THERMAL AND FLUID ANALYSES FOR GAS TURBINE COOLED VANE AND BLADE

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ABSTRACT

In a high temperature gas turbine, turbine vane and blade cooling designs require key technologies. The metal temperature of turbine cooled vanes and blades should be predicted in the design stage as accurately as possible to reduce the period of engine development, because the life prediction of turbine cooled vanes and blades is strongly dependent on the metal temperature. The problem of metal temperature prediction is essentially equal to obtaining the convective heat transfer boundary conditions on external and internal surfaces of the cooled vane and blade. Kawasaki Heavy Industries has focused attention on the accuracy of commercial computational fluid dynamic (CFD) software based on advanced computing in order to improve the accuracy of three-dimensional metal temperature predictions.

This paper presents an accurate analysis of thermal and fluid distributions for turbine cooled vanes and blades using the commercial CFD software FLUENT. Investigations consisted of five tasks. **Task 1** investigated static pressure (Mach number) and heat transfer coefficient for the vane external surface (NASA C3X). **Task 2** investigated film cooling effectiveness on the surface of a flat plate, a semi-circular cylinder incorporated with flat plate, and a two-dimensional vane. **Task 3** investigated mass flow rate for internal flow in the turbine cooled blade for an internal cooling structure consisting of typical serpentine passages with turbulence promoters (ribs) and pin fins arranged in the trailing edge region. Furthermore, heat transfer coefficient for a rectangular channel with consecutive turbulence promoters was also investigated. Our calculations were compared adequately well with published experimental data as well as our own fundamental test data. Additionally, the suitable selection of turbulence model and near-wall treatment, the number of mesh points (y^+), and run time were also investigated. **Task 4** involved a coupled analysis of the external gas-pass flows of the first turbine vane and blade to investigate the accuracy of static pressure (Mach number), mass flow rate, and other features. Finally, **Task 5** involved analyses of heat transfer of the turbine cooled blade by thermal conjugation of the internal and external fields of a first-stage turbine blade consisting of convection heat transfer and thermal conduction. Comparison of CFD results with actual engine test data clearly show that the analytical method, based on the commercial CFD software FLUENT, is useful for the prediction of blade temperature and can be applied routinely in the design stage of turbine cooled vanes and blades.

INTRODUCTION

In recent years, Kawasaki Heavy Industries has focused attention on the accuracy of commercial computational fluid dynamic (CFD) software based on advanced computing in order to improve the accuracy of three dimensional metal temperature predictions. In the design stage, the metal temperature of turbine cooled vanes and blades should be predicted as accurately as possible to reduce the period of engine development. This paper presents an accurate analysis of thermal and fluid distributions for turbine cooled vanes and blades using the commercial CFD software FLUENT. Our investigations consist of the following five tasks(Table 1).

Table 1. Accuracy Validation Items

Task	Analysis Item	Accuracy Validation Item	Analysis Target
Task 1	External Flow	Static Pressure	Vane
		Heat Transfer Coefficient	
Task 2		Film Cooling Effectiveness	Flate plate
			Semi-circular cylinder incorporated with flat plate
			Cooled Vane
Task 3	Internal flow	Mass Flow Rate	Cooled Blade
		Heat Transfer Coefficient	Rectangular Channel with Turbulence Promoters(ribs)
Task 4	Blade and Vane coupled external flow	Mass Flow Rate	First Stage Vane and Blade
		Static Pressure,etc	
Task 5	Blade and Vane coupled external flow ＋Blade internal flow ＋Metal Thermal Conduction	Metal Temperature	First Stage Vane and Blade

In addition, the following analysis methods were evaluated.

- Turbulence Model — Standard k-ε, RNG k-ε, Realizable k-ε
- Near-Wall Treatment — Standard wall functions , non-equilibrium wall functions , Two layer zonal model(now called enhanced wall treatment)
- Mesh — The number of mesh points , Y^+

By a trade-off between accuracy and run time, the k-ε turbulence model was selected in advance. Please refer to the Fluent User's Manual for information about the turbulence model and near-wall treatment.

ACCURACY VALIDATION

TASK1: STATIC PRESSURE AND HEAT TRANSFER COEFFICIENT FOR THE VANE EXTERNAL FLOW

To validate the accuracy of static pressure and heat transfer coefficient on the vane external surface, our calculations were compared with published experimental data[1] for the two-dimensional vane (NASA C3X, Figure 1).
This purpose was also to get a suitable combination for the following on estimating the static pressure and heat transfer coefficient.

