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Case studies in food freezing at very low temperature

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Abstract

Freezing is one of the most widely used and effective processes to preserve foods shelf-life during long periods of time. This paper focuses on very low temperature freezing, and a thermal model, based on literature formulations, was developed to calculate the food freezing time considering several kinds of food, with different sizes, shapes and chemical composition. Moreover, once evaluated the food freezing time as a function of temperature and velocity of the cooling fluid, a chart reporting the food production rate, the freezing time and the cooling capacity was developed to properly design the freezing equipment in terms of optimal choice of the process and type of freezer.

Keywords: Low temperature freezing; Food freezing time; Freezing proces design

1. Introduction

Every year, a huge amount of food is produced to satisfy the demand of consumers, which number is high and still rising. Nowadays, legislations concerning food storage methodology are becoming more restrictive in terms of final quality of food products and of transformation [1] and storage processes efficiency. In this scenario, freezing

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assumes a relevant role, as it is a suitable method to retard food deterioration preserving, in the meanwhile, the food organoleptic properties [2].

Traditional industrial food freezers are based on air-blast system technology [3], where cold air (the medium fluid) is adopted, due to its cheapness and the low risk of food contamination, to reduce the food temperature below the freezing point, until reaching a final temperature of about -18 °C in the inner part of the product. Typically, the medium fluid temperature varies from -40 °C to -20 °C, with a velocity that ranges between 1 and 6 m/s depending on the kind, size and shape of the food product to be processed. Food can be frozen through a batch process in a closed and insulated freezing room or an in-line process in a freezing tunnel.

A relevant factor affecting the final quality of frozen food products and, thus, the design of the food industry plant equipment, is the freezing time. This parameter is deeply conditioned by the food chemical composition, in terms of water content and percentage of soluble and insoluble solids [4], and by the properties of the medium fluid. During the freezing process, the phase change of the liquid content of food does not occur at constant temperature. Indeed, when the freezing process begins at the initial freezing temperature T_{f} , due to the crystallization of a portion of water, the concentration of solute in the remaining aqueous solution increases, thus reducing the freezing point of the unfrozen portion of the food. This phenomenon gradually leads to lower the temperature required to maintain and continue the freezing process, until the complete freezing of the product is reached. In this process, the ice fraction x_{ice} of food is an important parameter describing the variable food thermal properties. Quick-freezing process, using a medium at very low temperature (even under -90/-80 °C), can assure the quickly turning of the water contained in the food into minute ice crystals, avoiding damaging the food cell membranes [5], as it may happen during freezing at standard temperature (-40/-20 °C).

Usually, very quick-freezing processes are obtained by the adoption of a cryogenic fluid or of the impingement technology, as discussed in literature. In the work of Agnelli and Mascheroni [6], a cryogenic immersion freezer (using liquid nitrogen) coupled with an air-blast freezer (using air as medium fluid) was studied. The simulations and experimental results confirmed that reduced freezing time that can be obtained using medium fluids at a cryogenic temperature. The benefits of cryogenic freezing technique on the quality of frozen storage, in comparison with traditional air-blast systems, were also evaluated by Rodezno et al. [7] and by Kim et al. [5], where systems using a liquid carbon-dioxide and a liquid solution of calcium chloride were respectively studied. The cryogenic immersion technique allows to increase the heat transfer coefficient, thus reducing the freezing time, but its adoption is limited by the high cost of the liquid fluids and by the kind of food. Liquid nitrogen can also be adopted in tunnel freezers where, by means of particular nozzles, it is usually injected in proximity of the conveyor belt where food is placed to be processed. Here, absorbing a great quantity of heat by evaporation, the nitrogen cools down the tunnel at very low temperature. Alternatively, a favorable reduction of the freezing time can be achieved by impingement technology, which consists in using high velocity air jets (50÷100 m/s) directly to the food surface, with an air temperature usually equal to -20°C [8]. Even if this technique allows to reach freezing times comparable to those obtained by using cryogenic techniques, it can be applied only to a limited kinds of foods, characterized by an high ratio surface/volume (such as peas, slices of vegetables or meat etc.).

