Frost-Free Technology for Heat Exchangers Using Functional Coating

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ABSTRACT

In recent years, as energy saving has become an increasingly important social issue, refrigerated showcases in stores have been required to save energy. In response, Fuji Electric has been developing frost-free technology that uses functional coating to prevent frosting, which is an efficiency lowering factor in the heat exchanger of showcases. The functional coating can promote a state in which water does not freeze even at 0°C or lower (supercooling). We found that a functional coating film promotes supercooling of condensed droplets on small test pieces of aluminum simulating the surface of a heat exchanger.

1. Introduction

In recent years, energy saving has become an even more important social issue to achieve carbon neutrality. In this respect, it is also being required for showcases, or cooling and heating equipment for stores, provided by Fuji Electric. Fuji Electric has so far addressed energy saving of showcases by optimizing the air curtains, which cool the internal storage compartment, and defrosters, which obstruct cooling.(1) Air curtains, in particular, contribute to energy saving. We have optimized the airflow path and airflow volume of them using proprietary computational thermo-fluid simulation technology. On the other hand, defrosting consumes extra energy due to the heating and air blowing required to remove frost from the heat exchanger. In this paper, we will introduce a frost-free technology for heat exchangers using functional coating.

2. Heat Exchanger Issues

Figure 1 shows the basic structure of a showcase. The showcase is connected to a compressor unit, and the refrigerant is circulated by the compressor in the compressor unit. The refrigerant evaporates in the heat exchanger in the showcase, and the heat of vaporization cools the air flowing through the showcase and the interior of the showcase. Since the surface of the heat exchanger is cold, moisture in the air condenses on the surface of the heat exchanger when the moist air comes in contact with it. When the temperature of the heat exchanger surface falls below 0°C, the condensed water droplets freeze and form frost. Open showcases, as shown in Fig. 1, have no door, so the air inside the store, which is hot and humid, intrudes into the air curtain, inevitably resulting in frost on the surface of the heat exchanger. The growth of frost can block the airflow path of the heat exchanger, significantly impairing heat exchange performance. To deal with this issue, heaters and warm store air have been conventionally used to periodically heat the heat exchangers to melt the frost and drain it. Since latent heat of solidification and removal of frosted ice unnecessarily consume extra energy, if frosting of the heat exchanger can be prevented, these energies will no longer be needed, resulting in more energy savings than before.

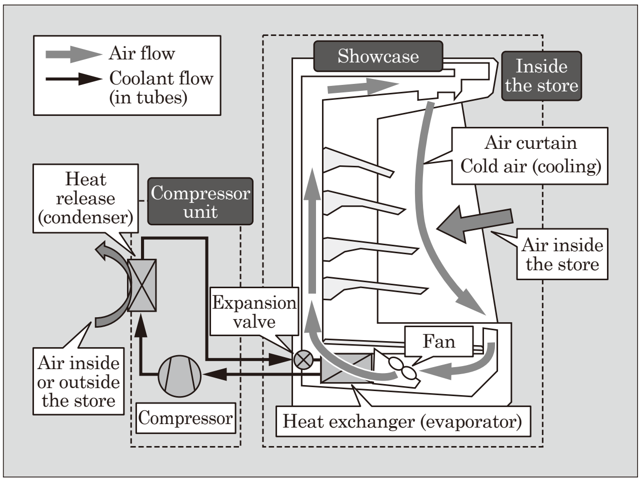

Fig.1 Basic structure of a showcase

2.1 Frosting mechanism in heat exchangers

Frosting on the surface of the heat exchanger starts with the freezing of condensation water drop-

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lets. In general, there are two possible mechanisms for freezing. One is called homogeneous nucleation, in which a freezing nucleus (ice nucleus) forms and freezes throughout the water without any clear freezing factors such as dust or dirt in the water. When this homogeneous nucleation alone dominates frosting, water is known not to freeze down to around −40°C. This state in which water does not freeze below 0°C is called a supercooling state. The other mechanism is called heterogeneous nucleation, in which dust and other foreign particles in the water form ice nuclei that cause the water to freeze throughout its entirety. Much of the freezing seen in natural phenomena is the latter heterogeneous nucleation.

