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HIGH TEMPERATURE DEMONSTRATION UNIT FOR A 1500°C CLASS GAS TURBINE

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BREAK

ABSTRACT

Tohoku Electric Power Co., Inc. and Mitsubishi Heavy Industries, Ltd. have begun a joint development program on key technologies for a next generation gas turbine which aims for a combined cycle efficiency over 55%. Under the program, advanced cooling technologies, better heat resistant materials and dry low NOx (DLN) combustion technologies are being developed. For verifying high temperature technologies, turbine testing is going to be performed using the HTDU (High Temperature Demonstration Unit) at Takasago Machinery Works, Mitsubishi Heavy Industries, Ltd..

This paper describes the general description of the HTDU facility and plans for testing a turbine at a firing temperature of 1500°C.

INTRODUCTION

The improvement of gas turbine thermal efficiency has been accomplished mainly by an increase in firing temperature and pressure ratio. As the combined cycle efficiency is strongly dependent on the firing temperature, increases in firing temperature of the industrial gas turbine has accelerated in this decade.

Currently, there is also a strong demand for efficient and clean power generation systems to meet tougher environmental regulations and energy saving requirements. The combined cycle power plant, composed of high firing temperature gas turbines using natural gas as fuel, is the best power generation system at the present to meet these efficiency and environmental regulation needs.

The evolution of firing temperature is shown in Fig.1. Firing temperature of the latest industrial gas turbine such as the Mitsubishi-Westinghouse 501F reaches 1350°C. A combined cycle using 501F has a thermal efficiency better than 53%. The next generation combined cycle power plant, which will be introduced at the beginning of next century, is expected to have thermal efficiency better than 55%. To achieve that efficiency, an advanced gas turbine (AGT) with a firing temperature around 1500°C will be needed.

Under these circumstances, Tohoku Electric Power Co., Inc. and Mitsubishi Heavy Industries, Ltd. started a joint technology development program to establish the key technologies of the 1500°C gas turbine. The objective of the program is to develop a DLN combustion system, advanced cooling and advanced heat resistant materials (Kano et al., 1991, Matsuzaki et al., 1992, Amagasa et al., 1993). In the program, new technologies have been developed mainly through the laboratory test. In addition to the tests, high temperature turbine testing utilizing the HTDU (High Temperature Demonstration Unit) is planned. The purpose of the test is to verify the cooling effectiveness of advanced cooling, heat shield effect of thermal barrier coatings and the mechanical characteristics of a directionally solidified blade.

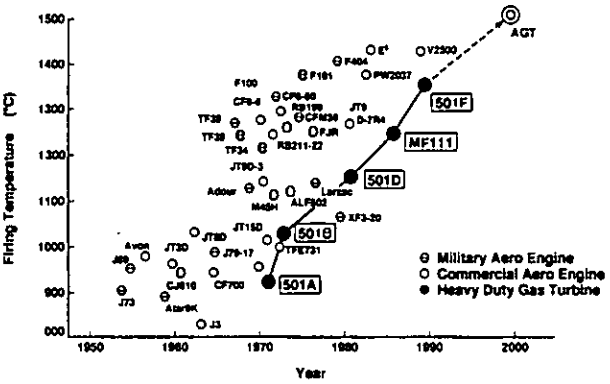

Fig.1 Evolution of firing temperature

This paper describes the outline of the high temperature turbine test and the HTDU.

HTDU

The test will be conducted at the gas turbine test facility in Takasago Machinery Works, Mitsubishi Heavy Industries, Ltd.. The schematic drawing of the test facility is shown in Fig.2 and the HTDU is shown in Fig.3.

The air source compressor has a pressure ratio of 16 and mass flow rate of 45kg/s, and is driven by a gas turbine having an output of 30,000kW. The main air flow is supplied at a temperature of 400°C and pressure of 15 ata. Three cooling air lines branch from the main air line; one is for the first vane cooling, and the others are for the first blade and exhaust diffuser cooling. All air flows are adjusted to the required value by control valves.

