

Introductory Investigation of Micro Wave Rotor

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ABSTRACT

In addition to the difficulty of structural integrity involving heat conduction and gas bearings, power-MEMS turbine system faces the critical problem of securing marginal thermal efficiency to produce positive required power, since the turbo-component efficiency becomes very poor due to the downsizing effect. Micro wave rotor is expected to be applied for the improvement of the performance of such ultra micro gas turbines, increasing the cycle pressure ratio and yielding the regenerative effect.

Wave Rotor compresses the air by pressure waves generated in the passages, and the prediction of their velocity is the most important factor in the wave rotor design. Because the inner flow dynamics is far different from that of an ordinary shock tube, efforts were made, first of all, to establish a way to closely correlate the numerical simulation with the experimental observation. Based on that investigation, an over-all simulation model was developed to assist the wave rotor design. With this model, an attempt was made to design a micro wave rotor applicable to kW size micro gas turbines, wherein leak flow effects were discussed with adjusted port configurations.

INTRODUCTION

When downsizing various kinds of machines, the power source also needs to become small. To meet this demand, a shirt button sized ultra micro gas turbine, as shown in Fig.1, was proposed by MIT (Epstein et al. 1997), where MEMS technology is to be fully employed for the benefit of low price mass production. Such ultra micro gas turbines are supposed to be utilized as the propulsion system for unmanned micro air vehicles or as the power supply of electric instruments and robots. Ultra micro gas turbine has higher energy density (power/weight) than conventional battery, therefore, it can have a large impact upon our modern life.

The performance of a gas turbine is much influenced by the maximum temperature and total pressure ratio. Realization of the ultra micro gas turbine therefore meets difficulty, because the downsizing effect leads to a decrease in the efficiency of each component, so that the total efficiency will become too low. One of the solutions for this problem is the usage of a heat exchanger to recover wasted energy, but the pressure loss through the ultra micro heat exchanger can be very large. Also, a heat exchanger may not be suited for an ultra micro gas turbine of propulsion purpose for a flying object. All these considerations necessitate the higher total pressure ratio with the system simplicity, which is a difficult task for the blades of an ultra micro compressor.

On the other hand, wave rotors are expected to have a potential of improving drastically the performance of a gas turbine system. A

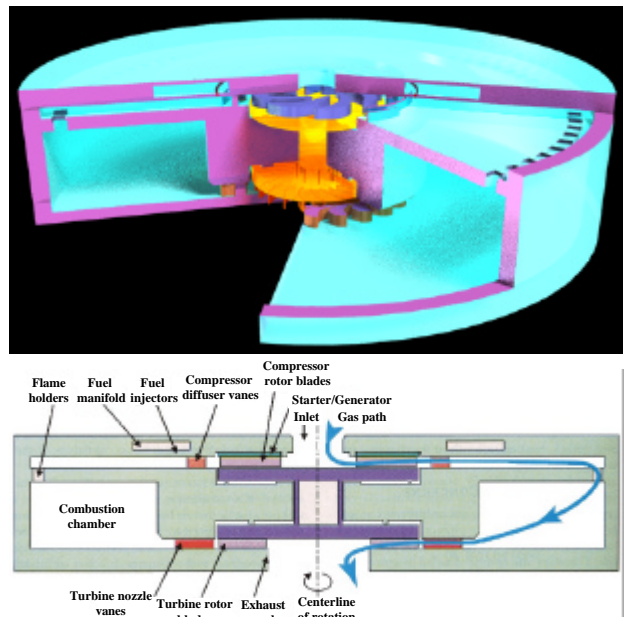


Fig.1 MIT Power MEMS Turbine Concept

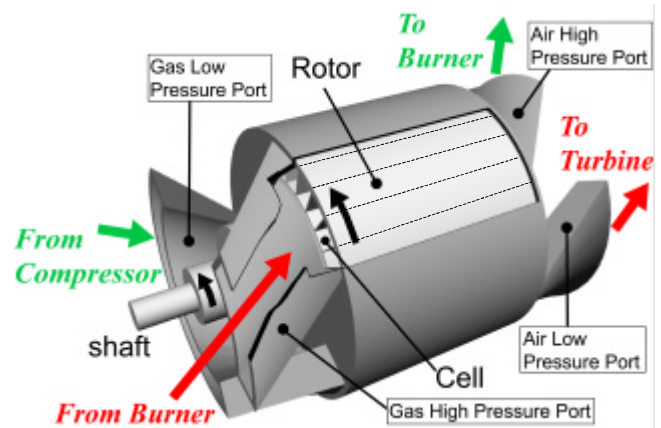


Fig.2 Wave Rotor

wave rotor consists of a rotor and ports as shown in Fig.2, and the rotor consists of many narrow channels called "cells", in which the working gas compression / expansion takes place. Each port, which is connected to the gas turbine component, charges or discharges the cells with fresh air or combustion gas, respectively.

