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Towards the Development of Finger-Top Gas Turbines

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ABSTRACT

The ultra micro turbine concept based on MEMS technology was proposed by MIT in 1997, and since then several projects have been initiated and sponsored by DARPA to facilitate development at various universities and research institutions in the US. The present authors, who belong to Gas Turbine Society of Japan, regard such ultra micro gas turbine engine systems as being crucial for mobile and environmentally friendly energy utilization technology in the future for general use anywhere in the world. This report describes our palm top-gas turbine (2-3kW, dry weight of 14.3kg including generator, 235,000rpm, outer diameter of 180mm, and length of 335mm) and our finger-top gas turbine test model (tens of W, 1,170,000rpm, outer diameter of 23mm, and length of 32mm). These developments represent the outcome of a NEDO-backed three-year international joint research project involving cooperation among Japanese universities, institutions and private firms, together with ONERA, CIAM and VKI, from FY2001 to FY2003.

Key Words: Gas turbine, Radial turbine, Radial compressor, Combustor, Recuperator, Generator, Gas bearing

1. INTRODUCTION

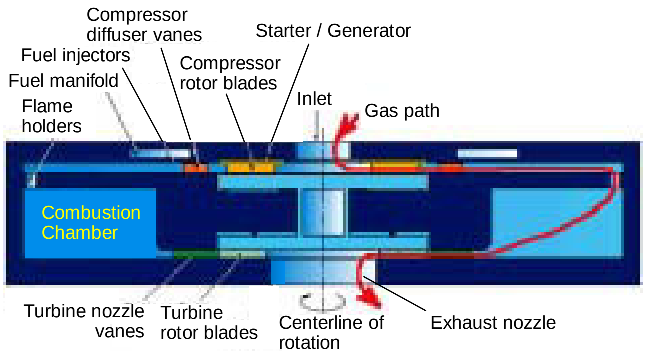
As part of the Power MEMS initiative, development of hydrocarbon- or hydrogen-fueled ultra micro gas turbines (UMGTs) is being sponsored by DARPA at MIT and other locations (see Fig. 1). (1) As noted in Table 1, UMGTs are characterized by about 15 times the energy density of the newest lithium batteries, and about 20 times the energy mass density, and are thus looked to as power sources in the future for diverse applications such as vehicles, communications equipment, robots, and aircraft.

Also, rapid progress is being made in compact distributed electrical power, and the practical development of UMGTs as power and heat sources having output of around several kW is anticipated, as well as hybrid gas turbines in combination with fuel cells. In support of these development efforts, consideration is being undertaken in a variety of related areas, including the realization of stable combustion in the micro domain, the development of high efficiency turbine compressors and high velocity gas bearings, the improvement of cycle efficiency by using regenerative heat exchangers, and the development of technologies for high speed motors and generators, CFD, and inter-element heat transmission analysis. Also being investigated are techniques for achieving smaller size and lower cost in combination with frequency converters, etc. Accordingly, progress is being made with respect to most of the constituent elemental technologies required for UMGTs. (3)

From FY2001, we began work on "palm-top" and "finger-top" UMGTs; the palm-top version (impeller diameter of approx. 40mm) is 10 times the size of that targeted by the MIT team (i.e., impeller diameter of 4mm), while the finger-top version is twice the targeted size (8mm). Practical development work in FY2002 resulted in design and fabrication of the palm-top gas turbine, as well as elemental prototypes and test equipment design for the finger-top model. (4) This paper presents an overview of these achievements.

Table 1 Specific energy (2)

	UMGT	$LiSO_4$
Power (W)	50	50
Energy (Wh)	175	175
Engine weight (g)	50	1100
Engine volume (cc)	50	880
Specific energy (Wh/kg)	3500	175
Specific energy (Wh/cc)	3	0.2



Arrangement	Single spool turbojet
Dimensions	12mm OD X 3mm long
Air flow	0.15gm/sec
Rotor speed	2.4million rpm
Power output	10-20W
Thrust	0.1-0.2N
Weight	1g
Fuel consumption	7g/h

Fig.1 The drawing and design features of MIT GT
(This was named 'micro turbine' by MIT)