Fig.4 shows a cross sectional view of the HTDU. The HTDU is originally constructed to demonstrate high temperature

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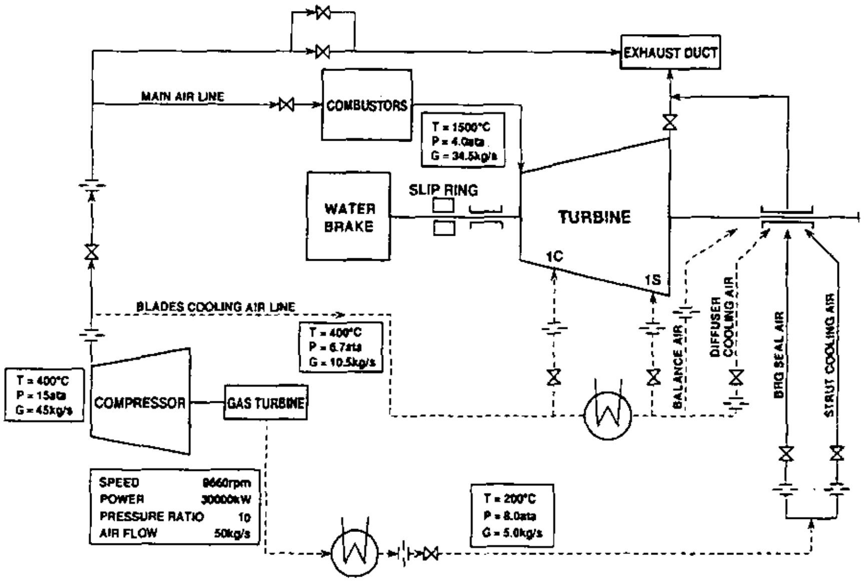

