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Development of a Gas Turbine Design Program Coupled with an Alloy Design Program - A Virtual Turbine

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ABSTRACT

This paper introduces research and development of a virtual gas turbine system (hereafter VT), which has been carried out in the "High Temperature Materials 21 project" (HTM21).

The VT is a simplified automatic gas turbine design program that can be used on personal computers with Microsoft®[1] Excel. The VT has the unique capability to accurately estimate the performances of a virtual gas turbine made of virtual materials with the aid of the alloy design program (ADP) developed by National Institute for Materials Science of Japan (NIMS) and the blade cooling characteristics and structural integrity databases developed by Japan Aerospace Exploration Agency (JAXA).

By using the VT, it becomes possible to simulate the power plant performances as well as the lives of high temperature components made of any newly developed Ni-base superalloys with arbitrary alloy compositions. As a result of the estimation of the air-cooled 1600 °C class GT by VT, it is concluded that only the combination of sophisticated cooling system, high temperature materials and thermal barrier coatings (TBCs) can realize a high temperature air-cooled GT with low CO_2 emission.

INTRODUCTION

The increase of thermal efficiency of a combined-cycle power plant is achieved by the increase of both gas turbine (GT) working pressure and temperature.

The development of blade cooling technologies and new materials have been supported the steady increase of TIT for more than several decades. And 1500 °C class land base large-scale GTs have been realized.

However, the increase in coolant consumption with the increase of GT inlet temperature (TIT) resulted in the reduction of the thermal efficiency of power plant. Moreover, the requirement of large amount of combustion air of premix type low-NOx combustor (introduced for environmental protection) restricts the TIT increase for air-cooled GT. Therefore, the modern 1500 °C class GT introduced the steam-cooling method to compensate the coolant air shortage. But this steam-cooling method cannot be used in a small, medium sized GTs and aero-engines for non-combined-cycle applications.

The sophisticated internal and external (film injection) cooling technologies, thermal barrier coatings (TBCs) and high temperature materials are expected to reduce coolant consumption of high temperature GTs.

Especially, the development of advanced high-temperature materials such as Ni-base single crystal (SC) superalloy is expected to realize the higher temperature GT with less coolant consumption. Since, the increase in the allowable temperature of TBC requires the increase in the base materials.

In the development of new materials, it had been impossible not only by the material researchers but also by the mechanical engineers or designers to realize the impact of new material application in the actual high temperature GTs. And to get the clear understanding of the impact for the material development is a strong driving force to the researchers and may support them to determine the fruitful research targets.

Based on the above noted backgrounds, a simplified but an automatic gas turbine design program has been developed and was coupled with the alloy design program (ADP) which has also been developed in the HTM21 project.

The system has successfully been applied to the simulation of the new material impact on the virtual high thermal efficiency power plants.

OUTLINE OF A VIRTUAL GAS TURBINE SYSTEM

Fig. 1 shows the basic structure of VT system. The system is build up with the module of thermal cycle design program (TCDP), gas turbine design program (GTDP), alloy design program (ADP) and gas turbine design databases (GTDD). The GTDD consist of material strength database (MTDB), the gas turbine structure database (GTDB), the cooling efficiency database (CCDB) and the structural integrity database (SIDB).

The standard inputs for the VT are the GT power output level, GT inlet temperature (TIT) and nozzle / blade materials. Since, the VT coupled with the ADP, the material selection can be an arbitrary composition of Ni-base SC superalloy.

The TCDP determines rotational speed, gas turbine pressure ratio and computes fuel flow rates to realize given TIT and send the information back to GTDP.

The GTDP designs a gas turbine under the given conditions by consulting other inter-connected design program outputs and databases. The most important function of GTDP is to estimate the nozzle and blade temperature and stress levels under the given coolant flow rate condition. These data are also used for the life estimation of the nozzle and blade.

The whole design processes are controlled by the macro and are repeated until the convergence criteria are satisfied.

THERMAL CYCLE DESIGN PROGRAM - (TCDP)

The TCDP controls the VT system by monitoring the overall plant heat and mass balance. The thermal power plant that can be designed by the present TCDP are a simple-cycle GT system or a GT/ST combined cycle system.

Fig. 2 shows the thermal cycle schematics of a combined cycle power plant. The ambient air is compressed through the compressor

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(from ① to ⑤) and then introduced to the combustor (from ⑤ to ⑦). The high temperature and high pressure gas flow which is generated by the combustor is then led to the turbine. The hot gas is expanded to the atmospheric pressure while generating power (rotating the generator). Still hot gas turbine exhaust gas is led to the heat recovery steam generator (HRSG) to generate steam (from ⑦ to ⑩). The generated steam is expanded in the steam turbine.

The present VT treat the working gas as a mixture of five component gases (N_2, O_2, H_2O, CO_2 and Ar). And the thermal properties are computed at all the points by referring to the temperature, pressure and gas concentrations.

The primary and the intended function of VT is to clarify the influence of development and introduction of new material such as Ni-base SC superalloy to virtual high temperature GTs. Thinking of the greenhouse effect, the influences may be measured by thermal efficiency of power plant and the CO_2 emission rate. And these values are computed in this TCDP.

The TCDP can burn liquid fuels as well as gaseous fuels. Therefore, the influence of fuel is also simulated.

