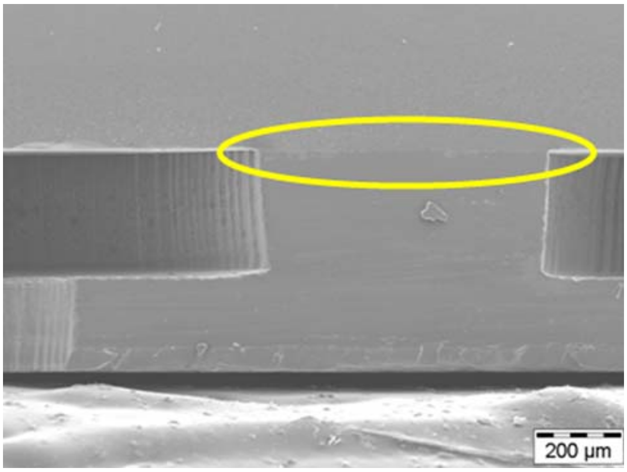

Fig. 10 Bond between silicon and glass wafers

4 Design of the UμWR test rig

The radial ultra-micro wave rotor will be fabricated, similar to the single channel test set-up. The channels will be created by isotropic etching of two wafers, each half the height of the channels and bonding the two wafers in the end. This way the channels will have a rounded cross-section for lower friction resistance (Fig. 13). Figure 14 shows cross-sectional views (top and side) of the computer rendering in Fig. 13.

For the wave rotor 500 μm thick wafers are going to be used, and the rotor will be made out of two wafers fusion bonded together. The process flow for microfabrication of the radial wave rotor test rig uses four wafers and nine masks. The process follows the same procedure as described in Sect. 3, but here it applies to both the rotor and

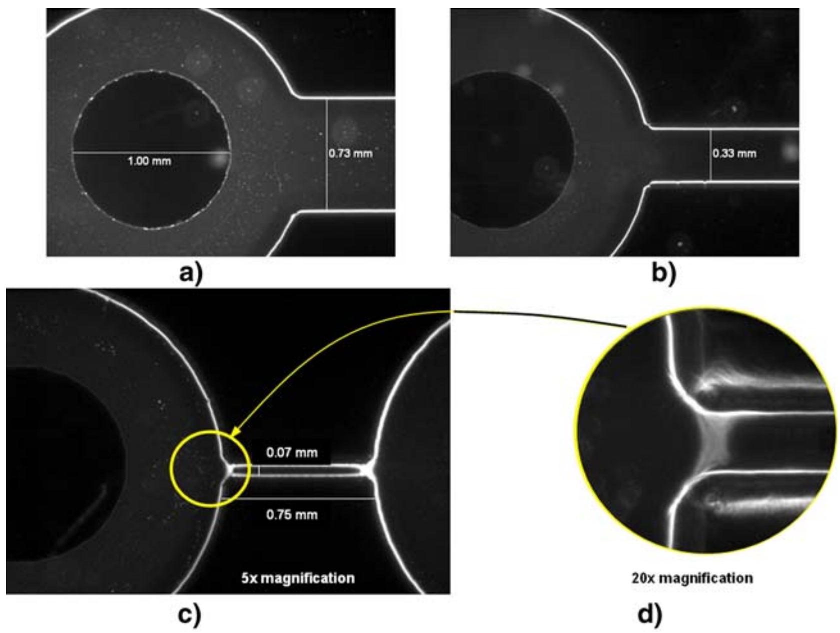

Fig. 11 a, b Optical inspection and visual measurements of channels geometry. c, d Light reflection interference when visualizing silicon channels with optical microscope

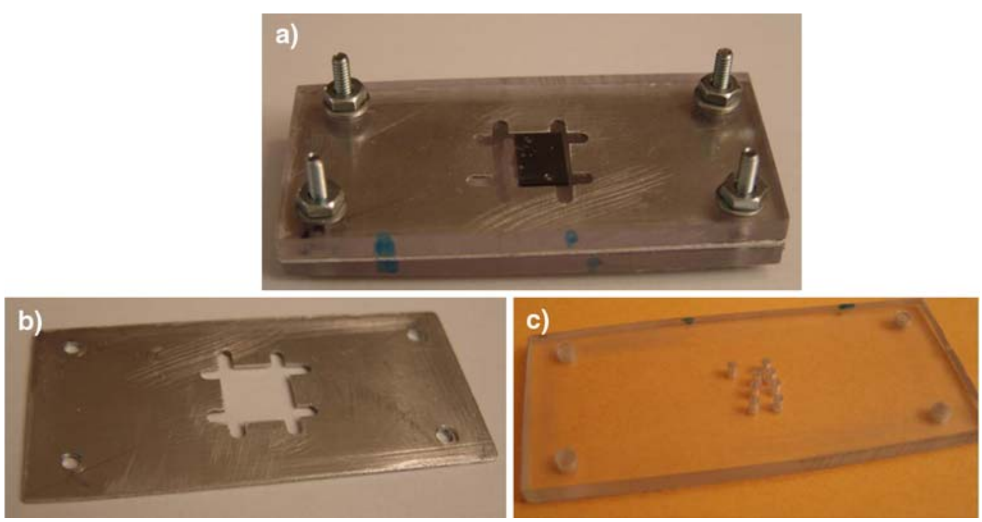

Fig. 12 Mounting bracket for the silicon chip. a Assembly. b Middle aluminum plate. c Bottom plate with access holes