Fig.2 Schematic drawing of test facility

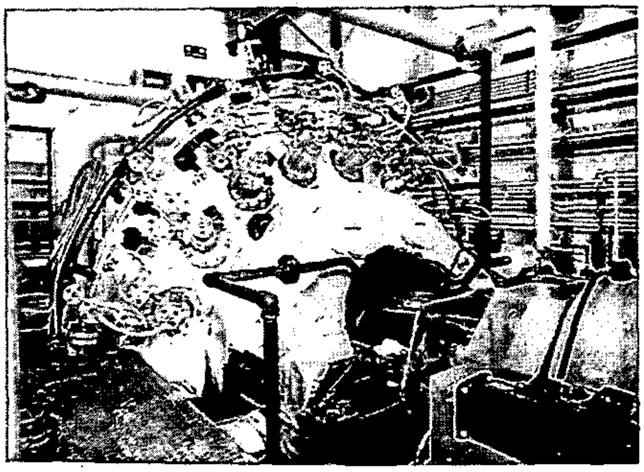

Fig.3 HTDU

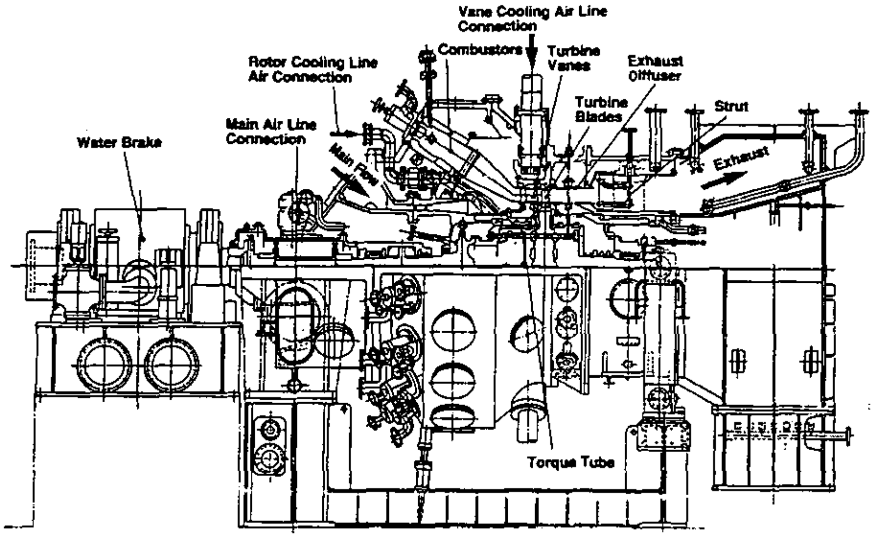

Fig.4 Cross sectional view of HTDU

technology applied to the 701F (Fukue et al., 1993). The turbine is a 0.6 scale of the 1st stage of the 701F. The HTDU consists of 16 can type combustors, single stage turbine (32 turbine vanes, 72 turbine blades), a exhaust diffuser, a turbine disc, a blade ring, an air separator and a torque tube. The turbine extracted power output is absorbed by a water brake.

The basic structure of the facility is described below.

- Diaphragm coupling between rotor and water brake
- Two bearing rotor with thrust bearing in inlet side and journal bearing in exhaust side
- Supporting system for absorbing the casing expansion and maintaining rotor alignment
- Short rotor over hung against rotor critical speed
- Horizontally split casings to facilitate easy inspection with the rotor in place
- Combustors and transitions, removable without lifting cylinder covers
- Direct cooling air supply system from air source compressor with the capability of measuring the flow rate of cooling air
- Water spraying inside the exhaust casing for turbine exhaust gas cooling
- Tangential exhaust casing struts to maintain rotor alignment
- Thermal expansion absorbing system of exhaust casing
- Thrust balance air system

AIR COOLED VANES AND BLADES

The vanes and the blades of the current HTDU are 0.6 scale of those of the first stage of the 701F. In order to investigate the cooling effectiveness of the advanced cooling, some of the vanes and blades will be replaced with those which have the cooling scheme of the AGT. Fig.5 shows the comparison of cooling schemes of the 701F and the AGT.

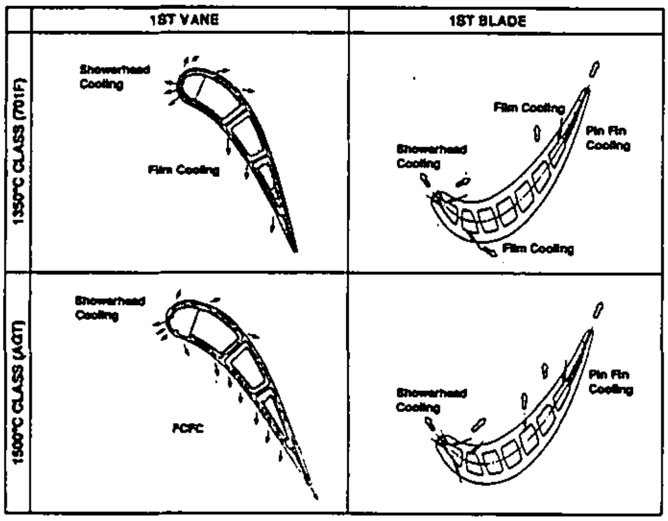

Fig.5 Cooling scheme for HTDU

The row 1 vane of the AGT has three cavities with cross-flow impingement cooling augmented by film cooling at the leading edge, pressure surface and suction surface. For the pressure surface, full coverage film cooling (FCFC) is applied to improve the cooling effectiveness. Pin fin in the trailing edge region is supplied with coolant flow from the afterward cavity and the cooling air is discharged from the trailing edge.

The row 1 blade of the AGT has three passages. One is a straight passage with film cooling at the leading edge. The second is a serpentine flow passage augmented by suction surface film cooling. The FCFC is also applied for the pressure surface cooling. The third is a cooling flow passage with pin fin rows in the trailing edge region. Air from the third flow passage is supplied for the pressure surface film cooling and the trailing edge cooling. The cooling air for the blade is cooled by air-cooler before feeding.

