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Construction of Cooling Effectiveness Database Applied to the Virtual Gas Turbine in HTM21 Project

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ABSTRACT

The virtual gas turbine system (VT) in High Temperature Materials 21 project (HTM21) is simplified simulation for the comparison of current materials with new materials under its practical use condition. It is very helpful for a materials developer to know about the effectiveness of new materials concretely. Therefore, it is necessary for the easy use and to reduce calculation time. For this purpose, we try general evaluation by referring open literatures. The advantage of this type simulation is that it can be used daily by materials developers. (The VT is not meant to be use for a design of a gas turbine system.)

We need a detailed database applied to the VT. Especially, the database of a high pressure turbine part is build by three groups such as computational fluid dynamics (CFD), heat transfer analysis and structure analysis. This database is verified by past experimental data of a gas turbine system. The experiment has been carried out by Hijikata et al. (1990).

This report concerns the cooling performance of the VT by the heat transfer analysis group, and describes the outline that computes a cooling effectiveness for the VT. Moreover, this report shows the example of calculation according to the outline and its installation in the virtual gas turbine system.

NOMENCLATURE

A = coefficient of film cooling formula
B = coefficient of film cooling formula
d = impingement hole diameter
= pin fin diameter
D = film cooling hole diameter
G = mass flow rate
M = blowing ratio
Nu = Nusselt number
P = pitch of film cooling holes
Pr = Prandtl number
Re = Reynolds number
s = equivalent slot width
S = source term
T = temperature
x = downstream distance
X = dimensionless downstream distance
z = lateral distance
Z = dimensionless lateral distance
β = mass flow rate ratio (%), $= Gc/Gg$
η = cooling effectiveness
η_{fc} = film cooling effectiveness
λ = thermal conductivity
φ = angle of a cylinder from stagnation point

Subscript

c = cooling air
f = film flow
g = main flow
w = wall surface

INTRODUCTION

The thermal efficiency improvement in power engineering systems is becoming increasingly important especially for reducing CO2 emission to prevent the global warming. High temperature materials are obviously playing key roles for the improvement of a gas turbine system. For this reason, High Temperature Materials 21 project (HTM21) was started at National Institute for Materials Science (NIMS), in June 1999.

High temperature materials 21 project

In the HTM21, we are developing superior Ni-base superalloys, ceramics, and refractory superalloys for turbine vane and blade materials to help realizing ultra-high efficiency gas turbines for power generations and advanced jet engines. Figure 1 shows the HTM21 project structure.

In particular, it is very important to evaluate the developed materials under its practical use condition of gas turbine engine. Under the recent advancement of computer hardware and software,

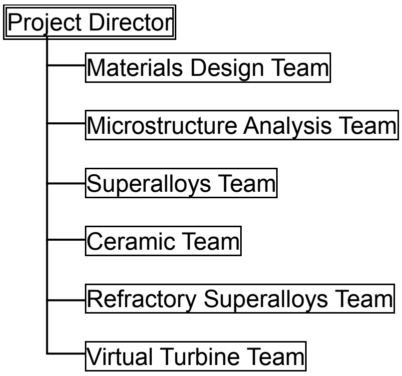

Fig. 1 High temperature materials 21 project structure.

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design and simulation of gas turbines are often performed with computers regardless of the existence of gas turbine hardware. Hence the virtual gas turbine system (VT) in the project has been constructed in a computer.

Virtual gas turbine system

Development of advanced high-temperature materials is conducted in HTM21. The virtual gas turbine system (VT) compares current materials with new materials by a gas turbine system under its practical use condition (Yoshida et al., 2001). In this virtual gas turbine system, performances, such as output power, thermal efficiency, CO2 emission rate, engine life cycle and so on, are evaluated in the design operation condition. It is very helpful for a materials development that materials developer knows about the above effectiveness of new materials concretely.

A researcher conducting a design and development of a gas turbine system has his evaluation and calculation method. Those methods are concrete evaluations. But they are not published, and a developer of materials is hard to use it. The present VT is aiming at a type of simplified simulation for the easy use. Moreover, this is to be used not only among researchers engaged in the project, but also by worldwide visitors to HTM21 home page. For this purpose, we try general evaluation by referring open literature.