2. EXAMPLES OF APPLICATIONS

There are numerous applications for mobile power supplies (see Fig. 2) (5) which require energy densities that cannot be delivered by primary or secondary batteries, such as robots, ultra compact UAVs (Unmanned Aerial Vehicles), exoskeletons, and portable information terminals, calling for output mass densities in the range of 0.1~0.6kW/kg and energy mass densities of 0.2~6kWhr/kg. Current outputs for Aibo, (6) Asimo, (7) and Ginger (8) shown in the figure are 6W/kg and 9W/kg (output/total weight), but engine output and energy densities are listed as envisioned at the practical development stage. Other UMGT applications include power supplies (mobile and distributed), ultra micro propulsion systems, vehicles (auxiliary power units), fuel cell hybrid power sources, (9) and ultra micro turbomachinery (cooling apparatus, pumps, compressors, etc.) taking advantage of the requisite elemental technologies.

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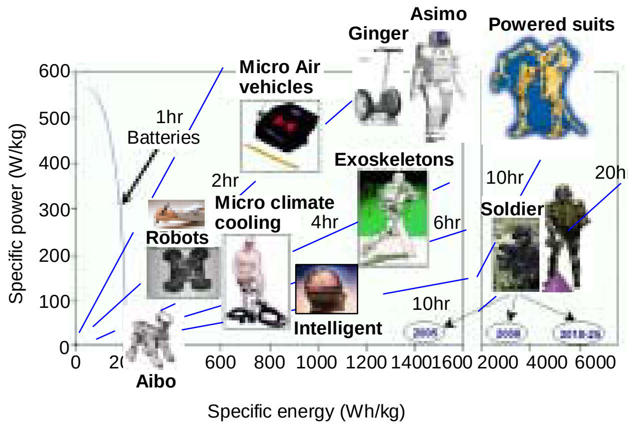


Fig. 2 Specific energy and applications [5]

3. OVERALL PLAN

3.1 Development Objectives

The objectives of the R&D work reported here were 1) to fabricate and test a prototype of the palm-top gas turbine, and 2) to conduct elemental testing for the finger-top gas turbine, directed towards practical development of ultra micro gas turbines and turbomachinery. These gas turbines and their compositional elements are for use in highly distributed power sources, high energy density mobile power supplies, and various types of turbomachinery.

3.2 Consideration of Design Specifications

Fig. 3 illustrates the relationship between the required fuel tank volume V (cc/Wh) and thermal efficiency, based on fuel tank volume in the case of 10% efficiency. As the requisite fuel volume (tank volume) is inverse proportional to thermal efficiency, improvement in efficiency is necessary for reduction of engine size and weight (including the fuel). Especially in cases where the operating duration is long, the fuel tank becomes larger than the engine itself, meaning that improved efficiency is essential to overall compactness and lightweight.

Efficiency η for the compressors and turbine wheels corresponding to the palm-top (40mm) and finger-top (8mm) gas turbines was calculated in conformance with the following formula.

$$(1-\eta)/(1-\eta r)=(Dr/D)^{1/N}=(Rer/Re)^{1/N} \cdots\cdots\cdots (1)$$

Where ηr and Dr (Rer) are the efficiency and wheel outer diameter (Reynolds number) for the standard size, and N is a number that changes with the Reynolds number (wheel outer diameter). N is taken as 5 for larger turbines and 4 for smaller ones, and is estimated to be 3 for a size of several millimeters. [11] Fig. 4 presents the simple cycle calculation results used in determining the design conditions and specifications (see Table 2) for the palm-top (40mm) and finger-top (8mm) gas turbines.

