Thermo-Fluid Simulation Technique for Achieving Energy Saving in Open Showcases

NAKAJIMA, Masato*　　ASADA, Tadashi*

ABSTRACT

More than half of the electric power load in open showcases used in stores such as supermarkets and convenience stores is heat invasion that comes from the front opening of the displays. In order to save energy on the showcases, it is necessary to improve the performance of air curtains that suppress this heat invasion. Air curtain performance changes over time based on the impact of frost formation on the evaporator. Fuji Electric has developed a thermal-fluid simulation technique for elucidating this phenomenon, and based on this technique, we have developed a new air curtain system. Demonstration results achieved improved energy saving of more than 30% compared with conventional systems.

1. Introduction

Stores such as supermarkets and convenience stores are required to save energy due to the amendment to the Act on the Rational Use. of Energy (Energy Saving Act) and its enforcement. Fuji Electric offers smart stores that make efficient use of energy to save on the energy consumed by an entire store. The equipment that consumes the most electric power in a store is refrigeration equipment such as an open showcase. With an open showcase, about 80% of the heat load is accounted for by heat invading through the air curtain and improving the performance of the air curtain is the key. The performance of air curtains varies with time due to the attachment of frost (frost formation) to the evaporator. Fuji Electric has developed a thermo-fluid simulation technique for clarifying this change in air curtains over time. We have also made use of this technique to develop a new air curtain system for saving energy.

2. Open Showcase Configuration

Figure 1 shows the structure of an open showcase. Open showcases do not have a door and the warm air entering through the front opening is blocked by using air curtains so that products are kept cool. The evaporator installed in the duct generates cold air, which is blown out of the air curtain outlet and the back outlets in the back panel by using a fan and drawn into the air inlet, forming an air curtain. The evaporator that generates cold air develops frost over time as shown in Fig. 2 because warm air containing moisture enters through the air curtain. The frost attached causes resistance in the air trunk and decreases the circulating air volume, which causes more air to enter through the front opening. Accordingly, in the development of open showcases, it is important to control the air flow of air curtains in view of changes in frost attachment over time.

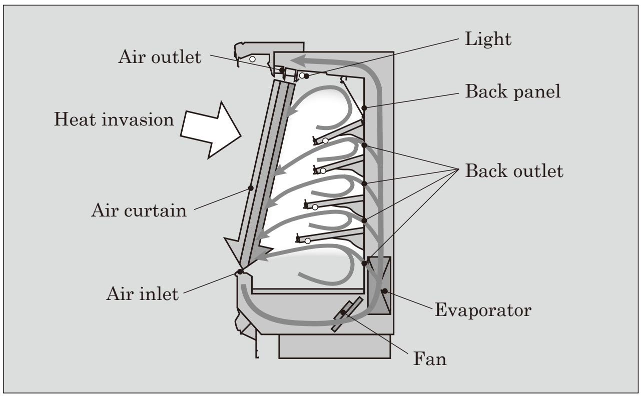


Fig.1 Open showcase structure

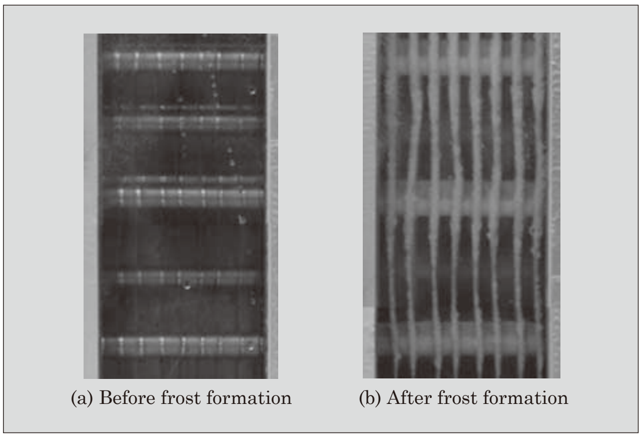


Fig.2 Frost formation phenomenon of evaporator

* Corporate R&D Headquarters, Fuji Electric Co., Ltd.

3. Simulation Technique

3.1 Incorporation of effect of frost formation

The flow of the developed simulation is shown in Fig. 3. With thermo-fluid simulation alone, as is the conventional way, the effect of changes in frost attachment over time cannot be taken into consideration. Hence, we independently developed and introduced a frost formation simulator that predicts the growth of frost. First, thermo-fluid simulation was conducted in the initial conditions with no frost formed to determine the temperature, humidity and velocity of the air drawn into the evaporator. Based on the temperature, humidity and velocity, the wind velocity according to the frost thickness, surface temperature of the frost and humidity of the air blown out of the evaporator were calculated in the frost formation simulator. The results were then reset to thermo-fluid simulation as the boundary conditions. We repeated this operation and proceeded to the calculation for the next period when the temperature and humidity changes of the air drawn into the evaporator were conversed. We completed the calculation when the specified period elapsed.