The VT has been built under collaboration with the Toshiba Corporation, National Aerospace Laboratory (NAL) and NIMS. At present, a medium scale gas turbine of 17MW class output power is adopted as the first virtual gas turbine system (VT-M10). In the near future, we will extend the work to the future gas turbine condition.

Although the VT is simplified simulation, we need a detailed database for the VT. The database of a high pressure turbine part has been build by three groups of NAL such as computational fluid dynamics (CFD), heat transfer analysis and structure analysis. Figure 2 shows the relation of the VT and three groups. It is difficult to conduct aerodynamics analysis, heat transfer analysis and construction analysis simultaneously, because a cooling construction of turbine vane and blade is complicated. Hence the CFD group conducts a calculation for a vane and a blade without cooling construction. Those data are provided to the heat transfer analysis group, and temperature distribution within the airfoil is calculated including an effect of cooling. These analysis results are provided to the structure analysis group. The each analysis results are introduced into the virtual gas turbine system for the simulation with higher fidelity.

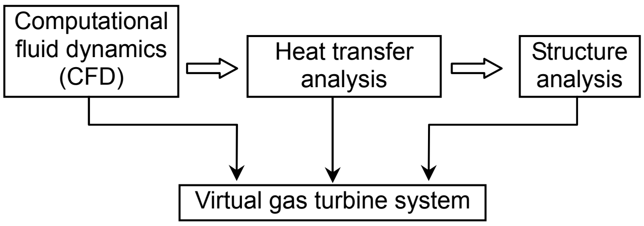
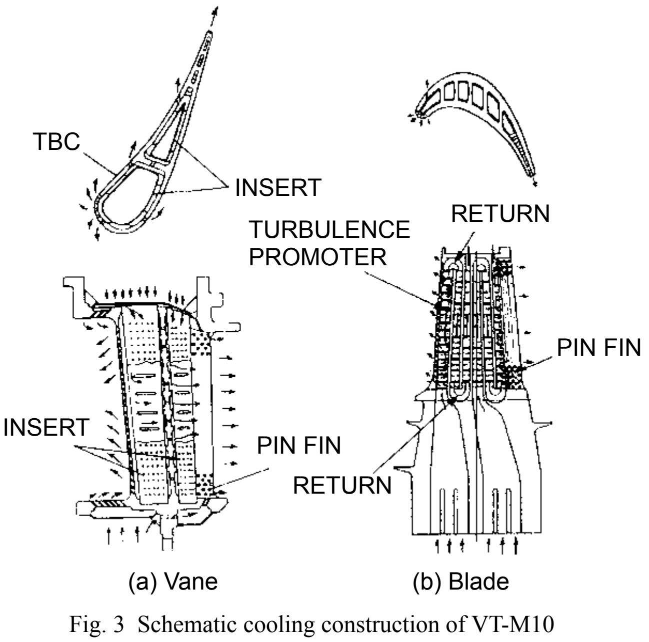


Fig. 2 Detail database construction to virtual gas turbine system.



(a) Vane (b) Blade

Fig. 3 Schematic cooling construction of VT-M10

This report concerns the cooling performance of the VT by the heat transfer analysis group, and describes the database constructions and formulations for performing temperature evaluation of the air-cooled airfoils of the VT. The examples of calculations according to the outline are also shown in both cases of the vane and the blade. Moreover, it is simply described how to install the cooling performance database in the virtual gas turbine system.

The cooling effectiveness database was constructed by using three-dimensional heat transfer analysis. This three-dimensional heat transfer analysis was based on the boundary conditions, such as external surface boundary conditions (heat transfer coefficient, gas temperature, film cooling effectiveness) and internal boundary conditions (heat transfer coefficient, cooling air temperature). The boundary conditions were prepared from the data and formula selected from the literatures and the result from CFD. The heat transfer coefficient changes by depending on the shape of turbine blade or the running condition. However, for a general and a typical evaluation, we selected an adequate data and formula by referring open literature as a representative case.

COOLING CHARACTERISTICS DATABASE

In order to evaluate wall temperature distribution of the air-cooled turbines, it is necessary to know cooling characteristics of the turbines resulting from heat transfer between air/gas flow and wall surface. Thus in the early stage of the work, a big scale database of cooling characteristics was constructed by referring open literature (about 1140 literatures). The database was arranged for each cooling construction such as film cooling, impingement cooling, serpentine cooling and pin fin cooling, respectively. By referring the database, formulations of cooling characteristics were made. Preparations for the database construction and the formulation are already described by previous papers (Matsushita et al., 2000, 2002).

