DESIGN AND SIMULATION
OF 500W ULTRA-MICRO GAS TURBINE GENERATOR

Sangjo Han, Jeongmin Seo, Jun-Young Park, Bum-Seog Choi*, and Kyu Hyung Do
Korea Institute of Machinery & Materials, Daejeon, Korea
*Presenting Author: bschoi@kimm.re.kr

Abstract: This paper presents the development of 500W ultra-micro gas turbine (UMGT) generator. The purpose of the paper is to check the feasibility and develop the prototype of the ultra-micro gas turbine with 500W electrical output. The ultra-micro gas turbine (UMGT) consists of a centrifugal compressor, a radial turbine, an annular combustor, and recuperators, and a high speed generator. It is designed to run 400,000rpm, compression ratio 3.0, and TIT 1200K. The requirement of UMGT is that the volume of UMGT should be less than 1L in the present research. To meet this goal, the layout of UMGT is chosen as a single shaft and direct connection between the gas turbine and the generator.

The compressor and turbine are chosen as radial type for small flow rate and high pressure/expansion ratio. In the present research, thermal cycle analysis of UMGT is conducted to determine the specification of the gas turbine. The required mass flow rate is 20g/s and expected efficiency is 10% with the recuperators. Based on the results from the thermal cycle analysis, each component is designed. The centrifugal compressor and radial turbine are designed and analyzed using 1-D and 3-D numerical simulation. For the combustor design, annular type combustor is selected instead of can type combustor to reduce the total volume. Six plate-stacked recuperators are symmetrically located outside of the combustor.

Keywords: micro gas turbine, centrifugal compressor, radial turbine, annular combustor, micro recuperator

INTRODUCTION

The popularity of mobile devices makes human experience rich and life convenient. The compactness is essential quality of mobile devices and their energy sources are usually battery. Lithium ion batteries are the most convenient energy source, but they are not appropriate for the usage of a long period time due to poor specific energy (W-hr/kg). Fuel cell is another energy source in the spotlight. In spite of high specific energy of fuel cell, fuel cell has poor specific power (W/kg). There is an energy source with high specific energy and power. Internal combustor engines shows excellent performance in power intensity and duration which results from the usage of hydrocarbon fuels

Among the internal combustor engines, micro gas turbines have higher power density than the other engines at micro-scale. MIT group developed a shirt button size gas turbine manufactured by MEMS technology [1]. Due to thermal loss, they are not enough to produce power for mobile application even though it shows strong technological impact. After their research, micromachine gas turbine is under development in many different groups [2, 3, 4, 5]. Several researchers present papers about design and optimization of each components [6,7]. So far, none of researchers runs UMGT system standalone up to full performance.

The development of an ultra micro gas turbine is under development by a group in Korea Institute of Machinery and Materials. The goal of the project is to prove the feasibility of a 500W level gas turbine within 1L volume.

THERMAL CYCLE ANALYSIS

To start the development of an ultra micro gas turbine, thermal cycle analysis is essential to decide mass flow rate, TIT, pressure ratio, power output and efficiency. The thermal cycle analysis is conducted to decide these parameters using GasTurb 11 [8]. Single spool with recuperator model in the program is applied for the thermal cycle analysis. Before thermal cycle analysis, TIT=1200K and pressure ratio (3) are suggested considering commercial alloy and general centrifugal compressor performance. Three cases are considered to decide mass flow rate. One is thermal cycle analysis with a recuperator and bypass cooling air (3% of main flow), another is thermal cycle analysis with a recuperator, and the other is thermal cycle analysis without a recuperator. For thermal cycle analysis, system parameters are in Table 1.

Table 1 System parameters in theraml cycle analysis

	Values	unit
Compressor efficiency	68	%
Pressure ratio	3	
Turbine efficiency	70	%
TIT	1200	K
Combustor efficiency	90	
Recuperator efficiency	75	%
Generator efficiency	80	%
Fuel heating values	43.124	MJ/Kg

These values are employed based on literature survey and considering small scale of the system. In this simulation, the mass flow rate is decided to be 0.02kg/s. With this value, more than 500W are obtained in all three cases. Expected efficiency in the system is 10.4% with a recuperator and 6% without a recuperator. Usually large industrial gas turbines have system efficiency over 35%. However, ultra-micro gas turbine has about 10% efficiency due to small scale and enhanced losses. After comparing three cases, the system with a recuperator and cooling air is employed for the ultra-micro gas turbine layout.