The optimization of GT pressure ratio is also incorporated in the TCDP and the user can select the modes from maximum power output and maximum thermal efficiency.

GAS TURBINE DESIGN PROGRAM – (GTDP)

The real design process of a gas turbine requires huge amount of calculations. What was the most important for the development of VT was to reduce the calculation time while retaining required accuracy. The GTDP must complete the aerodynamic, cooling and structural calculation in relatively short time on personal computers.

However, to get a clear difference for nozzle-row and blade-row for the stage to stage, the aerodynamic design is based on the velocity triangle calculation taking the cooling injection effects into account.

The points of cooling and structural design are the assessment of metal surface temperature for the oxidation or corrosion life evaluation, the nozzle bending stress and bulk temperature for the creep life evaluation and the blade centrifugal stress and bulk temperature for the creep life evaluation.

The influence of thermal barrier coating (TBC) is also considered in the GTDP.

The GT coolant flow rate must be determined to clear all the design limitations which came from the blade life considerations. However, this process requires much computational time, since the coolant flow rate must be given for all the nozzle and blade for all the stages and the changes in coolant flow rates influence the basic thermal cycle heat and mass balance. To solve this highly complicated system, VT has the outer convergence loop to balance the dependent variables (coolant flow rates, coolant temperature gas turbine stage load etc.) by the iterative procedure.

To minimizes the complexity of the user, most of the design parameters are given in database, such as rotor disk and blade proportion, internal cooling structure and external film cooling hole distributions for nozzle and blade, combustor outlet temperature distribution (pattern factor) and so on.

In the present VT version, medium-size 1300 ^{o}C class GT (Ishii et al. 1998) database is used. However, it will be upgraded to apply the next generation large-size 1700 ^{o}C class GT database with the sophisticated closed-loop cooling structure.

COOLING CHARACTERISTIC DATABASES

The cooling characteristics, namely, cooling efficiency versus coolant flow rate against the blade cooling configurations and the film cooling effectiveness databases are also very important for the correct blade metal temperature estimation.

These databases have been developed based on the experimental data and the results of advanced large-scale Computational Fluid Dynamics (CFD) research carried out by JAXA.

For example, the average and minimum cooling effectiveness for the first stage nozzle and blade are expressed as below.

<Nozzle>

average: $\eta\text{-av} = 0.714\,\{1-\exp(-0.47(Gc/Gg))\}$ (1)

minimum: $\eta\text{-mn} = 0.660\,\{1-\exp(-0.47(Gc/Gg))\}$ (2)

<Blade>

average: $\eta\text{-av} = 0.608\,\{1-\exp(-0.43(Gc/Gg))\}$ (3)

minimum: $\eta\text{-mn} = 0.507\,\{1-\exp(-0.43(Gc/Gg))\}$ (4)

Where, Gg is the main gas flow rate and Gc is the cooling gas flow rate. Fig 3 shows an agreement of the cooling effectiveness between experimental data and above noted equations.

However, these equations can only predict one-dimensional nature of the sophisticated blade metal temperature distribution. To take the two-dimensional surface temperature distribution effects into account, 3D-CFD with film cooling injection have been performed and the results will be reflected to the next generation VT.

Fig.4 indicates one of the CFD results of the unsteady 3D-simulation of the first stage cascades. The figure indicates the loss generation and the unsteady interaction between nozzle and blade. The results will be utilized for the future aerodynamic efficiency database.

Fig.5 indicates the nozzle surface temperature and streamline, considering the film cooling injection. The computed main flow gas temperature (Fig.6 (A)) , film cooling effectiveness and surface heat transfer coefficient (Fig.6(B)) gives the nozzle and blade surface thermal boundary conditions for the structural analysis.

Now, we have the detailed two-dimensional surface distributions of design variables with the aid of CFD. But, it is too heavy to treat the two-dimensional detailed distribution by the VT built on the Microsoft® Excel program. Therefore, by using the two-dimensional distributions, mean and minimum cooling effectiveness characteristic curves were derived for root, 10%, 30%, 50%, 70%, 90% and tip cross-sections. Fig. 7 indicates the sectional mean cooling effectiveness characteristic versus coolant flow rate ratio for the different nozzle height cross-sections. Fig. 8 shows the example of the minimum cooling effectiveness versus coolant flow rate curve for the 50 % nozzle height cross section.

By applying the newly developed cooling characteristic curves noted above, the estimations of creep and the oxidation lives becomes more accurate.

STRUCTURAL INTEGRITY DATABASES

The thermal and structural stresses are three-dimensional in nature. Since then, the 3D finite element structural analyses have been performed by using the 3D-CFD results as the boundary conditions.

Parametric structural analysis is under going to create the thermal and structural stress distribution knowledge base. Fig. 9 shows an example of a temperature and a thermal stress distribution for the first stage nozzle.

The 3D structural analysis outputs huge amount of numerical data. However, it is not possible to utilize all the details by the VT. Therefore, the maximum over the mean stress value for the important locations (leading edge, suction and pressure surfaces) are obtained for root, 10%, 30%, 50%, 70%, 90% and tip cross-sections and will be utilized as database.

The accuracy of the stress and life distribution will be improved by applying this new database.