HEAT TRANSFER ANALYSIS

Most of the modern gas turbines employ air-cooled turbine vanes and blades with complicated inner cooling construction. So the cooling constructions of the vane and blade of VT-M10 turbine were specified as shown in Figure 3. The outline that computes a cooling effectiveness for the vane and blade of VT-M10 is as follows.

First, by referring the cooling characteristics database, the data and the formulation that suit the cooling construction of the target vane and blade are selected.

Next, the boundary conditions, such as external surface boundary conditions (heat transfer coefficient, gas temperature, film cooling effectiveness) and internal boundary conditions (heat transfer coefficient, gas temperature), are prepared from the selected data, formula and the data provided by CFD group.

Based on these boundary conditions, the wall temperature distribution of airfoils is solved using three-dimensional heat transfer analysis. From the result, the cooling effectiveness distribution in specific conditions can be derived. Since the above-mentioned calculation depends on mass flow rate ratio of cooling air, the database of the cooling effectiveness to install in the VT is prepared for every mass flow rate ratio.

Each calculation is explained in detail as follows.

Numerical method

The temperature distribution within the vane and the blade is determined using three-dimensional analysis. The governing equation

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+S=0 \qquad (1)$$

where, T is the local airfoil temperature, λ is the thermal conductivity of the airfoil material and S is the source term. It is solved using the control volume method.

The main grid points are 59 (span wise) x 141 (chord wise) x 21 (thickness) in case of the vane, and 61 (span wise) x 182 (chord wise) x 21 (thickness) in case of the blade. The grids for inner partitions are consisting of about 600 grid points, respectively. The grids for pin fin are simplified according to demand from the structure analysis group. The individual geometry of pin fin was neglect, but it is treated as three (vane) and four (blade) partitions of the same volume.

This analysis includes effect of a thermal barrier coating (TBC). Hence, the thermal conductivity, λ varies for material, and the thermal conductivity between different materials was determined by harmonic average. The main airfoil materials were selected as TMS-75. The thermal barrier coating consists of a bond coating (NiCrAlY) applied directory to the alloy, and a ceramic top coat by Partially Stabilized Zirconia (PSZ). The thickness of the NiCrAlY bond coat is 0.1 mm on the TMS-75, and the thickness of the PSZ top coat is 0.2 mm on the bond coat. Moreover, the temperature dependency of the thermal conductivity was taken into account for each material (TMS-75, NiCrAlY and PSZ). Local conductivity was decided by the formula of the average conductivity for temperature.

External boundary condition

On the airfoil surface, the heat transfer coefficient and the gas temperature are specified. In a condition of 1400°C average turbine inlet gas temperature (TIT), gas temperature, velocity and pressure on the airfoil surface are provided from CFD group. The gas temperature distribution is directly used as a boundary condition. The heat transfer coefficient distribution is calculated using simplified formula as follows.

Flat plate [laminar flow]

$$Nu_l = 0.332\times Pr^{1/3}\times Re_x^{1/2} \qquad (2)$$

Flat plate [turbulent flow] (Johnson-Rubesin)

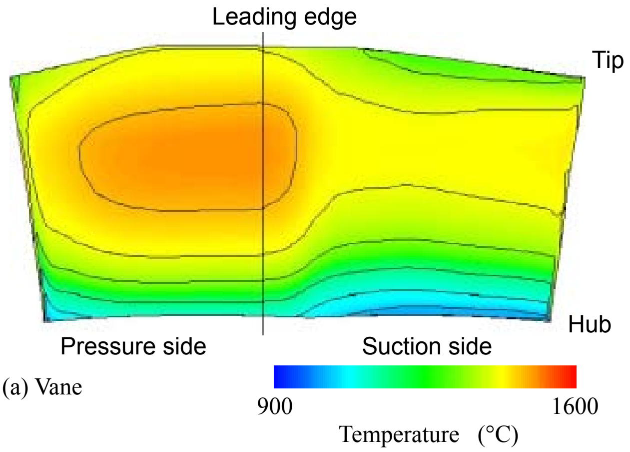
$$Nu_l = 0.0296\times Pr^{2/3}\times Re_x^{4/5} \qquad (3)$$