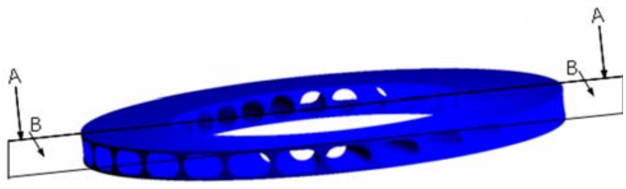

Fig. 13 Radial wave rotor with rounded cross-sectional channels

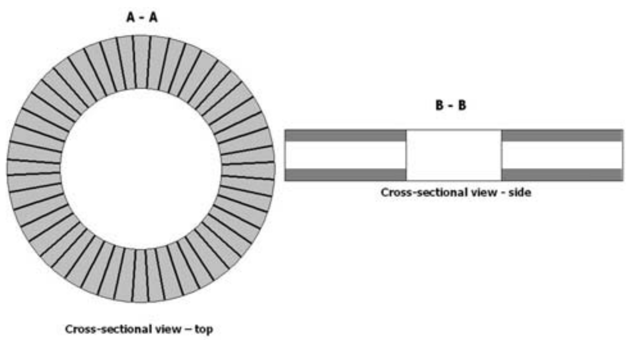

Fig. 14 Radial wave rotor. *Left* AÐA cross-section (from Fig. 13). *Right* BÐB cross-section

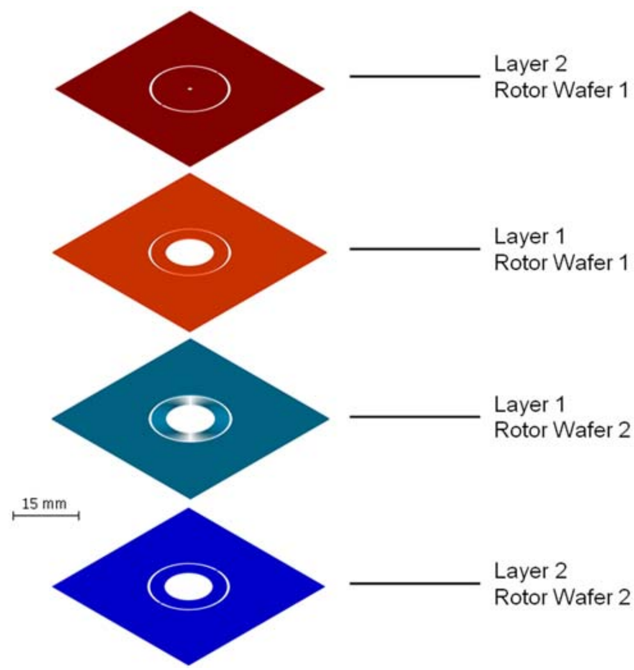

Fig. 15 Wafers used for rotor fabrication

the stationary plenums and ports. The ßow plenums are some cavities into which the ßuid comes from external sources. The ßow is collected and its pressure raised to speciÞcations and then directed to the wave rotor channels by means of ports.

Figure 15 presents the exploded view of the rotor with the four etched layers of the two wafers, while Fig. 16 presents a similar view of the stationary part comprising plenums and ports.

Figure 15, layer 1, both rotor wafers are the two halves of the actual channels, while layer 2 is used for fabrication of top and bottom walls of the rotor. Similarly, layer 1 in both wafers presented in Fig. 16 are used for etching the plenums, layers 2 and 3 of wafer 2 form the access holes for the piping, and layer 2 in wafer 1 seals the ports on the top side.

Figures 17 and 18 present cross-sectional views of these parts. It can be seen that the rotor part is made out of four layers (each involving a different etch step and utilizing a different mask), two for each 500 μm wafer, while the stationary part comprises Þve layers, two for the top wafer and three for the bottom wafer. The masks have alignment marks on them, under the form of etched rectangles, positive for one mask and negative for the other mask.

The complete rig assembly is shown schematically in Fig. 19, as a cross-sectional view. In Figs. 15, 16, 17, 18 and 19 the layers have been color-coded for better visualization of the manufacturing process.