ALLOY DESIGN PROGRAM – (ADP)

The ADP is developed at NIMS on the course of HTM21 project and has been integrated into the VT.

The ADP is used for the evaluation of the creep strength under the gas turbine operating condition for arbitrary compositions of SC superalloys. Many researchers were tried to predict the creep rupture life. For example, Durber, G. (1996) have been developed the prediction equation for the Larson-Miller parameter. His prediction equation shows a good agreement between actual and calculated Larson-Miller parameters, but it does not take the structural parameters such as γ / γ' lattice misfit, volume fraction of γ' phase into account. The proposed equation is shown below, where T_r is the creep rupture life in hours, σ is the applied stress in MPa, T is the temperature in Kelvin, A,B,C and D are the regression coefficients obtained from 197 creep rupture data of 36 different SC alloys, X_i is the composition of the I-th alloying element in atomic % , δ is the γ / γ' lattice misfit, and V_f is the volume fraction of γ' phase. Fig. 10 shows excellent agreement between the calculated and measured creep rupture lives with the Larson-Miller parameter. Table 1 shows structural parameters and properties that can be predicted by the present ADP.

$$\log10(T_r) = A+(B+CT/\sigma)\log10\sigma + D/T \quad (5)$$
$$A = a_0 + \Sigma a_i X_i + a_j \delta + a_k V_f \quad (6)$$
$$B = b_0 + \Sigma b_i X_i + b_j \delta + b_k V_f \quad (7)$$
$$C = c_0 + \Sigma c_i X_i + c_j \delta + c_k V_f \quad (8)$$
$$D = d_0 + \Sigma d_i X_i + d_j \delta + d_k V_f \quad (9)$$

APPLICATION EXAMPLES

The present VT is constructed on the Microsoft® Excel worksheet and Fig. 11 indicates the Input / Output worksheet of the VT system. The main inputs and outputs are listed below.

Inputs: Gas turbine output power level (e.g., 15 MW)
Turbine inlet temperature (e.g., 1200 °C)
Material selection
(e.g., Mar-M247, or a new SC alloy composition)
Outputs: Turbine gas path profile
Coolant flow rates
Thermal efficiency
CO_2 emission rate
Creep life of blade, etc.

VT is featured by the unique functions to evaluate the realizabilities of GT. Which are structural strength and life of GT cooled blades.

For example, computed rotational blade centrifugal stress is evaluated against the material strength under the 1300 °C - 15MW class turbine (Fig. 12). In the figure, gray broken line shows the centrifugal stress, and solid line shows the estimated creep strength for 10^5 hours. If these lines crossed over as shown in the left-hand side, the material strength is not enough to use under the given turbine condition. On the other hand, if optimal material or newly designed material with ADP is used, the relationship between centrifugal stress and the material strength is changed as that shown in the right-hand side figure.

VT can also estimate the creep deformation and the life consumption ratio of the blade. Fig. 13 indicates the elongation of blade in longitudinal direction against normalized creep rupture life. Fig. 14 shows the distribution of creep life consumption ratio in the blade height direction. It can be seen in the figure that around 30% height position is exposed to the most severe condition.

Fig. 15 and 16 indicate the realizability of the air-cooled 1600 °C class GT estimated by VT. And Table2 summarizes the calculation conditions. In this estimation, the advanced SC superalloy TMS-82+ (Hino et al. 2000) was used for all blade materials. Fig. 15 shows the relationship between the maximum allowable temperature of the blade metal (Limited by oxidation) and the TBC temperature of the turbine first stage blade. The gray zone indicates un-realizable zone due to the higher TBC surface temperature. The blade has to be strongly cooled against the high temperature gas exhausted from the combustor. As a result, a large amount of coolant has to be consumed at the blade under the prefixed cooling structure. However, the coolant consumption cannot be increased due to the existing coolant flow limitation (Okamura 1993). Fig. 16 exhibits the TBC temperature and the coolant flow limitations. The air-cooled 1600 °C class GT is only realizable in the narrow white zone indicated in Fig. 16. Therefore, it is concluded that only the combination of sophisticated cooling system, high temperature materials and TBCs can realize a high temperature air-cooled GT with low CO_2 emission.

CONCLUSION

Virtual gas turbine system (VT) has been developed by a combination of a gas turbine design program (GTDP) and an alloy design program (ADP). By using VT, we can estimate the plant performances (thermal efficiency, CO_2 emission rate, etc.) as well as lives of components for Ni-base new superalloys with arbitrary alloy compositions.

As a result of the estimation of the air-cooled 1600 °C class GT by VT, it is concluded that only the combination of sophisticated cooling system, high temperature materials and TBCs can realize a high temperature air-cooled GT with low CO_2 emission.

The typical simulation time required for the present VT is less than 5 minutes on the personal computers with Intel® Pentium® 4 / 2.0 GHz processor.

The present VT only simulates the GT for power plant, however VT technology can be applied to the virtual aero-engine. Further improvements of VT performance are still under going in the High Temperature Materials 21 project.