Cylinder

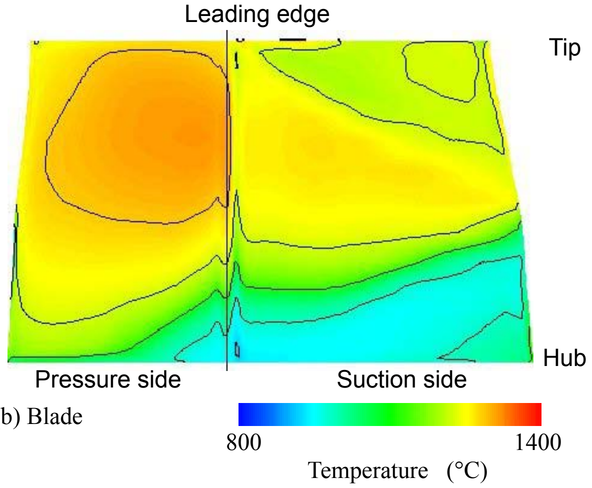
$$Nu_l = 1.14\times Pr^{0.4}\times Re_d^{1/2}\left(1-\left(\frac{\phi}{90}\right)^3\right) \qquad (4)$$

The formula was locally selected by surface curvature and Reynolds number of each position. Here, local Reynolds number was calculated by velocity distribution provided from CFD group.

Figure 4 shows the surface gas temperature distributions of the vane and the blade, and figure 5 shows heat transfer coefficient distributions of the vane and the blade, as examples.

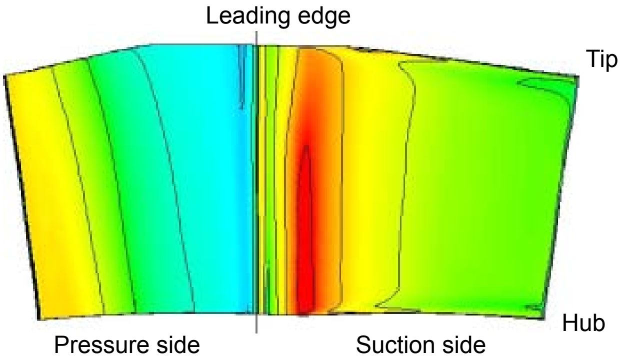


(a) Vane

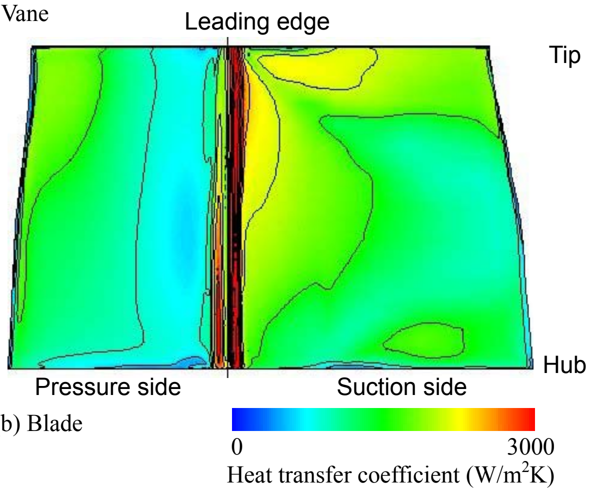


(b) Blade

Fig. 4 Surface gas temperature distribution (CFD)



(a) Vane



(b) Blade

Fig. 5 Surface heat transfer coefficient distribution.

Film-cooling

The film cooling effectiveness is specified by using the cooling characteristics database and formulation for film cooling. The film cooling effectiveness is defined as a dimensionless temperature,

$$\eta_{fc} = \frac{Tg - Tf}{Tg - Tc} \tag{5}$$

where, Tg is free stream gas temperature, Tf is film flow temperature, and Tc is cooling air temperature at the exit of injection hole (400°C). By referring the cooling characteristics database, the following formula was obtained for the film cooling effectiveness downstream of a single film cooling hole.

$$\eta_{fc}(X,Z) = \frac{A \times Exp\left[-B\left(\sqrt{(X+A)^2+Z^2}-X-A\right)\right]}{\sqrt{(X+A)^2+Z^2}} \tag{6}$$

$$X = \frac{x}{M \times s}, \qquad Z = \frac{z}{D}, \qquad s = \frac{\pi \times D^2}{4 \times P}$$

Where, x is downstream distance, M is blowing ratio, s is equivalent slot width, z is lateral distance, D is hole diameter, P is pitch of holes, and A, B are coefficients for data fitting.