The test will be conducted utilizing various kinds of blades to verify the cooling effectiveness of the FCFC vane and blade, heat shield performance of the thermal barrier coatings (TBC) and the mechanical characteristics of the directionally solidified (DS) blade. Tables 1 and 2 show the various kinds of vanes and blades that will be used for this HTDU test. In the test, the TBC which have various compositions and thicknesses will be used.

Table 1 Test items of row 1 vane

TYPE	NUM. OF VANES	COOLING SCHEME	MATERIAL	CASTING	TEST ITEMS		
					FCFC	TBC	DS
A	1	FCFC	ECY768	Conventional Casting		○	
B	2	FCFC + TBC$^{(*)}$	ECY768	Conventional Casting	○	○	○
C	1	FCFC + TBC$^{(*)}$	MM247	Directional Solidified			○
D	28	FILM + TBC$^{(*)}$	ECY768	Conventional Casting	○		

(*) Various composition and thickness will be used in the test.

Table 2 Test items of row 1 blade

TYPE	NUM. OF BLADES	COOLING SCHEME	MATERIAL	CASTING	TEST ITEMS		
					FCFC	TBC	DS
A	2	FCFC	INC738LC	Conventional Casting		○	
B	1	FCFC + TBC$^{(*)}$	INC738LC	Conventional Casting	○	○	
C	1	FCFC + TBC$^{(*)}$	MM247	Directional Solidified			○
D	1	FCFC + TBC$^{(*)}$	MM247	Conventional Casting			○
E	67	FILM + TBC$^{(*)}$	INC738LC	Conventional Casting	○		

(*) Various composition and thickness will be used in the test.

INSTRUMENTATION

The engine is extensively instrumented to measure performance, metal temperatures, vibratory stresses, natural frequencies of blades and other parameters as shown in Figs.6 and 7. At the turbine exit, a total pressure probe and a total temperature probe are fitted to obtain the turbine efficiency. Each of these probes has seven measuring points in the radial direction. Static pressure variation through the turbine is measured with pressure taps on the profile, inner and outer shrouds of a vane. Static pressure taps are also located on the rotating blade. Static pressure and temperatures in endwall cavities are also measured by pressure tubes and thermocouples. Those data are used for evaluation of cooling flow schedule.

As the cooling performance of the AGT utilizing FCFC highly depends on the film cooling effectiveness, the cooling air pressure of the vanes, rotor and blade will be measured and compared with the prediction.

Metal temperature of vanes and blades are measured by thermocouples embedded in the wall. There are several measuring points for each vane and blade (vane: 50% height, inner and outer shrouds, blade: 5%, 50%, 95% height, tip and platform). Output signals from the thermocouples fitted on the blade are transmitted to the data processing system by a slip ring. In addition to thermocouples on the rotating blade, the optical pyrometers are used to measure additional blade surface temperature location including tip and platform. Blade vibratory stresses will be measured by utilizing strain gauges and the data will be transmitted by the telemetry system.

The mass flow rates of main and cooling air lines are measured by orifices. The turbine extracted power output is measured by a water brake. The calibration of the water brakes will be performed several times during the test period. The fuel flow rate is measured by a turbine flow meter.

Blade tip clearances will be measured during the test using proximity type sensors.

MEASUREMENT ITEMS

Performance

- A1 Main flow rate
- A2 Main flow pressure
- A3 Combustor casing pressure
- A4 Speed
- A5 Lube oil temperature
- A6 Water brake power output
- A7 Main flow temperature
- A8 Fuel flow

Cooling

- B1 Row 1 vane cooling air temperature
- B2 Row 1 blade cooling air temperature
- B3 Row 1 vane cooling air flow
- B4 Row 1 blade cooling air temperature
- B5 Row 1 blade cooling air pressure