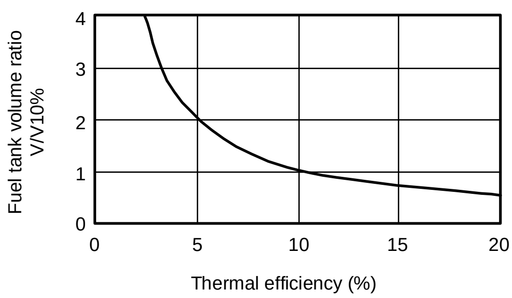


Fig. 3 Thermal efficiency vs. fuel tank volume [5]

Overall efficiency ηall is the product of turbine efficiency, compressor efficiency, and mechanical efficiency. In the case of a simple cycle, given a targeted overall efficiency for the finger-top model of 45%, and with thermal efficiency of approx. 7%, the pressure ratio is about 4 at the maximum efficiency point. As overall efficiency raises, the pressure ratio at the maximum efficiency point shifts to the high side. At 57%, the assumed overall efficiency of the palm-top unit, maximum efficiency is approx. 15% at a pressure ratio of about 7, or approx. 10% at a pressure ratio of 2.5.

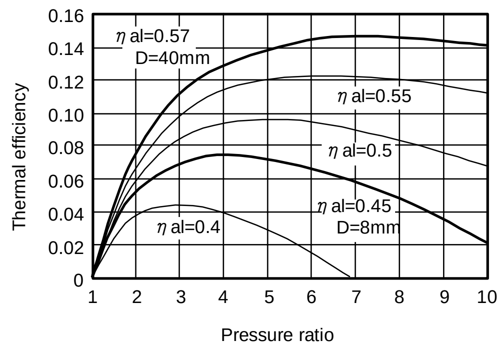


Fig. 4 Thermal efficiency of simple cycle UMGT [3]

Fig. 5 indicates the thermal efficiency calculation results for a UMGT having a regenerative cycle. The pressure ratio at the maximum efficiency point is lower in this case than in the case of a simple cycle, such that the circumferential speed can be reduced. In the case of the finger-top model (impeller outer diameter of 8mm) thermal efficiency is 7% for a simple cycle, and 15% in a regenerative cycle when the heat exchanger efficiency is 80%. The engine size with the attachment of the heat exchanger increases by 3 times that without it. [12] And, because fuel consumption decreases by half, the fuel tank volume is also reduced by about half in comparison with the simple cycle.

Based on the foregoing consideration of the simple cycle and regenerative cycle, as well as strength evaluation results, the design pressure ratio of the compressor was set at 2.5, with a turbine inlet temperature of 950˚C (1223K) (see Table 2).

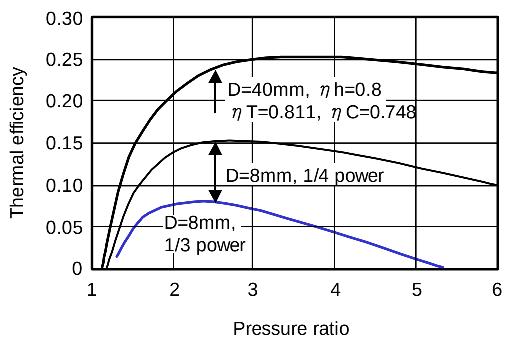


Fig. 5 Thermal efficiency of regenerated UMGT [4]

Table 2 Design feature

	Palm-top	Finger top
Compressor PR	2.5	2.5
TIT (K)	1223	1223
Flow rate (kg/s)	0.03	0.011
Rotational speed (rpm)	235,000	1,170,000
Turbine blade diameter (mm)	40	8

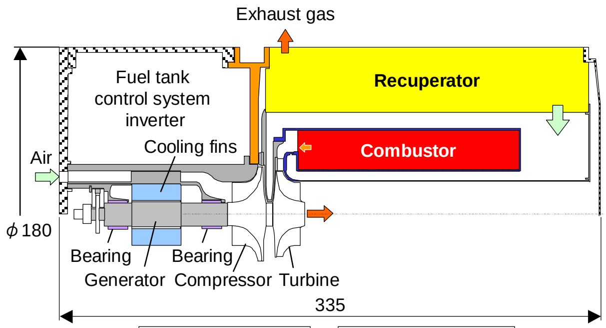
3.3 Design and Fabrication of the Palm-Top Gas Turbine

Four design conditions were established: 1) capability for either oil lubricated or gas bearings (since hydrodynamic bearings with a 12mm shaft diameter have yet to be developed for the design speed of 235,000rpm); 2) bending primary critical frequency for the shaft of at least the design speed (235,000rpm); 3) bearings not to be heated by combustion gas, and 4) low thermal transfer to the compressor impeller. A sectional drawing of the palm-top gas turbine is shown in Fig. 6.