A valuable alternative to cryogenic techniques and to the impingement is represented by air-blast freezing at very low temperatures, with values of around -90/-80 °C. Values of temperature in this range can be achieved, for example, coupling the freezer with a reversed Brayton cycle [9], where the fluid in this particular thermodynamic cycle can reach a temperature of about -140/-120 °C. In this paper, a thermal model, based on the Pham formula [10], of the freezing process with air-blast system at very low temperature is presented, which allows to evaluate the food freezing time and the proper design of the freezing equipment. This model can be applied to a wide set of food products: depending on the particular food size, shape, composition [11] and relative direction of the cooling air, the heat transfer coefficient between the medium and the food product has been evaluated by different formulation. A representative set of three food samples have been selected to describe the application of the proposed methodology. Indeed, the most suitable freezing process, in terms of type and mode (in-line process in tunnels, by batch in closed insulated rooms), can be determined depending on the peculiar food geometry and/or the available cooling capacity of the freezing plant and/or the medium fluid properties.

2. Thermal model

During freezing, foods are cooled by removing sensible and latent heat by means of a cooling medium. The process is a heat conduction problem, during which a phase change occurs inside the food product. The entire process can be divided into three steps: (1) food is pre-cooled from its starting temperature T_1 to the initial freezing temperature T_f (sensible heat); then (2) water contained in the food starts to solidify (latent heat) and finally (3) food is sub-cooled, until reaching the desired final temperature T_2 (sensible heat).

2.1. Food and medium fluid properties

Thermal properties of foods, essential for describing the dynamics of the freezing process, are strictly dependent on the composition and on the temperature of the product. The set of the main constituents of a food can be summarized as: water, proteins, fats, carbohydrates, fiber and vitamins. Foods composition, in terms of shares of each constituent, can deeply vary among different kind of food, but also, at a minor scale, within the same class of products, depending on the current quality and/or on the adopted recipe. The properties of foods (such as density, specific heat, etc.) can be thus evaluated as a combination of the properties of each constituent, which are estimated by relations proposed by Choi and Okos [12], as a function of the food temperature.

The freezing process is also influenced by the properties of the cooling medium. Indeed, the heat exchange is affected by the temperature and the velocity of the cooling medium. In the proposed thermal model, foods are cooled by air whose properties were evaluated by using the REFPROP database [13].

2.2. Determination of the heat transfer coefficient

The heat transfer coefficient h between the food and the cooling medium is a relevant parameter of the freezing process, since it describes the effectiveness of the heat exchange. It depends on the shape, size and kind of food and on the temperature and velocity (modulus and direction) of the medium fluid and can be calculated from the Nusselt number Nu. Modelling the food shape using elementary geometric forms (cylinder, sphere, flat plane, etc.) allows evaluating Nu by empirical formulations as a function of the Reynolds (Re) and Prandtl (Pr) numbers.

For example, in the case of food with a prevalent flat surface (e.g. slices of fruits or vegetables, hamburgers etc.) and a tangential direction of the medium fluid, Nu can be approximately calculated as [14]:

$$\begin{cases} Nu = 0.037\, Re^{0.8}\, Pr^{1/3} & \text{with } 5\cdot 10^5 \le Re \le 10^7 \text{ and } 0.6 \le Pr \le 60 \\ Nu = 0.664\, Re^{0.5}\, Pr^{1/3} & \text{with } Re < 5\cdot 10^5 \end{cases} \tag{1}$$

