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REVIEW ARTICLE

Air flow and product arrangement in food freezing environment: a review

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ABSTRACT

In food industries, the production capacity is strongly influenced by the rate of heat transfer in processes such as cooling, freezing, baking, drying, toasting, thawing or chilling. A higher rate of heat transfer can increase the production rate and may improve the quality of processed foods. In freezing processes, a faster freezing rate ensures the safety of the product against microbial growth and contamination. The convective heat flow is enhanced as the fluid motion increases. Air blast cooling processes are majorly ruled by the convective heat transfer, which relates the amount of transferred energy from the product surface to the cooling air. Wide variations in convective heat transfer coefficients may occur in different positions. This work reviews the effect of air flow and product arrangement on food freezing process because of their effect on the convective heat transfer coefficient.

Keywords: Thermal conductivity, refrigerating medium, cooling, freezing, food products

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INTRODUCTION

The International Institute of Refrigeration (1986) defines various factors of freezing time in relation to both the product frozen and freezing equipment. The most important are:

- Dimensions and shape of product, particularly thickness
- Initial and final temperatures
- Temperature of refrigerating medium
- Surface heat transfer coefficient of product
- Change in enthalpy
- Thermal conductivity of product
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Uses of energy level have a direct relation with the final cost of food products, so reduction of the freezing time is a major goal for industries. Food products are basically frozen in air blast freezing tunnels, where the cooling air flows around the food product. The rate of heat exchange between air and food is given by (1):

$$\frac{dQ}{dt} = hA\Delta T \qquad (1)$$

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where Q is the amount of energy (J) removed from food in time t (s); h is the convection heat transfer coefficient ($Wm^{-2}\ {}^{0}C^{-1}$); A is the heat transfer area of food (m^2); ΔT is the temperature difference between food and air temperature (${}^{0}C$).

There are various factors which influence the effectiveness of freezing on food preservation. Air velocity, degree of contact between the food and cooling medium, packaging and product thickness can all play a part in the speed at which an item of food is frozen.In the case of blast freezing, the air velocity plays a large part in increasing the speed when compared with conventional chest freezing. Slower freezing methods, such as chest freezing, create large ice crystals in food tissues which rupture cell membranes, causing loss of moisture once thawed. This is especially the case with fish, where the flesh is more fragile.A chest freezer has no air velocity as it is considered to be a still air freezer. The chest freezer is a unit which keeps a chamber at a constant temperature well below the freezing point of water (typically -12 to -18°C) using vapor compression. When food is placed in the unit it slowly freezes as the temperature of the food lowers to that of the air inside the freezer unit.

In industrial situations, the freezing process is very complex and food products act like a barrier to air flow, and heat transfer can be compromised. A careful investigation of product characteristics and processing conditions is must, as improper positioning of product and poor air circulation can cause longer cooling periods. If the system is not correctly designed, problems related to product or process qualities can appear. There is also need to consider proper packaging materials and the possibility of the existence of voids of air bubbles inside the package, as well as improper arrangement of products, which could lead to poor heat transfer and ineffective temperature reduction. The air blast freezer is commonly used freezing equipment due to its temperature stability and versatility for several product types. In general, air is used as the freezing medium in the freezing design, either as still air or forced air. Frequently air velocity and air temperature are the parameters which regard most attention from designers of air blast systems. However, it is also important to consider the ways this air will flow trough, as product distribution may directly affect the efficiency of cooling and freezing processes. Assessing the efficiency of freezing processes is a troublesome task.

Mathematical modeling of the freezing phenomena in food products has been mainly approached as a transient conduction heat transfer problem with phase change consideration and an external convective boundary. Modeling of the external flow outside the boundary layer, the boundary layer flow, the convective heat transfer around an object together with the heat transfer inside the object (sometimes called the conjugate problem) has proven difficult. Hence, most researchers have assumed an external heat-transfer coefficient either empirically or tried to determine it experimentally. Applying software packages known as commercial computational fluid dynamics (CFD) to this situation is difficult because the heat-transfer process is essentially unsteady both inside the food and on the boundary layer surrounding the food, with time-dependent nonlinear temperature conditions at the interface of the product and flow.