- Turbulence model — Standard k-ε, RNG k-ε, Realizable k-ε

- Near-Wall Treatment — Standard wall functions , non-equilibrium wall functions , Two layer zonal model
- Mesh — The number of mesh points , Y^+

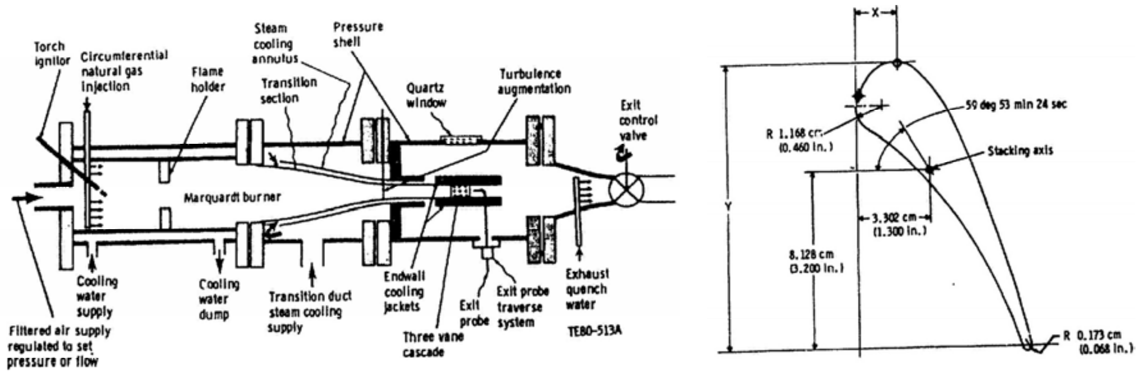
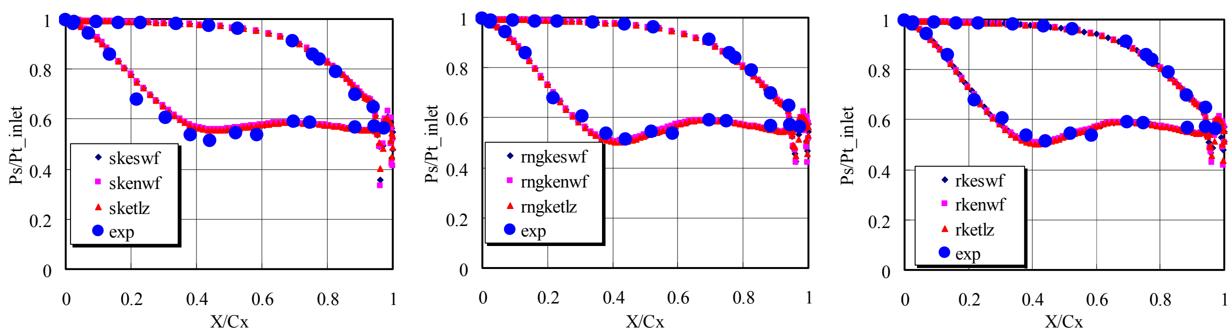
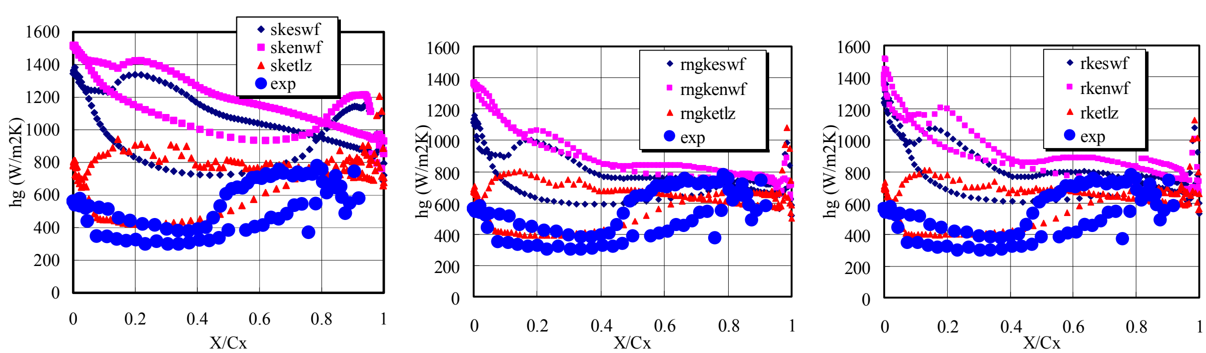


Figure 1: Experimental Apparatus and Vane[1]

The comparisons are shown in Figure 2(a) for static pressure and in Figure 2(b) for heat transfer coefficient.



(a) Static Pressure Distribution



(b) Heat Transfer Coefficient Distribution

Figure 2: Comparison with Experimental Data[1]

The following knowledge was obtained by this validation.

Static Pressure

- Both Realizable k-ε and RNG k-ε could predict accurately.
- The Standard k-ε prediction was not good, especially in the accelerated region of the suction side.
- There was no difference in prediction using either near-wall treatment.

