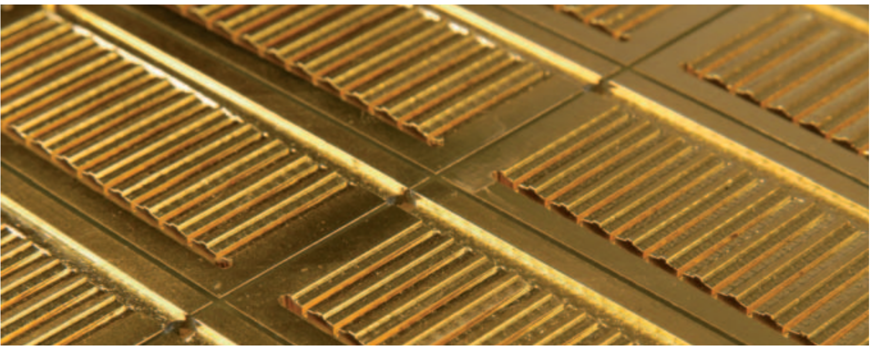
[Technical Digest]

PowerMEMS 2007

The Seventh International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications



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28 and 29 November 2007, Freiburg, Germany

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WORLD'S SMALLEST GAS TURBINE ESTABLISHING BRAYTON CYCLE

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Abstract: This paper reports the demonstration of the world's smallest class gas turbine engine. The developed engine, which is dramatically miniaturized in comparison with the existing ones, is as small as it can be easily held in one hand. The engine has a compressor of 16 mm diameter, a turbine of 17.4 mm diameter, an annular combustor and a dummy electromagnetic generator. The rotor is supported by externally-pressurized gas bearings instead of hydrodynamic gas bearings, which will be used in a practical engine. Brayton cycle was established at 360000 rpm, which is 62 % of the rated rotation speed. The engine is expected to be used in the applications of future mobile robots, personal vehicles etc.

Key Words: Miniature gas turbine engine, Brayton cycle, Hydroinertia gas bearing

1. INTRODUCTION

The progress of mechatronics and information technology will extend the applications of robots to areas outside of factories. Important applications of future robots include rescue and recovery in areas of disaster and various operations in dangerous or hazardous environments. For such applications, it is often difficult to find an electrical outlet to recharge secondary batteries, therefore the refueling of engines becomes preferable to recharging secondary batteries. The long operation time by single refueling is also important. Similar requirements also exist in personal vehicles such as a high-tech wheelchair, which will become more important in a coming aging society.

Common fuels such as gasoline, diesel oil, kerosene, propane and butane contain a huge amount of available energy in comparison with secondary batteries. This motivates many researchers in the world to develop miniature gas turbine engine generators with impellers of 20 mm diameter or less [1–10]. A gas turbine engine is cleaner than conventional reciprocating engines, and also has higher power per volume than fuel cells.

Tohoku University has started the development of miniature gas turbine engine generators in cooperation with IHI Corporation in 2000 [7–10]. We have recently succeeded in the demonstration of an engine of this class. The engine is the world's smallest class in terms of the diameter of impellers.

2. STRUCTURE OF ENGINE

Figure 1 shows the schematic structure of the developed engine. The outer size is about 10 cm in diameter and 15 cm in length. The core part of the engine, without experimental equipments, is smaller than the above size. It includes a compressor of 16 mm diameter, a turbine of 17.4 mm diameter, an annular combustor and a dummy electromagnetic generator. The impellers are connected by a shaft of 8 mm diameter, all of which compose one piece of Inconel as shown in Fig. 2. The rotor also has a weight around the center, which simulates the magnet of the generator. The total weight of the rotor is approximately 37 g. The combustor is a swirl flow type, and the flame is stabilized at the swirler step downstream.

The miniaturization of the engine has been realized by ultra-high speed rotation of small impellers. The rotation speed of the developed

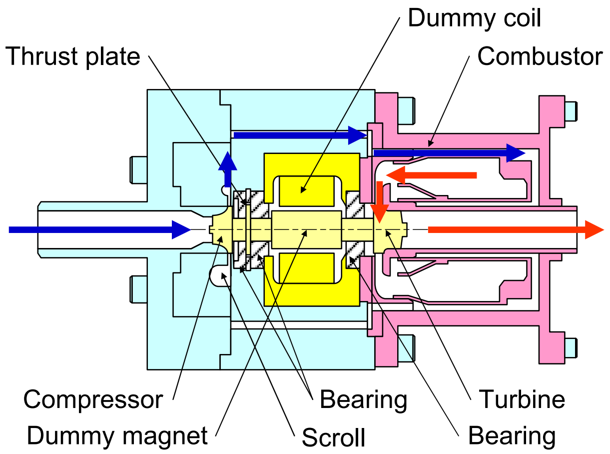

Fig. 1: Schematic structure of the miniature gas turbine engine.