A wave rotor is topped on a gas turbine as shown in Fig.3, and it plays a role of pressure and heat exchangers. Therefore, the total pressure ratio and maximum temperature can be drastically

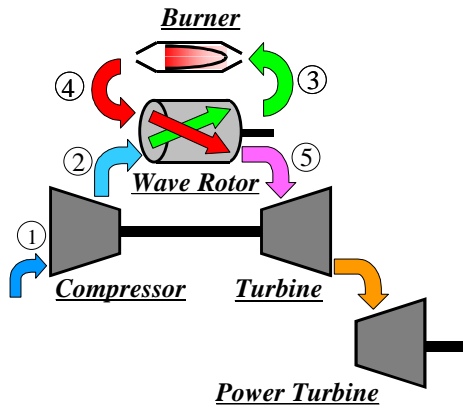


Fig.3 Wave Rotor Topped Gas Turbine

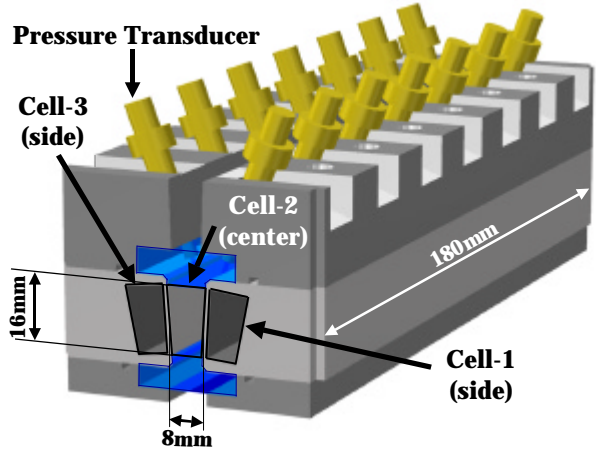
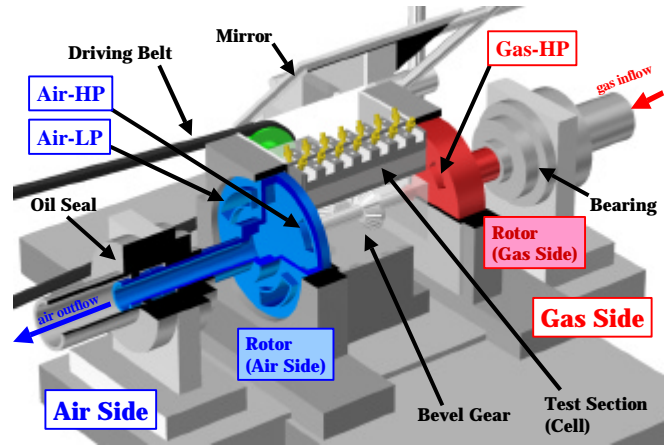


Fig.5 Equipment Concept

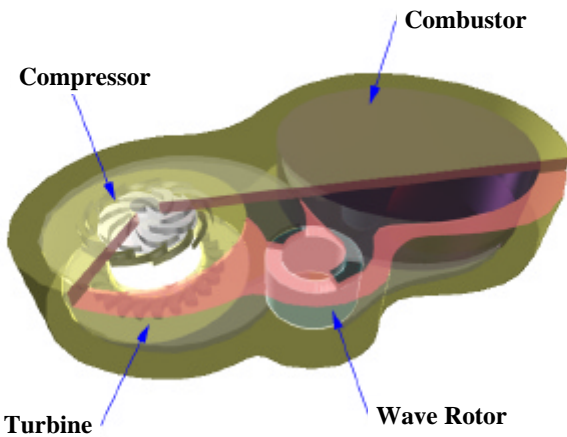


Fig.4 Micro Wave Rotor Topped MEMS Gas Turbine (imagination)

increased. Also, a wave rotor can be expected to help the realization of ultra micro gas turbine (Fig.4), because a wave rotor is generally supposed to have advantage over conventional impeller (Fatsis, et al. 1998, Wilson, et al. 1993). Therefore, under the support of NEDO International Joint Research Project, an innovative development is in progress to design a micro wave rotor that is applicable for such ultra micro gas turbines. (FY2001 NEDO contract report)

The crucial point in the wave rotor design is to exactly set the port opening/closing timings in accordance with shock and rarefaction waves traveling within a cell. Otherwise, the performance will be deteriorated by the generation of extra pressure waves and reverse flow. Therefore, it is necessary to know the propagation velocity of pressure waves in the wave rotor design, although the prediction of the propagating velocity of the pressure waves is not so easy, because the inner flow states are different from that of an ordinary shock tube.

In this report, numerical and experimental investigation of inner flow dynamics is presented. Depending on these results, an over-all simulation model is verified and applied for the design of a micro wave rotor suited for the operation of kW size micro gas turbines. The sensitivity of port timing adjustment upon the wave disturbances in the rotor cells will be discussed in some details.