Heat Transfer Coefficient

- It was suitable to use two layer zonal model as near-wall treatment.
- Both Realizable k-ε and RNG k-ε could predict roughly except in a partial region.
- This reason is that the flow field of this vane has transition from laminar flow to turbulent flow, while the k-ε turbulence model is applied to fully developed flow field.
- This can explain why predictive accuracy is not good in the region near the leading edge and in the laminar flow field of the suction side.

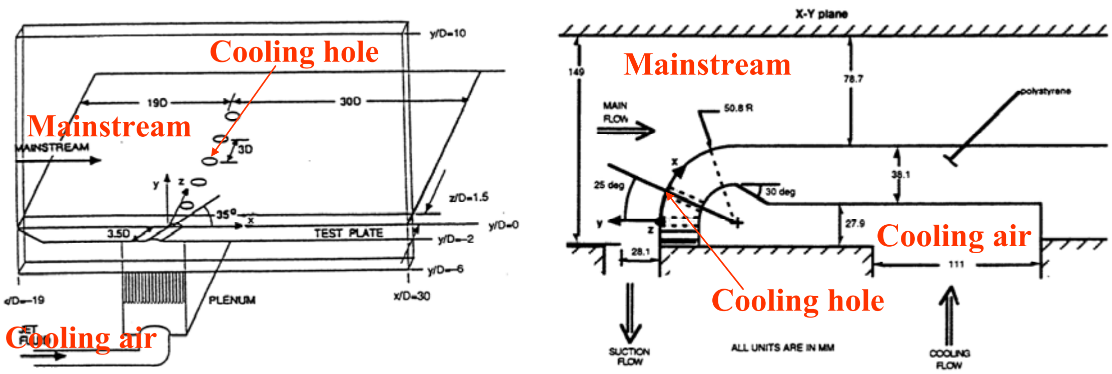
At the same time, Takahashi and Watanabe[2] reported the comparison of published experimental data with their calculation data about heat transfer coefficient on the vane external surface measured in flow field promoted turbulence transition by turbulence grid or rotational bar upside vane. According to them, their calculation using RNG k-ε turbulence model coincides with experimental data well.

For the reasons stated above, it is suitable to use Realizable k-ε or RNG k-ε as turbulence model and two-layer zonal model as near-wall treatment. Realizable k-ε turbulence model was selected in the next tasks in the interest of run time abbreviation, although there is no difference between them.

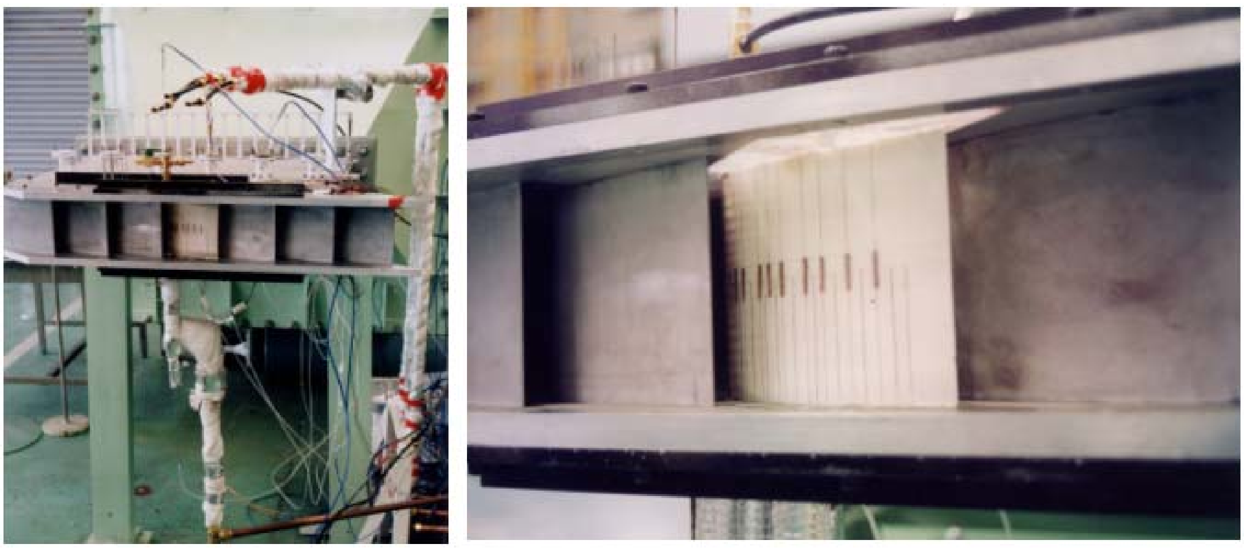
TASK2: FILM COOLING EFFECTIVENESS

To validate the accuracy of film cooling effectiveness for the vane and blade external surface, our calculations were compared with published experimental data on the surface of a flat plate[3], a semi-circular cylinder incorporated with flat plate[4], and a two-dimensional vane (Figure 3). The purpose was also to confirm whether our calculations could estimate the influence of the following on film cooling features.