Cooling Air System

- C1 Blade ring cavity pressure and temperature

Vibration

- D1 Blade vibration

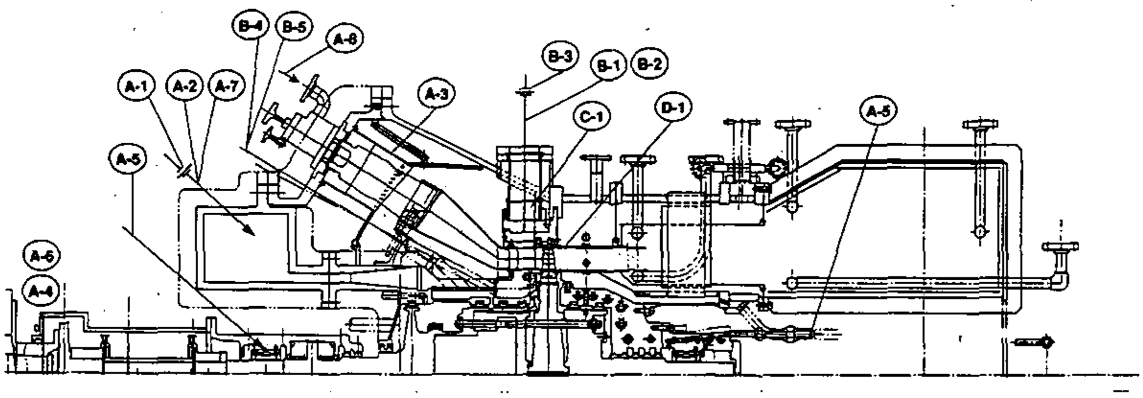

Fig.6 Measurement items

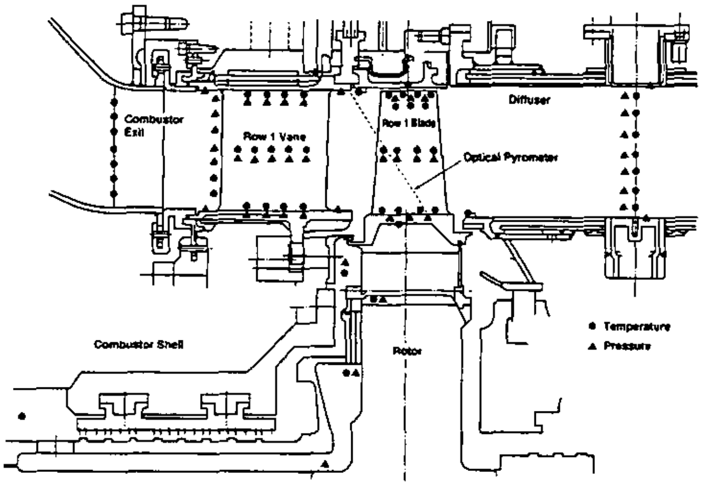

Fig.7 Instrumentation for vanes and blade

TESTS

The test will be carried out in steps to evaluate the turbine aerodynamic performance, cooling performance including TBC shield effect, and DS blade mechanical characteristics. Test conditions will be set to be equivalent to those of the operating condition of the AGT. Table 3 summarizes the test conditions. for the following steps:

(1) Aerodynamic Test (AT)

The purpose of the test is to evaluate the aerodynamic performance with several firing temperature, cooling air flow rate and at the design point. The aerodynamic test with various cooling air flow rate and the TBC application will help us understand the effect of film cooling air blowing rate to the turbine efficiency.

The aerodynamic test will be performed firstly under several speed and firing temperature. Each test conditions shown in Table 3 are equivalent to the AGT operating conditions.

In the test, it is possible to perform the test by varying the cooling flow rate to less than the design value due to lower gas temperatures.

(2) Hot Gas Test (HGT)

The purpose of the test is to evaluate the aerodynamic, cooling and mechanical characteristics of the AGT 1st stage turbine.

The hot gas test will be performed at various firing temperature. Each test condition shown in Table 3 is equivalent to the AGT operating conditions.