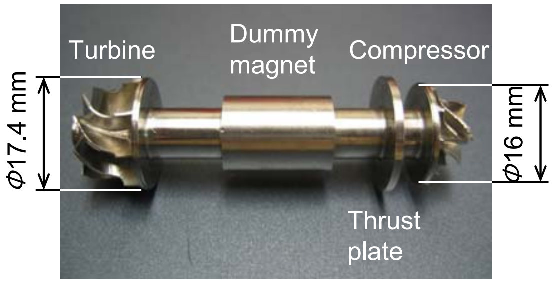

Fig. 2: Rotor with compressor and turbine impellers.

engine reaches 500000–600000 rpm, which is achieved using special air bearings referred as hydroinertia gas bearings [7, 8, 10]. The hydroinertia gas bearings are externally-pressurized gas bearings, and used just to test the engine and its components. In the future, they will be replaced by hydrodynamic gas bearings.

3. EXPERIMENTAL

3.1 Experimental Setup

Figure 3 is the diagram of an experimental setup for engine tests. The engine is set as the rotation axis becomes vertical under an exhaust gas receiver. The inlet of the compressor is connected to a pressurized air line, which is equipped with a pressure sensor, a flow control valve and a mass flow meter. Although hydrocarbon gas fuels can be used in a similar combustor, the risk of carbon monoxide made us decide to use hydrogen in this study.

Temperatures in the engine and air lines are measured using K-type thermocouples. The rotation speed of the rotor is obtained by detecting a black mark on the rotor using an optical fiber displacement sensor. The radial motion of the rotor is measured at the middle part using an eddy current displacement sensor, whose signal is used for a real-time bearing monitoring system described below. Figure 4 shows the engine under test.

3.2 Real-Time Bearing Monitoring System

To know how the engine is approaching the limit of rotation speed in real time is most important to prevent the fatal crash of the rotor-bearing system. We developed the real-time bearing monitoring system, which displays the radial motion of the rotor in time and frequency domains, the amplitude of rotor vibration versus the rotation speed, the flow rates of bearing air, a whirl ratio etc. as shown in Fig. 5.

We determined the maximum allowable amplitude of rotor vibration, at which the engine

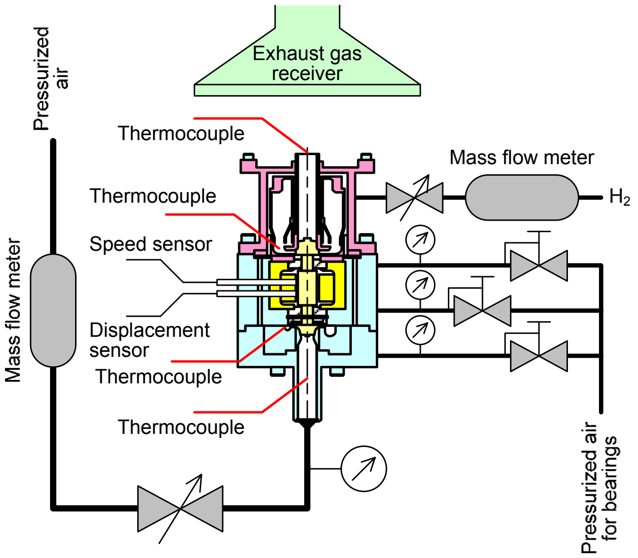

Fig. 3: Diagram of an experimental setup for engine tests.

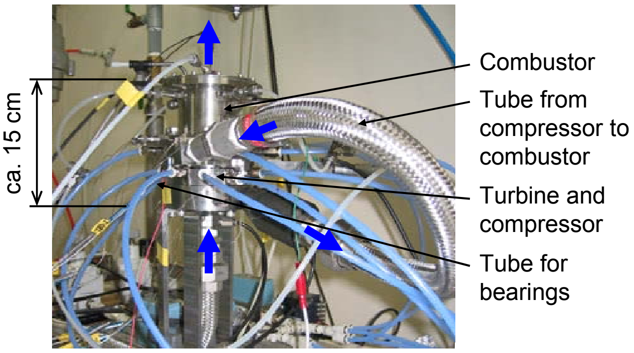

Fig. 4: Miniature gas turbine engine under test.