INNER FLOW DYNAMICS

The prediction of the propagating velocity of the pressure waves is necessary, though not so easy, for the wave rotor design. One of the reasons is that the inner flow states are different from those of an ordinary shock tube, because the cells are gradually opened/closed to the ports. For example, the primary shock wave appears as just compression waves at the beginning, and is intensified into a shock wave during the propagation, therefore, it is very difficult to predict

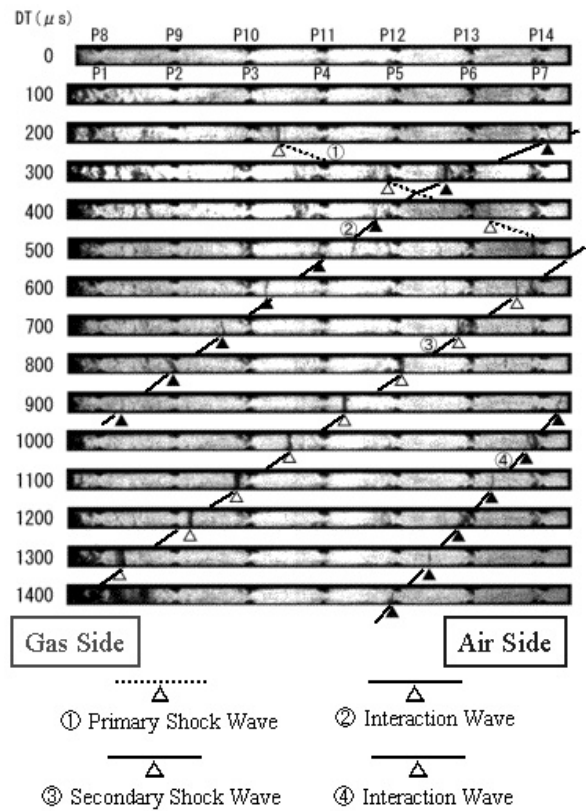


Fig.6 Schlieren Pictures (3 cells)

its propagation velocity theoretically. Therefore, both 2D numerical simulation and experimental visualization were performed to

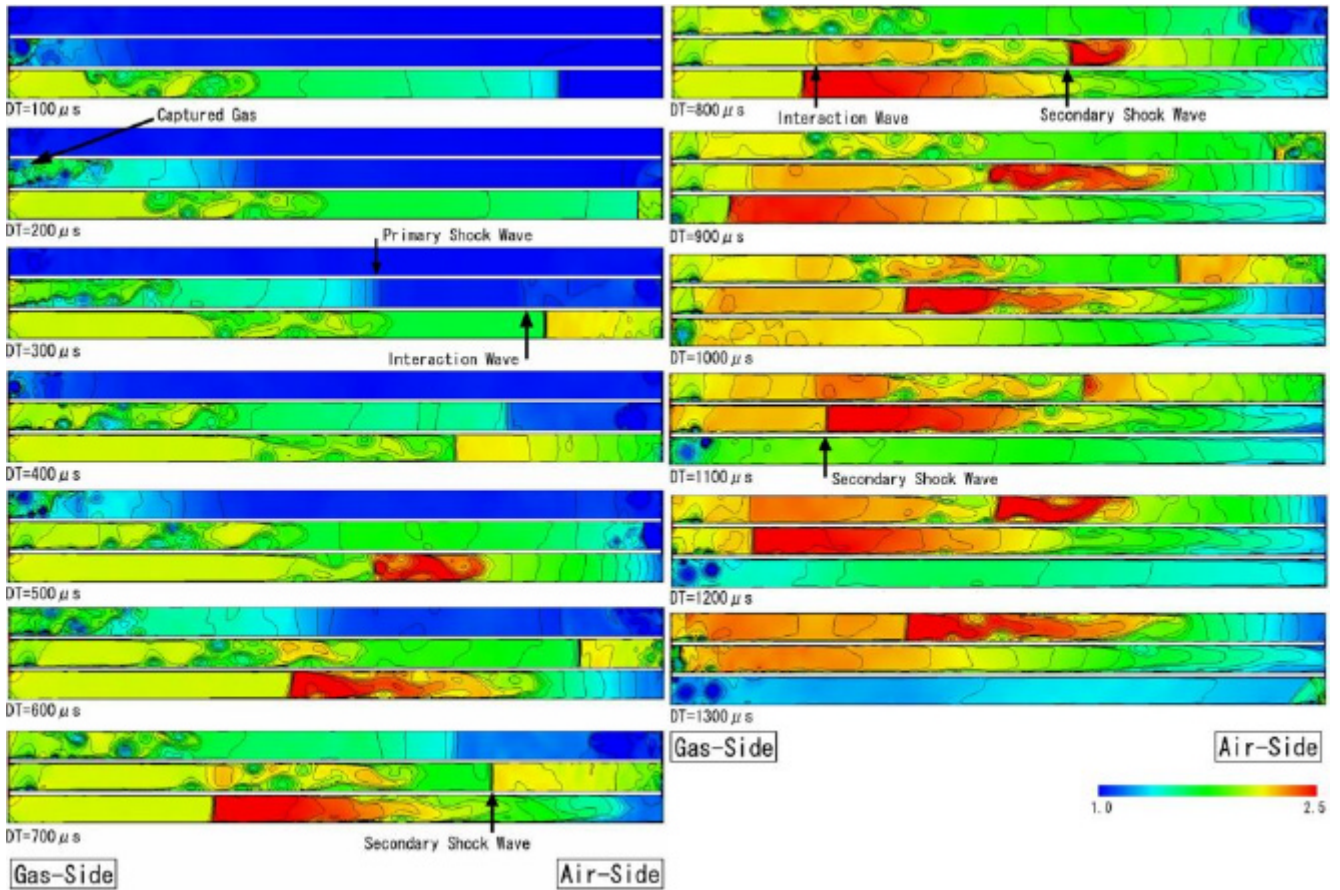


Fig.7 Density Contour (3 cells)

investigate the generation and propagation of the pressure waves.