For cylindrical shape volumes (e.g. carrots, sausages, cucumbers etc.) and medium fluid perpendicular to the lateral surface, Churchill and Bernstein equation [14] should be adopted

$$Nu = 0.3 + \frac{0.62\, Re^{0.5}\, Pr^{1/3}}{(1 + (0.4/Pr)^{2/3})^{0.25}} \cdot \left(1 + (Re/282000)^{5/8}\right)^{4/5} \quad \text{with } Re \cdot Pr > 0.2 \tag{2}$$

while for spherical items (e.g. peas, cherries, blueberries etc.), the Whitaker's formula [14]

$$Nu = 2 + \left(0.4\, Re^{0.5} + 0.06\, Re^{2/3}\right) Pr^{0.4} \left(\frac{\mu_{\text{medium}}}{\mu_{\text{food}}}\right)^{0.25} \quad \text{with } 3.5 \le Re \le 8\cdot 10^4 \text{ and } 0.7 \le Pr \le 380 \tag{3}$$

should be used. Once Nu is defined, h can be easily obtained as

$$h = \frac{Nu \cdot k}{l} \tag{4}$$

where k and l are respectively the thermal conductivity and characteristic length of the food item.

2.3. Freezing time formulation

Freezing time τ, an important descriptive index of a freezing process of foods, is strictly related to the final quality of frozen food products, and its estimation is an aid to the plant designing phase in food industry. It can be calculated by the governing equation of a heat conduction problem, which can be written by using the Fourier's law, without internal heat generation,

$$\rho c_\mathrm{p} \frac{\partial T}{\partial t} = \nabla \cdot (k \, \nabla T) \, . \tag{5}$$

With the following assumptions: (1) in the case of a one-dimensional and steady-state problem; (2) considering only the latent heat that has to be removed from the food; (3) without taking into account the sensible heat needed to cool down the food from T_1 to T_f (pre-cooling stage) and from T_f to T_2 (sub-cooling stage); (4) assuming the temperature and the thermal properties of the product being constant during the phase change, the freezing time formula proposed by Plank is

$$\tau_\mathrm{plank} = \frac{L}{T_\mathrm{f} - T_\mathrm{m}} \left(\frac{PD}{h} - \frac{RD^2}{k} \right) \tag{6}$$

where L is the latent heat, T_f the initial freezing temperature, T_m is the medium fluid temperature, h is the heat transfer coefficient, k is the thermal conductivity, P, R and D are shape food factors (for more detail see [4]).

To overcome Plank's formulation limits, Pham proposed a new formulation [10] where the sensible heat released by the food during pre-cooling and sub-cooling stages is considered. In addition, a mean freezing temperature T_fm, supposed to be 1.5 K below the initial freezing temperature T_f, has to be adopted to consider the effect of the temperature variation during the food phase change. The here adopted Pham's formulation is

$$\tau_\mathrm{pham} = f_\mathrm{pham} \sum_{\mathrm{i}=1}^{3} \tau_\mathrm{i} \tag{7}$$

where τ_1 represents the time required to reduce the temperature from T_1 to T_f (pre-cooling), τ_2 the time required to freeze the food and τ_3 the time to reduce the temperature from T_f to T_2 (sub-cooling). The correction factor f_pham, proposed by Pham [15], was introduced to take into account the effects of medium fluids at very low temperature (≪– 40°C) and it can be expressed as

$$f_\mathrm{pham} = 1 + 0.41 \cdot R_\mathrm{T}^{0.5} \cdot (1 - e^{-\mathrm{Bi}}) \, , \tag{8}$$

where R_T is the ratio between the food freezing temperature T_f and medium fluid temperature T_m while Bi represents the Biot number of the foods. More in detail, each time τ_i can be calculated as

$$\tau_\mathrm{i} = \frac{Q_\mathrm{i}}{h \, A_\mathrm{s} \, \Delta T_\mathrm{m,i}} \left(1 + \frac{Bi_\mathrm{i}}{k_\mathrm{i}} \right) \tag{9}$$

where: Q_i represents the heat to be extracted during each stage; h the mean heat transfer coefficient between food product and the medium fluid; A_s the food heat exchange surface; $\Delta T_\mathrm{m,i}$ the mean logarithmic temperature difference during the different freezing stages; Bi_i is the Biot number; k_i the Pham's formula coefficient. Parameters Q_i, $\Delta T_\mathrm{m,i}$ and k_i can be evaluated according to [4]. Once defined the initial and the final food temperature T_1 and T_2 of the freezing process, the heat Q_i only depends on the properties of the food product, in particular specific heat and density, and on the volume of the food item. The effect of the food shape on the freezing process is integrated within the mean heat transfer coefficient h, the Biot number Bi and the heat exchange active surface A_s.

