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Minimizing Quality Deteriorations of Refrigerated Foodstuffs as a Side Effect of Defrosting

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Abstract— **This paper proposes an optimization scheme for traditional refrigeration systems with hysteresis controllers and scheduled defrosts. It aims at minimizing the side effect of defrost cycles on the storage quality of refrigerated foodstuffs in supermarkets. By utilizing the thermal mass of air and products inside a display cabinet, this optimization scheme forces the compressor to work harder and cool down more prior to the scheduled defrosts, thus guaranteeing the product temperature after defrost cycles still to be within a controlled safe level.**

I. INTRODUCTION

Frosting of evaporator coils is a well known and undesirable phenomenon. Frosts decrease the performance of heat exchangers, so defrosting need to be done regularly. Nowadays there are basically two defrost control schemes: defrost-on-demand and scheduled defrost. Due to the shortcoming of defrost-on-demand related to extra sensor installations, the scheduled defrost is still the most commonly used defrost scheme in today's supermarkets.

Commercial refrigeration systems, during normal operations, the air temperature inside a display cabinet is normally controlled within a specific upper and lower bound by a hysteresis controller. This is sufficient to maintain the product temperature within an ideal level. When defrosting, the air temperature inside the cabinet will rise, so will the food temperature. Sometimes the temperature is so high that it even violates the regulation from food authorities. This higher than normal temperature storage will cause an extra quality loss to food products.

Currently for commercial refrigeration systems, there are no clear and reliable measures that can prevent frost formations, see [8], so defrosting has to be done regularly. Therefore for a traditional control, this side effect of defrosting to the storage quality is unavoidable. The only way to compromise is minimizing this side effect by some optimization schemes.

This paper proposes an optimization scheme to minimize the side effect of defrost cycles to the storage quality. By utilizing the thermal mass of air and products, the optimization scheme forces the compressor to work harder and cool down more prior to the scheduled defrosts, thus guaranteeing the food temperature after defrost cycles still to be within the controlled safe level.

This paper starts with a simple introduction to supermarket refrigeration systems, including hysteresis controllers, regulations on the storage temperature for different products, frost formations, defrost methods and defrost control schemes, etc., which is in Section II. Modeling and simulations of a hysteresis controller with scheduled defrosts, as well as the food quality loss during the refrigerated storage are in Section III. An optimization scheme is proposed in Section IV, followed by some discussions and conclusions in Section V.

II. COMMERCIAL REFRIGERATION SYSTEM AND FOOD STORAGE

A. Process description

A simplified sketch of the process is shown in Fig. 1. In the evaporator, there are heat exchanges between the air inside the display cabinet and cold refrigerant, giving a slightly super-heated vapor to the compressor. After compression the hot vapor is cooled, condensed and slightly sub-cooled in the condenser. This slightly sub-cooled liquid is then expanded through the expansion valve giving a cold two-phase mixture.

Display cabinets are located inside the store. Condensers and condenser fans are located on the roof of the store. Condensation is achieved by heat exchanges with ambient air.

B. Hysteresis controller

Display cabinet's temperature is normally controlled by a hysteresis controller which opens and closes the inlet valve, to control the flow of refrigerant into the evaporator, thus keeping the air temperature within a specific upper and lower bound. Fig. 2 shows an air temperature profile for a medium temperature storage in a supermarket, where the big temperature change is caused by a defrost cycle.

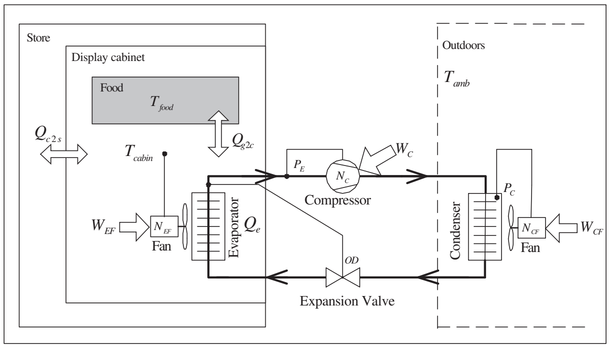

Fig. 1. Sketch of a simplified supermarket refrigeration system studied in this paper.