- Density ratio $Dr(=\rho_c/\rho_g)$
- Mass flux ratio of coolant to mainstream $M(=\rho_c V_c/\rho_g V_g)$
- Curvature of surface(acceleration/ deceleration of mainstream, i.e. acceleration factor)



(a) Flat Plate[3] **(b) Semi-circular Cylinder incorporated with Flat Plate[4]**



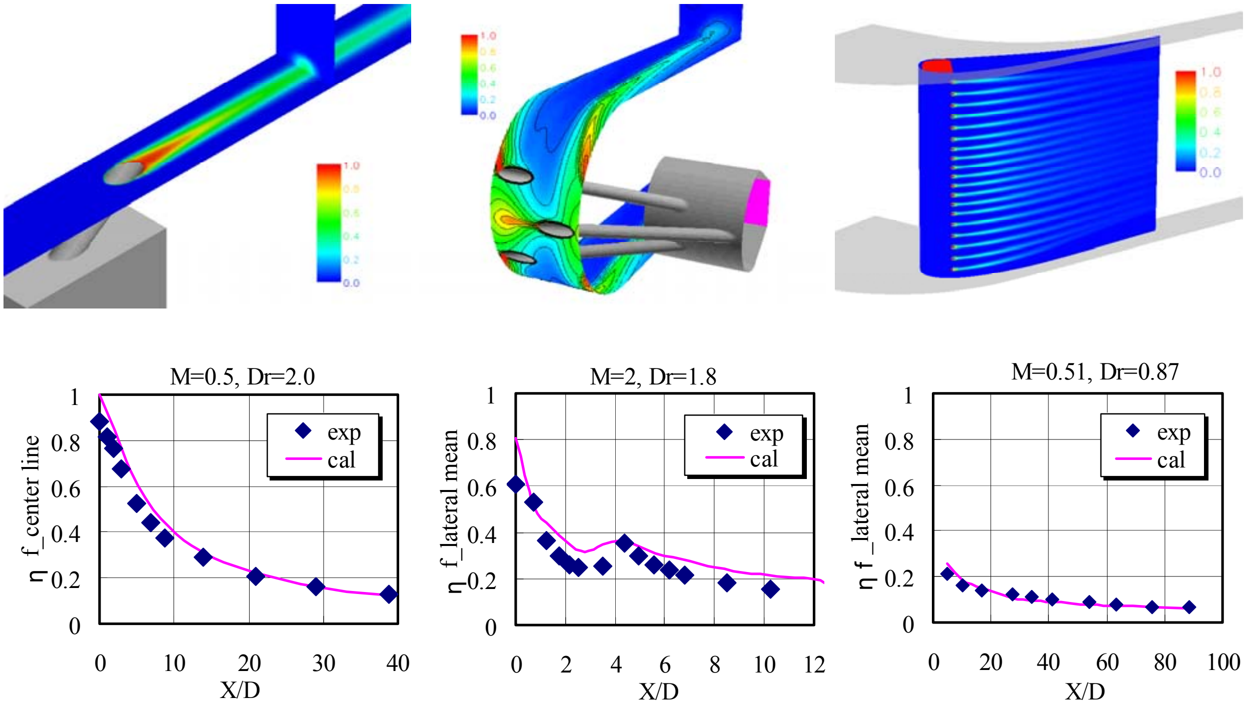
(c) Two-dimensional Vane

Figure 3: Experimental Apparatus

Example comparisons are shown in Figure 4. Realizable k-ε and two layer zonal model were used as the turbulence model and near-wall treatment.
The following knowledge was obtained by this validation.

- Film cooling effectiveness could be generally predicted.
- But when the mass flux ratio of coolant to mainstream M is so large that film cooling air penetrates through mainstream, film cooling effectiveness couldn't be predicted accurately.
- In addition, in the region near a film cooling hole, the calculation data was different from the experimental data.

It was confirmed that film cooling effectiveness can be generally predicted using the Realizable k-ε turbulence model and the two layer zonal model as near-wall treatment. But we should be careful of inaccuracy in the region near film cooling holes or in the case that M is so large that film cooling air penetrates through mainstream. These problems will be probably improved to some extent by controlling mesh resolution.



(a)Flat Plate[3] **(b) Semi-Circular Cylinder incorporated with Flat Plate[4]** **(c) Two-dimensional Vane**

Figure 4: Comparison with Experimental Data [3,4]

TASK3: MASS FLOW RATE AND HEAT TRANSFER COEFFICIENT FOR THE BLADE INTERNAL FLOW

<u>Mass flow rate for the blade internal flow</u>

To validate the accuracy of mass flow rate for the blade internal flow, our calculations were compared with experimental data using an actual engine blade beneath ambient pressure (Figure 5).
The comparison is shown in Figure 6.