Considering the complexity of the industrial process, this paper reviews the influence of air flow and product arrangement on food freezing process because of their effect on convective heat transfer coefficient.

COOLING AND FREEZING PROCESSES FOR FOOD PRODUCTS

Regarding the rapid increase in frozen foods production and consumption, there is growing interest in determining food thermal properties during freezing process for the development of new systems and improvement of processes equipments (Scott et al. 1992). Temperature reduction processes aims at reducing microbial growth and hence extending the shelf life of perishable food. Freezing and cooling processes are driven by the heat exchange between the product to be cooled and the cooling medium. Some researchers have presented models that can be used to assess the cost of food freezing by different methods (Becker & Fricke, 1999; Chourot et al., 2003).

Cooling and freezing of food is complex process. Freezing food basically depends on the amount of water that is present in the food and will convert to ice during the process. Prior to freezing, sensible heat must be removed from food until reaching the initial freezing temperature. Supercooling occurs when temperature reaches values below the freezing point and crystal nucleation starts. In pure water, heat is released during nucleation, causing a rise in temperature to the initial freezing point, and the temperature remains constant until all the water is converted to ice. However, it decreases slightly in foods, due to the increasing concentration of solutes in the unfrozen water portion. After that, during the phase change of water into ice, there is the removal of latent heat from the frozen product. It starts when most freezable water has been converted to ice, and ends when the temperature is reduced to storage temperature (Zaritzky, 2000).

Among most popular frozen food products are fruits and fruit pulps, normally used as raw material for processing industries as ice cream, yogurt, jams and others. Such products can be frozen in batch or continuous processing (Salvadori & Mascheroni, 1996). In order to make cooling processes financially affordable, studies based on information from manufacturers and users are necessary to design refrigeration equipment in accordance with the demanded application.

HEAT TRANSFER FOR COOLING PROCESS

Cooling time is directly influenced by the Biot number, defined by Equation 2:

$$Bi = \frac{hL}{k} \quad (2)$$

where h is the convective heat transfer coefficient (W/m^2°C), L is the characteristic length of the body (m), usually defined as the volume of the body divided by the surface area in contact with the cooling medium, and k is the thermal conductivity of the body (W/m°C). Values of Biot number close to zero ($Bi \rightarrow 0$), imply that the heat conduction inside the body is much faster than the heat convection away from its surface, and temperature gradients are negligible within the body. Within this condition, it can be assumed a lumped-capacitance model of transient heat transfer, leading to Newtonian cooling behavior. When the Biot number is large enough ($Bi \rightarrow \infty$), the internal resistance to heat transfer is much larger and it only can be assumed that the surface temperature is equal to the cooling medium, but not the interior of the body. For this situation, solutions of the equation of Fourier heat transfer are useful. In the case of Biot number is within the range of $0.1 < Bi < 40$, both internal and external resistance exist.

The factors such as thermal conductivity and diffusivity cannot be changed. Hence, the reduction of cooling and freezing time must be achieved by changing system variables such as temperature and velocity of the cooling air, and product arrangement.

PARAMETERS AFFECTING COOLING TIME

For industrial applications, cooling or freezing rate is the most essential parameter in the process when comparing different types of systems and equipment. Besides the characteristics of the products, the temperature removal time varies according to some parameters involved in the heat transfer process, such as size and areas of openings of the packaging and characteristics of the cooling medium. The cost of the cooling process is dependent on cooling rate, which is influenced by the opening area of packaging for air circulation, bed depth, temperature and speed of the cooling air (Baird et al., 1988).

The selection of the best cooling method varies according to the desired application and depends on several factors, including the cooling rate required, subsequent storage conditions and costs of equipment and operation. Systems properly designed may increase efficiency and reduce the cost of operation (Talbot & Chau, 1998).