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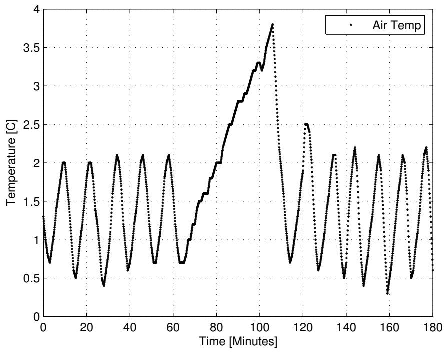

Fig. 2. One air temperature profile for medium temperature refrigeration.

C. Requirements on food storage temperature

In supermarkets, there are general requirements regarding the storage temperature for different foodstuffs in display cabinets. For example in Denmark, according to [1] and [4].

- Frozen food, the max. temperature is -18°C.
- Fresh fish and fish products, the max. temperature is +2°C.
- Milk, the max. temperature is +5°C.

The temperature here is the air temperature. In addition, there are also temperature requirements during the food processing and transportation.

D. Frost formation and defrost methods

Frosting of evaporator coils happens whenever the surface temperature of evaporator is below 0°C and humid air passes by. Frosts decrease the performance of the heat exchanger by decreasing the effective air flow area, and increasing the thermal resistance between the warmer air and the cold refrigerant inside the evaporator. In order to maintain a satisfactory performance, evaporators need to be defrosted regularly.

The most common defrost methods for medium and low temperature applications are:

- Off-cycle defrost: This is the simplest defrost method. Refrigeration is stopped, evaporator fans continue to move room air over the frosted coil surface, warm and melt frost.
- Hot/cool gas defrost: During a hot/cool gas defrost, the normal supply of cold refrigerant is stopped. The former involves the circulation of the hot gas from the compressor discharge manifold directly to the display cabinet, and the latter utilizes cooler gas from the liquid receiver. The hot or cool gas condenses on evaporators, releases heat to melt the ice from coils.
- Electric defrost: In this approach, the thermal energy to melt the ice is provided by an electric strip heater which is situated across the face of coils. During defrosting, the refrigerant supply to the evaporator is switched off, the electric heater is switched on, and evaporator fans blow the warm air heated by the strip heater through coils, melting the ice from the coils surface.

However, not all methods can be used in all circumstances. Normally, for medium temperature applications, the cheapest and least energy consuming means of defrosting is off-cycle. This method of defrosting is widely used in industries. For low temperature applications, the use of gas defrost is more energy efficient than electric defrost, but the considerable extra capital costs lead to a long payback period. Consequently, electric defrost is the most commonly used defrost method for low temperature applications.

E. Defrost control scheme

Nowadays there are basically two defrost control schemes.

- Defrost-on-demand: Initiating the defrost cycle only when necessary, see [6] and [7]. This approach normally uses one parameter to initiate and terminate the defrost process, such parameters could be: air pressure difference across the evaporator, temperature differential between the air and the evaporator surface, fan power sensing, etc.
- Scheduled defrost: Initiating the defrost cycle by a timer, normally a fixed number of defrost cycles per day. Defrosting is terminated either based on a fixed time or based on a temperature while with a maximum defrost time as a security.

The first scheme typically involves installations of additional sensors to detect frosts build-up. However, the harsh environment, where sensors have to operate, creates long-term reliability issues, that prevents its widespread adoption. So scheduled defrost is still the most commonly used defrost scheme in today's supermarkets. It is simple and uses a low cost controller.

III. MODELING

A. Modeling of a hysteresis controller with scheduled defrosts

The main modeling equations for a refrigeration system with a hysteresis controller are given in Table I (plus some equations correlating refrigerant properties, such as from the saturation temperature T to pressure p, from pressure p to enthalpy h, etc). There are two states: on and off. When on, compressor works at its full capacity; When off, compressor stops running. The pseudo code for scheduled defrosts is given in Table II. There are two states: normal and defrost. When normal, the controller shifts the state between on and off; When defrost, controller is on state off. Defrosting is initiated by a timer, and terminated based on a fixed time. Data for simulation are given in Table III, they are approximated to simulated a real plant.