Figure 2 shows the basic structure of a heat exchanger consisting of fins and tubes, and Fig. 3 shows the freezing mechanism of condensation water droplets in the heat exchanger. Air blown by the fan flows over the surface of the heat exchanger and is cooled. During the cooling, foreign particles contained in the air adheres to the surface of the heat exchanger and condensation water droplets, resulting in freezing due to heterogeneous nucleation. The amount of the adhered foreign particles is affected by the concentration of foreign particles in the air and the amount of air passing through the heat exchanger. Therefore, prevention of foreign particles adhesion is effective in preventing condensation water droplets from freezing. However, adhesion of foreign particles is practically unavoidable, and on the premise of this condition, we have to suppress ice nucleation of foreign particles to prevent frost formation.

3. Newly Developed Frost-Free Technology

3.1 Overview of substances that promote supercooling

Several substances reportedly maintain the supercooling state even when foreign particles adheres to them (supercooling promoting substances).[2] Most of them are supercooling promoting substances to be previously dissolved in water as additives. However, it is difficult to selectively and continuously add supercooling promoting substances to condensation water droplets naturally generated in a heat exchanger. On the other hand, Nagatomo et al. selected an amino acid compound called a tyrosine trimer as a supercooling promoting substance and combined it with a resin to make a coating material. They demonstrated that the application of this coating material to glass substrates promoted supercooling of water droplets on the surface of the coating film. However, this demonstration was conducted using glass substrates and a silver iodide additive (silver iodide is one of the typical ice nuclei materials) under conditions different from those in which heat exchangers are used.

3.2 Application to heat exchangers

To achieve frost-free heat exchangers, it is necessary to form a coating of the supercooling promoting substance on the metal heat exchanger surface. Figure 4 shows the molecular structure for the raw material of the functional coating to be applied to metal sur-

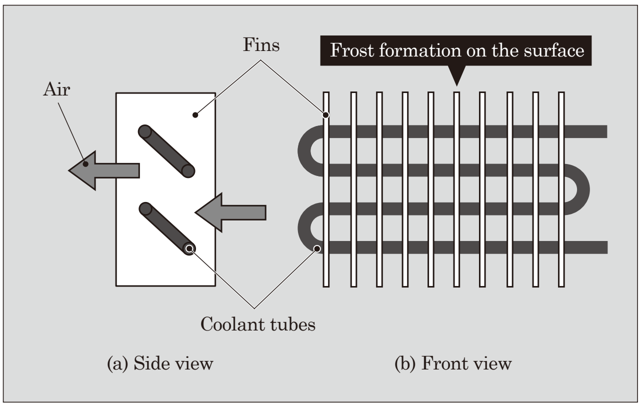


Fig.2 Basic structure of heat exchanger (fins and tubes)