For a fixed couple of values of T_m and v_m, the freezing time is thus deeply affected by both the composition and the geometry/size of the food product: the first affects the properties of the food, while the second is involved in the heat exchange. For example, foods with a great content of unbound water, which has specific heat higher than other constituents, a longer freezing time τ is required, with respect, for example, to fat-rich food. The geometry/size of foods, instead, affects the heat exchange in term of the ratio between external surface, brushed by the cooling medium, and volume: products with an higher ratio, such as small sized or thin sliced items, reach really shorter freezing times with respect to the others.

It should be noted that, for a given food product, considering a constant initial and a final temperature T_1 and T_2 and a fixed relative direction of the cooling medium respect to the product surfaces, the freezing time τ can be expressed as a function of the sole medium temperature T_m and velocity v_m.

3. Application to the design of the freeze process

The selection of the proper parameters for the freezing process design is not a trivial task, since favorable conditions for a profitable food process has to be guaranteed while fulfilling possible technical specifications and requirements of the existing facilities of the factory. The final quality of frozen foods is related to the resulting freezing time τ that, in the case of adequate placement into the freezer (for example, number of products on a single tray, etc.) that limits the thermal interaction among single food items during the freezing process, is only affected by the characteristics of the cooling medium. In this situation, the most appropriate freezing time for a specific food can be obtained by finding the proper balance between medium temperature T_m and velocity v_m. Obviously, T_m and v_m must satisfy the technical features of the plant and the food characteristics, not exceeding, for example, a maximum medium velocity to avoid food freezing-burn: this constraint is particular limiting in the case of high volume items. Therefore, the freezing process at very low temperature -90/-80 °C plays an important role, allowing to obtain fast freezing processes for a wider set of food products.

Given the food production rate G of the plant, which is the mass of food that is processed per unit of time (kg/h), the overall cooling capacity Q_c of the freezing plant can be easily computed as

$$Q_\mathrm{c} = G \cdot \Delta H \tag{10}$$

where ΔH is the difference in food specific enthalpy [4] between the initial value at a temperature of the food T_1 and the final value at temperature T_2. It can be noted that the required cooling capacity Q_c is not affected by the medium properties, but it is only related to the type of food, in terms of composition of constituents, characterized by different properties and, thus, different enthalpy difference ΔH. With the objectives of assuring a certain productive capacity G, and at the same time guaranteeing a freezing process with the more appropriate conditions, the freezing plant has to be designed to provide the appropriate cooling capacity Q_c, which allows the medium temperature T_m to be maintained constant.

Once the most suitable freezing time τ has been evaluated on the base of the type of food, the selection of the more appropriate configuration of the freezing equipment, in terms of choice between a batch or an in-line process, can be performed evaluating the size of the batch lot M, defined as

$$M = G \cdot \tau \tag{11}$$

Indeed, in case of foods with particularly short freezing times, a batch process, where products are frozen by lots in a closed and insulated room, with loading and un-loading procedures, is not recommended. In this case, the batch freezing process results in a sequence of too short cycles, during which a small mass of product M is processed. Since the time required to the loading and unloading procedure of lots into and out of the freezing room will affect the overall cycle timing, it results in an inefficient management of the freezing plant. In this case, an in-line process, in which foods are processed in freezing tunnel on a conveyor belt, is more advantageous and recommended.