The most important item of the test is the verification of cooling performance of the FCFC vanes and blades. The FCFC vanes and blades were designed by utilizing film cooling effectiveness obtained from a 2-D cascade test. The cooling performance of the FCFC vane was verified through a 2-D hot cascade test performed at a gas temperature of 1500°C. However, as the cooling performance of the FCFC blade is influenced by the rotating effect, main stream turbulence due to upstream nozzle and so on, it is necessary to verify its cooling performance by utilizing the rotating test facility.

Table 3 Test condition

	Firing Temperature (°C)	Speed (rpm)	Main Flow (kg/s)	Power Output (kW)	Inlet Total Pressure (ata)	Pressure Ratio (—)	Main Test Items
Aerodynamic Test	950	4600	35	6000	2.7	1.65	Aerodynamic Performance vs. Firing Temperature Aerodynamic Performance vs. Cooling Air Flow Rate Aerodynamic Performance at Design Point
	950	4800	35	6030	2.7		
	950	5000	35	6050	2.7		
	1000	5800	34	6150	2.7		
Hot Gas Test	950	6000	35	6050	2.7	1.65	FCFC Performance TBC Heat Shield Effect DS Blade Vibration
	1050		33	6250	2.8		
	1150		32	6400	3.0		
	1250		31	6600	3.1		
	1350		30	6700	3.3		
	1450		30	6900	3.4		
	1500		30	7000	3.4		Cooling Performance at Design Point Aerodynamic Performance DS Blade Vibration

The thermal barrier coating (Fig.8) is expected to play an important role in the AGT turbine. In the test, a rainbow test will be performed by varying thickness and composition of the TBC. The effect of TBC with various composition and thickness will be evaluated by comparing the metal temperature of TYPE A and B in Table 1 for vanes and in Table 2 for blades.

The directionally solidified blades will be used in the AGT for obtaining better creep rupture life and low cycle fatigue (LCF) life than the conventional cast blade. One feature of the directionally solidified blade (Fig.9) is the different material property from the equi-axed conventional blade. In the test, natural frequency of the DS blade will be measured by utilizing strain gauge and telemetry system.

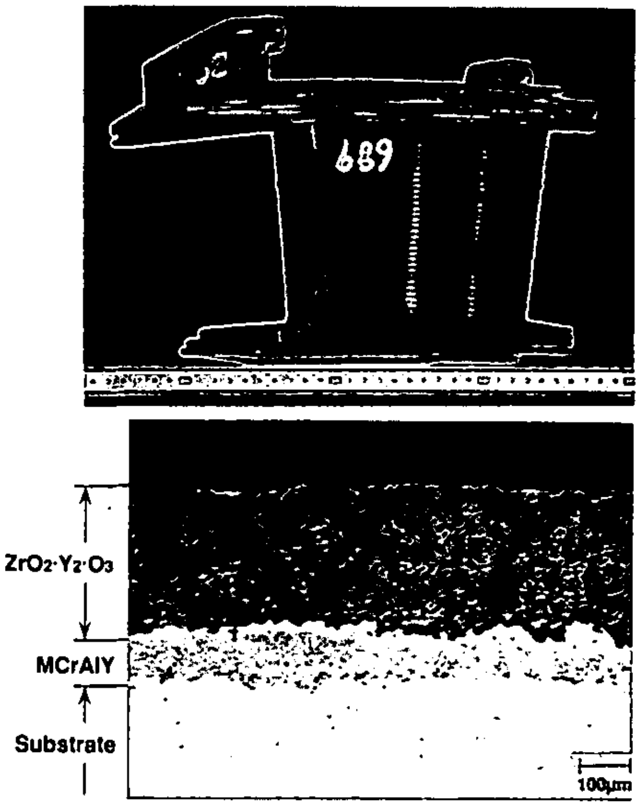

Fig.8 Appearance and microstructure of TBC coated vane of 100MW class gas turbine