The center shaft passes through the center of compressor impeller, the generating rotor, and the bearings, and is fixed to the rotor by means of a tension bolt for a unitary structure. Cooling fins placed along the air path to the compressor serve to cool the generator stator, while part of this suction air is diverted to cool the bearings and generator rotor. High pressure air exiting the compressor is fed to the regenerative heat exchanger, and, after heat exchange with exhaust gas, enters the inner and outer periphery of the combustor through air holes. This gas turbine is also designed for assembly/disassembly by means of 24 bolts on the outer periphery of the casing. (4)

An annular type regenerative heat exchanger and combustor were adopted in order to eliminate tubing and to realize a compact structure. An external view of the palm-top gas turbine is presented in Fig. 7, together with the main components, while the turbine wheel of the finger-top gas turbine is shown in Fig. 8.

When completed, this palm-top unit will be the world's smallest and lightest generating gas turbine, with planned output of 2~3kW, dry weight of 14.3kg (including the generator), and a volume of 8.5 liters. Following operational tests during FY2003, plans call for verification of the possibility of practical development.



Combustor	
Outer dia.	90mm
Inner dia.	40mm
Length	140mm

Recuperator	
Outer dia.	180mm
Inner dia.	110mm
Length	200mm

Fig. 6 A sectional drawing of a perm top gas turbine (4)

Fig.7 A perm top gas turbine and it's parts

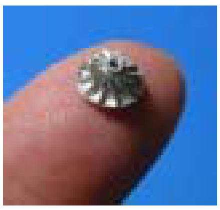


Fig. 8 A turbine wheel of a finger top GT Diameter 8mm

3.4 Design of the Finger-Top Gas Turbine Model

The same design conditions (Fig. 9) were set for the finger-top gas turbine test model as for the palm-top unit. In order to reduce the number of components and to facilitate easier assembly, the structure is assembled using a single bolt and nut. The assembly format was also adopted in order to make the scroll easier to change in accordance with changes in the shape of the turbine wheel (Fig. 8) and compressor, with a new structure to prevent leakage by raising the surface processing precision for the respective components. The bearings consist of the herringbone type with a flange attached for installation, and specially developed ultra micro tilting pad type gas bearings (bearing diameter of 3mm), together with thrust bearings on the side. In order to prevent excessive thrust, the degree of reaction of the turbine and compressor is appropriately set in the design. The center shaft serves as the rotor for the motor/generator, with sufficient space around the periphery for the stator (details omitted here). As a result of prototype tests, it has been decided to use a blade thickness of approx. 0.1mm for the turbine wheel and compressor impeller, with 12 blades (see Fig. 8). Current topics for R&D work during FY2003 include: 1) stabilization of the shaft vibration; 2) bearing load capacity, contact during start and stop, and endurance; 3) aerodynamic performance of the turbine and compressor; 4) ultra micro combustor; 5) heat exchanger; 6) CFD; and 7) inter-elemental heat flow.