Experimental Visualization

To visualize the inner flow of a wave rotor, test equipment adopting a new concept was set in the experiment (Fig.5). In this design concept, the cell is fixed stationary, whilst the ports are rotating, so that the reflecting schlieren method and the wall static pressure measurement can be employed directly to the stationary cells. A care is therefore needed that the “rotors” in Fig.5 mean the rotating ports to charge / discharge the working gas. These rotors are connected to a bevel gear, and driven by an electric motor. Here, Gas-HP settled side is called “Gas Side”, and the Air-HP settled side is called “Air Side”. In the experiment, compressed air with the room temperature is used as the combustion gas, and the pressure ratio between the gas and air is 2.6. The rotational speed is 4200rpm, and the mean rotor radius is 60mm. The cell length is 186mm, the width is 8mm, and the height is 16mm. Three cells are installed in the test section, because the effect of leak flow in the circumferential direction will appear from the interaction between the neighboring cells, while the effect of leak flow in the radial direction can be treated as the leak flow to the surroundings. Therefore, the object for the measurement is the cell at the centre.

Fig. 6 shows the schlieren pictures of the primary and secondary shock waves observed in this equipment. The number under “DT” at the left end of this figure indicates the time elapsed from the moment when Gas-HP starts opening upwards from the bottom at the cell end. The primary shock wave propagates to the right, but was not observed before DT=200μs, because the intensity of the primary shock was too weak at the beginning of the cycle. On the other hand, the secondary shock wave is always a normal shock wave, which propagates to the left.

Furthermore, extra pressure waves appear in the pictures (lines 2&4 index). These pressure waves are considered to be generated by the reflection of the primary shock waves at the neighboring cells

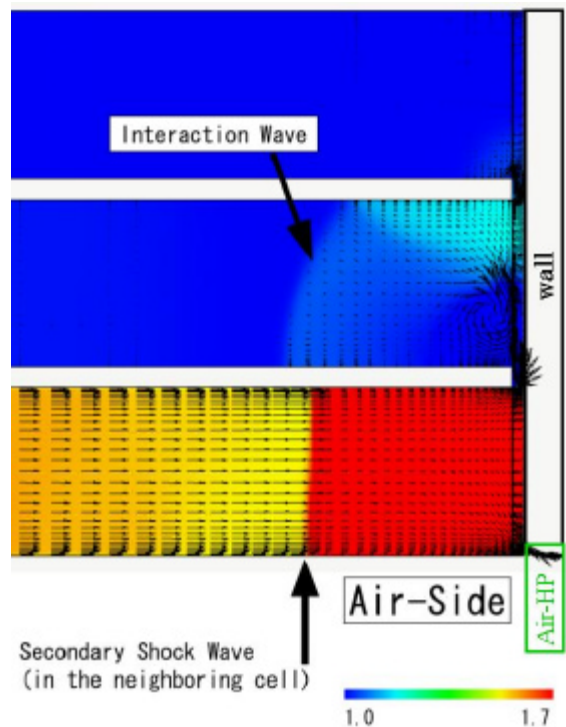


Fig.8 Interaction Wave

judged by its originating instances.

2D Numerical Simulation

In the present study, 2D numerical simulation at the mean radius plane was attempted to investigate the inner flow dynamics. The

governing equations are 2D Reynolds averaged Navier-Stokes equations with laminar viscosity. The solution scheme is based upon Finite Difference Method discretization, incorporating Chakravathy-Osher's 3rd order upwind TVD scheme with the van Leer's differentiable limiter. As for the time integration, the Jameson-Baker's four-stage Runge-Kutta scheme (fourth-order accuracy) was adopted.

The cell size, the ports' conditions, and any other conditions are set to the same as those of the experiment. The mesh is 601X31 in each cell. The inflow and outflow conditions are decided by solving one-dimensional (axial direction) Riemann problem locally with the application of Riemann invariance. In this simulation, leak flow effect in the radial direction, as well as that in the circumferential direction, is taken into account by estimating the flux across the surrounding conditions with the application of Riemann invariance.

Fig.7 shows a time series of the non-dimensional density contour wherein three cells are solved simultaneously just as in the experiments. The state in each port is assumed to be uniform during the calculation, and the ports are gradually opening to the cells from bottom to top.

The primary and secondary shock waves are seen to be in good agreement with the schlieren pictures, which has also been confirmed quantitatively by the time traces of wall static pressure measurements (Okamoto, et al. 2001). The interaction wave between the neighboring cells also appears in the numerical results. Fig.8 shows the enlarged illustration at the instance of the interaction wave generation. In this figure, the pressure rises at the cell end of the air side due to the reflection of the shock wave, which yields the flow in the circumferential direction through the clearance region, and finally the interaction wave is generated.