SYSTEM DESCRIPTION

In the present research, there are two requirements. One is power output, 500W from a generator, the other is the limitation of size, 1L volume which includes a compressor, a turbine, a combustor, six recuperators, a generator, and a control unit. The system layout consists of a generator, a centrifugal compressor, a radial turbine, an annular combustor, six recuperators in Figure 1 and Figure 2.

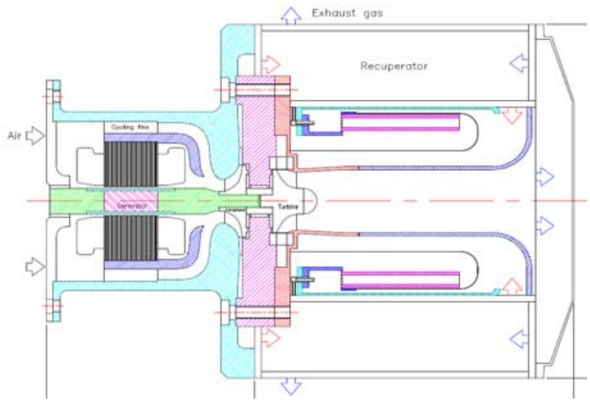

Figure 1 Schematics of the ultra-micro gas turbine

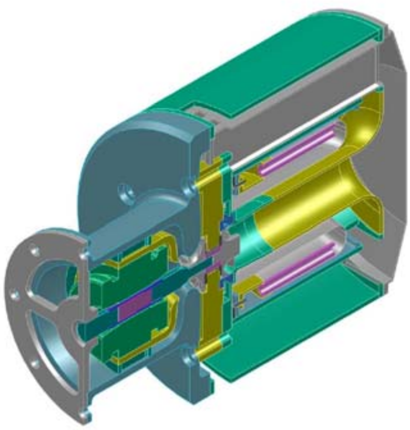

Figure 2 Three cutout of the ultra-micro gas turbine

To meet the volume requirement, the generator is located before the inlet of the compressor and is connected to the compressor and turbine directly. This layout helps to cool down the generator easily. Instead of can type combustors, an annular type combustor is suggested to make it compact.

CENTRIFUGAL COMPRESSOR

Due to small mass flow rate and relatively large pressure ratio, a centrifugal type compressor is selected for UMGT. To get higher efficiency in the small size compressor impeller, specific speed, 0.65 is chosen and the rotating speed is computed to 400,000rpm. The development is fulfilled using commercial 1-D program and 3-D CFD code. The procedure of the development consists of 1-D meridional design and 3-D CFD design. First, based on specific speed, the basic dimensions of the impeller are decided. Second, the off-design performance of the impeller is analyzed in 1-D design program varying pressure ratio and rotating speed. The design parameters are listed in Table 2. The efficiency is a little bit higher than that of the thermal cycle analysis. However, it could be lower than that of the simulation due to the small scale of the impeller. The consumed power of the impeller is reasonable considering the thermal cycle analysis. The vainless diffuser is selected for the lower performance and manufacture problems of a vain diffuser.

Table 2 Compressor design parameters

	Item	unit	value
Flow	Speed	rpm	400,000
	Mass Flow Rate	kg/s	0.02
	Inlet Volume Flow Rate	m3/s	0.0163
Impeller	Blade Number	-	7+7
	Reference Radius	mm	11.4
	Tip Clearance	mm	0.1
	Exit Angle	deg	-43
Performance	Total Pressure Ratio		3.055
	Total Isentropic Efficiency	%	74.61
	Input Power	W	2910

The efficiency, power, pressure ratio are evaluated varying mass flow rate from 50% to 100% of the design speed in off-design analysis. There are plotted in Figure 3 and Figure 4. For the design speed, full 3-D CFD evaluation is conducted and shows good agreements with 1-D off design analysis in Figure 3 and Figure 4.