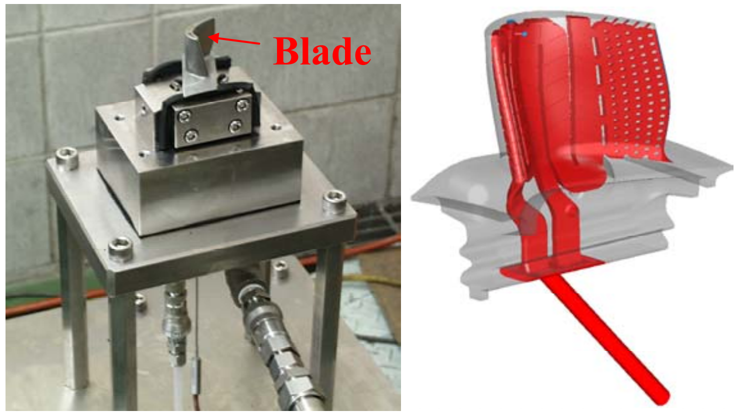


Figure 5: Experimental Apparatus and Blade Internal View

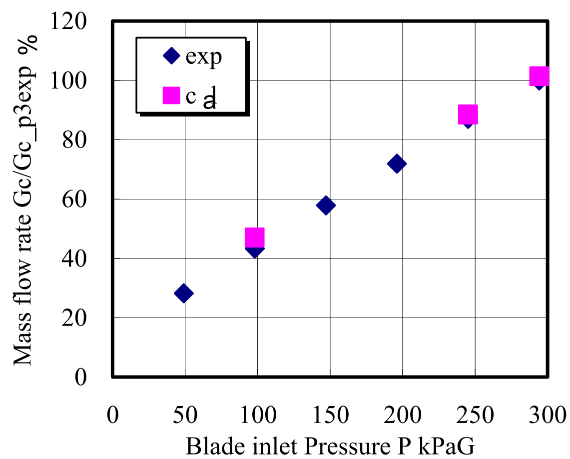


Figure 6: Comparison with Experimental Data

The following knowledge was obtained by this validation.

- The mass flow rate for the blade internal flow could be predicted precisely.

It was confirmed that mass flow rate for the blade internal flow can be predicted precisely using the Realizable k-ε turbulence model and the two layer zonal model as the near-wall treatment.

Heat Transfer Coefficient on the Blade Internal Surface

To validate accuracy of the heat transfer coefficient on the blade internal surface, our calculations were compared with published experimental data[5] . A rectangular channel with consecutive turbulence promoters (ribs) was selected as analysis target.
The purpose was also to confirm the influence of aspect ratio(W/H, Figure 7) in a rectangular channel in estimating the heat transfer coefficient.

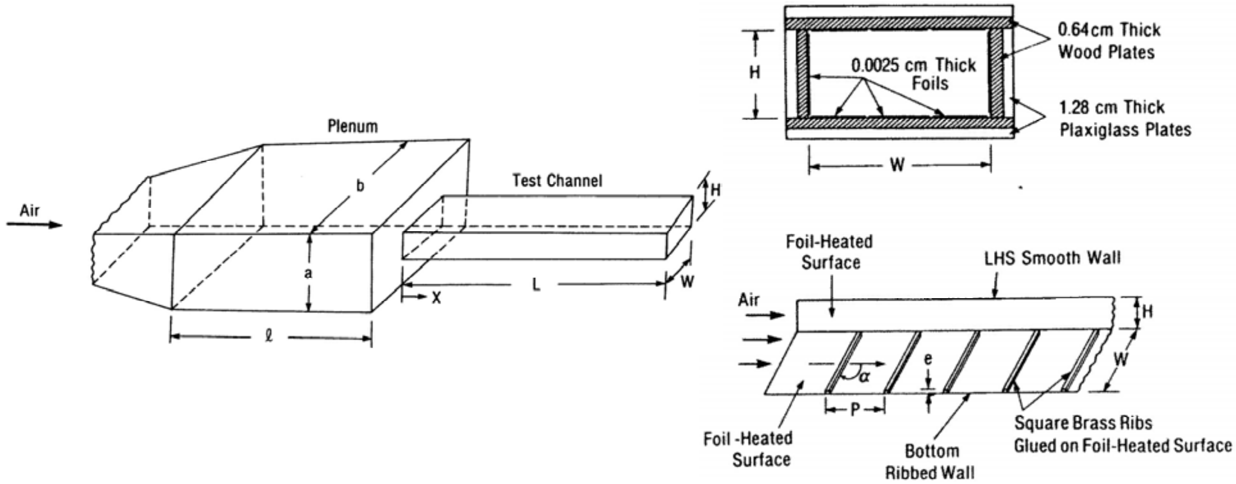


Figure 7: Experimental Apparatus[5]

The height and width of a rib are widely different from the radial height and cord length of a blade. Generally speaking, a huge number of mesh points will be required for the blade internal flow analysis and the conjugate analysis (**Task 5**). This is not realistic in the design stage. Therefore, the near-wall mesh was composed to be the same size as rib height and width. Consequently, in some regions, Y^+ was outside applicable range for the two layer zonal model, i.e. $Y^+ > 4$.