In case of in-line processes, the required food production rate G and freezing time τ of the product must be assured by the properly set-up of the width and the velocity of the conveyor belt and of the freezing tunnel length. The adoption of this configuration is limited, however, to values of freezing times that assure the constructive feasibility of the tunnels. Indeed, long freezing times can be obtained by both increasing the tunnel length or reducing the conveyor velocity, but, in order to guarantee the required food production rate G, a too low velocity of the belt will lead to an excessive belt width. In the last case, a batch process should be preferred.

For a batch process, particularly relevance resides in the mass of the batch lot, which can be processed in the insulated room with a particular set of temperature T_m and velocity v_m of the cooling medium, and cooling capacity Q_c of the freezing plant. With this aim, a chart of the batch lot size has been defined (see Fig. 1.b), in which iso-mass curves has been calculated as a function of the food production rate G, freezing time τ and of the cooling capacity Q_c. Therefore, given the production capacity G, the required cooling capacity $Q_\mathrm{c}$can be easily obtained and, moreover, depending on the desired freezing time τ (or cooling medium temperature T_m), the proper size of the lot to be processed by batch can be obtained.

4. Case studies

The analysis of the trade-off between a batch process or an in-line process is here applied to three different case studies: (1) sausages, (2) peas and (3) slices of pineapple. The selected products represent different foods in terms of composition, size and shape. For each sample, standard values of composition [11] were adopted and the shapes were approximated by elementary geometric objects, depending on the heat exchange surface: a cylinder for the sausage, a sphere for the pea and a flat plate for the slice of pineapple. Air was selected as medium fluid since its cheapness, large availability and low risk of contaminating foods. Composition and shape data of the selected foods are reported in Table 1.

Table 1. Composition of food products and geometrical data

	Sausage	Pea	Pineapple
Moisture fraction content: x_{wa} [%]	51.08	78.86	86.50
Protein fraction content: x_{pr} [%]	14.25	5.42	0.39
Fat fraction content: x_{ft} [%]	31.33	0.40	0.43
Carbohydrate fraction content: x_{ca} [%]	0.65	14.46	12.39
Fiber fraction of carbohydrate: x_{fb} [%]	0.00	5.10	1.20
Other fraction content: x_{ot} [%]	2.70	0.86	0.29
Bound water fraction: x_{bw} [%]	$0.4 \cdot x_{\mathrm{pr}}$	$0.4 \cdot x_{\mathrm{pr}}$	$0.4 \cdot x_{\mathrm{pr}}$
Initial temperature: T_1 [°C]	5	5	5
Initial freezing temperature: T_{f} [°C]	-1.7	-0.6	-1.0
Final temperature: T_2 [°C]	-18	-18	-18
Latent heat: L [kJ/kg]	171	263	289
Radius [cm]	1.25	0.3	5.5
Height [cm]	10	-	1.0

The results are reported into two types of charts that are related by reporting the same freezing time. The first one (Figs. 1.a-3.a) reports the freezing time as a function of the medium temperature and of the medium velocity. The second one (Figs. 1.b-3.b) reports the freezing time as a function of the food production rate and the cooling capacity. On this chart, iso-mass curves representing the batch size are also drawn. Once identified a suitable range of freezing time, as a function of the medium temperature and velocity on the first chart, it is possible to pass to the second chart where, the batch size lot can be found intersecting the same freezing time range with the desired food production rate. These charts were computed to determine the adequate lot size as a function of freezing time and of the desired food production rate G. For example, the vertical line indicated in Fig. 1.b-3.b is representative of all the different combination of design parameters (medium velocity and temperature) that assure a certain food production rate into a certain freezing time and that can be found on the first chart.

In particular, the time τ required to cool down and freeze the selected food products, from an initial temperature T_1 equal to 5°C until reaching a final temperature T_2 of -18°C, was evaluated with a medium temperature T_{m} and velocity v_{m} varying within the ranges (-110/-30 °C) and (0.4/20 m/s) respectively. In Figs. 1.a-3.a the resulting freezing time values τ for sausages, peas and slices of pineapple are reported as function of T_{m} and organized by curves for a set of discrete values of v_{m}. With the operative ranges, in terms of T_{m} and v_{m}, of an air-blast freezing system at very low temperature [9], highlighted by grey areas in Figs. 1a-1.3, the freezing time of sausages, peas and slices of pineapple results to be within the ranges of (7/14), (0.7/1.5) and (14/28) minutes respectively.