ACKNOWLEDGEMENT

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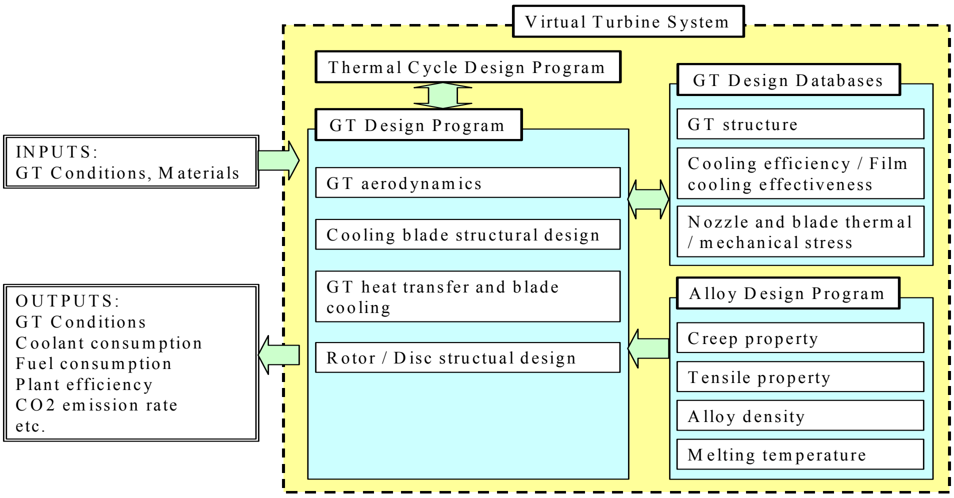


Fig. 1 Structure of virtual gas turbine system

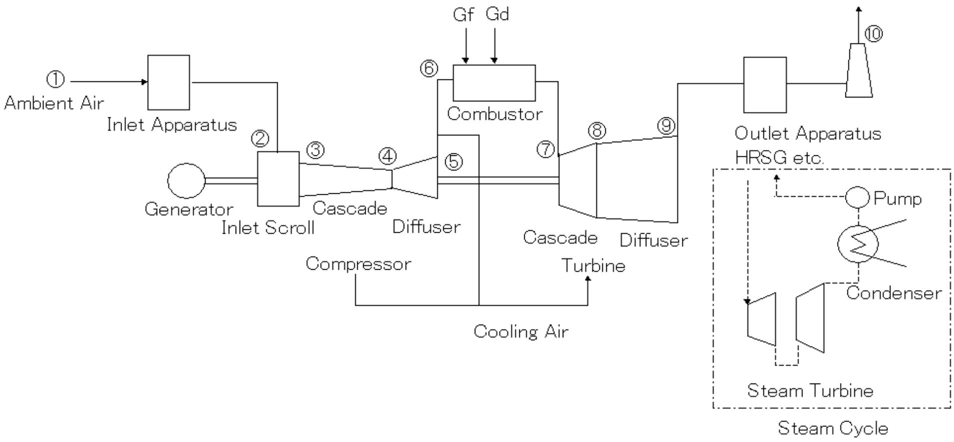


Fig. 2 Virtual gas turbine combined cycle plant diagram

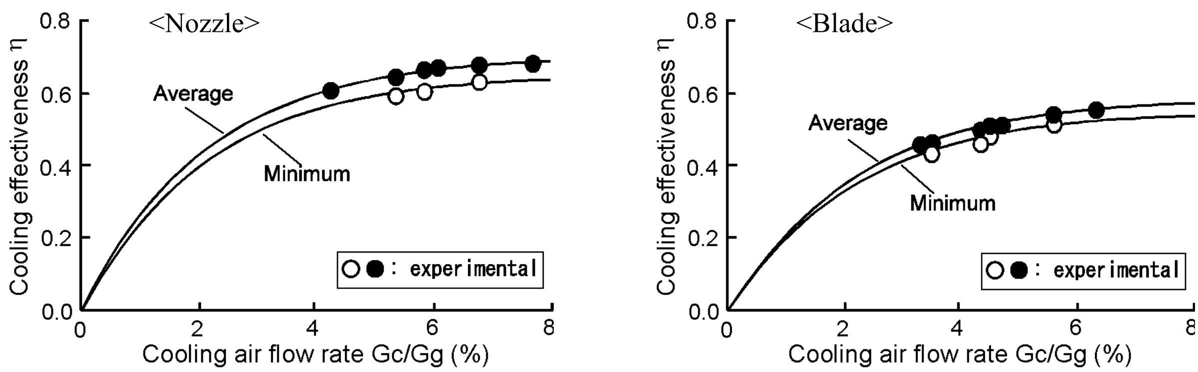


Fig. 3 Agreement of the cooling effectiveness between experimental data and prediction formulas (Matsushita et al. 2000)