An example comparison is shown in Figure 8 for heat transfer on the surface with turbulence promoters (rib).

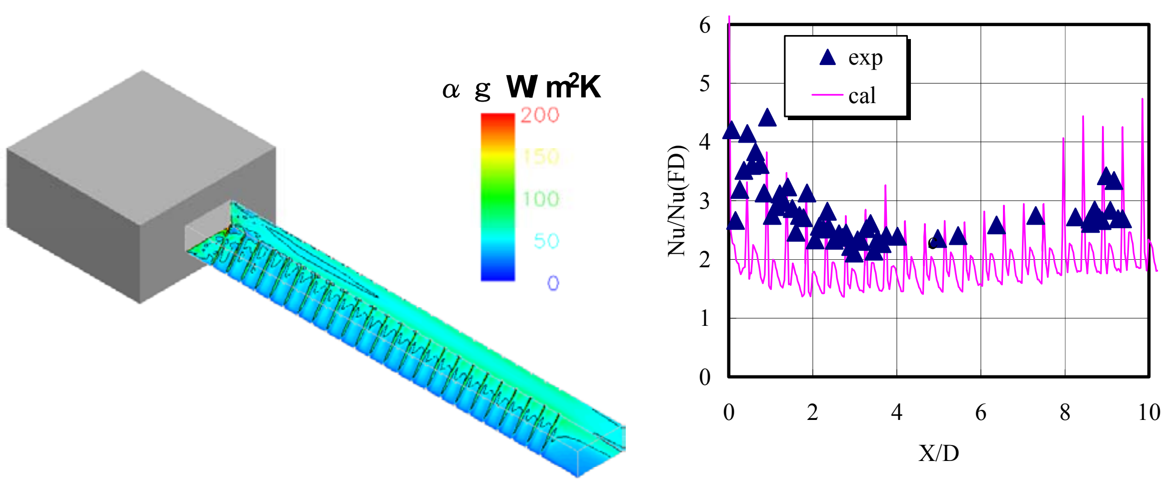


Figure 8: Comparison with Experimental Data[5]

The following knowledge was obtained by this validation.

- Heat transfer coefficient is predicted underneath experimental data.
- Similar to the prediction of the heat transfer coefficient on the vane external surface (**Task 1**), the accuracy in undeveloped region (x/D<3) is not good.
- The same tendency as above was also revealed for the other aspect ratios of the rectangular channel.

For the reasons stated above, the heat transfer coefficient on a surface with turbulence promoters (ribs) will be predicted underneath experimental data using the Realizable k-ε turbulence model and the two layer zonal model as the near-wall treatment.

TASK4: STATIC PRESSURE, MASS FLOW RATE,AND OTHER FEATURES FOR GAS-PASS FLOWS OF THE FIRST TURBINE VANE AND BLADE

To validate the accuracy of static pressure, mass flow rate, and other features for a coupled analysis of the external gas-pass flows of the first turbine vane and blade, our calculations were compared with predicted data based on actual engine test data.
Task4 was required before conducting the conjugate analysis in **Task 5**.
An example comparison is shown in Figure 9.

