Basic Technology Development of Turbine Generator Cooling Technologies

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Abstract

Turbine generator cooling technologies are essential and factors for the improvement of quality and performance of products. As a part of our "bold R&D programs" and for a prototype development of a turbine generator, we took into account the various cooling technologies available. Currently, what matters most in cooling is the air flow-static pressure characteristics of cooling fan. This is known as P-Q curve.

Due to recent rapid development of thermal fluid analysis technology, three-dimensional (3D) analysis became common practice in the industrial world. The improvement of data accuracy in the P-Q curve directly relates to analytical accuracy. In order to grasp the P-Q curve that contribute to the improvement of accuracy in thermal fluid analysis, we recently performed verification of a turbine generator prototype. In addition, we experimented a wind tunnel experiment on a full-scale fan and conducted various experiments using a smaller model. During actual experiments, we examined differences of results between 3D fluid analysis and the above experimental results. In doing so, we obtained the P-Q curve results that reflect better experimental results and improved simulation analysis accuracy. In addition, we worked on ventilation and thermal calculations by using a general purpose one-dimensional simulation tool (1D tool).

1 Preface

For the development of rotary machines (generator, motor, etc.), design verification by three-dimensional (3D) analysis or one-dimensional (1D) simulation became fairly common. To attain improved prediction accuracy, it is important to compare and evaluate the analysis results and experimental results. We are currently working on a compact and light weight design of a turbine generator through the improvement of cooling efficiency. To achieve such goal, we are making concerted efforts in using 1D simulation tools (1D tools) in order to improve the analytical accuracy by verifying the actual experimental results. We are also working on the acceleration (shortening) of the design work period. This paper introduces: 3D analysis of 4-pole turbine generators, optimization of the cooling structure, and our ID tool-based development programs.

2 Analysis and Experiments on Rotating Machine Cooling Structures

Our turbine generators are air cooled. The cooling air circulates inside the generator by axial fans located on both sides of the rotor. For a compact and light-weight design, we are working on various measures.

Fig. 1 shows an outline of the new structure. The axial fan was drastically changed and careful measures taken to obtain optimal cooling efficiency within a limited amount of air volume.

Fig. 2 shows a workflow of new structure development programs. We frequently compared the analysis results and actual experimental results and in so doing, we raised the accuracy level of 3D overall analysis. We conducted the prototype design work and verified the cooling effects by using the actual prototype. The details of ventilation cooling development are shown below. We are focusing on (1) the P-Q curve (the air flow-static pressure curve

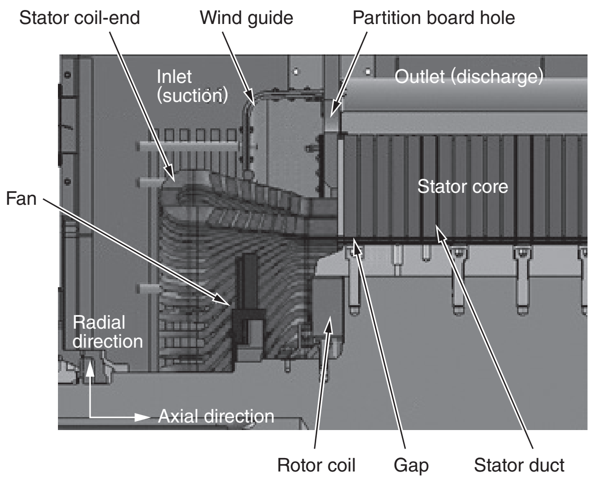

Fig. 1 Outline of New Structure

An outline of the new structure is shown. There is a fan inside the stator winding coil-end in the axial direction. After the air that has entered from the intake section passes through the stator coil and it is boosted by the fan. The cooling air is diverted into a gap in the direction-flows through the stator duct and the air flow through the wind guide-partition plate hole. Then, the air is merged just in front of the exhaust part.