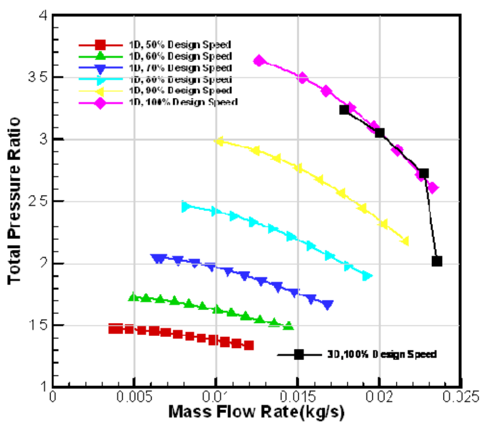

Figure 3 Total pressure ratio by the compressor

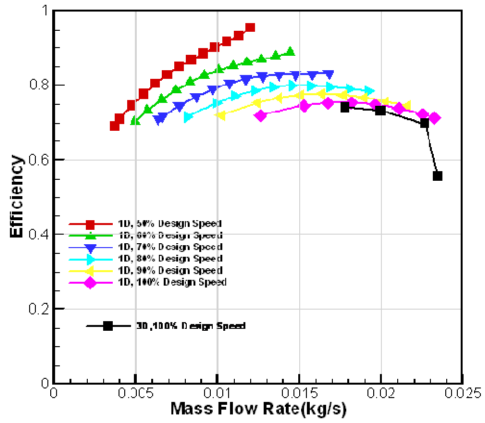

Figure 4 Efficiency of the compressor

RADIAL TURBINE

One stage radial turbine is suggested to obtain more than 4kW and total to static pressure expansion ratio 2.6. Compared with the impeller design, the radius of the turbine rotor is constrained by material fatigue of high temperature. The tip speed is limited by 410m/s so that it becomes high loading rotor design. The loading coefficient of the rotor is 1.3. As mentions before, the design procedure is similar to that of the impeller – 1-D meridional design, 3-D full CFD. The meridional design parameters are listed in Table 3. The blade diameter is 20mm and smaller than the diameter of impeller.

Table 3 Turbine design parameters

	Item	unit	value
Flow	Speed	rpm	400,000
	Mass Flow Rate	kg/s	0.02
	Inlet Volume Flow Rate	m3/s	0.0241
Nozzle	Blade Number	-	20
	Reference Radius	mm	16
	Exit Angle	deg	73.9
Rotor	Blade Number	-	8
	Reference Radius	mm	10
	Tip Clearance	mm	0.1
	Exit Angle	deg	-43
Performance	Total Pressure Ratio(TT)		2.52
	Total Pressure Ratio(TS)		2.98
	Total to Static Isentropic Efficiency	%	70
	Out Power	W	4521

In Figure 5, the high efficiency is obtained at U/C~0.7. However, the limitation of blade tip speed and high expansion ratio choose U/C=0.5 and lower efficiency. Off-design analysis show large operation region for different rotating speed in Figure 6. Since the performance of the turbine is constrained by the operation range of the compressor, the operation range of the turbine should be based on the compressor map. However, the relation between a compressor and a turbine is not considered in the evaluation of the performance of the turbine in Figure 6.

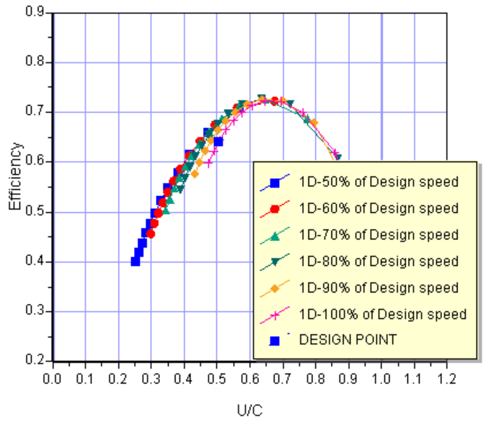

Figure 5 Blade speed vs efficiency by the turbine

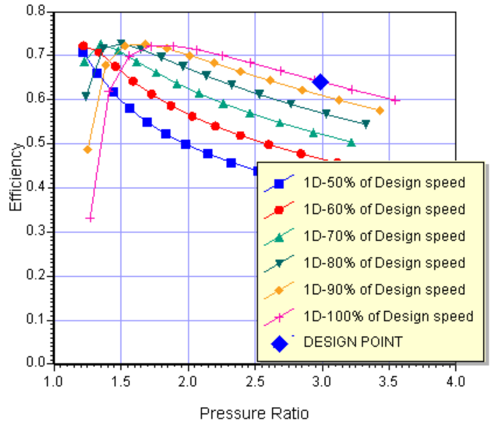

Figure 6 Efficiency by the turbine

ANNULAR COMBUSTOR

The larger component of the system is a combustor. Previously multiple-can type combustor is considered due to the flame instability problem. Other advantage of can type combustor is that the combustor performance test is easier compared with that of the annular type combustor. In spite of these merits, the combustor layout changes from can type to annular type to meet the volume requirement of the project.