It can be observed that, for low air velocity values, a reduction of the air temperature involves a remarkable decrease in the freezing time. Comparing the obtained freezing time of the selected food samples, the effects of the food composition and of the geometry/size on the heat exchange (between food and cooling air) can be observed. In particular, the effect of the food composition can be easily identified comparing the behavior of sausages (Fig. 1.a) and slices of pineapple (Fig. 3.a), which are food samples with a remarkable difference in the water content. In the case of the first sample, the same temperature difference $T_2 - T_1$ can be obtained in a significantly shorter time (about half time) with respect to the second one. Whereas, the effect of the geometry/size of different foods on the heat exchange is particularly evident in the freezing of peas (Fig. 2.a), where shorter times, with also an order of magnitude of reduction, can be achieved comparing to product with a lower ratio surface/volume, such as slices of pineapple (Fig. 3.a), a food product with different shape but a similar content of unbound water.

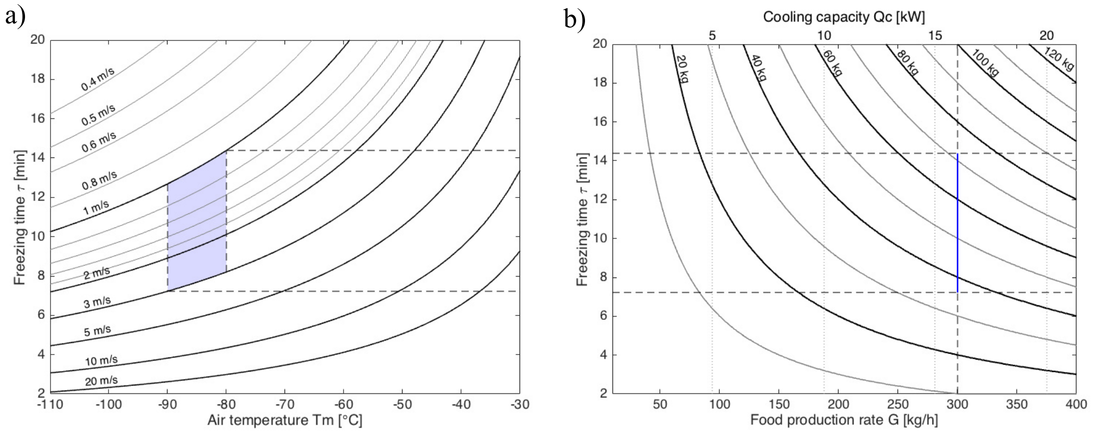

Fig. 1. Food sample: Sausage. (a) Freezing time as a function of air temperature and velocity. (b) Chart for freezing process design.

