

Influence of Airflow Field on Food Freezing and Energy Consumption in Cold Storage

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Abstract. Currently most food products are cooled and frozen in air-blast cold storage to prolong storage time. The airflow field distribution in storage has a great impact on the process of food freezing and energy cost by that. In this paper, a transient model of food freezing considering airflow field was developed to simulation the temperature profile of air and food products during freezing process. A lumped parameter model was used to predict the temperature and moisture profile of air, which connected all other components together, such as air coolers, food products, envelop enclosure and refrigeration system. A finite difference method was employed to model the heat transfer inside food products during freezing, where the mass transfer was neglected as the food products were wrapped with polystyrene films. Unit load factor method was applied to calculate the sensible heat refrigeration capacity and thus the total capacity of air coolers. The simulation was conducted on a large cold storage filled with large quantities of packaged food products. Results show that there are great differences in airflow field distribution at different locations in cold storage, which lead to spacial differences in freezing time required. Inappropriate set point of freezing time prolongs freezing process unnecessarily and leads to extra energy consumption. Operational mode of air coolers has a great impact on the total energy consumption, as they consume energy themselves and release equivalent heat into storage simultaneously.

1 Introduction

Freezing and cooling are widely used food preservation methods, and air-blast freezing is the most effective way due to the forced convection occurred between air and food products. The quality of frozen foods mainly depends upon airflow field distribution due to great spacial difference in common case of air-blast freezer. The simulation of airflow field is an essential procedure in the design and optimization of refrigeration system, as well as in ensuring the freezing quality.

Numerical methods constitute a promising way to simulate airflow field and the accuracy depends on accurate knowledge of thermal properties and mathematical models[1-5]. Lovatt developed a simplified model to predict the heat release of freezing process, which requires fewer computational resources compared with numerical simulation[6-7]. Khadije proposed a heat and mass transfer model during storage of part-baked Sangak traditional flat bread considering evaporation and condensation phenomena[8]. Miroslawa used a validated model to simulate the heat and mass transfer phenomena occurring in cold storage chambers for vegetables, which used UDF to give special attention to the modelling of interrelationship between phenomena occurring in the bulk of vegetables and in the heat exchanger of a cooling unit[9]. Degner evaluated the influence of freezing rates on the microstructure, stability and physicochemical properties of model

emulsion-based sauces[10]. Parpas presented an air temperature distribution and refrigeration system dynamic coupling model to assess the performance of air distribution systems used in chilled food processing areas and its energy consumption impact[11]. Defraeye evaluated the performance of several steady Reynolds-averaged Navier-Stokes turbulence models and boundary layer modelling approaches for a single sphere as a representative model for many spherical food products[12]. Chourasia studied the effect of the parameters of the product and the operating conditions on heat and mass transfer in the stack of bagged potatoes during the transient cooling and at steady state using the CFD modeling approach[13].

Most existing operation strategies of air-blast cold storage rely on the freezing time, which ensures that thermal center temperature of food is reduced to target point(-15°C or -18°C) in a limited period of time. Due to the spacial difference in airflow field distribution, food products are frozen at different speeds at different locations. Therefore, the freezing time should be chosen based on the food products under minimum freezing speed, which need more time to finish the freezing process. The objective of the work is to simulate the food freezing process and incorporate airflow field distribution to analyze the operation strategy and energy consumption.

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2 Models

In order to evaluate the temperature profile of food products during freezing process in cold storage, a finite difference model was employed to calculate the heat transfer inside food. Since food products studied in this paper were wrapped with polystyrene films, moisture transfer was neglected and thermal resistance of packaging was incorporated in governing equations. Two kinds of packaging material (carton box and iron box) were considered in the modeling to study the influence of packaging. The governing equations, initial condition and boundary conditions for single food freezing are shown in Eq. (1).

$$\left\{ \begin{array}{l} \rho_m \frac{\partial H_m}{\partial t} = \nabla^2 u_m \quad (0 < y < \delta_m/2, t > 0) \\ H_m(y, 0) = H_m^0 \quad (0 \leq y \leq \delta_m/2) \\ \frac{\partial u_m(y, t)}{\partial y} \Big|_{y=\delta_m/2} = h_a [T_m(\delta_m/2, t) - T_a] \\ \frac{\partial u_m(y, t)}{\partial y} \Big|_{y=0} = 0 \\ du_m = k_m dT_m \end{array} \right. \quad (1)$$

Where H_m represents the volume enthalpy of food products and enthalpy method is used to deal with the latent heat at the stage of phase change during food freezing, u_m represents the Kirchhoff transformation which deals with the rapid change in thermal conductivity around the freezing point, h_a is the calculated average surface heat transfer coefficient around food products based on the air velocity and air turbulence intensity using Eq. (2). A numerical model of wind tunnel containing food product was constructed to calculate the fitting coefficients C , m and A using the nonlinear least square method.

$$Nu = CRe^m Pr^{1/3} Tu^A \quad (2)$$

A separate CFD model was employed to simulate the airflow field in cold storage and the exported data was used to calculate the maximum and minimum velocities and determine the relative locations. Results are shown in Fig. 1, which implies great difference in velocity distribution. Maximum velocity (4.24 m/s) happens near to the outlet of air coolers. As the air flows around food products, velocity decreases gradually and forms into a vortex where a minimum velocity (0.48 m/s) is detected.

