Optimal Operation Strategy and Energy Consumption of Food Freezing Process in Cold Store

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Abstract. A transient model of food freezing process in cold store was developed to investigate operation strategy, which was further optimized to minimize the energy consumption. Current food freezing control was based on freezing time which was controlled by airflow distribution, including temperature and velocity in common air-blast cooler. The simulation was conducted on the example of the experimental cold store, considering heat and mass transfer between air, food products and other components. Evaporation temperature of refrigeration system and fan speed of air coolers were chosen as the control variable. Results show that in any specific case of food freezing, an optimal operation strategy can be found to satisfy the freezing time requirement and minimize the energy consumption.

1. Introduction
Freezing and cooling are more effective ways to maintain superior sensory and nutritional qualities compared to other methods, such as canning and dehydration. The quality of frozen foods depends upon the control variables of freezing process, including air temperature, velocity and turbulence intensity in common case of air-blast freezer. The most commonly used operation strategy of food freezing is based on freezing time to ensure that the thermal centre temperature of food products decreases and reaches to the target point(-15°C or -18°C) in limited freezing time.

Numerical simulations are commonly used methods in the research field of food processing and optimal control. Fikiin developed a mathematical model to determination of the unsteady-state temperature and enthalpy field, as well as the cooling and freezing time[1]. Lovatt proposed a model to predict the heat load of food freezing, which requires fewer computational resources compared with numerical simulation[2-3]. Recently, there are more and more applications of CFD on evaluating the heat and mass transfer during food freezing[4-13], which can be used to predicting the food processing but not suitable to the optimization of operation.

In most of existing cold storage, evaporation temperature is the only controlled variable, while air coolers are switched on and off to keep a constant temperature in cold store. However factors affecting food freezing process does not only include air temperature, but also airflow velocity. Meanwhile, much quantity of heat is released into the storage space by air coolers while running. The objective of the work was to study and model the food freezing process and incorporate fan speed of air coolers to optimize the operation strategy and reduce the energy consumption.

2. Models
In order to evaluate food freezing process in cold store, coupled air heat and mass transfer among air, food products and other components have to be considered in governing equations. Air inside cold
store was treated as a lumped parameter model as shown in Eq. (1) and (2), where spatial differences of air parameters were ignored.

\[ M_a \frac{\partial H_a}{\partial \tau} = \sum Q = Q_w + Q_f + Q_p + Q_e \]  

\[ M_a \frac{\partial X_a}{\partial \tau} = -X_{ae} \]  

where \( M_a, H_a, \) and \( X_a \) represents air mass, enthalpy and moisture content, \( Q_w, Q_f, Q_p \) is the released heat from envelop enclosure, fan of air coolers and food products repetitively, and \( Q_e \) is the refrigeration capacity of air coolers.

For roof, floor and side walls of cold store, heat release from envelop enclosure was simplified as a lumped parameter model due to the thermal inertia. For food products, a validated model was employed for simulating temperature change and phase change during food freezing, based on the movement of freezing front towards the thermal centre. Detailed models refer to [2-3].

Air coolers drive air to circulate and carry off the heat load by food products, meanwhile the heat generated by air coolers was released into cold air directly. The sensible and total heat transfer between indoor air and coolers was modelled based on unit load factor as follows:

\[ Q'_{es} = U_{LE} \cdot \Delta T_{ae} \]  

\[ Q'_{e} = m_a (H_{ai} - H_{ao}) \]

where \( T_{ai} \) and \( H_{ai} \) is the inlet air temperature and enthalpy of air coolers, \( T_{ao} \) and \( H_{ao} \) is the outlet air temperature and enthalpy of air coolers, \( m_a \) is the air flow rate of air coolers running at full speed. In order to control the fan speed of air coolers, refrigeration capacity and heat released of air coolers was adjusted at partial speed as follows:

\[ Q_e = Q'_{e} \cdot \left( \frac{F_{an_s}}{F_{an_s}} \right)^{N_e} = Q'_{e} \cdot \left( \frac{m_a}{m_{ao}} \right)^{N_e} \]  

\[ P_{fan} = P'_{fan} \cdot \left( \frac{F_{an_s}}{F_{an_s}} \right)^{N_e} = P'_{fan} \cdot \left( \frac{m_a}{m_{ao}} \right)^{N_e} \]

Modelling on energy consumption of refrigeration system was simplified by coefficient of performance:

\[ P_{ref} = \frac{Q_e}{\epsilon_R} \]  

where \( P_{ref} \) and \( \epsilon_R \) represents the power consumption and COP of refrigeration system.

The modelling was conducted on a large cold store (18m x 8m x 8m) containing 1200 food products to be frozen. Six air coolers was located on the ceiling with rated flow rate 10000 m³/h and 1.1 kW power for each air cooler.

3. Result and discussion

Fig. 1 shows the temperature change during food freezing when evaporation temperature was kept as -32°C and air coolers runs at full speed mode. Food temperature profile can be split into three stages, which represent pre-cooling, phase change and sub-cooling in freezing process. Food temperature decreases apparently in pre-cooling and sub-cooling stages, whereas negligible temperature change can be observed in phase change due to the latent heat release. The observed gradual change in air temperature could be attributed to the interaction between air and other components.
Fig. 1. Temperature change of air, food products and refrigerator.

Fig 2 shows the evaporation temperature and energy consumption with air coolers running at full speed for extended freezing time. As the fan speed kept as constant, freezing time needed for food products increases with evaporation temperature, meanwhile energy consumption decreases. From the perspective of energy conservation, freezing time should be as long as possible. However longer freezing time always implies lower quality of freezing food, the freezing time cannot be extended without limitation.

Fig. 2. Evaporation temperature required and energy consumption to accommodate different freezing time with air coolers running at full speed.

Fig 3 shows the fan speed and energy consumption with constant evaporation temperature for extended freezing time. As the evaporation temperature kept as constant, fan speed required decreases as the freezing time increases. Similar trend can be observed for energy consumption.

Fig. 3. Fan speed required and energy consumption to accommodate different freezing time with a constant evaporation temperature.

Operation strategy and energy consumption for a constant freezing time(44h) are shown in Fig 4. To complete the freezing process in demanded freezing time, the fan speed decreases with the evaporation temperature. The result indicates that lower evaporation temperature and larger fan speed
are both beneficial for food freezing. For energy consumption including refrigeration system and air coolers, a minimum value exists as the operation strategy changes. So for any specific food products and freezing time required, there is always an optimal operation strategy to ensure a minimum energy consumption.

![Graph](image)

**Fig. 4.** Operation strategy and energy consumption for a constant freezing time.

### 4. Conclusions

This research was initiated to investigate the operation strategy and energy consumption of food freezing in cold store. Models for components in cold store were established to predict the coupled interaction, including air, food products, air coolers and refrigeration system. The models were capable of predicting the temperature profile and calculating the energy consumption. Analysis shows that extended freezing time always implies lower energy consumption. On the premise of freezing quality, freezing time should be as long as possible. For a specific freezing time, there is an optimal operation strategy of evaporation temperature and fan speed to ensure a minimum energy consumption.

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