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

Hiroshi SAEKI¹, Tadaharu YOKOKAWA², Hiroshi HARADA², Yoshitaka FUKUYAMA¹ and Toyoaki YOSHIDA³

¹ Toshiba Corporation
² National Institute for Materials Science of Japan (NIMS)
³ Japan Aerospace Exploration Agency (JAXA)

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® 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 CO₂ emission.

OUTLINE OF A VIRTUAL GAS TURBINE SYSTEM

Fig. 1 shows the basic structure of VT system. The system is built 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 (GTDDB), 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.

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.

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...
component gases (N₂, O₂, H₂O, CO₂ and Ar). And the thermal
influence of development and introduction of new material such as
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 CO₂ 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 gas turbine pressure ratio is also incorporated in the
GTDP, so the user can select the modes from maximum power
output and maximum thermal efficiency.

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: \( \eta_{av} = 0.714 \{1-\exp(-0.47(Gc/Gg))\} \)
minimum: \( \eta_{mn} = 0.660 \{1-\exp(-0.47(Gc/Gg))\} \)

<Blade>
average: \( \eta_{av} = 0.608 \{1-\exp(-0.43(Gc/Gg))\} \)
minimum: \( \eta_{mn} = 0.507 \{1-\exp(-0.43(Gc/Gg))\} \)

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 knowlede 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
between the calculated and measured creep rupture lives with the VT system. The main inputs and outputs are listed below.

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 $\gamma/\gamma'$ lattice misfit, volume fraction of $\gamma'$ phase into account. The proposed equation is shown below, where $T_r$ is the creep rupture life in hours, $a$ 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 %, $\delta$ is the $\gamma/\gamma'$ lattice misfit, and $V_f$ is the volume fraction of $\gamma$ 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.

$$\log(10T_r) = A + \frac{B}{CT} + a + \frac{a}{VT}$$  \hspace{1cm} (5)

$$A = a_0 + \sum a_i X_i + a_\delta + a_\delta V_f$$  \hspace{1cm} (6)

$$B = b_0 + \sum b_i X_i + b_\delta + b_\delta V_f$$  \hspace{1cm} (7)

$$C = c_0 + \sum c_i X_i + c_\delta + c_\delta V_f$$  \hspace{1cm} (8)

$$D = d_0 + \sum d_i X_i + d_\delta + d_\delta V_f$$  \hspace{1cm} (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 realizable 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 realizable life of the air-cooled 1600 °C class GT estimated by VT. And Table 2 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**

This study was performed as a part of the research activities of “High Temperature Materials 21 project” under the collaboration of Toshiba Corp., JAXA and NIMS. The authors would like to express their thanks to the Ministry of Education, Culture, Sports, Science and Technology for the support of the project.

**References**


Virtual Turbine System

Thermal Cycle Design Program
GT Design Program
GT Design Databases
GT aerodynamics
Cooling blade structural design
Cooling efficiency / Film cooling effectiveness
Nozzle and blade thermal / mechanical stress
Alloy Design Program
Creep property
Tensile property
Alloy density
Melting temperature

INPUTS:
GT Conditions, Materials

OUTPUTS:
GT Conditions
Coolant consumption
Fuel consumption
Plant efficiency
CO2 emission rate etc.

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)

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

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)

<table>
<thead>
<tr>
<th>Structural parameters</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction and composition of ( \gamma / \gamma' ) phases</td>
<td>Creep rupture life of SC alloys at arbitrary temperature and stress</td>
</tr>
<tr>
<td>Lattice parameter</td>
<td>Ultimate tensile strength at 900deg.C</td>
</tr>
<tr>
<td>Alloy density</td>
<td>Yield strength at 900deg.C</td>
</tr>
<tr>
<td>Liquidus temperature</td>
<td>Hot corrosion resistance</td>
</tr>
<tr>
<td>Solidus temperature</td>
<td>Elongation at RT</td>
</tr>
<tr>
<td>Perfect solution treatment window</td>
<td></td>
</tr>
</tbody>
</table>

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.

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

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