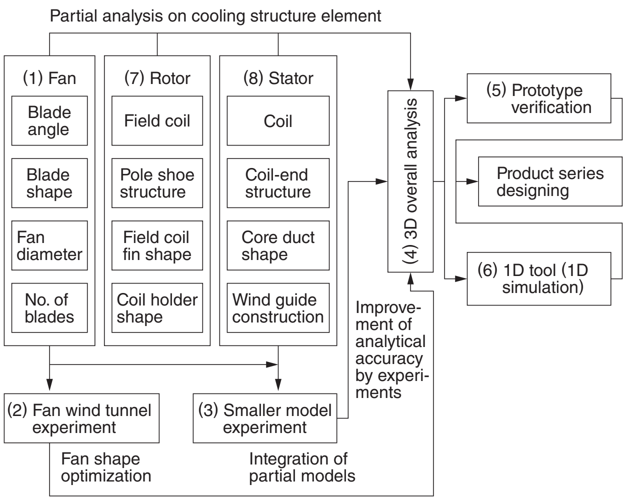

Fig. 2 Workflow of New Structure Development Programs

We aim to improve overall analytical accuracy through partial analysis of elements and various experiments. The obtained results will be used for the development of product series designing through prototype verification works and improvements of 1D tools.

of cooling fan) and (2) the related 1D tool.

2.1 Fan Characteristic Analysis

In order to accomplish optimal design for cooling fans, we firstly examined the mounting angles and positions of the fan blades by using analysis software. **Fig. 3** shows definition of the blade angle for a fan and **Fig. 4** shows our study

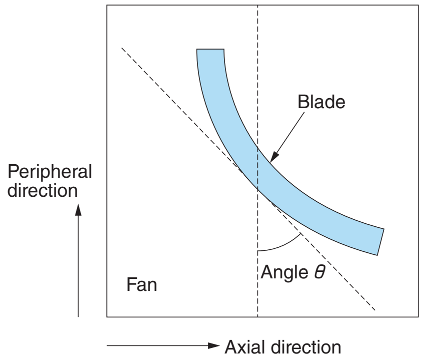

Fig. 3 Definition of Blade Angle for a Fan

Definition of blade angle for a fan is shown. Blade connection in the center and Angle θ in peripheral direction are defined as the blade angle.

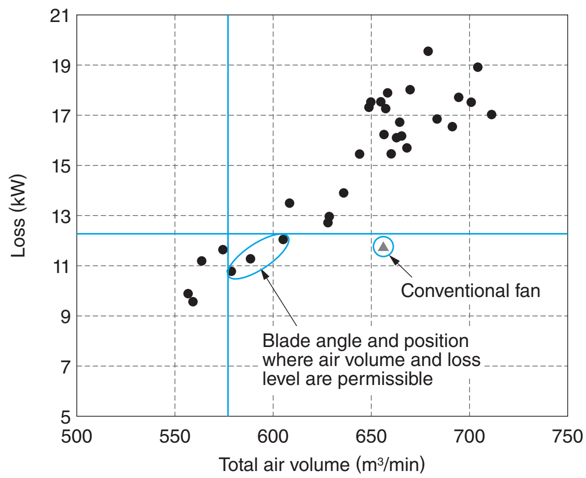

Fig. 4 Study Result on Fan Blade Angle and Position

The measured values of air volume and loss are shown. The data was obtained when the fan blade angle and position were changed. Since the fan diameter is shorter than that of a conventional fan, the air volume became smaller if loss is kept the same. We could obtain the suitable blade angle and position while maintaining both loss level and air volume needed for cooling within the permissible level.

result on fan blade angle and position. If we assume that losses are kept unchanged in the design, the air volume became lower compared with a conventional fan design. We confirmed the suitable fan blade angle and position within the permissible range in terms of necessary air volume for cooling and level of tolerable loss.

2.2 Confirmation of Fan Characteristics by Wind Tunnel Experiment

Prior to verification of overall prototype ventilation cooling under the new structure design, the prototype fan went through a wind tunnel experi-

Fig. 5 **Wind Tunnel System**

An external appearance of the wind tunnel system is shown. The basic configuration conforms to JIS B 8330. In this structure, cooling air entering from the inlet duct flows to the downstream side in axial direction.