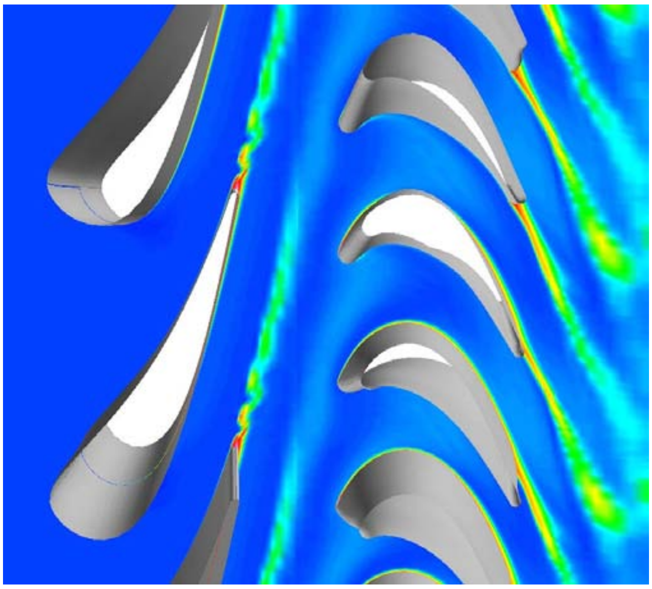
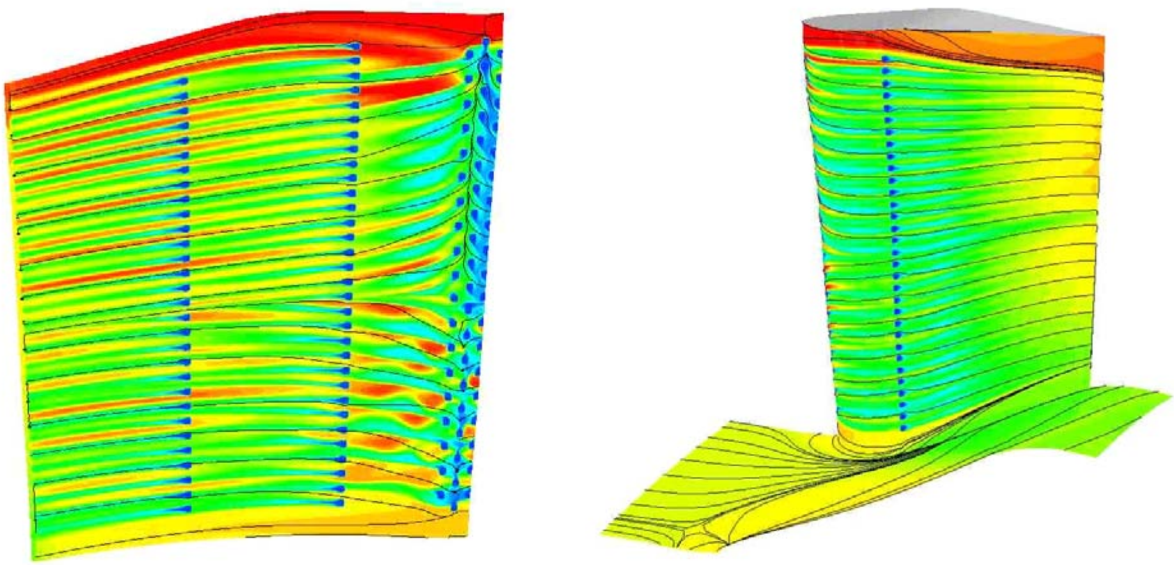


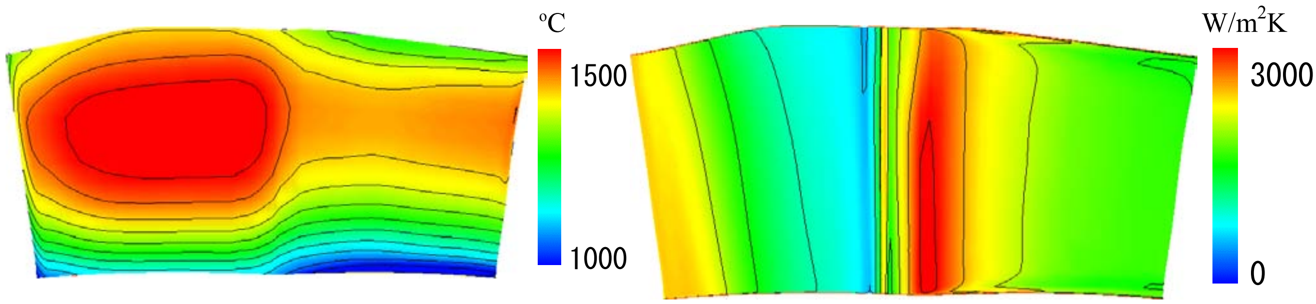
Fig.4 Example of three-dimensional unsteady gas turbine stage CFD. (Saiki et al. 2002)



(A) Nozzle surface temperature distribution

(B) Nozzle surface streamline visualization

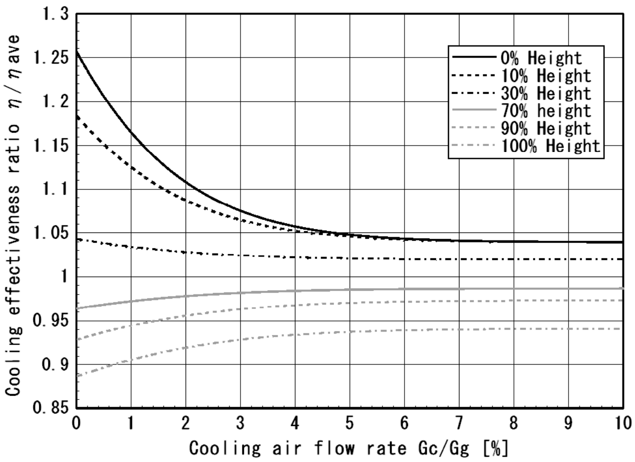
Fig.5 Example of three-dimensional film cooled gas turbine nozzle CFD. (Nishizawa et al. 2002)