Talbot & Fletcher (1996) made a comparison of efficiency between an air blast system and a storage chamber. A reduction of 6.7 ^{0}C in a hour and 14.6 ^{0}C in 2.5 hours in case of air blast system and 2^{0}C in a hour and 3.5 ^{0}C in 2.5 hours in case of storage chamber was found with grapes as food product.

AIR FLOW

Air is chosen as cooling agent in many situations, for example, in air blast freezers. The two main reasons for the use of air in refrigeration systems are: the low energy consumption to move it and to pass it by the product and the space distribution of the air velocity around of the product.

The selection of a freezer can have an important effect on energy consumption. In a blast freezer, additional energy is required to operate fans and the resulting heat from the fans increases the refrigeration load. The total power input per unit of frozen products might be two to three times higher in a blast freezer than in a plate freezer for the same freezing rate. But the major drawback with the plate freezer is that it requires the food products to have a regular shape. During air blast chilling/freezing, the heat transfer from the cold air to the inside of foods must pass two layers of thermal resistance: the external resistance between cold air and the surface of the foods and the internal resistance inside the solid foods. As a general rule for food cooling and freezing, the Biot number should not exceed 5 (Mattarolo,1976).

Cooling time in a forced air systems is dependent on airflow rate and product thermal load, which affects the amount of energy required to move the air around the product and inside the system. The airflow varies according to the speed and amount of air flowing through products and its variation results in longer or shorter freezing time. Cortbaoui et al. (2006) reported that a correct orientation of the air flow inside the equipment and around the product can significantly reduce processing times. Surface area of contact between products and cooling air and products arrangement are other parameters that affect forced air cooling (Baird et al., 1988; Fraser, 1998).

In a well designed and properly operated freezer, the velocity of the air passing over the product must be the same everywhere on the tunnel.In this way; all products are frozen almost uniformly. It is of great importance that the tunnel should be designed in such a way that the resistance posed by the products to the flow of air is equal for all air flow cross-sections. The spaces between trays should be uniform, and the spaces below, above and on the sides of trolleys should be kept at minimum. Otherwise the air will take the path of least resistance and flow without hitting the product, rendering the freezing process inefficient.

Forced air conventional cooling methods are an efficient alternative for removing the heat load of fruits and vegetables. Air exhaustion is another technique which improves the air distribution in the products surrounding and is used usually inside cooling chambers for creating low pressure regions surrounding the products. The cooling air flows through this low pressure region between the small opening areas, reducing the product temperature (Talbot & Fletcher, 1996; Talbot & Chau, 1998). The possibility of adapting a cold room for use as a system for forced air represents an economical advantage of this process (Talbot & Fletcher, 1996).

Baird et al. (1988) has reported that the velocity of cooling air influences directly the operational cost of cooling systems, as it can change with the increase of air velocity in the system. The lowest costs were obtained with air velocities between 0.1 and

0.3 m/s. To study the cooling of plastic balls filled with a solution of carrageen, Allais et al. (2006) showed that increasing the speed of air flow, ranging from 0.25 m/s to 6 m/s, reduced the half-time cooling of samples from 800 s to 500 s. But this variation is exponential, and the reduction tends to be smaller from speed of 2 m/s. Results obtained by Vigneault et al. (2004a,b) for cooling process using forced air show that air flows above 2 l/s.kg and air velocities of insufflations higher than 0.5 m/s cause no influence on half-cooling time of the samples.

METHOD FOR MEASUREMENT OF AIR FLOW VELOCITY

In food freezing, the air velocity profile determines the efficiency and the homogeneity of the treatments that the product is being submitted. In equipment used in the food processing, the air flow is generally turbulent and transient. Due to strong variability of the air velocity in the space and time, its measure is considered as a great problem, producing results not very accurate and indispensable in the air flow rate determination and heat transfer calculations.