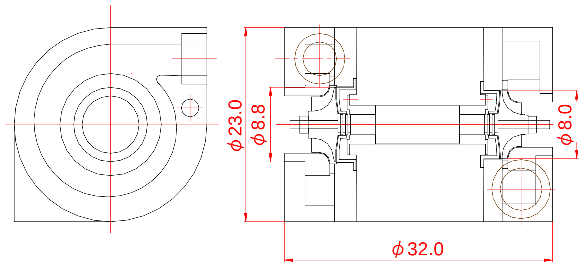


Fig. 9 A test model of a finger top gas turbine

4. ELEMENTAL TECHNOLOGIES

4.1 Combustors

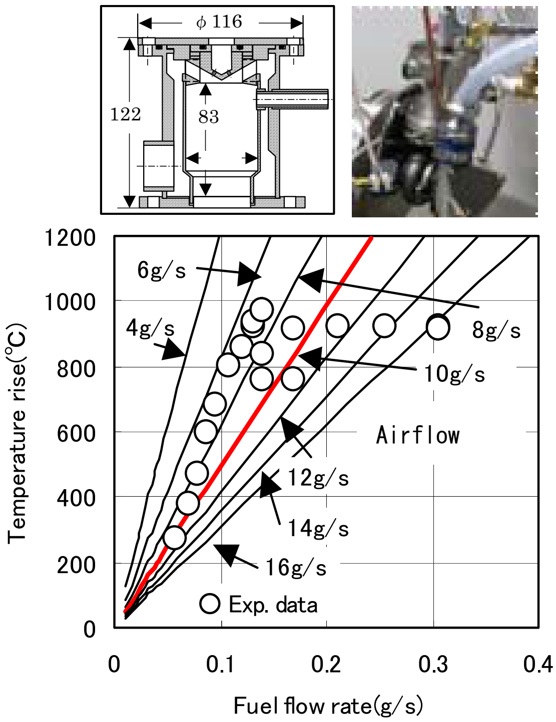


Fig.10 Can type combustor and its test results (3)

Design, fabrication, and testing were conducted for the annular type combustor to be used in the finger-top gas turbine, (13) as well as prototyping and testing of the can type combustor for the palm-top unit. A sectional drawing of the latter is presented in Fig. 10.

This combustor features a swirler and fuel nozzle at the center. In order to facilitate low cost and miniaturization, there are a total of only 11 parts, consisting of the outer cylinder, the inner cylinder, the swirler, the fuel nozzle, the upper plate, and 6 bolts.

Fig. 10 shows the results of atmospheric combustion tests, taking airflow as a parameter, with fuel flow on the x-axis and temperature rise on the y-axis. The design airflow is 10g/s, which is equivalent to 30g/s at a pressure ratio of 3. In the tests, the combustor demonstrated stable combustion across a wide range of airflow rate, from 60 to 160% of the design value. Unstable phenomena such as blowout and after burning were observed in tests using the ignition characteristics indicated in the upper part of Fig. 10, together with turbine and compressor matching test equipment. Accordingly, the fuel nozzle was modified for improved ignition characteristics.

4.2 Turbines

The flow analysis results for a 2D design turbine rotor (left side of Fig. 11) are presented in Fig. 12. In the reverse camber blade on the right side of the figure, static pressure declines at the inlet, with pressure nearly constant through to the outlet, and with separation in the vicinity of the outlet such that there is no longer any blade function. Based on these calculations, it was determined that there was no need to produce reverse camber blades. The blades on the left exhibit smooth acceleration and nearly uniform blade surface load, and are predicted to deliver superior cascade performance. It will be necessary in the future to develop a blade type that enables reduction in loss from trailing edge thickness, seemingly unavoidable in compact turbines.

In aerodynamic testing of 2D and 3D turbines at palm-top size, 3D performance was 83% at a pressure ratio of 2.5, and 2D performance was about 10% lower. Tests are being conducted for improvement, but it has been decided in the meantime to adopt 3D turbine wheels.

Fig.11 2D and 3D radial turbines for perm top gas turbines [14]

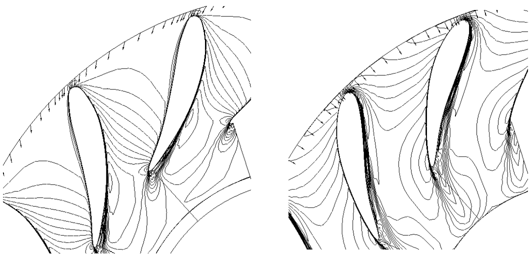


Fig.12 Velocity distribution between 2D turbine blades calculated by CFD [15]