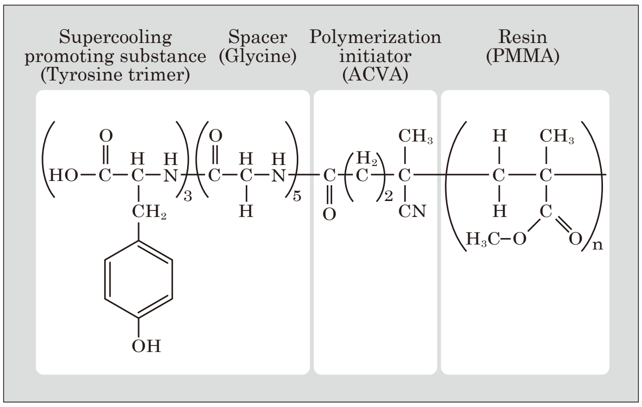


Fig.4 Molecular structure of raw material for functional coating

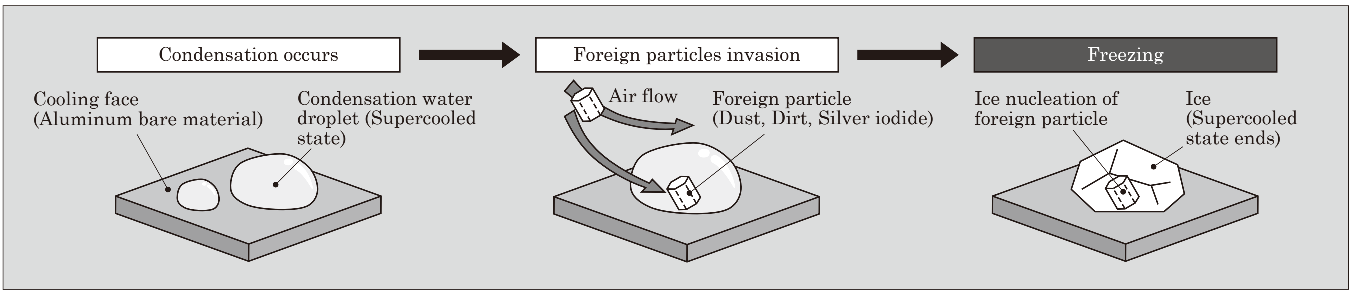


Fig.3 Freezing mechanism of condensation water droplets on heat exchangers

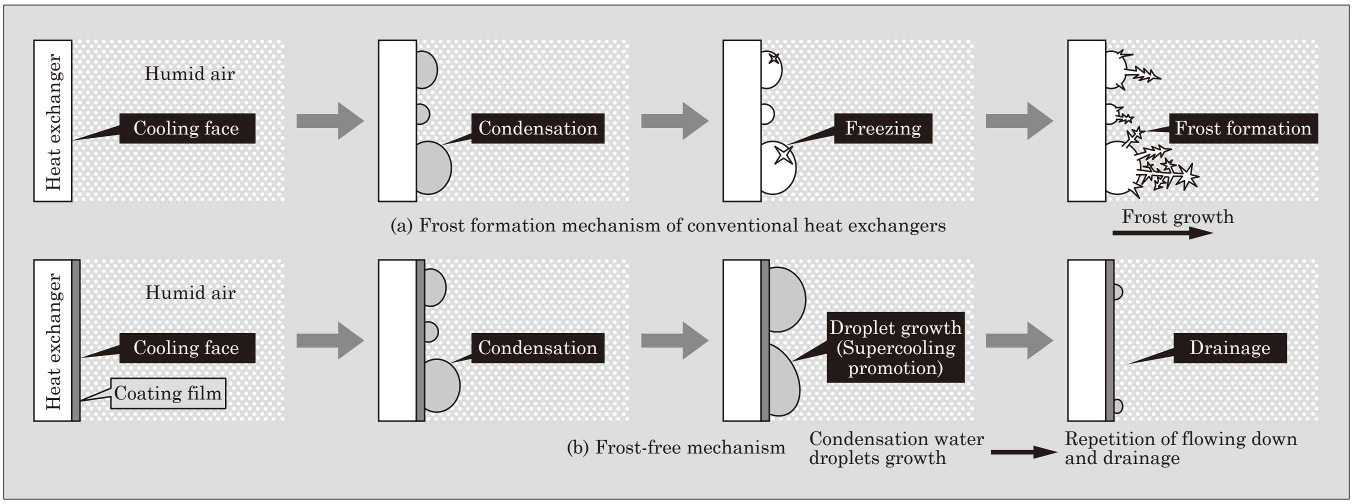


Fig.5 Mechanism of frost-free technology

face. The raw material, made by combining a resin to be physically adsorbs on the metal surface with a supercooling promoting substance, was dissolved in a solvent to form a coating. We have confirmed that this functional coating can be applied to aluminum, which is the surface material of the heat exchanger.

Figure 5 shows the frost-free mechanism using the functional coating. Condensation forms on conventional heat exchangers at low temperatures, and foreign particles in it turns into ice nuclei, causing freezing. On the other hand, the condensation water droplets on a heat exchanger coated with the functional coating remain supercooled even at temperatures below 0°C, thanks to the action of the supercooling promoting substance in the coating. Condensation water droplets in a supercooled state grow and increase in mass over time, and flows down and drains when gravity exceeds its adhesion to the condensation surface. The repetition of condensation and drainage enables continuous cooling and frost-free operation.