The current prototype is designed just for combustor experiment, not for gas turbine experiment. It consists of twelve fuel nozzles, one heater for ignition, outer liner, inner liner, outer/inner casing, air inlet port, exhaust gas outlet. The fuel nozzle holes and outer liner of the combustor chamber are clearly observed in Figure 7.

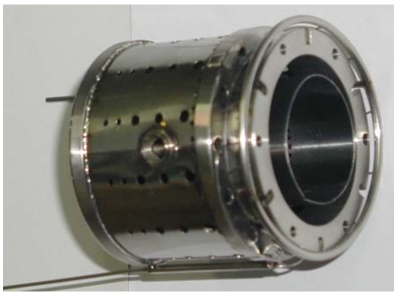

Figure 7 Annular combustor prototype

PLATE STACKED RECUPERATOR

To improve the efficiency of the system, the usage of recuperators is suggested in the thermal cycle analysis. The design of the recuperator is described in Figure 8. The recuperator system is composed of six recuperators. Each recuperator consists of 11 stacked plates and has two different inlets and outlets for heat exchange between compresses air and exhaust gas. Six plate-stacked recuperators are symmetrically located outside of the combustor.

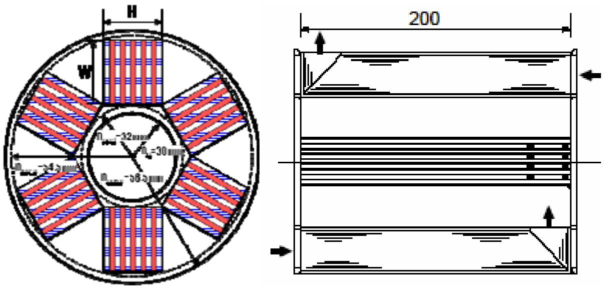

Figure 8 Plate stacked recuperator schematic

CONCLUSION

An ultra-micro gas turbine generator is designed for 500W power generation within 1L volume. To minimize design errors and optimize development procedure, the thermal cycle analysis is conducted. Based on the project requirement, 500W and volume less than 1L, the system layout includes a directly connected single shaft, a centrifugal type compressor, a radial type turbine, annular type combustor, and six plate stacked recuperators. The thermal cycle analysis shows that the mass flow rate, 0.02kg/s and 400,000RPM can produce more than 500W with 10% efficiency. The suggested efficiency and performance of each component are confirmed to be possibly achieved in 1-D and 3-D evaluations. The annular combustor is designed for a stand-alone experiment. To improve efficiency of the system, a recuperator system is designed with six plate-stacked recuperators.

ACKNOWLEDGEMENT

This work was supported by the Next Generation Military Battery Research Center program of Defense Acquisition Program Administration and Agency for Defense Development.

REFERENCES

[1] Epstein A H 2004 Millimeter-scale, micro-electro-mechanical systems gas turbine engines *ASME J. Eng. Gas Turbines Power* **126** 25-26

[2] Isomura K et al 2003 Development of micro-turbo charger and micro-combustor as feasibility studies of three-dimensional gas turbines at micro-scale *ASME Paper GT2003-38151*

[3] Lee Y B, Kwak Y S, Kim C H, Oh J, Chung J T 2007 Feasibility Study of 100Watts Class Micro Turbocharger for Micro Gas Turbine Engine *PowerMEMS 2007*, pp 221-224

[4] Stevens T., Rogiers F., Baelmans M. 2007 Integrated Design of A Micro Recuperator in A Gas Turbine Cycle *PowerMEMS 2007*, pp 253-256

[5] Peirs J., Waumans T., Liu K., Reynaers D. 2008 Measurement of Compressor and Turbine Maps for An Ultra-Miniature Gas Turbine *PowerMEMS 2008*, pp 413-146

[6] Feffaris E et al 2007 Production of a miniature Si3Ni4-TiN ceramic turbine impeller by die-sinking EDM *PowerMEMS 2007*, pp 229-232

[7] Waumans T et al 2007 Design and testing of aerodynamic thrust bearings for micro turbomachinery applications *PowerMEMS 2007*, pp 257-260

[8] Kurzke J 2005 How to Create a Performance Model of a Gas Turbine From a Limited Amount of Information *ASME GT 2005-68537*