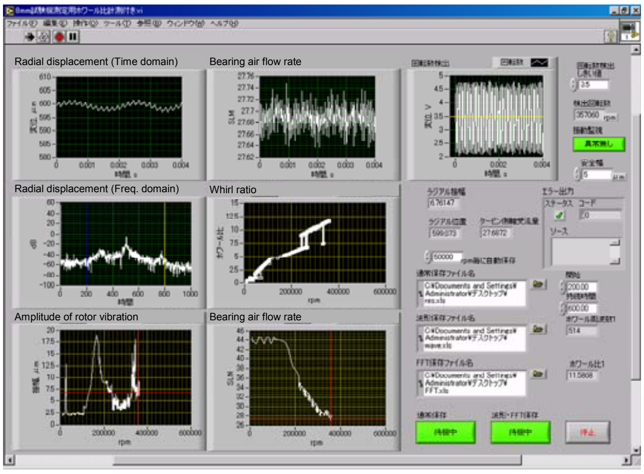

Fig. 5: Display image of the real-time bearing monitoring system.

is slowed down, by taking account of the journal bearing gaps. The journal bearing gaps in high temperature operation are different from the initial ones due the difference of thermal expansion between the rotor and the bearings. Therefore, they are predicted from the flow rates of bearing air based on the calculated relationship between the bearing gap and the flow rate of bearing air.

3.3 Result

The performance of the compressor and the bearings were measured in cold and hot states. Figure 6 shows the performance of the compressor measured in cold state. The flow rate, pressure rise and adiabatic efficiency are normalized by each designed value. It was confirmed that the adiabatic efficiency approached the designed value at 55 % and 70 % of the rated rotation speed of 580000 rpm.

The rotor-bearing system was tested up to 500000 rpm and 460000 rpm in cold and hot tests, respectively. In the hot tests, the clearance of the journal bearing on the turbine side was enlarged by taking account of the difference of thermal expansion between the rotor and the bearing, which is made of zirconia ceramics. The optimized journal bearing gap was 30 μm and 38 μm for the cold and hot tests, respectively.

Figure 7 shows the vibration of the rotor at 400000 rpm and 460000 rpm in high temperature operation. At 460000 rpm, whirl, which is the low frequency element of vibration found in Fig. 7, limited the maximum rotation speed.

For the operation of the engine, startup air was introduced from the compressor inlet. After the combustor was ignited around 100000 rpm, the rotation speed was increased by adjusting the flow rate of air and hydrogen. We finally confirmed that pressure at the compressor inlet became negative (minus a few kPa below the atmospheric pressure), when the rotation speed was 360000 rpm and the combustor temperature was 800–900 °C. Figure 8 shows the pressure at the compressor inlet with the combustor temperature, rotation speed, air flow rate and compressor pressure rise, all of which are normalized by each rated or designed value. This result clearly demonstrates that Brayton cycle was established, because the engine could continue to rotate, even if the inlet of the compressor was disconnected from the air line and opened to the atmosphere.

4. CONCLUSION

We succeeded the operation of the world's smallest class gas turbine engine with a compressor impeller of 16 mm diameter. Brayton

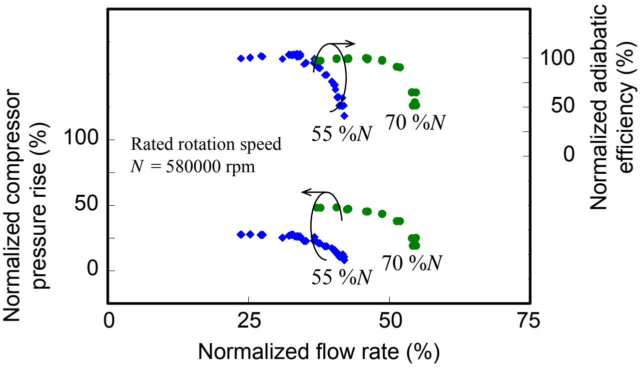

Fig. 6: Measured compressor performance in cold state.

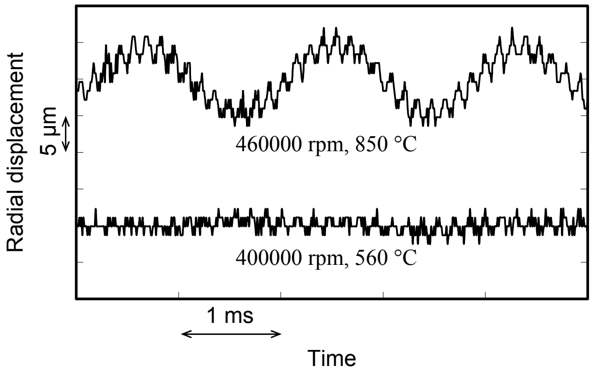

Fig. 7: Vibration of the rotor at 400000 rpm and 460000 rpm in high temperature operation.