In the VT vane and blade, lots of film cooling holes are disposed both in the chord wise and span wise direction. Based on the principle of the superposition of effectiveness, the above formula can be superposed according to the locations of the individual holes. The superposed formula was given as follows.

$$\begin{aligned} \eta_{fc} = {} & \eta_{fc}(X,Z) \\ & + \left(1-\eta_{fc}(X,Z)\right) \times \eta_{fc}(X,Z-z_1) \\ & + \left(1-\eta_{fc}(X,Z)\right) \times \eta_{fc}(X,Z+z_1) \\ & z_1 = P/D \end{aligned} \tag{7}$$

Figure 6 shows a film cooling effectiveness distribution of the VT vane and blade as examples. The mass flow rate ratio of cooling air is 6% in the case of the vane, and it is 4.5% in the case of the blade. The mass flow rate of each exit is determined from relation of the surface static pressure (provided from CFD group) and internal constant total pressure. So the injection of the treading edge is about 48% (vane) and 56% (blade) of total cooling air.

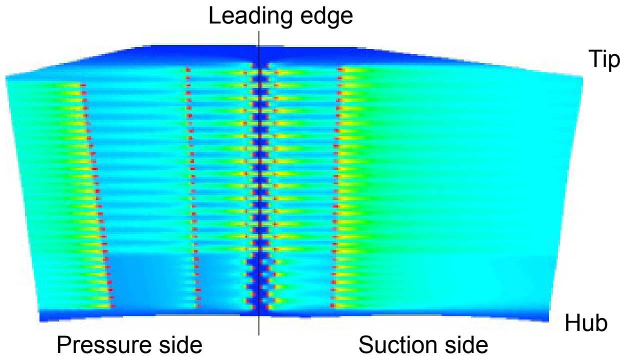
Internal cooling condition

The convective heat transfer coefficient and the coolant gas temperature are specified as boundary conditions on the walls of internal coolant passages.

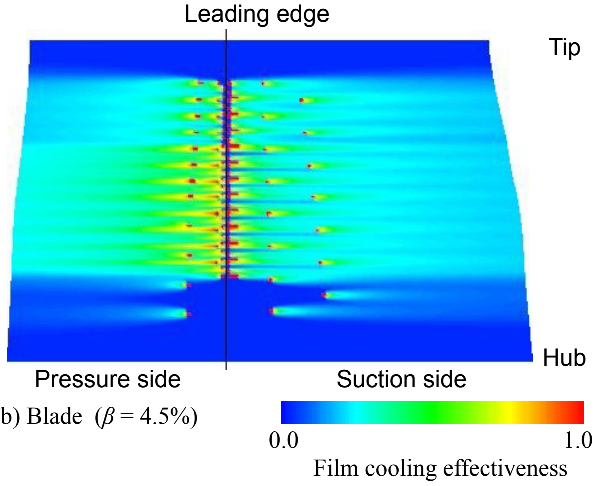
The coolant gas temperature distribution is calculated by the interpolation between the inlet constant temperature (400°C) and the exit temperature. But, this temperature distribution is not so accurate, because the exit temperature was decided arbitrarily. For an accurate boundary condition, simplified aerodynamics analysis in internal cooling passage will be done in the future. The convective heat transfer coefficient is calculated by using the formula according to the cooling construction. In the case of vane, combinations of impingement and pin fin cooling are used to cool internally. In the case of blade, combinations of serpentine and pin fin cooling are adopted. The formula of each cooling construction was followed in the present case.