3.3 Verification of effects

(1) Evaluation of the supercooling promotion effect

We reproduced the actual conditions of the heat exchanger to evaluate the supercooling promoting effect of the functional coating on the condensation water droplets. We prepared the evaluation sample by applying the functional coating to small pieces of aluminum (D20 mm × W20 mm × t2 mm) that simulated the fins of a heat exchanger. In order to reproduce the naturally occurring condensation water droplets on the surface of the heat exchanger, we used an evaluation stage to simulate the air flow on the heat exchanger with the air maintained at a constant temperature and humidity by a bubbler unit, as shown in the system configuration diagram of the condensation water droplets evaluation in Fig. 6. When cooling the sample, we set the conditions for the cooling surface temperature based on the micro-liquid freezing method to measure the temperature at which the condensation water

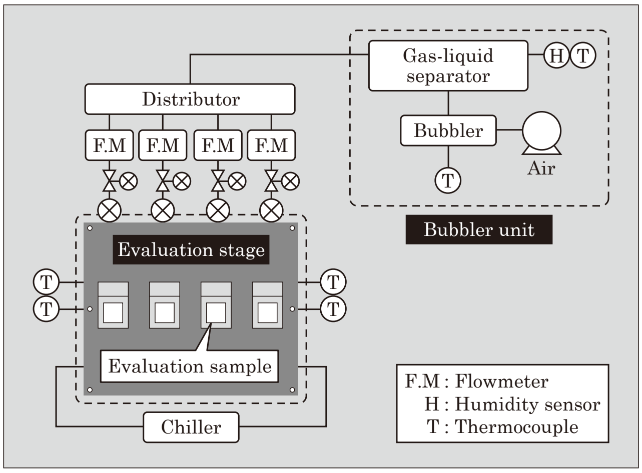


Fig.6 Condensation water droplets evaluation device diagram

droplets freeze. The air temperature and humidity were set to 20°C and 65% respectively based on the actual conditions of the heat exchanger. The evaluation index "anti-ice nuclear activity value" is defined as the freezing temperature of the bare material without coating minus the freezing temperature of the coating sample. We determined the freezing of condensation water droplets when any part of the water droplets on the whole surface was frozen.

Table 1 shows the evaluation conditions under which a heat exchanger was reproduced (condensation water droplets evaluation conditions). As a result of evaluation under the conditions of Table 1, the anti-ice nuclear activity value was 4.2 K. Table 2 shows the results of the principle evaluation (silver iodide additive evaluation) conducted by Okamoto, et al. using drops of easily-freezing water (silver iodide additive), based on previous literature as a reference. As a result of evaluation under the conditions of Table 2, the anti-ice nuclear activity value was 2.3 K. These results showed that the anti-ice nuclear activity value in the condensation water droplets evaluation was on the positive side, similar to the evaluation of the silver iodide addi-

Table 1 Condensation water droplets evaluation for reproducing a heat exchanger

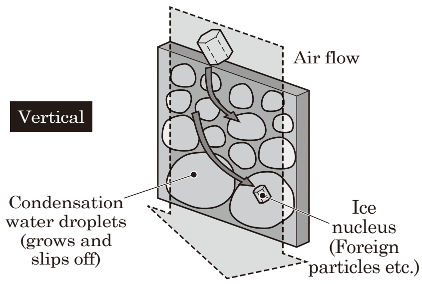
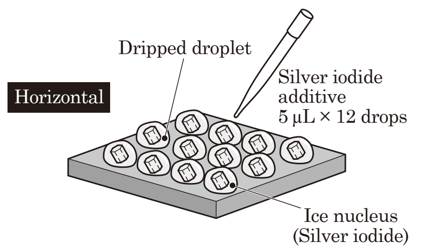
Item	Evaluation conditions
Cooling surface temperature (°C)	−26 to +4
Cooling rate (°C/min)	0.2
Air temperature (°C)	20
Air humidity (% RH)	65
Air velocity	Natural convection
Sample posture	

Table 2 Evaluation of silver iodide additive

Item	Evaluation conditions
Cooling surface temperature (°C)	−18 to 0
Cooling rate (°C/min)	1.0
Air temperature (°C)	25
Air humidity (% RH)	− (Desiccant installation)
Air velocity	Natural convection
Sample posture	

tive, enabling us to confirm the supercooling promotion effect. Based on the results in Table 1, it appears that the film of the functional coating can promote supercooling even with a water quality and cooling method similar to that of the actual operation of a heat exchanger.