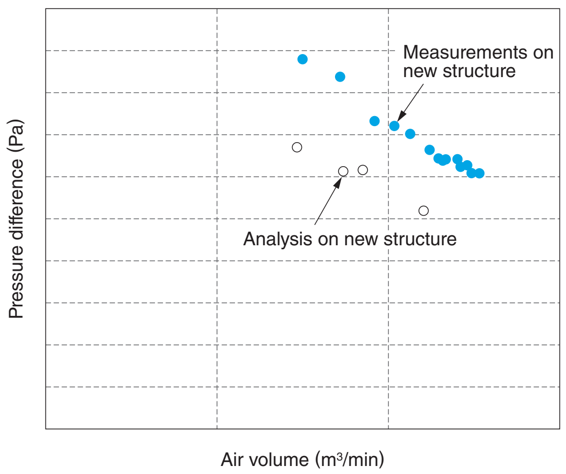

Fig. 6 **P-Q Curve Obtained from Wind Tunnel Experiments**

The P-Q curve in a new structure are shown. The data was obtained from wind tunnel experiments. In regard to changes and gradients in air volume and pressure difference, the results show the similar level between actual measurements and analytical values. The pressure difference with the same air volume, however, tends to indicate somewhat a higher value.

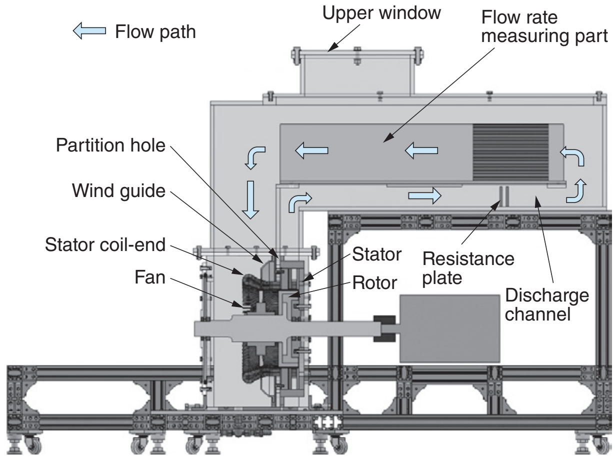

Fig. 7 **Outline of Smaller Model Experiment Equipment**

The outline of smaller model experiment equipment is shown. A flow path for flow velocity measurement was located on top. The stator formed by a 3D printer, coil-end, wind guide, fan, and the rotor were accommodated in a transparent acrylic water tank inside of which was partitioned by divider plates on the front and rear sides of the fan. Pressure levels in a space before and after the divider plate were measured by a pressure gauge. Flow velocity distribution was measured by a flow meter inserted from the upper window.

ment. We made the wind tunnel system whose basic configuration is in accordance with JIS B 8330※1. **Fig. 5** shows the wind tunnel system.

Fig. 6 shows P-Q curve obtained from the wind tunnel experiments. In the experiment, the pressure difference tended to be slightly higher at the same air volume. However, the experiment results and analysis results both showed that the changes in air volume and air pressure difference were same level. This is the same with the gradient.

2.3 Smaller Model Experiment

In order to verify the effects of (1) fan peripheral structure design obtained by analysis and (2) blade angle design change, we produced a smaller model experiment device. In designing the smaller model, the Reynolds number around the fan periphery was adjusted to be identical with that of the prototype as close as possible. For this purpose, dimensions were reduced to one fifth, the fluid used was fluorinated inert liquid, and the number of rotations was kept at 0.6 times.

Fig. 7 shows the outline of the smaller model experimental equipment. In order to acquire P-Q curve, the equipment has a structure that measures the pressure and flow rate by changing the flow resistance. This resistance change was made by changing the size of the resistance plate installed in the discharge part in the water channel.

Fig. 8 shows the P-Q curve (by prototype conversion) obtained from smaller model experiments. The experimental values were obtained by measuring (1) the flow velocity distribution in the upper channel, (2) the pressure in the upstream of the fan and (3) the pressure in the back of the stator.

The results reveal that by increasing the blade angle, the flow rate and pressure of the P-Q curve increase. It also shows that by changing the fan position, the flow rate increases both the fore and rear position and the pressure decreased. Regarding the comparison on the results of experiment and analysis, the analysis results are smaller in both flow rate and pressure. It is considered likely that this is because the analysis was made by steady-state analysis to shorten the analysis time.