B. Simulation of a hysteresis controller with scheduled defrosts

Simulation of a hysteresis controller with scheduled defrosts are shown in Fig. 3. It simulates a controller which controls the air temperature to be within an upper and lower

TABLE I

MODELING OF A REFRIGERATION SYSTEM WITH A HYSTERESIS CONTROLLER

when operating state off
mass flow of refrigerant: $m_{ref} = 0$
cooling capacity: $Q_e = 0$
compressor power: $W = 0$
heat flux condenser: $Q_c = 0$
evaporating temperature: $T_e = T_{cabin}$
condensing temperature: $T_c = T_{amb}$
switch to state on, if $T_{cabin} > T_{bound,upper}$
when operating state on
$m_{ref} = V_d \cdot \eta_{vol} \cdot \rho$
$h_{ic} = (1 - f_q)/\eta_{is} \cdot (h_{is} - h_{suc}) + h_{suc}$
$Q_e = m_{ref} \cdot (h_{suc} - h_{oc})$
$W = m_{ref} \cdot (h_{is} - h_{suc})/\eta_{is}$
$Q_c = m_{ref} \cdot (h_{ic} - h_{oc})$
$0 = Q_e - UA_e \cdot (T_{cabin} - T_e)$
$0 = Q_c - UA_c \cdot (T_c - T_{amb})$
switch to state off, if $T_{cabin} < T_{bound,lower}$

$Q_{loss} = UA_{s2c} \cdot (T_{store} - T_{cabin})$
$\dot{T}_{food} = (mCp_{food})^{-1} \cdot UA_{c2f} \cdot (T_{cabin} - T_{food})$
$\dot{T}_{cabin} = (mCp_{cabin})^{-1} \cdot (-UA_{c2f} \cdot (T_{cabin} - T_{food}) - Q_e + Q_{loss})$

TABLE II

MODELING OF A REFRIGERATION SYSTEM WITH SCHEDULED DEFROSTS

when normal
timer on
operating state switch between on and off
count up
switch to defrost, when *count* $= t_{df,ini}$
timer reset
when defrost
operating state off
count on
switch to normal, when *count* $= t_{df,duration}$
timer reset

bound of 5.0°C and 0°C respectively. Defrosting is initiated every 5 h and lasts 1.3 h. The relation between the outdoor ambient temperature T_{amb}, the condensing temperature T_c, the cabinet air temperature T_{cabin}, and the evaporating temperature T_e is shown in Fig. 4.

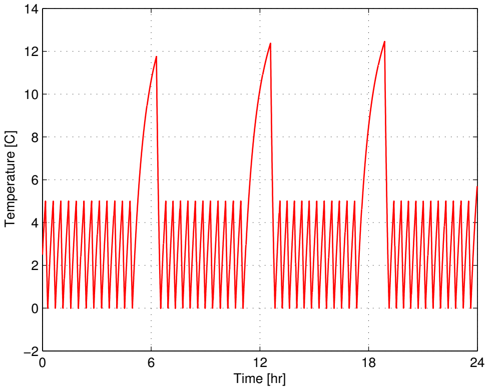

Fig. 3. Cabinet air temperature profile for a medium temperature storage, with three defrost cycles.

TABLE III

DATA USED IN THE SIMULATION

superheat: $T_{sh} = 3\,\mathrm{k}$
sub-cooling: $T_{sc} = 2\,\mathrm{k}$
volumetric capacity: $V_d = 3.3e-3\,\mathrm{m^3\,s^{-1}}$
volumetric capacity fraction: $\eta_{vol} = 0.7$
heat loss factor: $f_q = 0.20$
isentropic efficiency: $\eta_{is} = 0.5$
heat transfer coefficient: $UA_{s2c} = 80\,\mathrm{W\,K^{-1}}$
heat transfer coefficient: $UA_{c2f} = 60\,\mathrm{W\,K^{-1}}$
heat transfer coefficient: $UA_c = 1000\,\mathrm{W\,K^{-1}}$
heat transfer coefficient: $UA_e = 1000\,\mathrm{W\,K^{-1}}$
heat capacity^a: $(mCp)_{cabin} = 300\,\mathrm{kJ\,K^{-1}}$
heat capacity: $(mCp)_{food} = 450\,\mathrm{kJ\,K^{-1}}$
quality parameter: $D_{Tref} = 0.2\,\mathrm{day^{-1}}$
quality parameter: $T_{ref} = 0\,°\mathrm{C}$
quality parameter: $z = 10\,°\mathrm{C}$

[a] Combined values for air inside the cabinet, walls etc.