Impingement cooling (Walz's and Nakatogawa)

$$Nu_d = 0.368 \times Re_d^{0.566} \times Pr^{0.36} \times \left(\frac{d}{r}\right)^{0.434} \tag{8}$$

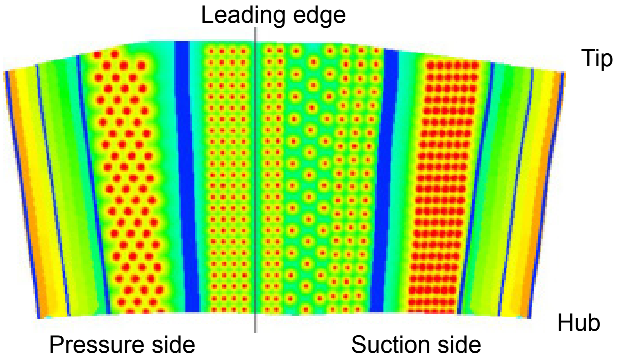


(a) Vane ($\beta = 6.0\%$)

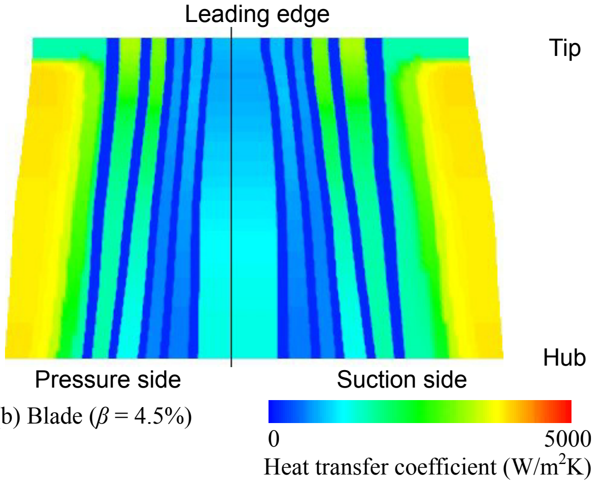


(b) Blade ($\beta = 4.5\%$)

Fig. 6 Film cooling effectiveness distribution.



(a) Vane ($\beta = 6.0\%$)



(b) Blade ($\beta = 4.5\%$)

Fig. 7 Cooling heat transfer coefficient distribution.

Pin fin cooling (Metzger)

$$Nu = 0.135 \times Re_d^{0.69} \times \left(\frac{x}{d}\right)^{-0.34} \qquad (9)$$

Serpentine cooling (Kays and Crawford)

$$Nu = 0.022 \times Re_{De}^{0.8} \times Pr^{0.5} \qquad (10)$$

In each passage, mass flow rate is a total of the film cooling injection. In impingement cooling, the injection from all holes in each passage is same condition, so Reynolds number is the same. In the case of pin fin cooling, Reynolds number was based on local velocity calculated by the injection of the treading edge, and pin fin diameter. The velocity of serpentine passage was calculated by local passage area and local mass flow rate considering of the film cooling. The effect of ribs is neglected in the present case.

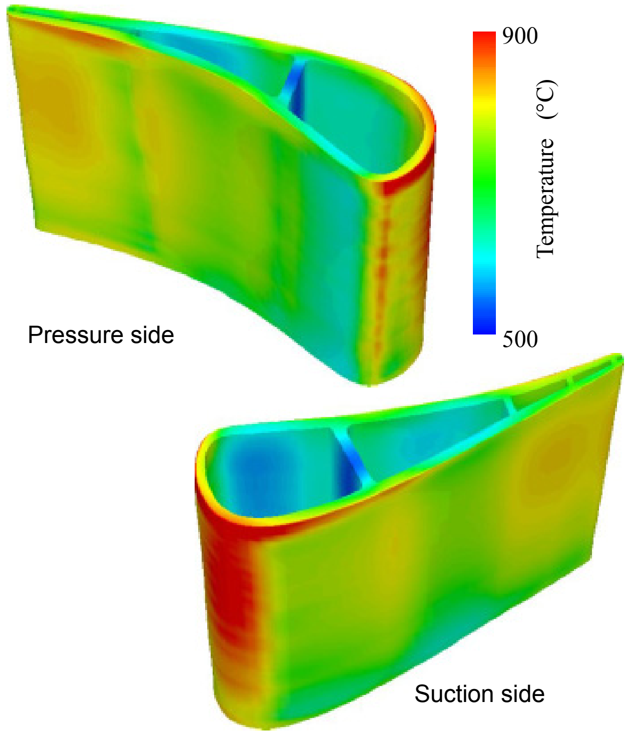


Fig. 8 Wall temperature distribution of the vane (β = 6%)