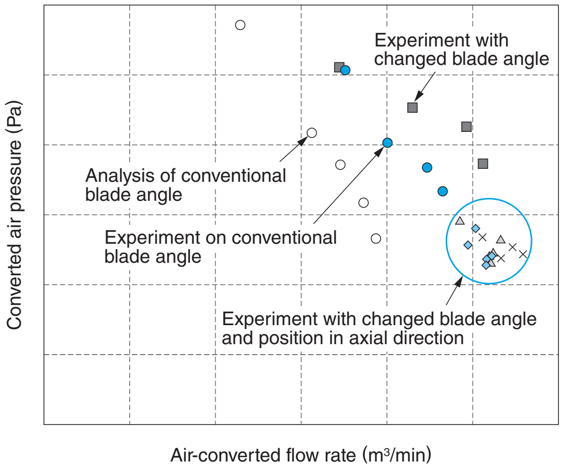

Fig. 8 P-Q Curve Obtained from Smaller Model Experiments (by Prototype Conversion)

The result of conversion is shown. The data was converted from the P-Q curve defined by measuring equipment into those applicable to the prototype. According to the P-Q curve of a fan with a conventional blade angle, both air flow and pressure were increased when the blade angle was increased. In addition, the air flow was slightly increased when the position was changed in axial direction. In that case, pressure was decreased. The result of analysis indicates that both air flow and pressure were lower.

2.4 Prototype Verification

For the new structure, in parallel with the design work, an experiment on the periphery of the fan and a 3D overall analysis were conducted. The results were reflected in the prototype. Since the prototype will be the basis for future design, this fan design will be a model fan for future similar calculation. The air flow distribution and pressure distribution were therefore, measured in order to obtain the detailed P-Q curve of the prototype.

Fig. 9 shows the comparison of the actual measured results and analysis results on the air flow distribution of the prototype. In the 3D analysis, the analysis area is limited to one side divided into two in the axial direction.

Furthermore, to improve analysis accuracy, the scale of mesh was changed from the conventional 30 million mesh by expanding to about 150 million mesh. The number of meshes and the shape were optimized.

The difference between the analysis values and the measured values in terms of total air volume at the stator side and rotor side is about 10%. The results show the both values are nearly same level.

Fig. 10 shows the pressure distribution of the prototype. The largest difference between the measured and analyzed pressure values at the five loca-

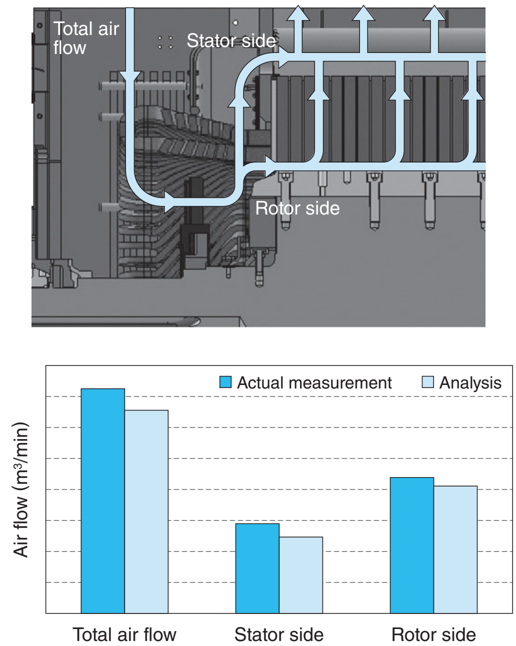

Fig. 9 Air Flow Distribution of the Prototype

A schematic diagram of cooling air flowing inside the machine is shown at the upper stage. An air flow distribution in the empirical prototype is shown at a lower stage. The difference in total air flow was approximately 10% between experiment and analysis. The air flow ratio was about 40% on the stator side and about 60% on the rotor side. These values shows these are similar values between experiment and analysis.