(A) Main flow gas temperature

(B) Surface heat transfer coefficient

Fig. 6 First stage nozzle surface boundary condition distribution obtained by 3D-CFD analysis (Matsushita et al. 2002)



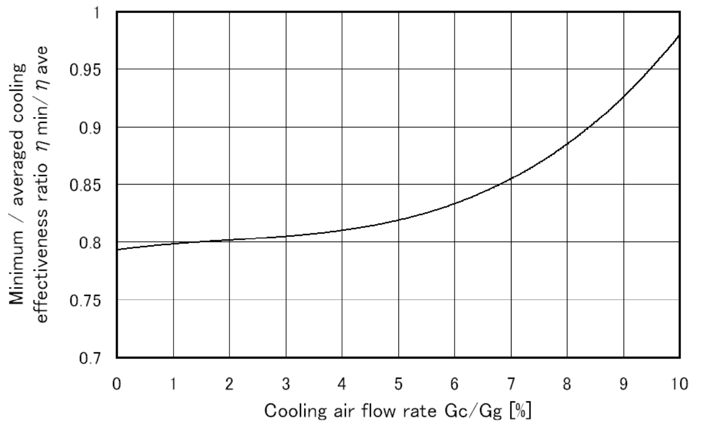
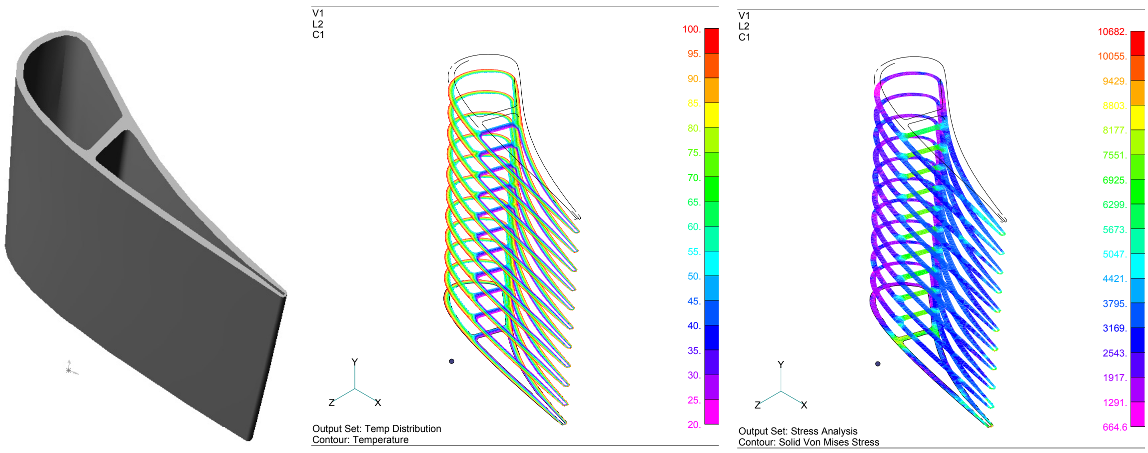


Fig. 7 One-dimensional cooling effectiveness curves for different nozzle height cross sections

Fig. 8 Minimum / averaged cooling effectiveness ratio curves for 50 % nozzle height cross section



(a) 3D solid model (b) Temperature distribution (c) Thermal stress distribution

Fig.9 Thermal stress analysis of virtual turbine nozzle (Chen et al. 2002)

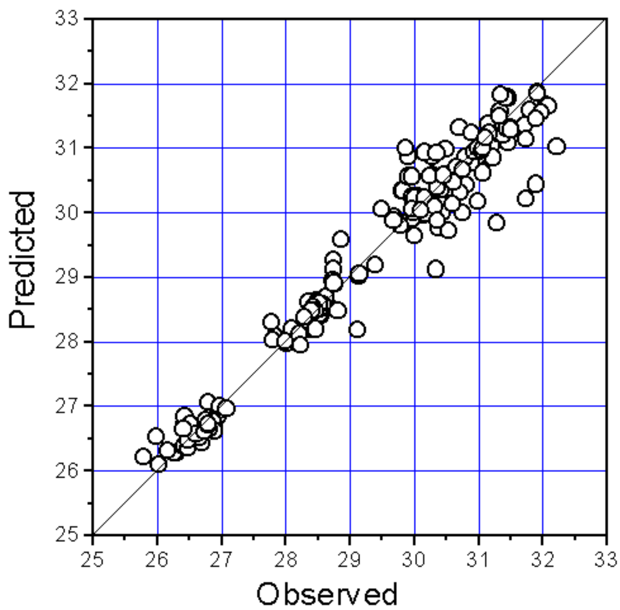


Fig. 10 Agreement between calculated and experimental creep rupture lives (Saeki et al. 2002)

Table. 1 Structural parameters and high temperature properties predicted in ADP (Saeki et al. 2002)