4.3 Heat Exchangers

Pin-fin and plate-fin types, as well as PMHEs (porous matrix heat exchangers), and PCHEs (printed circuit heat exchangers), are being developed for improved heat exchanger performance. An example of a disc shaped plate can be seen in the AGT1500 and micro gas turbines from Capstone, proving to be a highly advantageous structure. In the research presented here, so as to facilitate low-cost fabrication over a short period using existing production equipment, an arrangement of 8 square plate type cores were arranged in a ring to serve as the recuperative heat exchanger for the palm-top gas turbine. [16] The targeted temperature effectiveness is at least 80%, with the weight to be held to under 6kg. Also, assuming the use of MEMS technology for processing ceramic material at the size envisioned by the MIT project, so as to yield an recuperator capable of tens of W output, a new shape was designed for the heat exchanger core. As a result, it is predicted that effectiveness of 50% can be obtained for an engine of the same size, or 80% for twice the size. [17]

As noted above, in order to reduce the overall size including the fuel tank for UMGTs used for long durations, an efficient and compact recuperative heat exchanger is essential, and further research is required to achieve greater miniaturization and higher effectiveness.

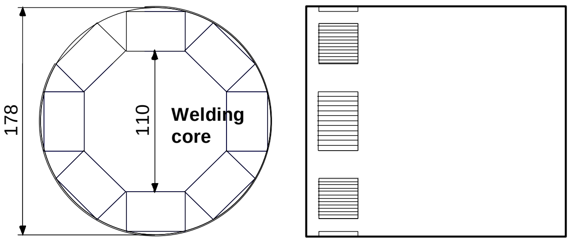


Fig.13 A plan of a heat exchanger [5]

4.4 Motor-Generators

A permanent magnet type, high speed motor-generator was adopted, with an internal neosium magnet placed inside the rotor, and a newly developed silicon-embedded type ultra thin magnetic plate [18] used in the stator. A 5kW test motor was fabricated, [19] and motor tests were conducted up to 180krpm using a centrifugal compressor as a dynamometer. Stable operation was confirmed at up to 160,000rpm, but damage to the windings (thought to be due to over-current) occurred at 180,000rpm. Accordingly, the design is being reconsidered, including sensor-less control.

Some 30~40% of design speed (70k~94krpm) is sufficient for starting motors, such that tests were undertaken mainly as a generator. Development is required for lightweight, compact frequency converters capable of converting 50/60Hz electricity to 400W at 1.2~1.6kHz and several W at 6.9~7.8kHz for high speed starting motors, as well as those capable of converting high frequency sinusoidal waveform electricity to direct current 3kW at 3.9kHz and to tens of W at 19.5kHz for high speed generators. Accordingly, high speed rotational testing is being conducted as a high-speed generator, including controllability.

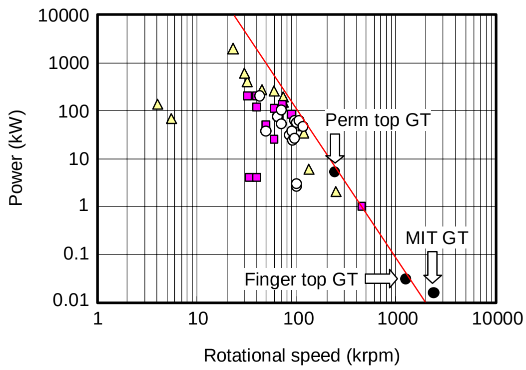


Fig.14 High speed motors and generators

High-speed motor and generator data is presented in Fig. 14, comparing the relationship between rpm and output (output is inversely proportional to the cube of rpm), for evaluation of various design values and results obtained by other researchers. Plotting the planned output for the palm-top gas turbine, finger-top gas turbine, and MIT's button type gas turbine, it can be seen that these three units represent the highest levels in the world. Frequency converters are required from 200Hz to 4kHz for compact high-speed compressors, pumps, and other compact high-speed turbomachinery; from 1kHz to 2kHz for micro gas turbines; and from 2kHz to 30kHz for UMGTs. Thus, the development of low cost, compact, and lightweight converters is thought to be a determining factor in terms of forthcoming development of high-speed turbomachinery and UMGTs.

4.5 Gas Bearings

The use of oil-lubricated bearings necessitates a supply pump, a lubricating oil tank, and supply lines, thus hindering miniaturization accompanying higher speed. For this reason, test fabrication was undertaken for ultra micro gas bearings, based on the foil type [20] [21], tilting pad type and herringbone type. A sectional drawing of the bearing test rig is shown in Fig. 15. In rotational tests up to 60krpm, rapidly taking the new gas bearings to high speed from a stationary position, no abnormalities were observed with respect to the shaft or bearing surfaces.