The frost calculation model in the frost formation simulator is shown in Fig. 4. Growth of frost is mainly influenced by the temperature of the cooling surface and the temperature, humidity and velocity of the air flowing through the evaporator, and these have been used as parameters to build a frost calculation model. When frost is formed, the frost's surface temperature is used instead of the temperature of the cooling surface. The frost formed is distributed in the direction of flow of the evaporator. A large amount of frost is attached especially on the inlet side, where the temperature and humidity of air are the highest. For this reason, to more accurately predict frost formation it is necessary to run a simulation of frost distribution in the direction of flow of the evaporator. Accordingly, we used a model of an evaporator divided into several sections in the direction of flow and predicted the frost thickness and thermal conductivity in the respective sections based on the temperature and humidity of the air drawn in. The frost thickness was used as the basis to calculate the pressure loss of the evaporator and the humidity after dehumidification. Then, the air temperature and humidity calculated were passed on to the following section. In this way, calculation is performed in all sections in this model.

Changes in the average temperature inside showcase over time were calculated by simulation with frost formation taken into consideration. The results were then compared with the result of measurement (see Fig. 5). There is no change in the temperature without frost formation taken into consideration. By considering frost formation, however, the temperature was found to rise over time, which agreed with the actual trend. The temperature rise is due to frost formation that not only decreases the heat exchange amount between the evaporator and the circulating air but also lowers the wind velocity of the air curtain, which causes more air to enter through the front opening.