DESIGN DATA BASE

As described above, it is necessary for the wave rotor design to accurately simulate the pressure waves generated in the cells. It has been confirmed that 2D numerical code can simulate the pressure waves precisely, but its calculating cost is too expensive to be used in the wave rotor design. Therefore, more practical over-all simulation model has been developed to assist its design (Okamoto, Thesis 2002, also to be submitted in ISABE2003). To reduce the

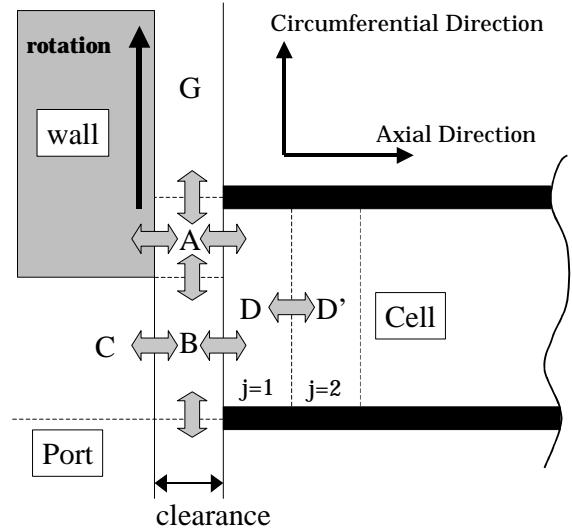


Fig.9 Modeling of Gradual Opening Effect & Leak Flow Effect

CPU cost, a cell is treated as 1D calculating region, although the inner flow dynamics is far different from that of a normal shock tube. Therefore, to simulate the pressure waves precisely, three dominant factors are taken into account in this simulation model, that is,

- 1: gradual passage opening (time elapsed for a cell against ports)
- 2: viscosity (wall friction due to unsteady fluid motion)
- 3: leak flow (in the cell to cell as well as radial directions)

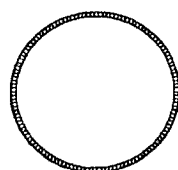
These factors have been pointed out to be dominant on the wave rotor performance by experiments (Wilson, 1998, Wilson, et al. 1993).

For the treatment of "gradual passage opening" and "lake flow" effects, the volume at the end of a cell is divided into two: one is opened to a port (Volume B), and the other is closed (Volume A) as shown in Fig.9. And the condition of Volume D, which corresponds to the boundary condition, is calculated with the flux between the surrounding volumes. Also for the leak flow effect, the flux between

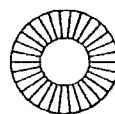
Table1 Summary of Geometries in Experiments

() calculated with atmospheric value

	NASA (3 port)	NASA & Allison	Kentfield	G.E.	Comprex® (ABB)	Equipment (this study)	Micro Wave Rotor (this study)
Length [m]	0.46	0.152	0.28	0.3	0.0932	0.186	0.069
Mean Radius [m]	0.15	0.0815	0.074	0.058	0.048	0.06	0.02325
Number of Passages	130	52	30	36	34	1 or 3	30
Cell Width [m]	0.007	0.00875	0.015	0.01	0.009	0.008	0.004
Cell Height [m]	0.0102	0.0223	0.0559	0.0231	0.01	0.016	0.003
Clearance [mm]	variable	0.1	0.18	0.64	0.15	0.5	0.1
Rotating Speed [rpm]	4000	16800	6000	19000	14000	4200	32151
t	(0.0824)	0.194	(0.392)	(0.0982)	0.467	0.554	0.311
F	(0.0169)	0.00365	(0.00464)	(0.0081)	0.00668	0.00838	0.0119
G	variable	0.00897	0.00644	0.0554	0.03	0.0625	0.0667



NASA (3-Port)



Kentfield



G.E.

the neighboring cells is taken into account for the interaction, as well as the flux in the radial direction for the leak flow to the outside. As for the treatment of “viscosity” effect, the momentum loss by wall shear stress is estimated depending on the Rayleigh flow analogy.

The verification of this over-all 1D simulation model was achieved by comparing the results with those of 2D numerical simulation, whence the propagating velocities of the pressure waves and the resultant primary shock wave, the interaction wave as well as the secondary shock wave, were all found to agree very well, although slight difference in the wave traces behind the interaction wave was observed. The latter derives from that the interaction wave is generated by the jet in the circumferential direction (Fig.8), and is affected by its shear stress and the vortex formation, which cannot be taken into account in this 1D simulation model.

The critical issue of wave propagation in designing the rotor cell becomes thus tractable, the remaining factors are concerned with the losses associated with the wave rotor operation, that are more or less dependent upon experimental data which are unfortunately available very few. Table 1 shows a summary of the previous experiments, in which available geometrical particulars are listed in some details with sketches underneath. The dominant factors written above are correspondingly characterized by the nondimensional parameters described below. Each parameter may be advantageously used in comparing the wave rotor performance amongst various geometries.

Gradual Passage Opening $t = \frac{\text{Passage Opening Time}}{\text{Wave Travel Time}} = \frac{b}{w} \cdot \frac{a}{L}$

Viscosity $F = \frac{\sqrt{\nu \cdot L/a}}{D_h}$

Leak Flow $G = \frac{2d}{H}$

Nomenclature

a : sound speed b : cell width w : tangential velocity of the rotor
 ν : kinematic viscosity D_h : hydraulic diameter of the passage
 δ : clearance H : cell height

MICRO WAVE ROTOR

It is necessary to match the wave rotor as a component of the ultra micro gas turbine system. A wave rotor design by NASA Glenn Research Center (Snyder, et al. 1996) was herein referred in designing the present micro wave rotor.