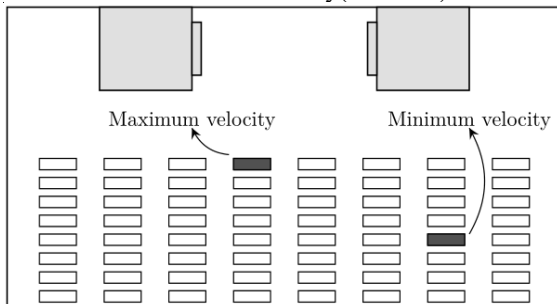


Fig. 1. Locations of maximum and minimum velocities in cold storage

CFD simulation results also suggest rather uniform distributions of air temperature and moisture, which

exhibit little divergence at different locations. Thus in the modeling of air temperature and moisture, air was treated as a lumped parameter model as shown in Eq. (3), where spatial differences of temperature and moisture were ignored.

$$M_a \frac{\partial H_a}{\partial \tau} = \sum Q = Q_w + Q_f + Q_p + Q_e \quad (3)$$

$$M_a \frac{\partial X_a}{\partial \tau} = -X_{ae} \quad (4)$$

Where M_a , H_a and X_a represent air mass, enthalpy and moisture content, Q_w , Q_f , Q_p are the released heat from envelop enclosure, fan of air coolers and food products repetitively. and Q_e is the refrigeration capacity of air coolers.

Heat load from envelop enclosure was simplified as a lumped parameter model due to the thermal inertia. Six air coolers were located at the top of cold storage, which drive air to circulate and carry away the heat released by food. Refrigeration capacity and heat load of air coolers were modeled based on unit load factor as follows:

$$Q_{es} = U_{LF} \cdot \Delta T_{ae} \quad (5)$$

$$Q_e = m_a (H_{ai} - H_{ao}) \quad (6)$$

Where Q_{es} and Q_e represent the sensible heat load and total heat load of air coolers, T_{ai} and H_{ai} are the inlet air temperature and enthalpy of air coolers, T_{ao} and H_{ao} are the outlet air temperature and enthalpy of air coolers, m_a is the air flow rate of air coolers running at full speed. Coefficient of performance was used to calculate the energy consumption of refrigeration system:

$$P_{ref} = \frac{Q_e}{\epsilon_R} \quad (7)$$

where P_{ref} and ϵ_R represents the power consumption and COP of refrigeration system respectively.

3 Result and discussion

Fig. 2 shows the temperature profile for carton box packaged food during freezing process as evaporation temperature kept as -38°C . Freezing time was set as 68h for carton box packaged food, and the target temperature for thermal center was set as -18°C . Air temperature and moisture content decrease gradually as the food products get frozen. In pre-cooling and sub-cooling stages of freezing process, food temperature decreases apparently, whereas little temperature change is observed in phase-change stage due to latent heat release. Food temperature decreases from 10°C to -30°C in carton case, which is much lower than the target temperature. The freezing time is set more than enough to finish the freezing process, which may consume extra energy for extended freezing process. As freezing process proceeds, the food temperature under average and minimum velocities gets close to each other gradually.