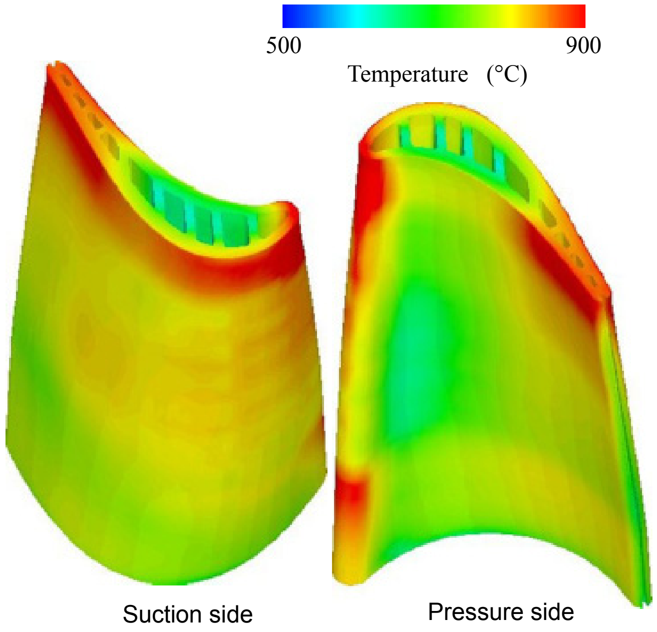


Fig. 9 Wall temperature distribution of the blade (β = 4.5%)

Figure 7 shows the convective heat transfer coefficient distribution. The heat transfer coefficient at joint of the partition is no use, because of the conductive calculation. Also, the heat transfer coefficient on the cooling wall of the partition is approximately calculated between values of both side joint positions.

Result

The temperature distribution of airfoil material is calculated by three-dimensional heat conduction analysis from boundary condition calculated individually.

Figure 8 and figure 9 show the wall temperature distribution within the vane and the blade as an example, respectively. The results clearly indicate that the temperature distribution is considerably different from no cooling case by the cooling effect.

More databases will be accumulated by analysis with various cases of mass flow rate ratios.

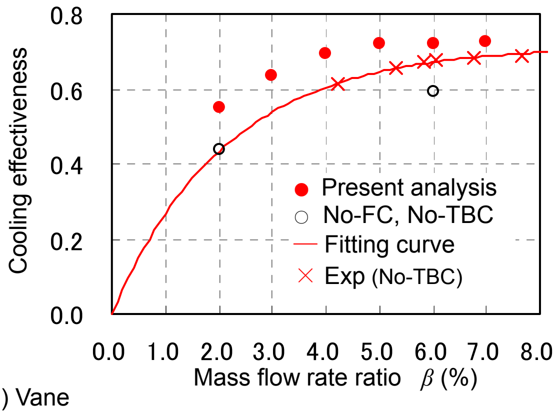
Additionally, a database and a formula in each calculation are easily replaced with others in order to update the database.

APPLICATION TO THE VT

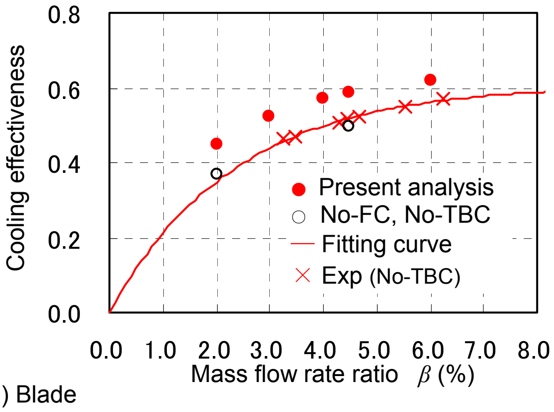
So far we have outlined the way and the examples of calculation of a cooling effectiveness for the VT.

Lastly, it is simply described to install the cooling performance database in the virtual gas turbine system.

The one-dimensional cooling formulation is temporary installed in the VT. This formulation was a fitting curve constructed by referring some related experimental data by Hijikata et al. (1990).