Specification

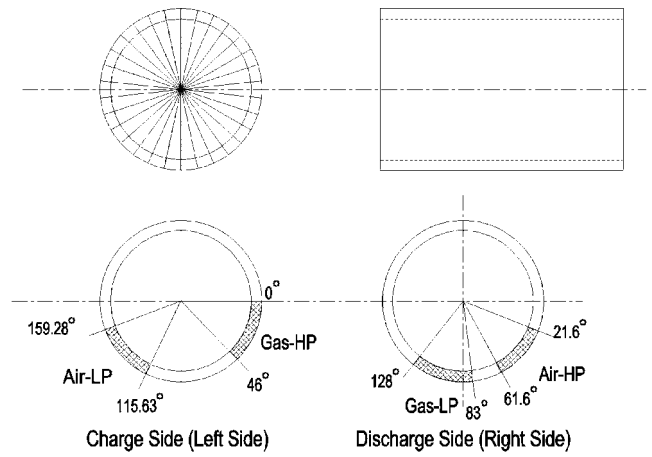
The total pressure and temperature at the compressor outlet are assumed to be 0.304[MPa] and 440[K] respectively, and the states of the ports were settled as shown in Table2. The specification designed by these values is shown in Fig.10 and Case1 in Table3.

Table2 Conditions in the Ports

	Gas-HP	Air-LP	Air-HP	Gas-LP
P ₀ [atm]	9.2	3.0	10.1	3.7
T ₀ [K]	1248	440	907	973

Table3 Configurations of the Ports

	Case1	Case2	Case3
Gas-HP [degree]	0-46	0-46	0-46
Air-LP [degree]	115.63-159.28	116.63-160.28	296.13-339.78
Air-HP [degree]	21.6-61.6	21.6-71.1	21.6-71.1
Gas-LP [degree]	83-128	84-129	263.5-308.5



Cell Number	30
Cell Length	0.069 [m]
Cell Width	0.004 [m]
Cell Height	0.003 [m]
Mean Rotor Radius	0.02325 [m]
Rotational Speed	32151 [rpm]

Fig.10 Preliminary Design (Case1)

The comparison of the present design in terms of nondimensional parameters is also given against the other geometries in Table 1. Due to the assumed clearance value of 0.1mm, F and G parameters are found to be a bit larger.

Port Adjustment

Fig.11 shows the total temperature contour of Case1. This result may be considered as almost the design point. However, a pressure wave, which propagates into Gas-LP, can be seen in this result. A pressure wave incident like this will increase the instability of the states inside the port, which will influence on the other component of a gas turbine as a result. Therefore, it will be better to avoid this situation.

This extra pressure wave is revealed to be generated when Air-HP is closed to the cell. That is, Air-HP starts to be closed before the expansion wave, which is generated by the Gas-HP closing, reaches to the right end. Therefore, the timing of Air-HP closing has better be readjusted to remove that extra pressure wave (Case2 in Table3).

Fig.12 shows its result, and the latter wave disappears, so that the stability of the states in Gas-LP is improved in this design.

The distance between the Air-HP and Gas-LP is not strictly decided by the pressure wave motion, and it should be long enough so that the condition in the cell becomes stable. In this study, Case3 in the Table 3, in which this distance is set to be longer than Case2, was also calculated and compared.

Fig.13 and Fig.14 show the total pressure contour of 0.0, 0.1, and 0.2mm clearance in each case. Here, the pressure, when the cell starts to be opened to Gas-LP, should be noticed, because the pressure rise of Gas-LP corresponds to the contribution to the whole cycle.

When the clearance is 0.0mm, there seems to be no difference between Case2 and Case3. And the pressure drops according to the increase of clearance, because the leak flow between Air-HP and Gas-LP increases.

Table4 shows the ratio of the leak flow and the mass flow in the Air-LP. Here, only qualitative discussion is possible, because the surrounding condition of the rotor is considered to be constant in this simulation, although the pressure in the rotor cavity will be changed by the leak flow. This result shows that the Case2 of 0.2mm clearance is better than the Case3 of 0.1mm clearance. This means that the leak flow is mainly generated between the high-pressure and the low-pressure ports at either side. Therefore, the shorter the distance between Air-HP and Gas-LP, the better the performance