The air flow over the surface of a product being frozen cannot be measured simply. In reality the air immediately adjacent to the surface of the product is stagnant due to the friction between the air and the surface of the product. This stagnant air forms a boundary layer which acts as a resistance to heat transfer. The layer thickness depends on air velocity, degree of turbulence and other factors.

Resende and Silveira Jr. (2002a, b) suggested that several measurements in the cross-section of the air flow could lead to a more accurate determination of the air velocity. The average velocity is therefore used for determination of the air flow in the selected position, according to (3):

$$V = \int_S v dS \tag{3}$$

In this equation, V is the flow (m^3/s), S is the total area (m^2) and v is the velocity vector (m/s).

PACKAGING AND STORAGE

Packaging affects the heat transfer coefficients of food items in several ways and it acts as a barrier to the transfer of heat energy from the food by acting as insulation to the food item, thus lowering the heat transfer coefficient. Packaging may also create air-filled voids and bubbles around the food item which further insulates the food and lowers the heat transfer coefficient (Becker and Fricke, 2004). Results presented by Santos et al. (2008) showed that freezing process of meat in cardboard boxes is underrated and the processing time sometimes is not enough for all the samples to reach the desired temperature. Replacing cardboard boxes by metal perforated boxes produced a reduction of up to 45% at the freezing time for this product.

Becker and Fricke (2004) developed an algorithm using iterative techniques to estimate the surface heat transfer coefficients of irregularly shaped food items based upon their cooling curves, considering the density of the food item and the packaging. This algorithm extends to irregularly shaped food items existing techniques for the calculation of the surface heat transfer coefficient previously applicable to only regularly shaped food items, taking into account the concept of equivalent heat transfer dimensionality. In this method, the density used to calculate the heat transfer coefficient is affected by the packaging, as it is calculated from the mass of the food item plus the packaging and the outside dimensions of the package around the food item, generating results for the heat transfer coefficient for the food within its packaging.

An important parameter for improved performance of an air blast cooling system is the apertures and gaps that the packages and pallets must have to allow the circulation of the cold air through the packed product in order to achieve rapid and uniform heat transfer between the cooling air and the product (Vigneault et al. 2004a; Zou et al., 2006a, b). Results obtained by Talbot & Fletcher (1996) showed the importance of proper cooling system design, proving that the larger the opening area in the packaging, the lower the requirement on refrigeration and air circulation systems to obtain a more uniform cooling rate. Meana et al. (2005) showed that the empty regions between the plastic containers that are used in the cooling of strawberries by forced air influence significantly the cooling time of the products. According to Baird et al. (1988), opening areas smaller than 10% of the total area of the box can significantly increase the cost of cooling processes. Castro et al. (2003) suggest that an opening area of 14% is appropriate for a rapid and uniform cooling process. Large opening areas can lead to poorly designed boxes that are not suitable for industrial processing. The main goal is to get an optimal opening area of the boxes to enable a low freezing time without, however, affecting the mechanical structure of boxes.

CONVECTIVE HEAT TRANSFER COEFFICIENTS (h)

The factor with most significant influence on freezing time is the convective heat transfer coefficient, h. this parameter can be used to influence cooling/freezing time through equipment design and should be analyzed carefully. At low magnitudes of the convective heat transfer coefficient, small changes will influence the freezing time in a significant manner.

Freezing time and corresponding refrigeration load depends upon the surface heat transfer coefficient for the freezing operation. Convective heat transfer is related to the amount of energy transferred from the product surface when it is in contact with the refrigerating fluid. It (h) depends on condition in the boundary layer, which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamics and transport properties. Regarding the wide range of convective heat transfer coefficients (h) reported, it is important to calculate this coefficient in order to understand different operating conditions of distinct cooling systems and compare to any new systems developed.