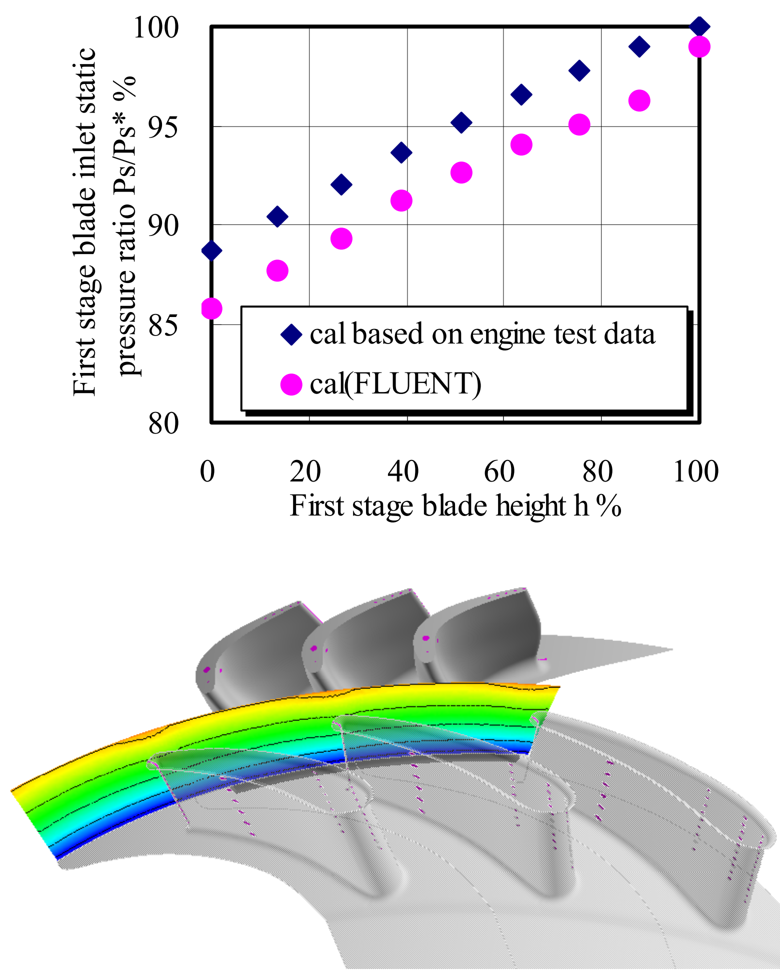


Figure 9: Representative Analysis Result

The results are the following.

- Static pressure distribution for radial direction of first blade inlet could be predicted within 3% compared with predicted data based on the actual engine test data.
- The radial mach number distribution predicted for the first blade inlet coincided with the predicted data based on the actual engine test data, except for the region affected by the boundary layers of both the hub side and the shroud side.
- Mass flow rate of blade outlet could be predicted within 1.2% compared with design data.

For the reasons stated above, it was confirmed that some features for the external gas-pass flow field of the first turbine vane and blade will generally be predicted well.

TASK5: METAL TEMPERATURE OF THE FIRST TURBINE COOLED BLADE

Finally, to validate the accuracy of metal temperature of the first turbine cooled blade, conjugate heat transfer analysis was conducted. That is analyses of heat transfer of the turbine cooled blade by thermal conjugation of the internal and external fields of a first-stage turbine blade consisting of convection heat transfer and thermal conduction. All analysis methods (mesh, turbulence model, and near-wall treatment) used in above Tasks were reflected in this conjugate heat transfer analysis.
Analysis conditions are the following (Figure 10).