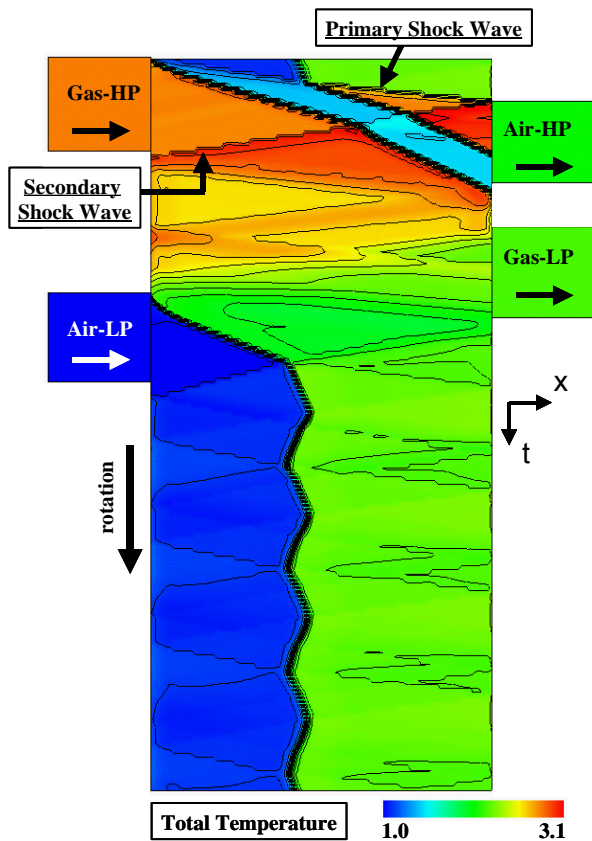


Fig.11 Non-dimensional Total Temperature Contour (Case1)

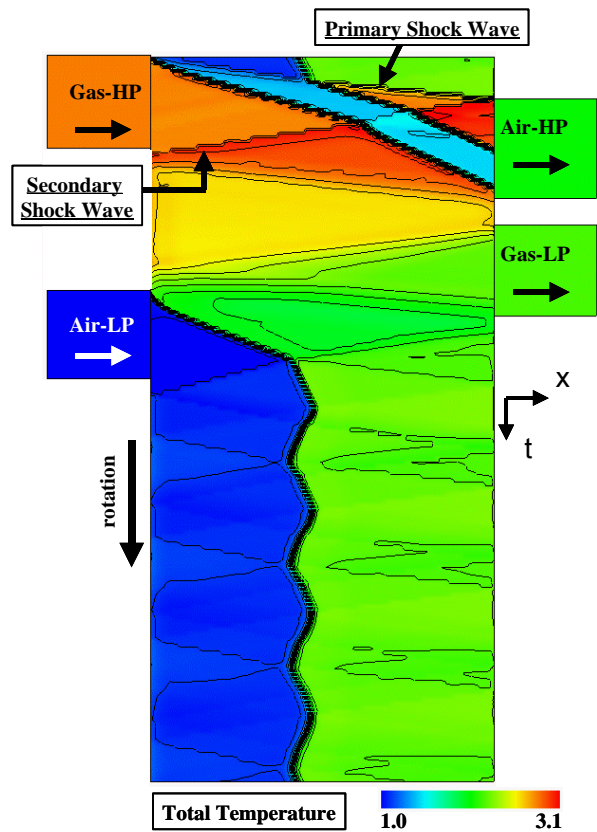


Fig.12 Non-dimensional Total Temperature Contour (Case2)

will become. In the design of ultra micro wave rotors, this tendency will be intensified, because the leak flow effect will have larger influence on the performance than in the conventional turbo machine. From all these consideration, the optimized distance between Air-HP and Gas-LP is at the minimum the cell width, because a cell should not be opened to two ports at the same instance.

Table4 Leak Mass Flow Rate Comparison

Clearance [mm]	Leak Mass Flow Rate [%]	
	Case2	Case3
0.0	0.0	0.0
0.1	25.8	42.0
0.2	38.0	56.5

SUMMARY

To improve the ultra micro gas turbine performance, wave rotor mechanism may be applicable and promising. In this study, a micro wave rotor model for kW size micro gas turbines has been designed. In designing wave rotors, the propagating velocity of the pressure waves has to be precisely predicted. Therefore, the steps described below were measured.

First, investigation of inner flow dynamics was performed by 2D numerical simulation and experimental visualization. According to these results, over-all 1D simulation model was developed to assist the wave rotor design. This model considers three dominant loss factors, that is, gradual opening, leak flow, and viscosity, and it was confirmed that this practical model yields good agreement with 2D numerical simulation.

With this practical simulation model, a micro wave rotor was designed and the effect of port adjustment upon the wave

disturbances within the rotor cells was carefully examined. It has been revealed that the distance between Air-HP and Gas-LP has large influence on the leak mass flow rate, leading to the deteriorating total performance. This distance, therefore, must be as short as possible, that is, at the minimum of the cell width in the micro wave rotor design.

