VERIFYING HEAT TRANSFER ANALYSIS OF HIGH PRESSURE COOLED TURBINE BLADES AND DISK

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INTRODUCTION

To improve the performance of gas turbines, the specification for turbine inlet temperature continues to increase. One example is the super/hypersonic transport propulsion system research project in Japan which began in 1989 and has recently been completed. A turbine inlet temperature was planned in the 1700°C class. To demonstrate cooling and heat transfer technology, a core engine test was conducted. Measurement data were compared with predictions for a vane, a blade, and a disk. CFD analysis was carried out for verification of the heat transfer coefficient which was adopted from a heat conduction analysis over the disk.

EXPERIMENTS

A single stage high pressure turbine, installed in a high temperature core engine[1](Fig. 1), was instrumented at many measurement points for metal and secondary air temperatures, and for static pressures. The inlet temperature of the core engine was controlled by a inlet heater. The maximum turbine inlet temperature(TIT) was 1700°C. The maximum discharge temperature of the high pressure compressor was about 560°C. The turbine inlet pressure was about 0.25MPa. Although this pressure means lower heat flux than in actual engines, it also causes lower measurement error for thermocouples. Steady state and a transient conditions were measured. During transient operation, the TIT was lower because the inlet heater was not operated.

The turbine blades and vanes were fully film-cooled by shaped holes. The inside of blades and vanes were cooled by impingement and turbulence promoters as seen in conventional turbine blades. A film hole configuration was selected after a few basic tests at low temperature[2,3]. Prior to the engine test, scaled up model tests were conducted in a hot wind tunnel for verification of cooling design. A thermal barrier coating was not used in order to measure a net cooling performance in the engine test. The surface temperature on the vanes, blades, and disks were measured by embedded thermocouples. For the vane, small diameter stainless sheath thermocouples were set in a groove on the vane. For the blade, alumel and chromel lines were set on the surface with alumina coating. For the disk, the spot welded junctions of the sheathed thermocouple edges were covered with Inconel thin plate. Heat conduction errors at the junction of thermocouples resulted in errors of about 20°C for the vane and blade, and about 3°C for the disk.

RESULTS AND DISCUSSIONS

The original cooling design showed the predicted high cooling effectiveness in the scaled up model test. After manufacturing of actual turbine blades and vane, the core engine tests were carried out. Fig. 2 shows distributions of cooling effectiveness, defined as

$$\eta=(Tg-Tw)/(Tg-Tc),$$

where Tg is the assumed gas temperature calculated from verified cycle analysis and measured temperature profiles in combustor rig tests; Tw is the measured surface temperatures; Tc is the measured compressor discharge air temperature.

Results showed a high cooling effectiveness and flat distribution for the vane and the blade. A prediction was carried out using an in-house 2D heat conduction analysis for three sections: 20%, 48% and 80% span from the hub. Measured and predicted cooling effectiveness agreed well for both blade and vane. One exception is the blade tip near the trailing edge where a lower effectiveness was measured than was predicted due to tip leakage flow.

The measured transient temperature change showed faster response than predicted on the front face of the disk surface. This means that the heat transfer coefficient applied in the predictions is too low. The prediction was carried out on an axi-symmetric model with 3D corrections provided by commercial heat conduction analysis software. To understand the cause of this phenomena, CFD analysis was applied to the disk cavity using a standard k-ε model with wall function[4]. The rotor-stator cavity is not geometrically simple and has bolt heads on the rotor side. Fig. 3 shows two flow vectors and the distributions of the heat transfer coefficient. The difference between two analyses is that one includes bolt heads, and the other is an axi-symmetric model. The bolt heads produce different secondary flow near the disk surface. Both results of analysis show higher heat transfer coefficient compared with original h_{base}, which was estimated by a correlation for a simple rotor-stator cavity. The lower of the two, with the bolt head model, produces a better agreement between measured and predicted temperature response.

CONCLUSIONS

The core engine test was completed successfully at a turbine inlet temperature 1700°C. Conclusions of this paper are as follows:

1. The turbine blade and vane with shaped holes showed high cooling effectiveness in the core engine test. Measured cooling effectiveness agrees well with predictions.
2. For the geometrically complicated disk cavity, the results of CFD analysis showed the higher heat transfer coefficient which is expected from the measured temperature response on the disk. The CFD model including bolt heads showed better results than an axi-symmetric model.