In NASA's Oil-Free Turbomachinery Project, endurance testing (0~40krpm in 20sec and 30,000 times repetition) was performed on foil gas bearings coated with PS304 (60%NiCr, 20%Cr_2O_3, 10%BaF_2CaF_2, 10%Ag) and having a bearing diameter and bearing width of 35mm, with the achievement of wear of approx. 10μ [22] plans call for engine testing of these bearings in the EJ11 engine. (Fig. 16)

Gas bearings having such high temperature endurance would increase the degree of freedom in the design of gas turbine engines, and would help reduce costs. These sorts of gas bearings are expected to enable new structures for UMGTs with greater compactness.

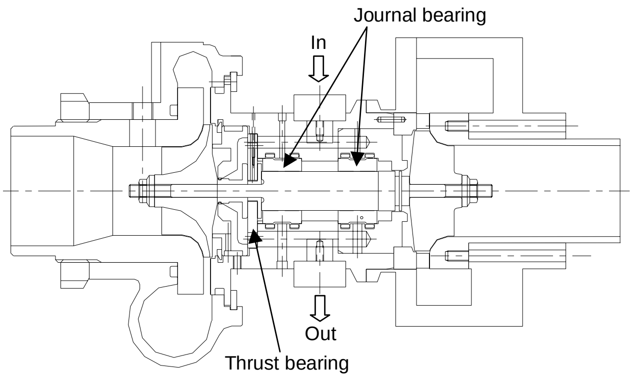


Fig. 15 A test rig for the gas bearings

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ig. 16 Gas bearing and turbofan engine EJ11

4.6 Manufacturing Technologies

CVD and etching methods, developed for the manufacture of electronics, can likely be applied in the manufacturing of ultra micro components. Nevertheless, as a result of the use of CVD for the 8mm 2D turbine and 5-axis NC processing for the 3D type (blade shape with thickness of approx. 0.1mm as indicated in Fig. 17), it was confirmed from evaluation of machined surface roughness, etc. that machining is also a possibility for such processing. Plans call for the selection of technologies that will satisfy cost requirements, considering from the outset the requisite materials and manufacturing technologies for mass production.

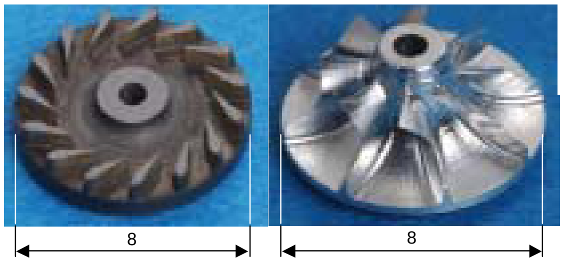

Fig.17 8mm Turbine wheels

4.7 High Temperature Inter-Element Heat Transfer

The influences on aerodynamic performance and temperature distribution were also estimated for inter-element heat transfer accompanying heat exchanger temperature effectiveness and pressure loss. The gas temperature assumed in the turbine flow path was based on the results of flow analysis. It was found that heat transfer through the casing wall surfaces could have a recuperative effect in heating compressor outlet air. The substantial decrease was predicted in terms of the turbine inlet gas temperature, as well as an increase in the compressor inlet air temperature. These effects would substantially reduced efficiency, and it is clear that further work is required for accurate analysis and for insulation countermeasures at required locations. [3]

Calculations were performed with respect to the structure in Fig. 18, considering the amount of heat transfer between the compressor impeller and turbine wheel (for which there is substantial deterioration in performance due to invasive heat), [23] and the amount of heat transfer in the space ring was 58%, the amount of radiant heat was 28%, and the amount of heat transfer in air and the divide plate was 15%. Given these results, it was decided to change the space ring from stainless steel to ceramic, and to insert a reflecting plate in the center of the divide plate.