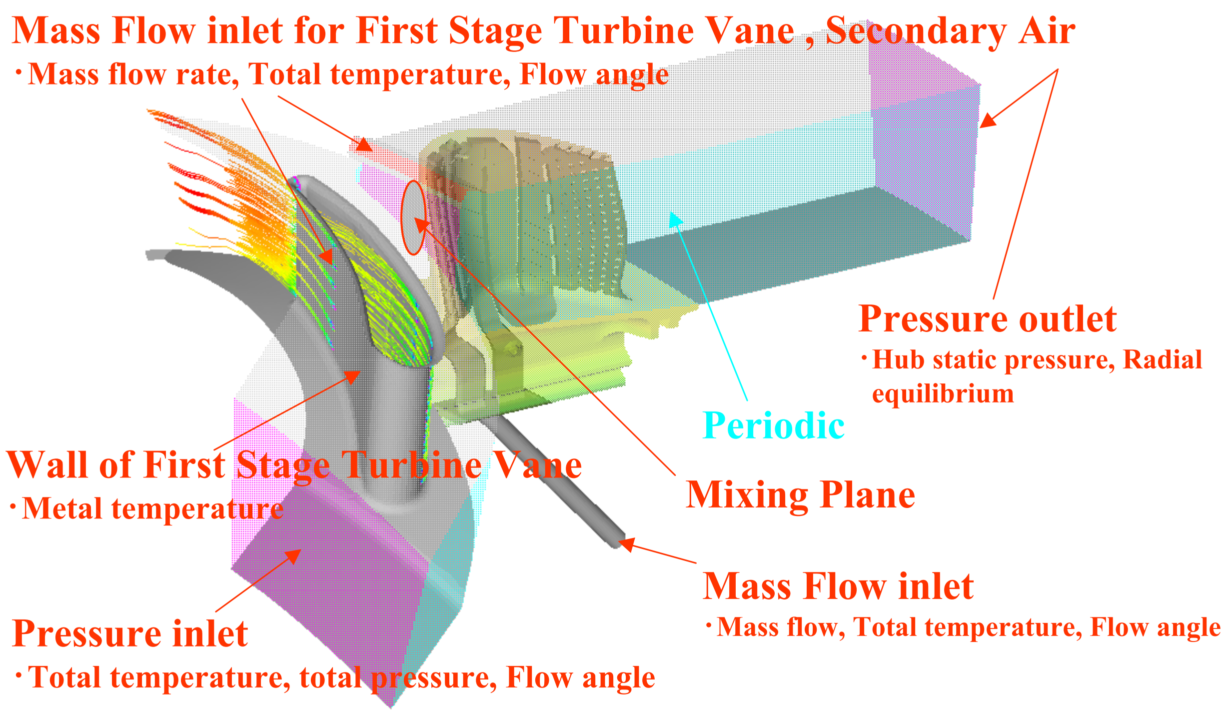


Figure 10: Schematic View of Boundary Conditions

A representative example is shown in Figure 11. Predicted metal temperature qualitatively coincided with engine test data and overhaul blade condition with similar geometry.

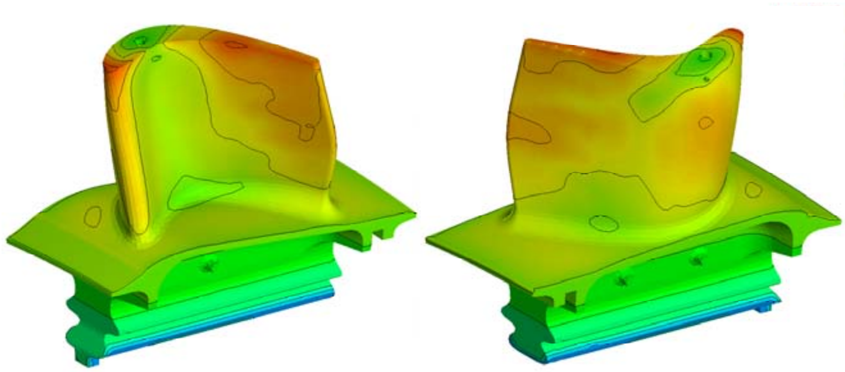


Figure 11: Representative Analysis Results

CONCLUSIONS

Fluid analyses for the external and internal flow fields of cooled blade and a coupled fluid analysis of the external flow fields of a first-stage turbine vane and blade were conducted to validate the accuracy of factors (static pressure, heat transfer coefficient, film cooling effectiveness, mass flow rate, etc) which affect metal temperature prediction. The commercial CFD software Fluent was used to conduct the above analyses. The realizable k-ε turbulence model and two layer zonal model as the near-wall treatment were selected. The number of mesh points was restricted to solve within a reasonable run time. After conducting the above analyses and confirming their accuracy, a metal temperature analysis for a cooled blade was conducted by thermal conjugation of the internal and external flow fields of a first-stage blade consisting of convection heat transfer and thermal conduction. The following findings were obtained.

- Static pressure on external surfaces of the vane and blade, and mass flow rate of the external and internal flow in the cooled blade can be predicted accurately.
- The heat transfer coefficient on external and internal surfaces of the cooled vane and blade can not be predicted accurately. In this case, our analytic method has a tendency of overestimation for the blade external surface and underestimation for the blade internal surface in heat transfer coefficient. As a result, metal temperature will be predicted higher than it should be.
- Film cooling effectiveness can be roughly predicted. But in the case that mass flux ratio of coolant to mainstream M is so large that film cooling air penetrates through mainstream, and in the regions near film cooling holes, film cooling effectiveness can not be predicted accurately.
- Metal temperature of cooled blade by thermal conjugation analysis coincides with actual engine test data qualitatively.

Consequently, the analytical method based on the commercial CFD software FLUENT is useful for the prediction of blade temperature and can be routinely applied in the design stage of turbine cooled vanes and blades.

Analysis accuracy will be probably improved to some extent by controlling mesh resolution.

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NOMENCLATURE

Cx	axial cord length
D	diameter of film cooling hole
Dr	density ratio (=ρ_c/ρ_g)
Gc	mass flow rate of cooling air
Gc_p3exp	mass flow rate of cooling air at blade inlet pressure=294 kPa
h_g	heat transfer coefficient
M	mass flux ratio of coolant to mainstream (=$\rho_c V_c/\rho_g V_g$)
Nu	Nusselt number
Nu(FD)	Nusselt number of fully developed smooth tube
Ps	static pressure
Ps*	static pressure at first stage blade height = 100 %
Pt	total pressure
X	axial distance from leading edge
W/H	aspect ratio in a rectangular channel
η_f	film cooling effectiveness

ρ	density
exp	experimental data
rkeswf	Realizable k-ε with standard wall functions
rkenwf	Realizable k-ε with non-equilibrium wall functions
rketlz	Realizable k-ε with two layer zonal model as near-wall treatment

SUBSCRIPTS

c	cooling air
g	gas