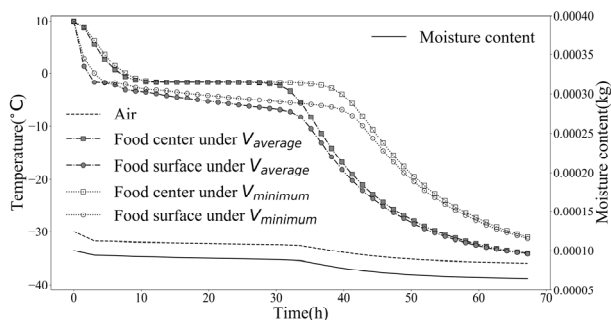


Fig. 2. Temperature profile for carton box packaged food during freezing process

Fig. 3 shows the temperature change for iron box packaged food product. Air temperature and moisture content in cold storage for freezing iron box packaged food are consistent with the result for carton box packaged food. Due to the smaller thermal resistance of iron box, the iron box packaged food exhibits a larger temperature difference between food surface and thermal center than carton box. Freezing time was set as 44h for carton box packaged food, and the target temperature for thermal center was set as -18°C . At the end of freezing process, the food temperature under average velocity has already been reduced lower than target temperature, and the food product under minimum velocity just reaches the target temperature and finishes the freezing process. The freezing time set point is suitable for iron box packaged food products, which ensures that the food product under minimum velocity finishes the freezing process in the freezing time. Obvious differences in freezing curves can be observed among food products under different velocities, which suggest non-uniform distribution of airflow field in cold storage. It costs 22 hours to pass through the phase change process for food under average velocity, while that number is 32 hours for food under minimum velocity. Based on the definition of freezing rate by IIR(The International Institute of Refrigeration), the food product under minimum velocity is frozen at a minimum freezing rate. Further analysis shows that freezing quality differs between food products at different locations.

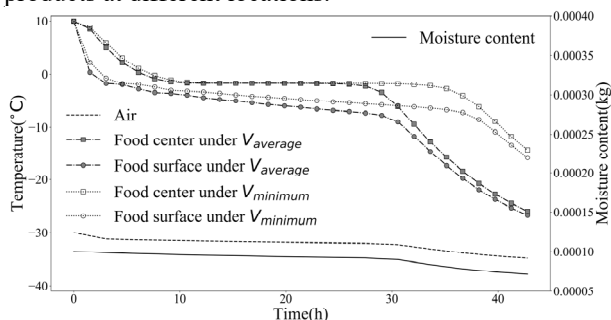


Fig. 3. Temperature profile for iron box packaged food during freezing process

Fig. 4 shows the refrigeration capacity and energy consumption with constant evaporation temperature and fan speed. As the fans of air coolers are running at a constant speed, energy consumption and heat load of air coolers are kept at a constant value along the freezing process. A trend similar to food temperature profile can be observed on refrigeration capacity and energy consumption, which divides the curves into three stages.

The change of refrigeration capacity and energy consumption are much closer to the trend of surface temperature, which determines the heat release by food products. At early stage of freezing process, food temperature starts from the initial temperature and decreases gradually, refrigeration capacity and energy cost by refrigeration system is much large than air coolers because of the fully operating system. As the process proceeds, food temperature decreases to phase transition temperature and the decline of energy consumption and refrigeration capacity slows down due to a smaller change of food temperature and heat release. At later stage of freezing process, energy consumption of refrigeration system is getting closer to the energy cost by air coolers. As the freezing process is nearing completion, the full speed running mode of air coolers has little benefit on food freezing. In addition, a considerable amount of heat is released into the storage and even more energy needs to be consumed to eliminate the heat load by air coolers. For any specific food products and freezing time set point, there is an optimal operation strategy for air coolers and refrigeration system to ensure a minimum energy consumption.

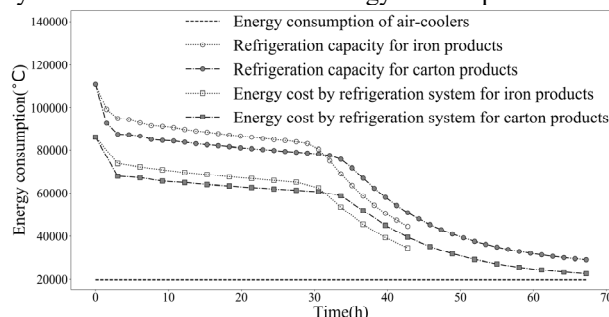


Fig. 4. Refrigeration capacity and energy consumption during freezing process

4 Conclusion

This research was initiated to investigate the airflow field and the effects on food freezing. Heat and mass transfer models between food products, air and air coolers were established to predict the freezing process and the temperature profiles. A separate CFD model was employed to calculate the average velocity and minimum velocity of airflow, as well as the relative locations. Two kinds of packaging material were considered for the food products. Analysis shows that the set point of freezing time is too large for carton box packaged food, which prolongs the freezing process unnecessarily and reduces the food temperature much lower than the target point. At early stage of freezing process, refrigeration system accounts for the largest share of energy consumption. As the process proceeds, energy cost by refrigeration system decreases with food temperature, which makes the air coolers account for an increasing proportion of total energy consumption. Full speed operational mode for air coolers exerts extra heat load on the refrigeration system, thus more refrigeration capacity and energy consumption is used to eliminate the heat released by air coolers.

Acknowledgment

The authors wish to acknowledge the support of the National Natural Science Foundation of China (No.51508341) and the Foundation of Liaoning Educational Committee(No.L2015450) for this work.

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