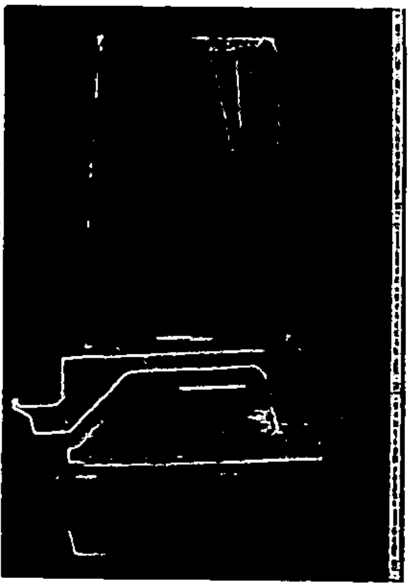

Fig.9 Macrostructure of trial manufactured DS blade of 150MW class gas turbine

At the last stage of the test, HTDU will be run at a firing temperature of 1500°C to demonstrate the aerodynamic performance, cooling characteristics and mechanical integrity of the turbine. The equivalent condition is also shown in Table 3.

DATA ANALYSIS

Measuring the turbine inlet mean gas temperature accurately is very difficult since there is a severe temperature distribution at the combustor exit. Accordingly, it will be estimated from the enthalpy balance using the mass flow rate of the air and fuel entering the combustor and the burning efficiency obtained through the combustion test.

The turbine overall pressure ratio will be defined by the value obtained from the total pressure probe installed on the leading edge of the 1st vane and the area weighted total pressure at the turbine exit.

The cooling air and the leakage air mixed in the turbine flow path will be estimated by the flow network calculation using the estimated gaps, the measured pressures and temperatures in the cavities and the flow path.

The turbine total aerodynamic power output is defined as the sum of the measured power by the water brake (W_{wb}), bearing loss (L_{bg}), pumping loss due to cooling air (L_p) and windage loss (L_{wd}). Among these values, the pumping loss and disk windage loss are estimated analytically. The turbine total aerodynamic power output (W_{total}), is then defined by the following equation.

$$W_{total}=W_{wb}+L_{bg}+L_p+L_{wd} \qquad (1)$$

The turbine efficiency, which is defined by the ratio of the turbine adiabatic work to actual output, is rather complicated in the case of the air cooled turbine, owing to cooling flow effects on work performed. In the analysis, the turbine total isentropic work is defined as the sum of the isentropic expansion work of the flow mixed into the turbine flow path.

The turbine total-to-total basis efficiency was defined by the following equation:

$$\eta=\frac{W_{total}}{\sum Gi\,(\Delta His)\,i} \qquad (2)$$

where,

Gi : mass flow rate entering the flow path

(ΔHis)i : adiabatic isentropic work

In order to analyze the local cooling effectiveness of vanes and blades, it is necessary to know the local gas temperature. The local gas temperatures will be estimated by the following procedure. For the first stage vane, the local inlet temperature is estimated by the mean gas temperature obtained from the enthalpy balance and the combustor exit temperature distribution obtained from the combustor test.

The blade inlet total temperatures will be estimated by the turbine through flow calculation. The estimated turbine inlet mean gas temperature, the circumferentially averaged radial gas temperature distribution obtained from the combustor test, the inlet mass flow rate, cooling flows, leakage flows, and the measured inlet total pressure will be used as input for the program. Based on the gas temperature estimated, the cooled blade cooling effectiveness will be obtained as a function of cooling air flow rate.

SUMMARY

The paper described the outline of the high temperature turbine testing utilizing the HTDU. The test will be carried out in the 3rd quarter of this year as the final step of the joint development program between Tohoku Electric Power Co., Inc. and Mitsubishi Heavy Industries, Ltd. aiming at the development of the key technologies of the AGT. The purpose of the test is the verification of the high temperature technologies applied to the AGT. The test results will be fed back to the turbine design of the AGT.

ACKNOWLEDGEMENT

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