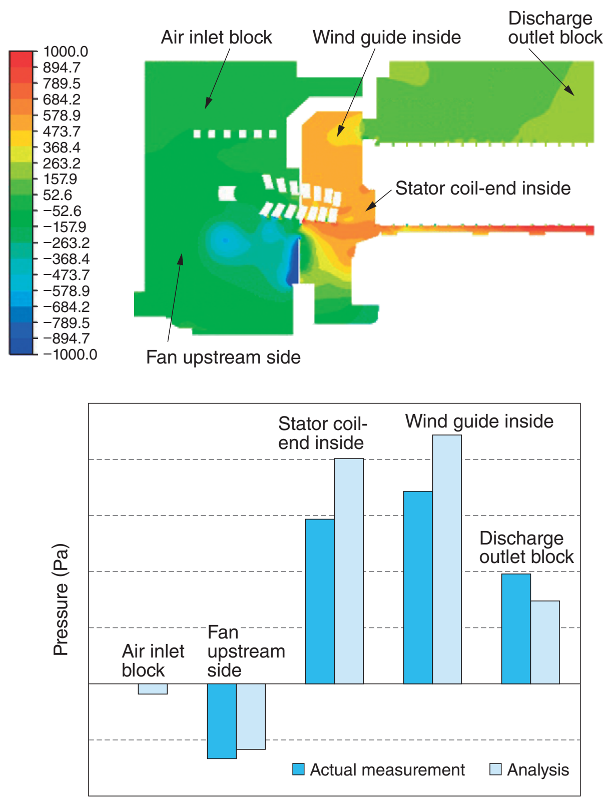

Fig. 10 Pressure Distribution of the Prototype

The result of pressure distribution analysis and comparison between actual measurement and analysis are shown.

tions of inside the generator is about 26% at the coil-end mid-neutral point. The difference in the pressure distribution is larger compared to that of the air flow rate distribution. The cause is due to the turbulence model used in this analysis. Further, in this analysis, inside the stator winding coil-end and inside the air guide, the presence of separation flows (causing unsteady flows) is noticeable. The static pressure tends to be overestimated in such separation flow area. In any case, the usefulness as a method for predicting the flow of cooling air inside the generator was confirmed with practical analysis accuracy.

Fig. 11 shows the P-Q curve of the prototype. Against analysis values, the measured values are about 20% smaller than the analysis values. The measured values are higher values than the analysis values. This shows a different trend compared with those of the wind tunnel experiment and the smaller model experiment.

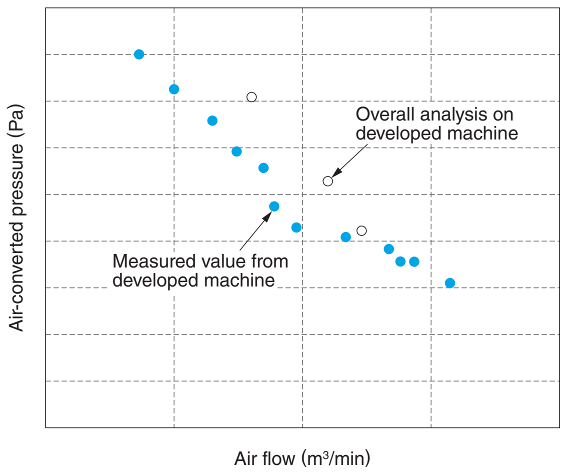

Fig. 11 P-Q Curve of the Prototype

The result of P-Q curve measurement obtained during the prototype verification is shown. Compared with analytical result, values from actual measurements tend to be lower by approximately 20%. This tendency was somewhat different from that of wind tunnel experiments and smaller model experiments.

2.5 1D Tool

In order to achieve fast designing for a turbine generator series, we adopted the FloMASTER (made by Mentor Graphics Corporation) to use as a 1D tool for 1D simulation for heat transmission and