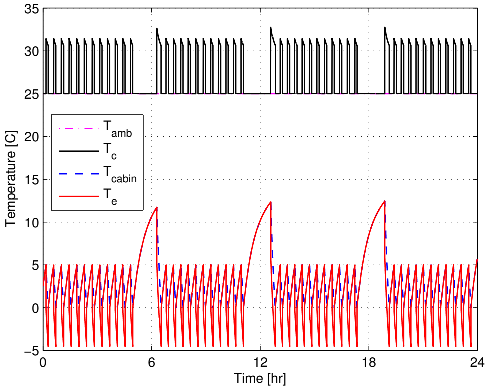

Fig. 4. Ambient, condensing, cabinet and evaporating temperature profile for a medium temperature storage, with three defrost cycles.

The work of compressor is shown in Fig. 5. After each defrost cycle, the compressor needs to work harder for a period of time, in order to bring the cabinet temperature back to its normal level.

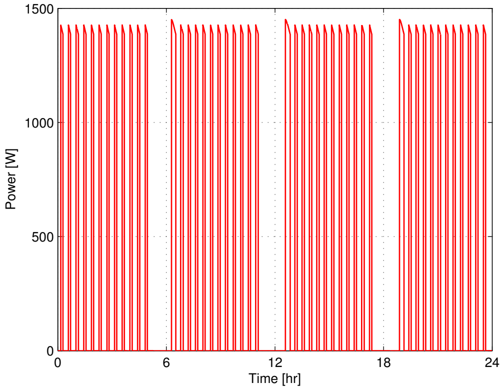

Fig. 5. Power consumption of compressor with on-off controller and scheduled defrost.

C. *Modeling of quality decay for refrigerated foodstuffs*

During food processing and storage, a lot of ”chemical” reactions occur. In general, chemistry ”reaction kinetics” are often treated in terms of reaction rates under specified conditions. In food processing, the actual reaction rate is interesting, but only as a means of obtaining the most interesting information: the integral effect, i.e. the accumulated effect after some processing steps or storage periods with varying conditions.

Examples of ”chemical” reactions are:

- Loss of vitamins
- Growth of microorganisms
- Enzymatic, non-enzymatic browning
- Changes in color
- Toughness due to oxidation

Food quality decay is determined by its composition and many environmental factors, such as temperature, relative humidity, light etc. Of all the environmental factors, temperature is the most important, since it not only strongly affects reaction rates but is also directly imposed to the food externally. The other factors are at least to some extent controlled by food packaging.

Food temperature T_{food} is determined by the cabinet air temperature T_{cabin}. For simple calculations, we lump the food into one thermal mass, therefore a uniformed temperature, and assume there is only convective heat transfer between air and foodstuffs. Normally, the surface temperature of food is different with its central layer. See details in [2].

$$(mCp)_{food}\frac{dT_{food}}{dt} = -UA_{c2f}(T_{food} - T_{cabin}) \qquad (1)$$

Food quality loss $Q_{food,loss}$ can be calculated as follows:

$$Q_{food,loss} = \int_{t_0}^{t_f} 100 \cdot D_{T,ref} \exp(\frac{T_{food} - T_{ref}}{z})dt \qquad (2)$$

Where $D_{T,ref}$, T_{ref}, z are quality parameter. For fresh fish product, such as cod, they are 0.2 day^{-1}, 0°C, and 10°C respectively. See details in [3].

The quality loss in % per minute for fresh lean fish products, such as cod is shown in Fig. 6. It shows that the quality decay rate and temperature is not linear related, high temperature causes relative higher quality decay rate.

D. *Simulation of quality decay for refrigerated foodstuffs*

Here we use a cabinet for storing and selling fresh fish products such as cod as an example. Its controller controls the cabinet temperature to be within an upper and lower bound of 2.8°C and 1.2°C respectively. We assume fish products are loaded into the display case at 2.0°C. Simulation of the cabinet air and food temperature with normal defrost cycles is shown in Fig. 7. It shows that during and after the defrost cycle, food temperature will rise and stay above 2°C for a period of time. But if no defrosting, the food products will be kept around 2.0°C, as shown in Fig. 8. The quality loss of products in 2 days with and without defrosting is shown in Fig. 9. Defrost cycles cause about 3.8% extra quality loss in 2 days.