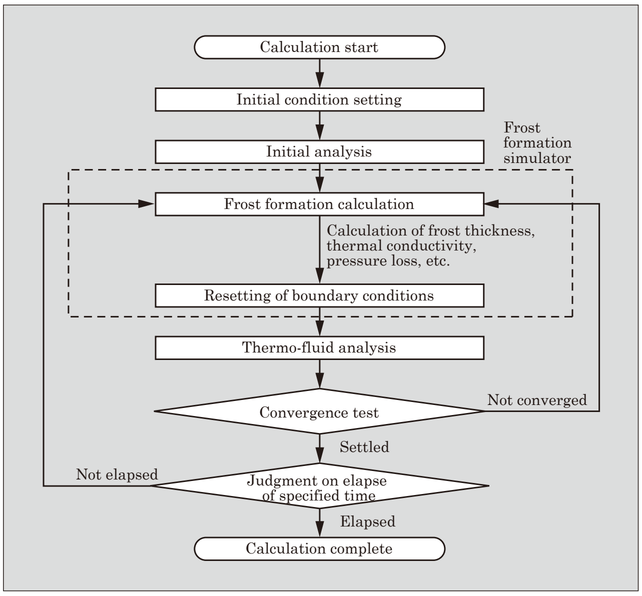


Fig.3 Flow of simulation

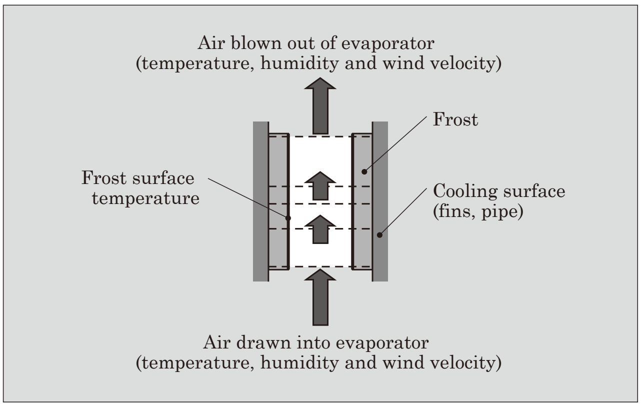


Fig.4 Frost calculation model

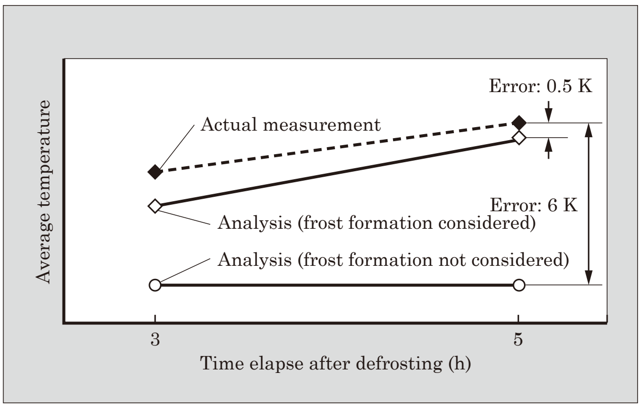
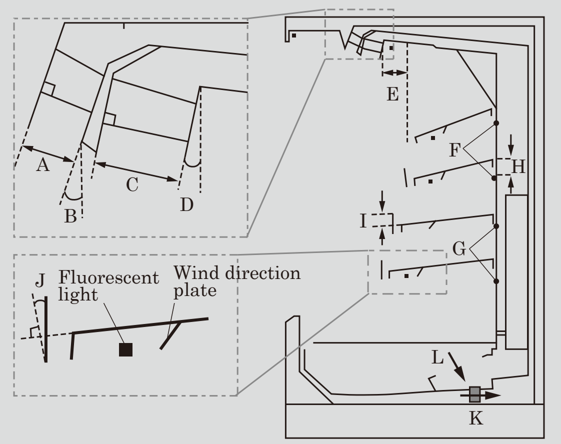


Fig.5 Example of change in average temperature inside showcase over time

3.2 Optimization design technique

As shown in Fig. 6, there are many factors involved in controlling the air curtain of open showcases and we have developed an optimization design technique for balancing them. Figure 7 shows the flow of a design that uses the technique. Open showcases may come in many different models and the number of factors may vary depending on the model. An ability to accommodate multiple factors is also required. Accordingly, we determined the parameters for the calculation samples based on Latin hypercube design (LHD), which allows the number of factors to be freely specified. Next, based on the calculation samples arranged, the analysis model is created by using the showcase design tool that applies the thermo-fluid simulation technology described in 3.1 (see Fig. 8) to perform analysis. Then, the results of analysis (characteristic values) were used to approximate the response surface using a radial basis function (RBF) network and the optimal solution was found by particle swarm optimization (PSO). For example, for the design of the open showcase shown in Fig. 6 with 12 factors, we calculated samples with 66 different conditions to obtain the optimal solution.



A	B	C	D	E	F
Outer width	Outer angle	Inner width	Inner angle	Inner position	Back width 1
G	H	I	J	K	L
Back width 2	Back position	Fence height	Fence angle	Outer wind velocity	Wind velocity

Fig.6 Factors involved in air curtain control of open showcases

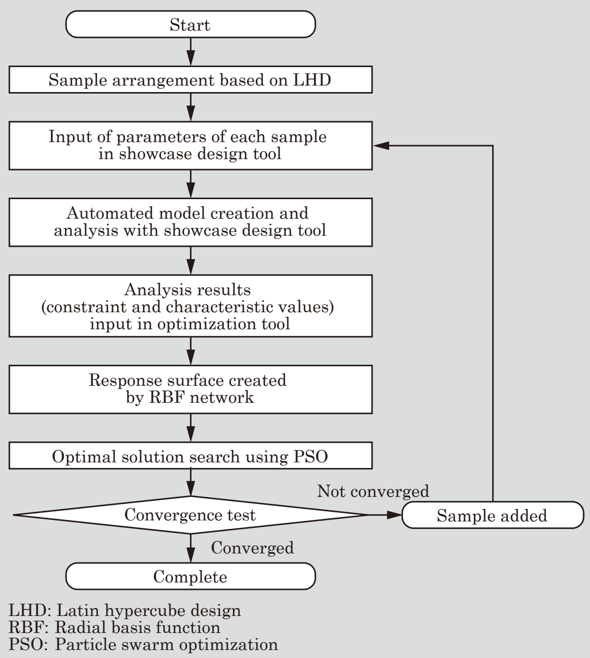


Fig.7 Design flow by optimization design technique

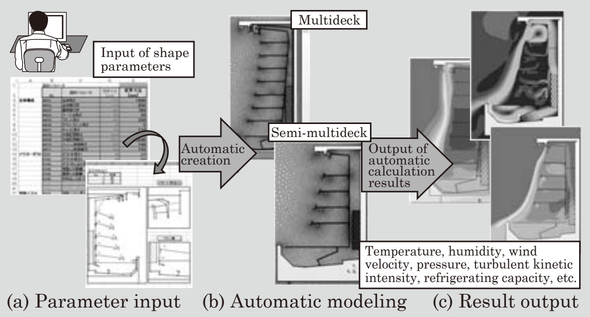


Fig.8 Showcase design tool

The showcase design tool developed for the purpose of creating many sample models and reducing the analysis time can create meshes, execute analysis and display the results simply by using general-purpose software (Excel*1) to input parameters of each sample, as shown in Fig. 8.