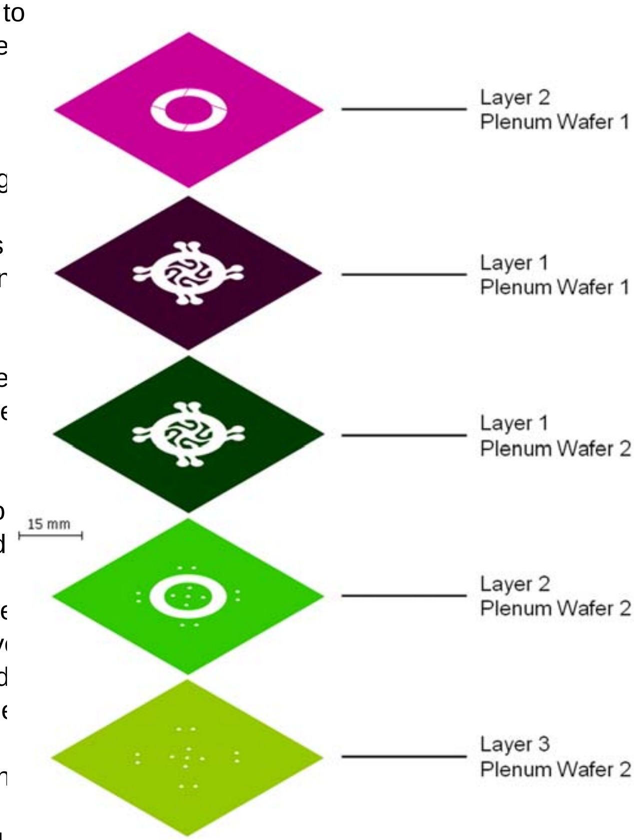

Fig. 16 Wafers used for ports and plenums fabrication

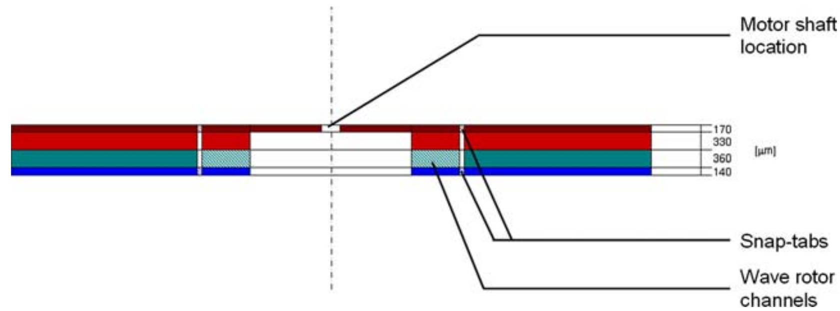

Fig. 17 Cut-view of the rotor wafersÕ assembly

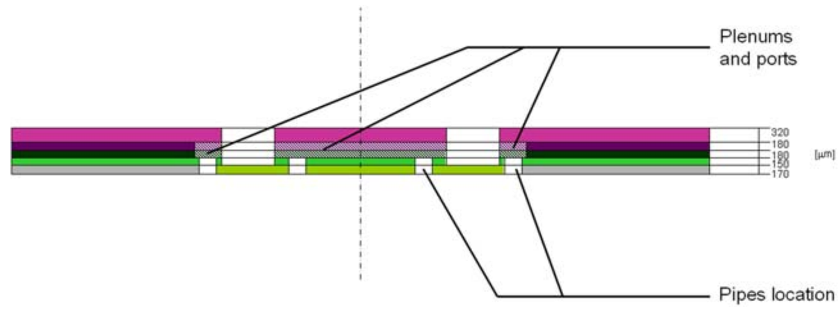

Fig. 18 Cut-view of the portsÕ and plenumsÕ wafer assembly

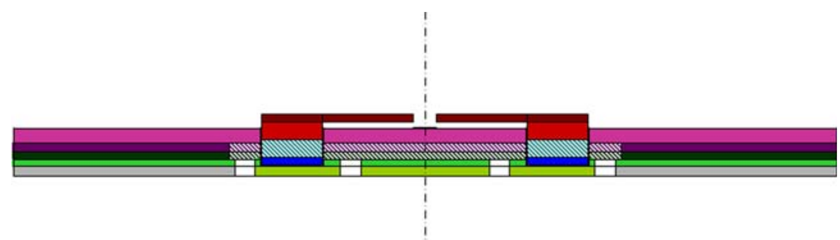

Fig. 19 Full wave rotor assembly

5 Summary and conclusions

A microchannel test rig was designed and fabricated as a Þrst step towards proving experimentally the advantage of topping an ultra-micro gas turbine with a wave rotor. This advantage was already proven analytically and numerically, showing that efÞciency of shock wave compression in channels with diameters below 100 μm and length of several mm is above 70%. The test results will be beneÞcial not only to wave rotor research, but to microßuidics and microscale shock wave research as well. By having one side of the channels manufactured out of clear glass, optical measurements (Schlieren method) can be performed, tracing the shock velocity and dissipation. At the same time, pressure and temperature gages will be placed on the two stainless steel pipes, which direct the ßow in and out of the microchannel. This measurement will be used in calculation of the pressure increase, temperature increase and thus compression efÞciency. The simple manufacturing process used for fabrication of microchannels rendered good geometry, with small wall asperities and sharp corners.

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