(a) Vane



(B) Blade

Fig. 10 Cooling characteristics of VT-M10

Figure 10 shows the one-dimensional cooling effectiveness distribution with respect to cooling air mass flow rate ratio. The cooling effectiveness defined by

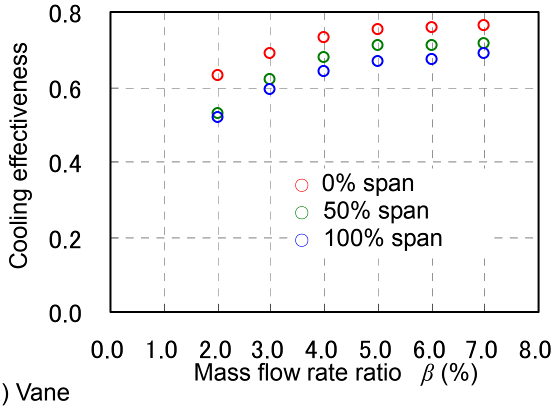
$$\eta = \frac{Tg - Tw}{Tg - Tc} \qquad (11)$$

where Tg is turbine inlet gas temperature, Tc is cooling air inlet temperature, Tw is turbine wall temperature.

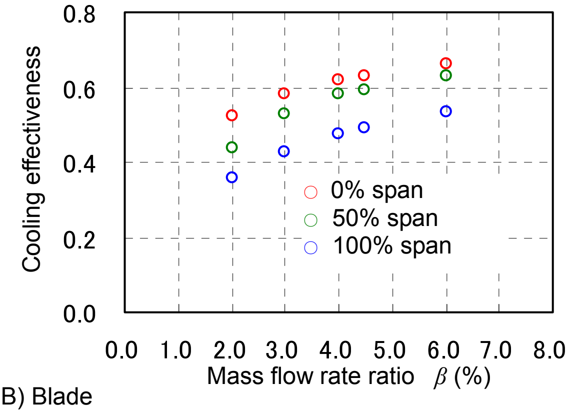
The average cooling effectiveness of the present analysis is also shown in Figure 10 for comparison. The results indicate that the cooling effectiveness in the present case is strong. The reason is that the experimental data was not included the effect of TBC. Additionally, the main reason is that the present analysis used simplified heat transfer equation, and not included the effect of a curved surface and a rotation. It is important to consider these effects even for a simplified simulation. Although we need not such strictness as are necessary to calculate for a researcher conducting a design of a gas turbine system, we are planning to include complicated heat transfer calculation of each cooling construction as a future work. Moreover this database will be upgraded by referring available experimental data of a gas turbine system.

In the present examples, the databases are not directly used, because these are not evaluated the accuracy as the value. Therefore the relative values that took into account the difference between the experimental data condition and the design operation condition are used in the VT.

The VT is a type of simplified simulation for the easy use and to reduce calculation time. Accordingly, the three-dimensional cooling performance, which was prepared by the present analysis, cannot be directly used in the VT. In other words, the three-dimensional cooling performance databases were partially used. For example, Figure 11 shows the cooling effectiveness, which was averaged at each span position instead of the whole airfoil surface. This span averaged cooling effectiveness is used for the creep life calculation. Besides, the maximum temperature, which was selected from three-dimensional database, is the key criteria in evaluating a material.



(a) Vane



(B) Blade

Fig. 11 Span averaged cooling effectiveness

CONCLUDING REMARKS

This paper reported the cooling performance of the vanes and blades of the virtual gas turbine system (VT), and described the database constructions and formulations for performing temperature evaluation of the air-cooled airfoils of the VT. In addition, the example of calculation according to the outline and the installing in the virtual gas turbine system were shown.

Thus the three-dimensional evaluations of wall temperature of the turbines were introduced into the VT. Currently, for the simulation with higher fidelity, more databases are accumulated by analysis with various cases.

Moreover we are planning to include complicated heat transfer calculation of each cooling construction as a future work. This database will be upgraded by referring available experimental data of a gas turbine system.

Since the VT is essentially constructed for evaluations of new materials, it should be a type of future advanced gas turbine. Hence, we will extend the work to a high level VT system whose TIT is 1700°C class, in the near future.

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