In addition, Fig. 7 shows how the condensation water droplets in the supercooled state drain over time. Based on the evaluation conditions in Table 1, in order to observe the time elapse of the cooling process, the cooling temperature needs to be kept constant at a representative temperature of 0°C or lower, and the air velocity needs to be kept constant by forced convection that simulates a real environment. The photographs in the figure show how condensation water droplets grow and drain over time.

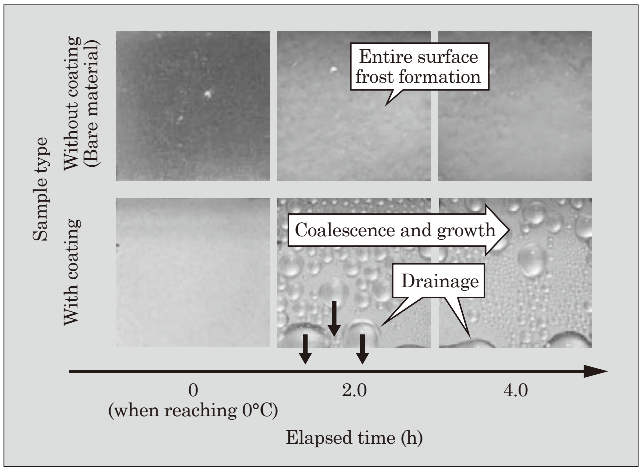


Fig.7 How the condensation water droplets in the supercooled state drain

Based on these results, we demonstrated that the designed functional coating film can promote supercooling of condensation water droplets in the heat exchanger and make it frost-free.

(2) Estimation of energy-saving effects

Frost formation occurs when condensation water droplets freeze, thus involving a phase change. This results in condensation latent heat being consumed during condensation and solidification latent heat being consumed during freezing. These two latent heats are waste energies when a heat exchanger cools air. Heat exchangers that apply frost-free technology can save energy because they no longer require solidification latent heat. Unlike conventional defrosting methods using heater, frost-free technology requires no heater power. In light of the above, we estimated the energy-saving effects of applying the frost-free technology to heat exchangers.

By using our in-house standards as conditions, we estimated the energy consumption of a conventional heater defrosting system and that of the frost-free technology. The calculation suggested that the energy-saving effect of the frost-free technology over the heater defrosting system was 7% per year for a three-foot refrigerated multi-deck showcase.

In addition, since the functional coating of this frost-free technology can be applied to conventional heat exchangers, energy-saving effects can be obtained without changing the size of the heat exchanger or the volume of the internal storage compartment.

4. Postscript

In this paper, we described a frost-free technology for heat exchangers using functional coating. This functional coating is a technology that can be applied not only to showcases but also to many other types of refrigeration equipment that use heat exchangers for cooling. Since the evaluation was conducted using small pieces of aluminum, we plan to confirm the supercooling promotion effect on the actual scale of a heat exchanger in the future. A challenge in commercialization is to reduce the production cost of the supercooling promoting substance, which is the raw material used in the coating film. In the future, we will work to overcome these challenges and develop a fully-established frost-free technology that contributes to the realization of a carbon-neutral society.

Finally, it should be noted that the supercooling promoting substance used in this development was the result of joint research with Professor Yoshiaki Hirano of Kansai University. We are grateful for his valuable contributions.

References

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(2) Tagawa, E. et al. Anti-Ice Nucleation Activities of Tyrosine Peptide. Biocontrol Science. 2018, 23(2), p.81-83.

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