Structural parameters	Properties
Fraction and composition of γ / γ' phases	Creep rupture life of SC alloys at arbitrary temperature and stress
Lattice parameter	Ultimate tensile strength at 900deg.C
Alloy density	Yield strength at 900deg.C
Liquidus temperature	Hot corrosion resistance
Solidus temperature	Elongation at RT
Perfect solution treatment window	

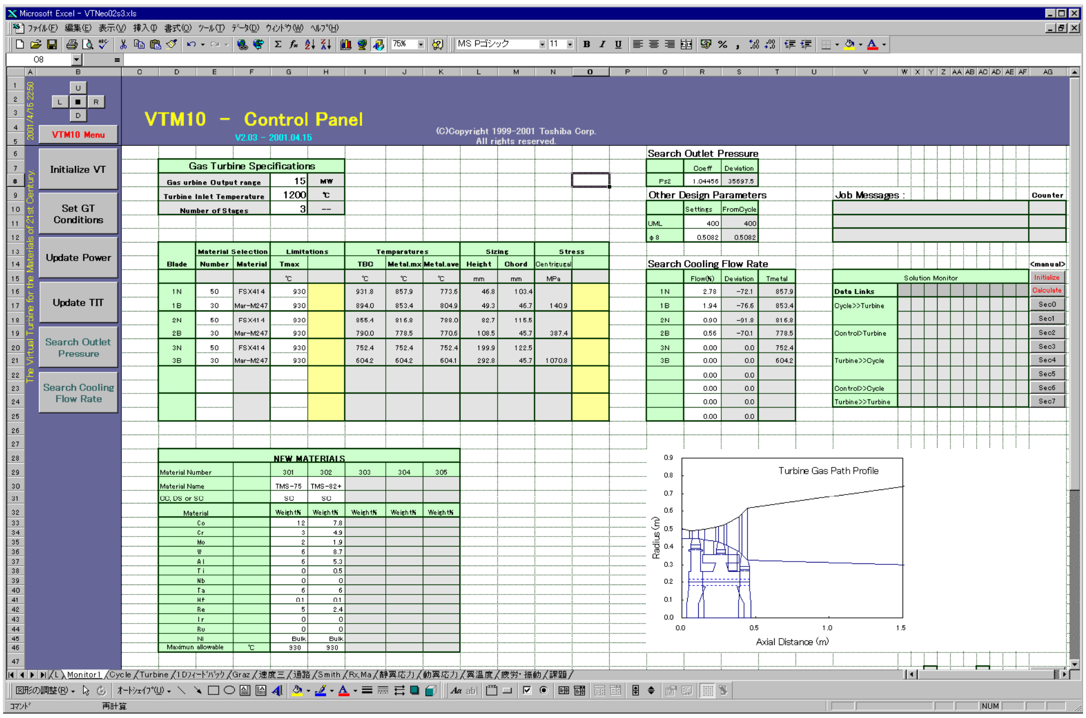


Fig. 11 Input / Output worksheet of VT system (Saeki et al. 2001)

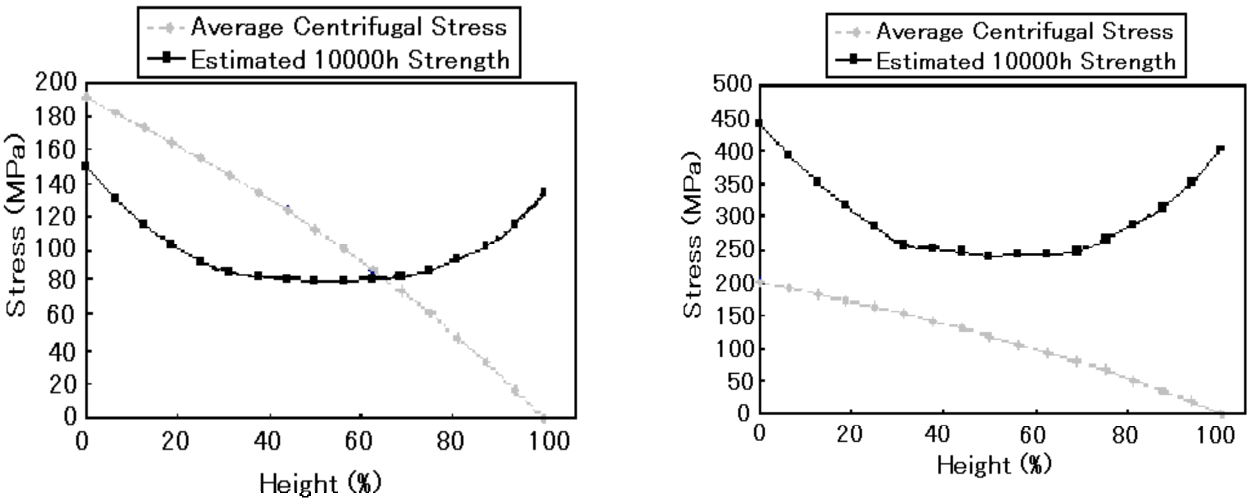


Fig. 12 Relationship between rotational blade centrifugal stress against the material strength formulas (Saeki et al. 2002)