4. Effect of Application of Simulation Technique

For the new air curtain system developed by using the optimization design technique and the conventional system, we simulated the wind velocity and turbulent kinetic energy distributions (see Fig. 9 and 10). The conventional system is characterized by a high wind velocity that is used to maintain the external air blocking performance from the air outlet to the inlet of the air curtain. This causes the turbulent kinetic energy to rise, increasing the amount of warm air dragged in at the front opening. Meanwhile, in the new air curtain system, the cold air from the back outlets is gradually mixed with the air curtain, which reduces the supply air flow velocity of the air curtain, decreasing the turbulent kinetic energy and hence the amount of warm air dragged in.

We built a demonstration model based on this simulation result and performed evaluation. The re-

*1: Excel is a trademark or registered trademark of Microsoft Corporation of the U.S.

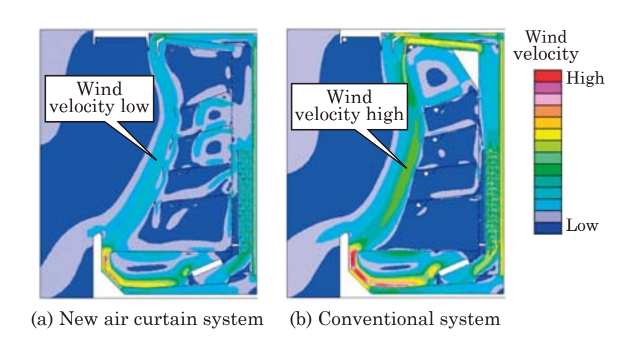


Fig.9 Results of simulation of wind velocity distribution

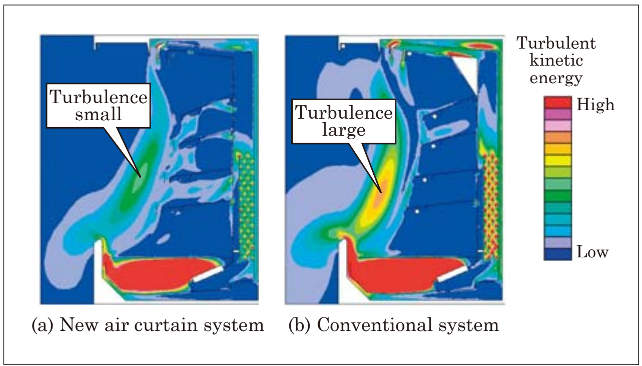


Fig.10 Results of simulation of turbulent kinetic energy distribution

sults showed we had successfully saved energy by over 30% as compared with the conventional system. In addition, the decrease of the air entering through the front opening has allowed the refrigerant evaporation temperature to increase by approximately 4K. This reduces the amount of frost developed, which is also considered to have contributed to energy saving.

5. Future Development of Simulation Technique

Fuji Electric is studying open showcases to work

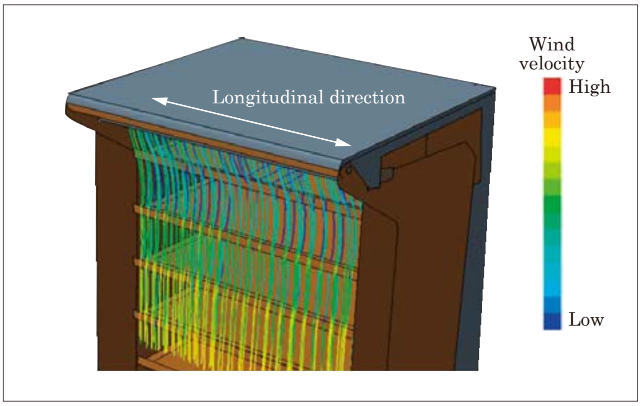


Fig.11 Example of air flow analysis by 3D simulation

on a 3D thermo-fluid simulation technique for achieving further energy saving and enhancing the design of a showcase that cannot be simulated by 2D cross sections. Figure 11 shows an example of air flow analysis by 3D thermo-fluid simulation. We have made use of 3D simulation to develop a structure that provides a uniform wind velocity distribution in the longitudinal direction of air curtains. In this way, we intend to establish technology for verifying the air flows in the 3D directions of air curtains and in ducts in the future. The aim is to further improve the energy efficiency of open showcases.

6. Postscript

We have developed a thermo-fluid simulation technique for open showcases that takes frost formation into consideration and realized energy savings by using a new air curtain system that applies an optimization design technique. In the future, we intend to further the application of this simulation technique to development and design so that we can offer even more ecological and energy-saving open showcases.

Fuji Electric
Innovating Energy Technology