ACKNOWLEDGEMENTS

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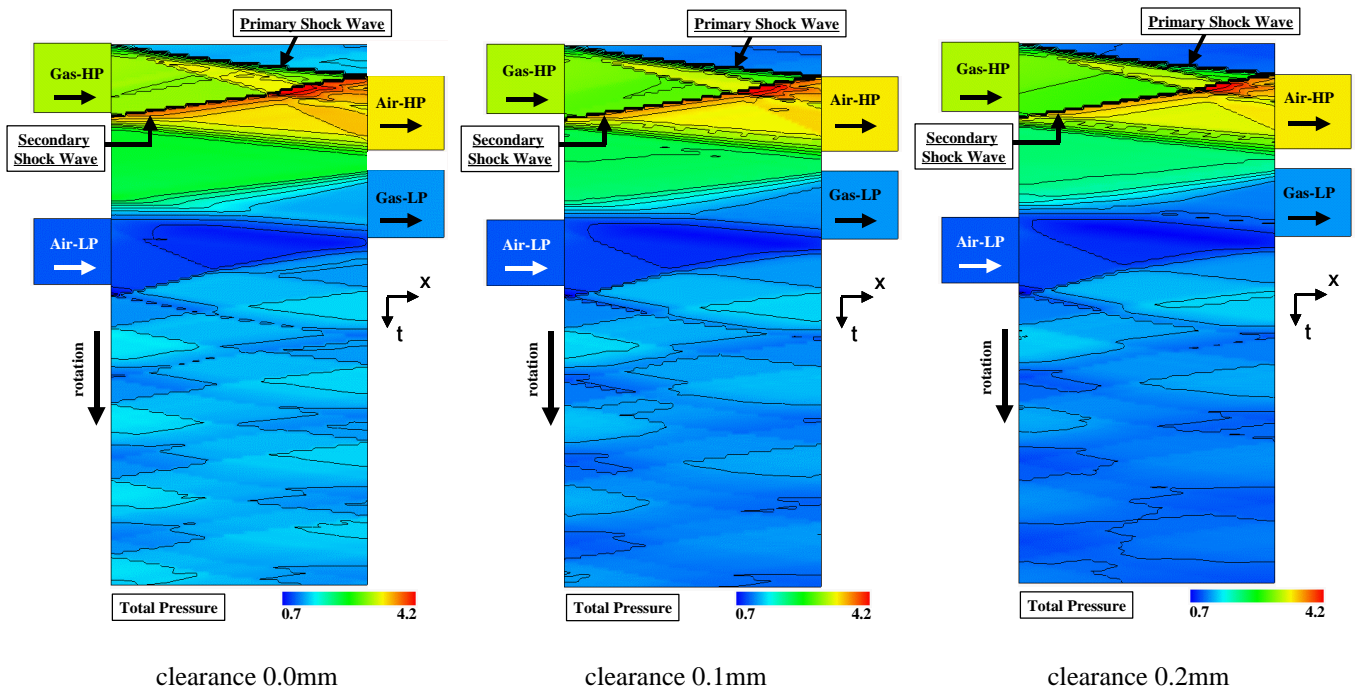


Fig.13 Non-dimensional Total Pressure Contour (Case2)

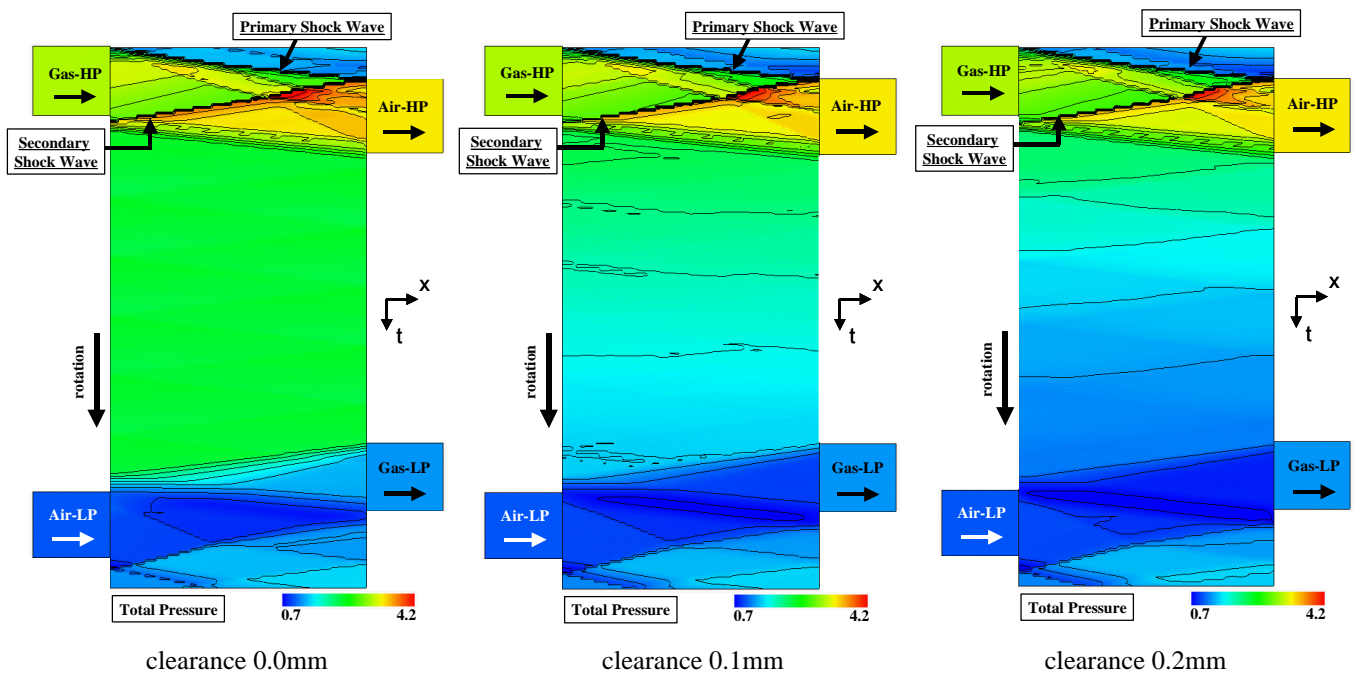


Fig.14 Non-dimensional Total Pressure Contour (Case3)