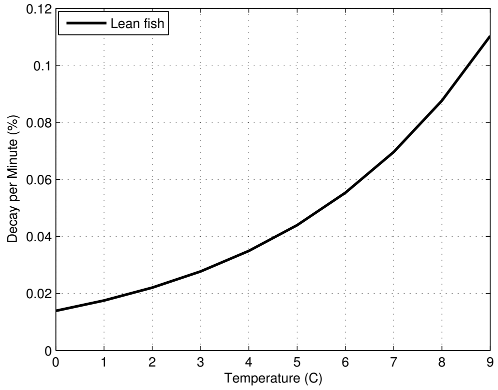

Fig. 6. Quality decay per minute for fresh lean fish product.

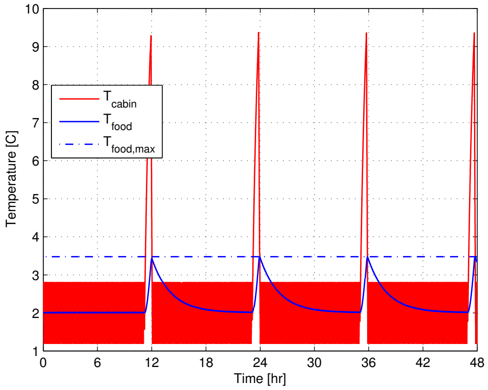

Fig. 7. Air and food temperature profile with normal defrost cycle.

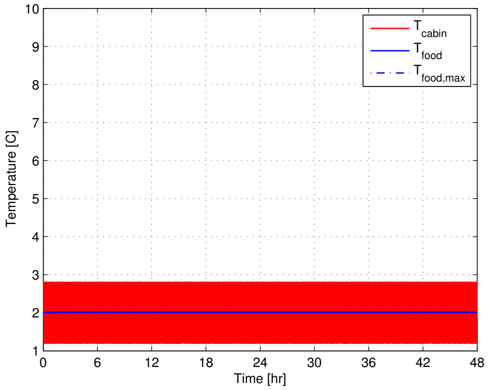

Fig. 8. Air and food temperature profile profile, if there is no defrost.

Above simulation shows that the defrost cycles do cause an extra quality loss to the refrigerated foodstuffs, and sometimes even lead the storage temperature to exceed its maximum allowable value. While nowadays, there are no cheap solutions to realize frost free for commercial

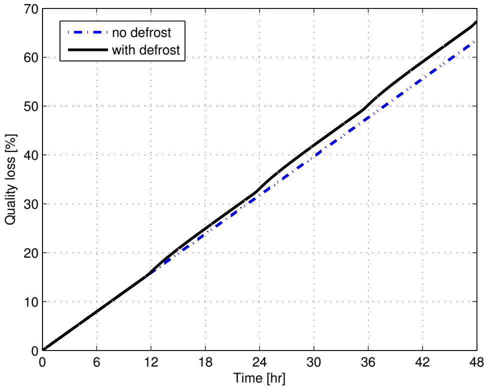

Fig. 9. Comparison of the food quality loss in % in 48 h, with and without defrost.

refrigeration systems, so defrosting has to be done in order to maintain a satisfactory performance of the refrigeration system. One way to compromise is optimizing the defrosting.

IV. OPTIMIZATION

Model of a refrigeration system with a hysteresis controller and scheduled defrosts is implemented in *gPROMS*® [5]. Optimization is done by a dynamic optimization, with the following objective function:

$$\begin{aligned} &\min_{(T_{bound,lower},T_{bound,upper})} J \\ \text{where} \quad & J = \int_{t_0}^{t_f} W(t)\,\mathrm{d}t \\ \text{subject to} \quad & T_{food} \leq T_{food,max} \end{aligned}$$

Here the maximum temperature of products after defrost cycles is restricted to be 2°C for fresh fish products, and the first 6 h after each defrost cycle is blocked to be the normal setting, and thereafter a new time invariant setting is used for optimization, result is shown in Fig. 10.