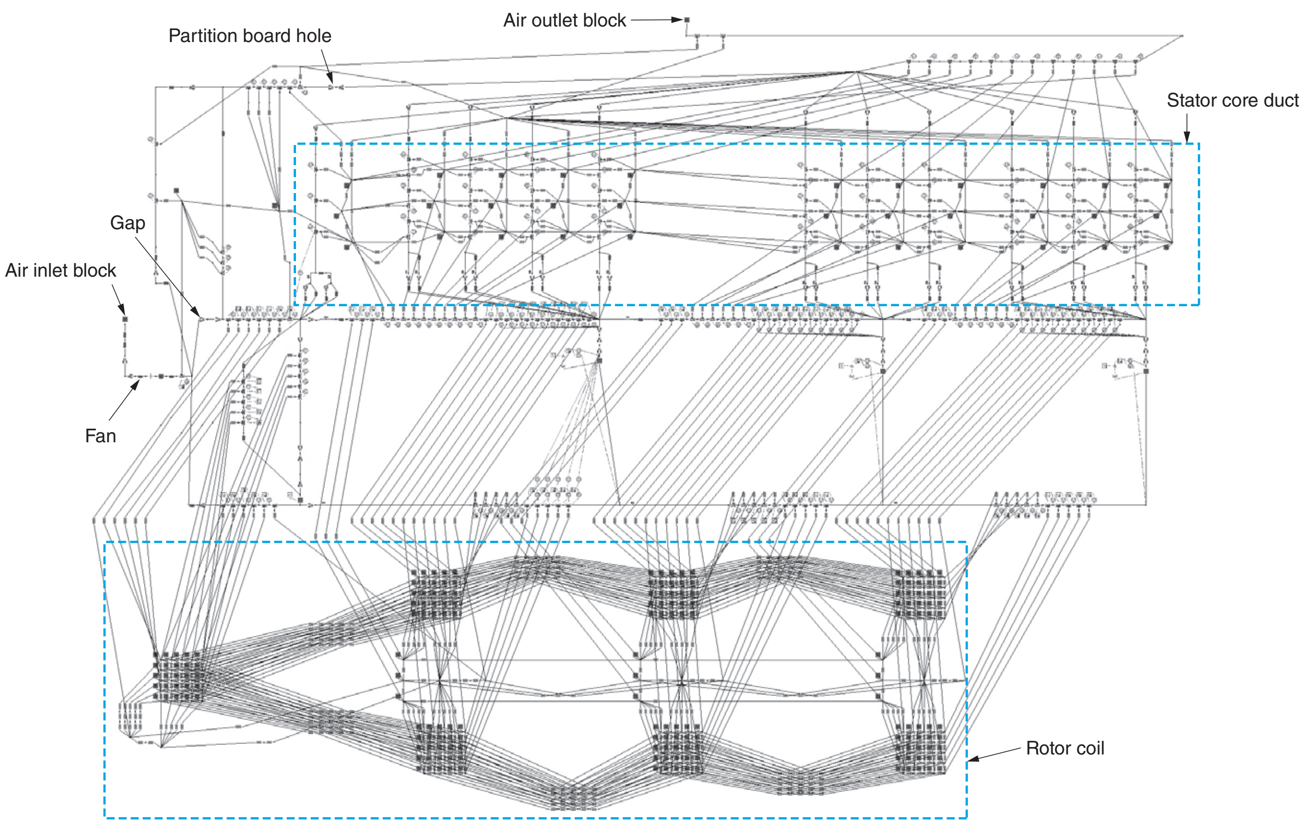

Fig. 12 Outline of a Model Made by the 1D Tool

An Outline of a model made by the 1D tool is shown. Solid or space at each part is regarded as the node point. Ducts are aligned on the stator and coils are arranged on the rotor expressed in a cross-section consisting of 5 × 5 points. By entering the required variables in the input sheet, the FloMASTER makes ventilation calculation on the background.

fluidization. The 1D tool is used to display a block diagram of the operational principle and functions of a unit or a component. The related data are expressed in equations and given in each block. In the case of our 1D tool, model fan data obtained from aforementioned study are displayed. In addition, by inputting variables and heat volume relating to the ventilation structure and shape, we can output air volume distribution and temperature distribution in a diagram of generator cross-section in axial direction.

Regarding the computation model, just like 3D analysis, the analysis area is limited to one side divided into two in the axial direction. Calculations that take into account the pipe reduction loss and pipe expansion loss in the axial direction of the gap are now possible. **Fig. 12** shows outline of a model made by the 1D tool. The result of air flow computation for the prototype by using the ventilation model of this tool showed the similar results of the actual measured values. The availability of this tool was, therefore, a confirmed fit for the practical design work tool for the air flow computation. We are now in a final adjusting stage to complete it as a 1D tool for ventilation cooling and temperature computation.

3 Postscript

This paper introduced how we came to develop 1D tools for optimizing the cooling structure and series design of the 4-pole turbine generator through the comparison work between the analysis values and experimental values. We improved the accuracy of analysis by conducting basic verification processes such as fan wind tunnel experiments and smaller models experiments. We reflected the results into the prototype design. In doing so, we obtained computation model for model fan data which serve as the basis of our future design.

In the future, we aim to develop more higher-quality quality and high-reliability designs for our turbine generators. For this purposes, we have to upgrade the further accuracy level of the 1D tools. By drawing on what we learned from experiment results this time and various analysis undertakings, we will work to further improve our basic core technology on related cooling technologies.

(Note)

※1. JIS B 8330: Method of Blower Testing and Inspection