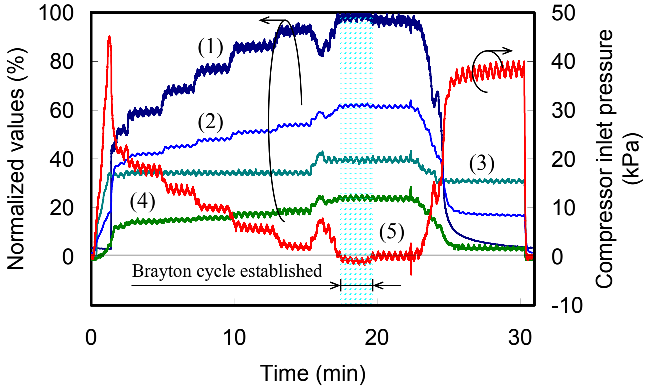

Fig. 8: Result of the engine test, demonstrating the establishment of Brayton cycle: (1) Combustor temperature, (2) Rotation speed, (3) Air flow rate, (4) Compressor pressure rise, (5) Compressor inlet pressure.

cycle was established at 360000 rpm, which is 62 % of the rated rotation speed. This result opens the application of miniature gas turbine engine generators to mobile robots, personal vehicles etc. In this study, we used the externally-pressurized gas bearings, still needing help by the external pressure source. The fully-self-sustaining operation of the engine will be achieved using hydrodynamic gas bearings in the future.

ACKNOWLEDGEMENTS

We appreciate past students in Tohoku University and Tohoku-Gakuin University, especially Takashi Genda, Satoshi Goto and Yuki Endo, for their efforts in this project.

Tohoku University was supported by the New Energy and Industrial Technology Development Organization (NEDO) of Japan, Industrial Technology Research Grant Program. Tohoku-Gakuin University was partly supported by The Asian Office of Aerospace Research and Development (AOARD), Grant No. F62562-03-T-0452 and FA5209-05-P0234, Program manager Dr. Brett Pokines.

REFERENCES

[1] A. H. Epstein, Millimeter-Scale, Micro-Electro-Mechanical Systems Gas Turbine Engines, *Trans. ASME J. Eng. Gas Turbine Power*, 126, 2003, pp. 205–226.

[2] S. Kang, J. P. Johnston, T. Arima, M. Matsunaga, H. Tsuru, F. B. Prinz, Micro-Scale Radial-Flow Compressor Impeller Made of Silicon Nitride – Manufacturing and Performance –, *Proc. ASME Turbo Expo 2003*, Atlanta, USA, June 16–19, 2003, GT2003-38933.

[3] J. Peirs, D. Reynaerts, F. Verplaetsen, A Microturbine for Electric Power Generation, *Sensors and Actuators A*, 113, 2004, pp. 86–93.

[4] E. Matsuo, H. Yoshiki, T. Nagashima, C. Kato, The Development of the Ultra Micro Gas Turbines, *J. Jpn, Inst. Energy*, 84, 2005, pp. 192–199, in Japanese.

[5] O. Dessornes, J. Guidez, Y. Ribaud, T. Courvoisier, C. Dumand, M. Orain, Z. Kozanecki, P. Helin, P. Le Moal, P. Minotti, Three Technological Bricks for a Micro Turbine Concept for Micro Power Generation, *Technical Digest of PowerMEMS 2005*, Tokyo, Japan, November 28–30, 2005, pp. 65–68.

[6] X. C. Shan, Z. F. Wang, Y. F. Jin, M. Wu, J. Hua, C. K. Wong, R. Maeda, Studies on a Micro Combustor for Gas Turbine Engines, *J. Micromech. Microeng.*, 15, 2005, pp. S215–S221.

[7] S. Tanaka, K. Isomura, S. Togo, M. Esashi, Turbo Test Rig with Hydroinertia Air Bearings for a Palmtop Gas Turbine, *J. Micromech. Microeng.*, 16, 2004, pp. 1449–1454.

[8] K. Isomura, S. Tanaka, S. Togo, M. Esashi, Development of High Speed Micro-Gas Bearings for 3-Dimensional Micro-Turbo Machines, *J. Micromech. Microeng.*, 15, 2005, pp. S222–S227.

[9] K. Isomura, M. Murayama, S. Teramoto, K. Hikichi, Y. Endo, S. Togo, S. Tanaka, Experimental Verification of the Feasibility of a 100W Class Micro-scale Gas Turbine at an Impeller Diameter of 10 mm, *J. Micromech. Microeng.*, 16, 2006, pp. S254–S261.

[10] S. Tanaka, M. Esashi, K. Isomura, K. Hikichi, Y. Endo, S. Togo, Hydroinertia Gas Bearing System to Achieve 470 m/s Tip Speed of 10 mm-Diameter Impellers, *Trans. ASME J. Tribology*, 129, 2007, pp. 655–659.