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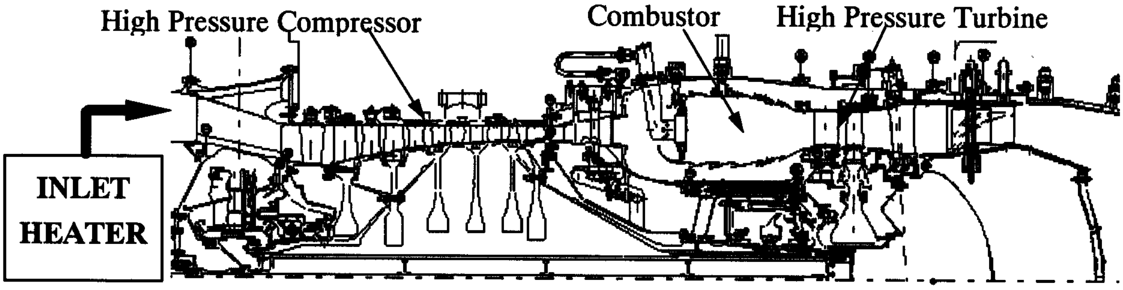
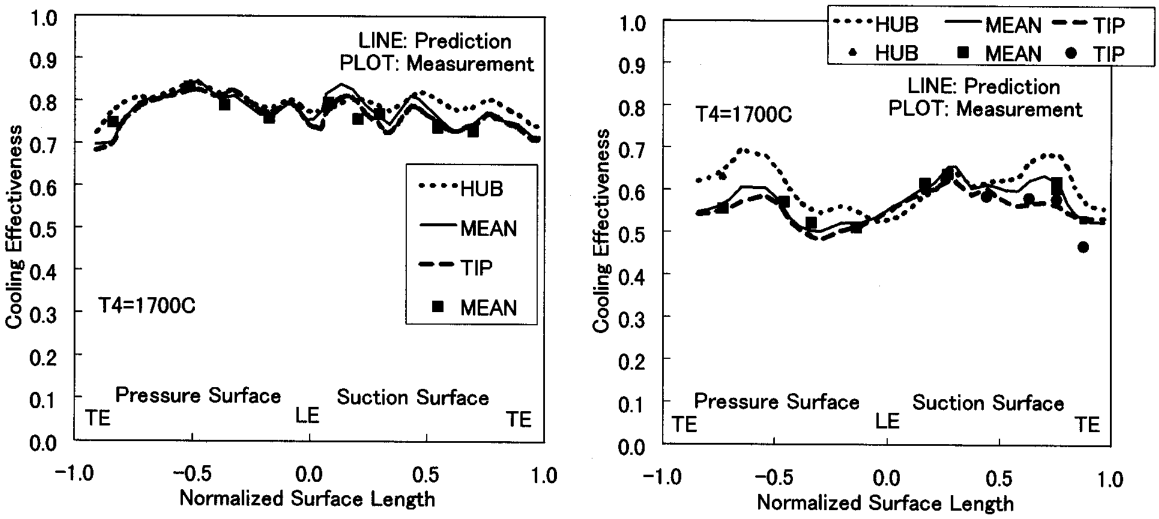


Fig. 1 High Temperature Core Engine



(a) Vane (b)Blade

Fig. 2 Comparison of measured and predicted cooling effectiveness

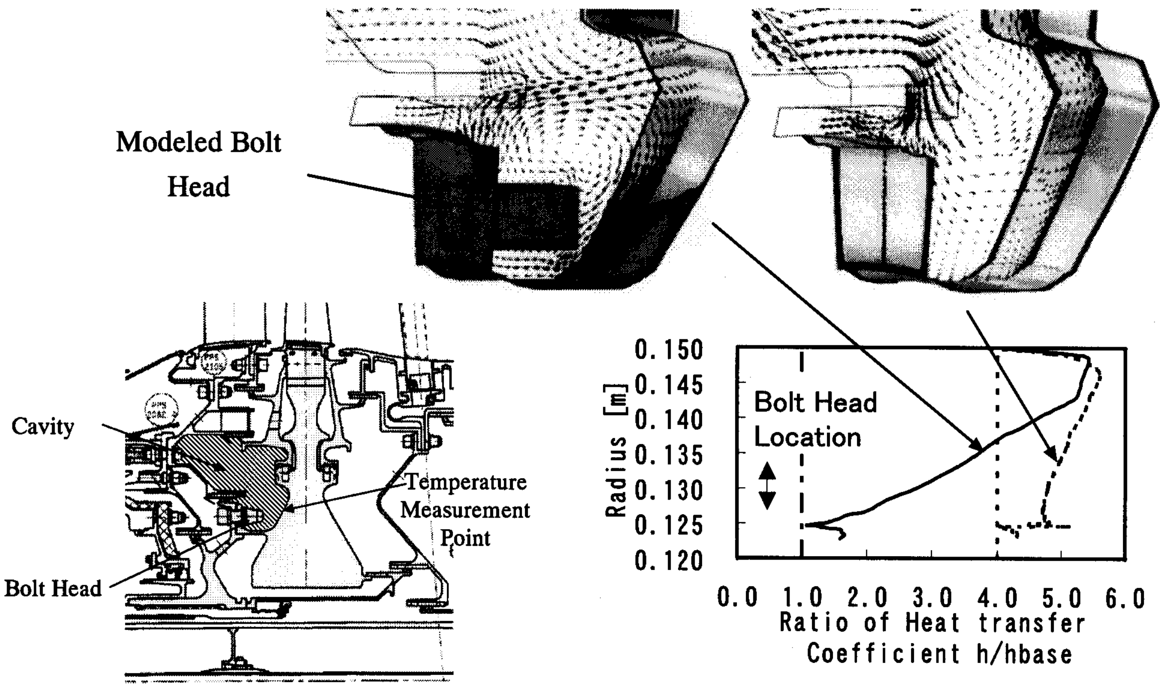


Fig. 3 CFD results for the disk