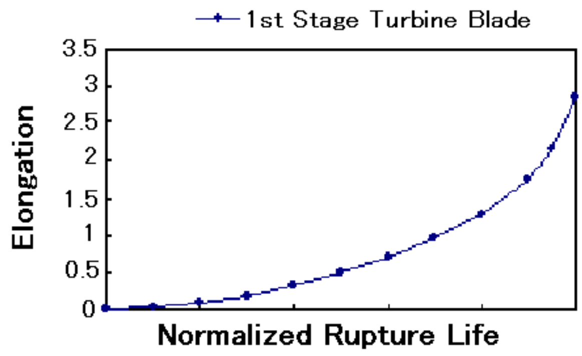


Fig. 13 Elongation of the blade against creep rupture life (Saeki et al. 2002)

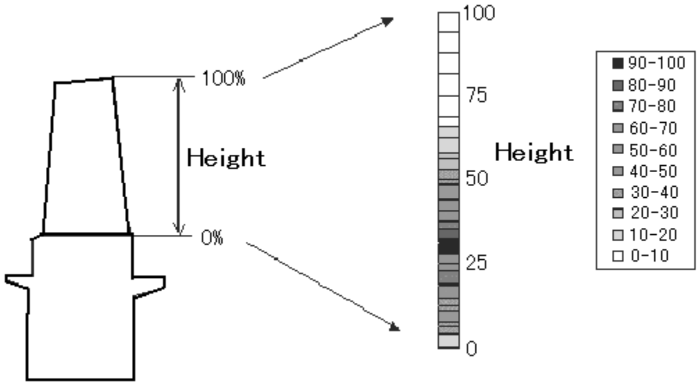


Fig. 14 Distribution of creep life consumption ratio at each part of the blade (Saeki et al. 2002)

Table 2 Design conditions used for the estimation of the Turbine Blade Temperature shown in Fig. 15.

Item	Condition
Fuel	LNG
Turbine stage	4
Materials	TMS-82+ (blade, vane) with TBC
Air flow rate	88.6 kg/s
GT power output level	30 ～ 40 MW
GT pressure ratio	30
Turbine Inlet Temperature	1600 °C

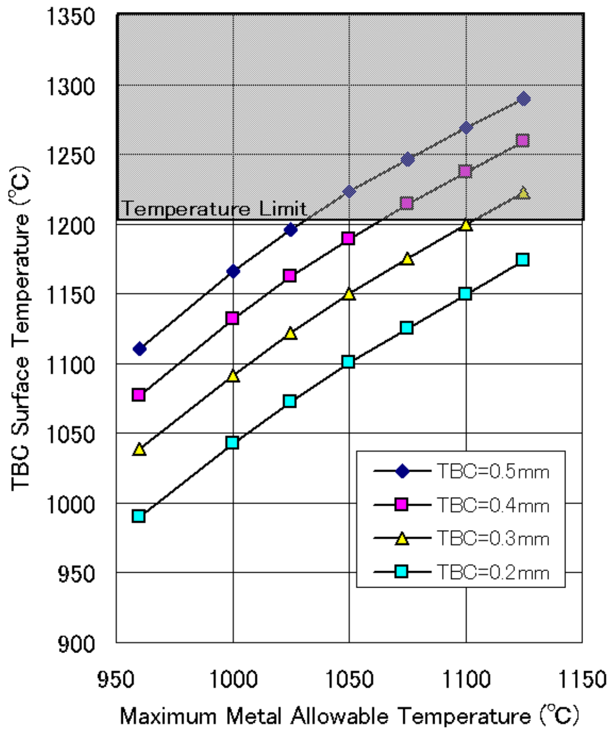


Fig. 15 Relationship between the maximum metal allowable temperature and the TBC surface temperature of the turbine first stage blade estimated by VT

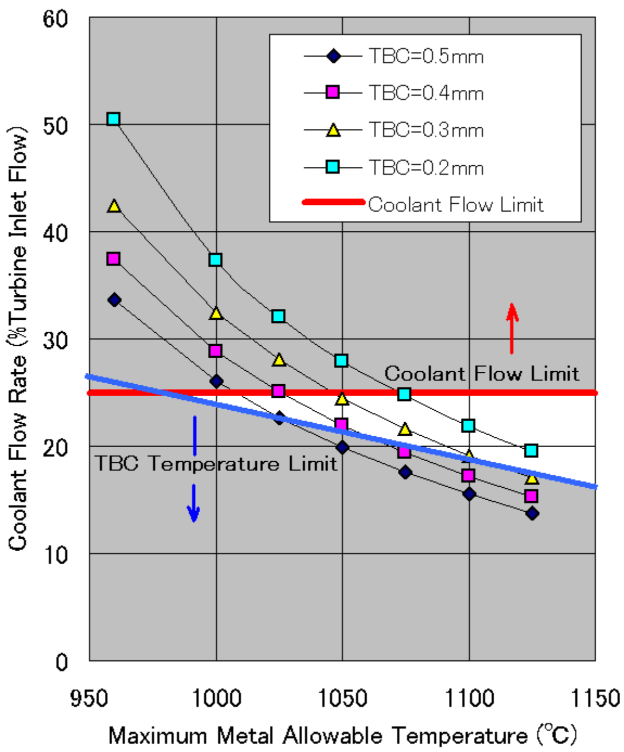


Fig. 16 Relationship between the maximum metal allowable temperature of the turbine first stage blade and the coolant flow rate for all turbine cascade estimated by VT