Few numbers of studies have been performed to measure or estimate the surface heat transfer coefficient during cooling or freezing of food items. Dincer (1995) experimented with figs under forced air cooling in air blast systems and found heat transfer coefficient values varying in-between 21.1 to 32.1 $Wm^{-2}\,^{0}C^{-1}$for air velocities of 1.1 to 2.5 ms^{-1}. Dincer and Genceli (1994) in another cooling experiment with air velocities in the range of 1 to 2 ms^{-1} found h values in the range of 28 $Wm^{-2}\,^{0}C^{-1}$ to 52 $Wm^{-2}\,^{0}C^{-1}$for cylindrical products (cucumber). Mohsenin (1980) obtained h values in the range of 20 to 35 $Wm^{-2}\,^{0}C^{-1}$ for forced air systems with air velocity from 1.5 to 5.0 ms^{-1}. Mohamed (2008) found that accurate descriptions of the boundary conditions are very difficult for industrial situations, and software solutions such as CFD will not be effective in solving the momentum and heat transport equation without precise information of inputs.

Temperature measurements in steady state

This method has its own limitations, since it requires a constant temperature and air velocity of cooling medium which is not practicable. The value of h is calculated by dividing the amount of energy added by product of surface area of the heating element and temperature difference between cooling medium and the heating element.

Temperature measurements in transient state

Temperature measurement in transient state condition consists of a metallic test body with a known high thermal conductivity being used to minimize the temperature gradient during the heat exchange between the cooling medium and the product ($Bi<0.1$), allowing the test body to have an almost uniform temperature during the cooling process. When the internal resistance of the test body to heat transfer is neglected, an energy balance conducts to the convective heat transfer coefficient. By Newton's cooling law, the rate of heat transfer in a given volume of control is given by equation 1. The variation of energy in a metal body with constant properties is given by the equation:

$$\frac{dQ}{dt} = \rho V c_p \frac{dT}{dt} \quad (4)$$

where ρ is the density, V is the volume and c_p is the specific heat of the metallic body, respectively. Combining equations 1 and 4, integrating and adopting the initial boundary condition T (t = 0) = T_i, leads to the solution for the temperature variation as a function of time

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{\frac{-hAt}{\rho c_p V}} \quad (5)$$

Which shows that the cooling process has an exponential behaviour, as also verified by several authors for horticultural products (Mohsenin, 1980; Dincer, 1995).The calculation of h may be made through the equation (5) as below after mathematical rearrangement:

$$h = \frac{\rho c_p V}{A \Delta t} \ln\left[\frac{T_i - T_\infty}{T - T_\infty}\right] \quad (6)$$

Where T is the current temperature, T_i is initial temperature and T_∞ is freezer environment temperature all in ^{0}C. Basically this method uses a high thermal conducting material with assumption that it has constant thermal properties within temperature variation range.

Resende et al. (2002), Mohamed (2008) and Barbin et al. (2010) reported experiments using the described method for obtaining convective heat transfer coefficients from the cooling curves obtained for a metallic test body, indicating the capability of the present method in handling complex boundary situation such as encountered in industrial systems. Results for convective heat transfer coefficients were reported by Barbin et al. (2010), comparing two air flow direction in the same equipment, concluding that this is a useful method for studying temperature reduction processes.

CONCLUSION

The freezing of food is one of the most significant applications of refrigeration. The freezing process mainly consists of thermodynamic and kinetic factors, which can dominate each other at a particular stage in the freezing process. Major thermal events are accompanied by reduction in heat content of the material during the freezing process. In order for freezing operations to be cost-effective, it is necessary to optimally design the refrigeration equipment. This requires estimation of the freezing times of foods. Freezing time of foods depends upon various factors, whose precise values are required for estimation of freezing times. Out of several factors, influencing freezing time, air velocity and product arrangement are important considerations. Accurate descriptions of the boundary conditions are very difficult for industrial air blast systems. Even software solutions such as CFD will not be effective in solving the momentum and heat transport equation without precise information about inputs. Hence, an attempt has been made in this paper to review the available methods for predicting the effects of air flow and product arrangement inside the freezing chamber.

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