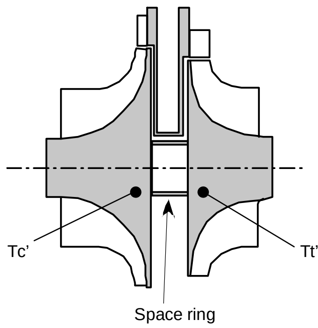

Fig. 18 A heat transfer analysis model

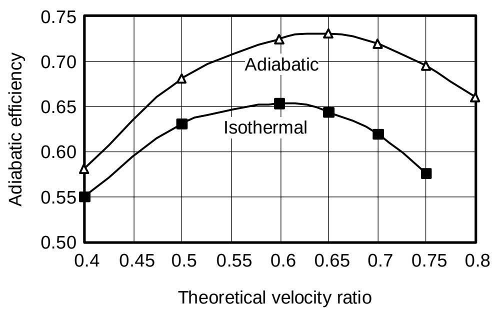

Fig. 19 Variation of efficiencies by adiabatic and isothermal walls [4]

Fig. 19 presents calculation results for efficiency when CFD is used for the insulating wall and isothermal (700K) wall. With respect to the isothermal wall, heat release from the wall surface causes reduced flow velocity at the nozzle exit, such that efficiency drops by 8% compared to the insulating wall, and the theoretical velocity ratio shifts toward the smaller side by 0.05. These results indicate the necessity of preventing heat release from the nozzle and wall surface upstream from the nozzle.

Table 3 Total plan of the research project

FY2001	FY2002	FY2003
◎ Target ; realization of elements ◎ 10 times model（40mm） ○ 2D turbines and compressors ○ 3D turbines and compressors ○ Can combustors ○ Oil lubricated bearings ○ Foil gas bearings ◎ One and two times models ○ Combustor (4mm) model tests ○ Fabrication of blades(8mm) ◎ Design and fabrication of test facilities and measurement system	◎ Target; design/fabrication of model GT ◎ Palm-top GT ○ Design, fabrication, test Turbine blade diameter 40mm Compressor wheel diameter 44mm Annular combustor Recuperator Permanent magnet generator ◎ Finger top GT ○ Aerodynamic test blade (8mm) ○ Design of test facilities ○ Fabrication of recuperator	◎ Target; realization of GT ◎Palm-top GT ○ Realization test Turbine inlet temp. 900℃ Compressor PR. 2.5 Generator output power 2kW Recuperator ○ Control systems ◎Finger Top GT ○ Aerodynamic test rig ○ Engine design Out put power tens of W

5. R&D PLANS

R&D plans from 2001 to 2003 are presented in Table 3. Operation testing of the palm-top gas turbine is being conducted during 2003, as well as elemental testing of the finger-top gas turbine.

6. AFTERWORD

A prototype has been fabricated as the world's smallest and lightest palm-top gas turbine (2~3kW output, dry weight of 14.3kg including the generator, and cubic volume of 8.5 liters) and plans for a finger-top gas turbine test model (output of tens of W) have been developed. Verification testing is to be conducted on the former during FY2003, with elemental testing to be performed with respect to the latter. These gas turbines will be able to use either liquid hydrocarbon fuel or gaseous fuel such as propane or hydrogen. A wide range of applications is envisioned, including both emergency and ordinary power generation, and power supplies for communications systems, robots, and UAV. R&D work is proceeding, aimed at the early realization of practical devices.

This R&D work was consigned by NEDO in FY2001 as an international joint research project on energy and the environment known as Practicing research of button sized gas generators, and in FY2002~2003 as the same type of project entitled Leading R&D to practice Ultra Micro Gas Turbines, centered on the Institute of Industrial Science at the University of Tokyo. These projects have received cooperation from various Japanese universities and firms, as well as ONERA in France, CIAM in Russia, and VKI in Belgium.

With respect to high-speed motors and generators, results have been adopted from the Development project on ultra high speed motors and generators for fuel cells, conducted during FY2001 new enterprise creation program by Nagasaki prefecture. With respect to compact aerodynamic testing equipment, results have been adopted from Development project on high-speed computer CPU direct air-cooling systems, sponsored by METI as an FY2001 Regional development consortium research project.

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