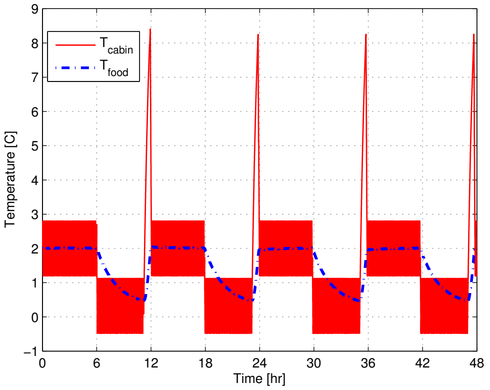

Fig. 10. Optimization: the food temperature is never allowed to exceed its maximum allowable value.

A comparison of food temperature, quality loss in 2 days under normal defrost cycle, and the optimization solution is shown in Fig. 11 and 12.

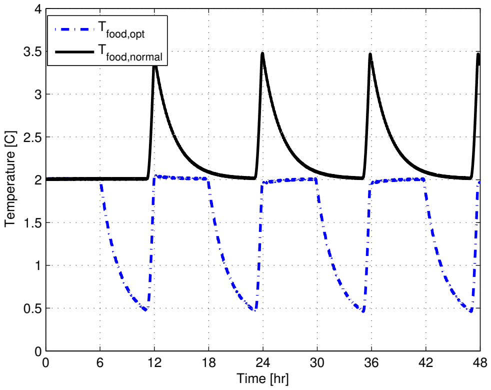

Fig. 11. Comparison of the food temperature under normal defrosting and optimization.

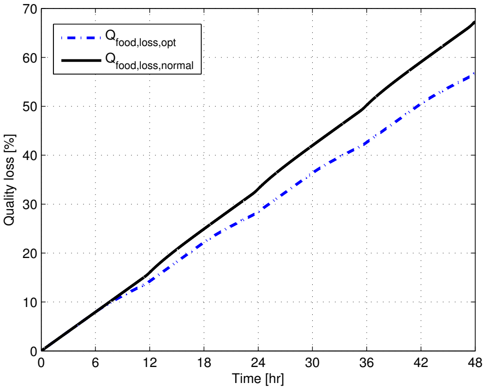

Fig. 12. Comparison of the food quality loss in 48 h under normal defrosting and optimization.

To cool down the product in advance, in order to prevent the food temperature after defrost cycles from violating the regulation, the compressor has to work harder than normal case. A comparison of the energy consumption in 48 h under normal defrosting and the optimization solution is shown in Fig. 13.

As shown in figures, in 2 days, for the optimization solution, the energy consumption is 76.2 MJ, quality loss is 56.8%. For normal case, the energy consumption is 71.0 MJ and quality loss is 67.3%.

V. DISCUSSION AND CONCLUSION

This paper deals with the problem caused by defrost cycles in supermarket refrigeration systems. The traditional hysteresis controller with a fixed upper and lower bound ensures the foodstuffs to be kept within a regulated temperature, but only in normal operations. When defrosting, the defrost cycle will raise the product temperature to a much higher level,

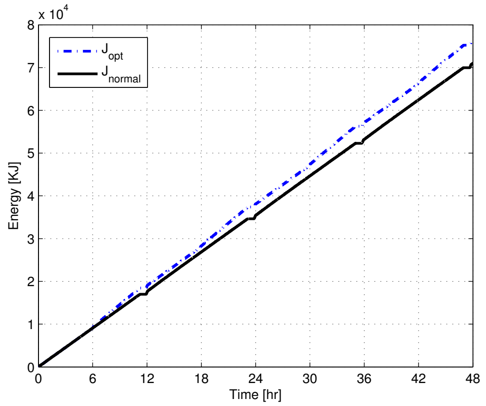

Fig. 13. Comparison of the energy consumption in 48 h under normal defrosting and optimization.

and cause an extra loss to its storage quality. To solve this problem, one way is to modify the system, realizing frost free, so no defrosting is needed. Another way is to modify the control of the system, minimizing the risk of defrosting. We focus on the latter.

By utilizing the thermal mass of the air and products inside display cabinets, this optimization scheme forces the compressor to work harder and cool down more prior to the scheduled defrosts, thus guaranteeing the product temperature after defrost cycles to be within the controlled safe level.

How to deal with the case related to defrost-on-demand, where the next defrost cycle is difficult to predict, and how to cope with the situation related to the dynamic loading of products, where the thermal capacity varies, require further investigations.

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