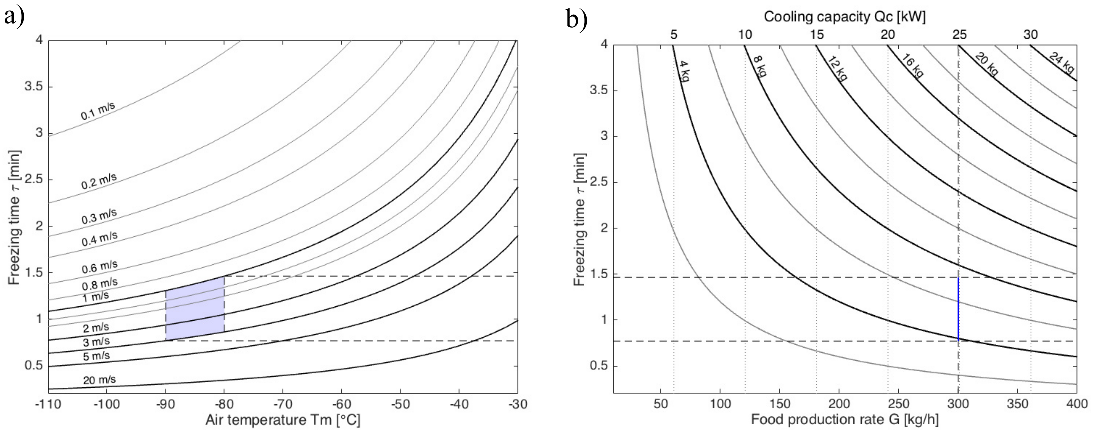

Fig. 2. Food sample: Pea. (a) Freezing time as a function of air temperature and velocity. (b) Chart for freezing process design.

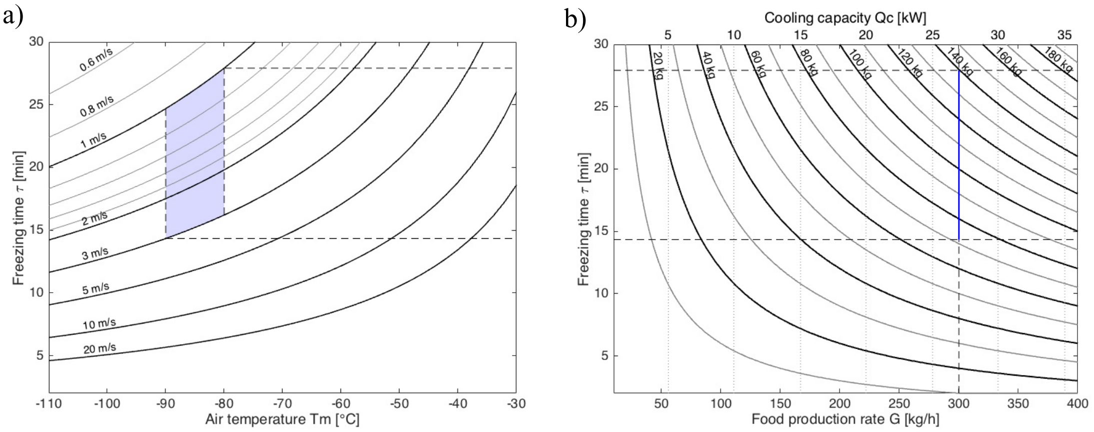

Fig. 3. Food sample: Pineapple. (a) Freezing time as a function of air temperature and velocity. (b) Chart for freezing process design.

The second chart can be used to size the freezing plant and to verify the options of using a batch or tunnel process. With the aim to freeze a certain quantity of food per unit of time G ensuring, at the same time, the maintenance of the more appropriate process environment (in terms of constant value of the medium temperature T_{m}), the designed freezing plant equipment must, of course, provide a suitable cooling capacity Q_{c}. Consider, for example, a plant with a desired food production rate G of 300 kg/h: the differences in contents composition of food samples deeply affect the required cooling capacity Q_{c}, which results in 16 kW for sausages (Fig. 1.b), 25 kW for peas (Fig. 2.b) and 27 kW for slices of pineapples (Fig. 3.b). Once the ranges of freezing time τ for each food sample (highlighted by horizontal dashed lines in Fig.1.a to 3.a), obtained by the proper trade-off between values of T_{m} and v_{m}, has been determined, the most adequate lot size, in term of mass of food product, can be evaluated. At this point, the freezing time is uniquely determined and plays a key role in deciding whether a batch or in-line process should be used. Processing all the three food samples in the same environment (with medium temperature within the range (-90/-80 °C) and velocity of (1/3 m/s), the size of the required lot M, derived by Eq. (11), are determined to be in the range (35/70 kg) for sausages (Fig. 1.b), (4/7 kg) for peas (Fig. 2.b) and (70/140 kg) for slices of pineapple (Fig. 3.b). In the case of peas, for example, a batch process is not reasonable.

5. Conclusions

In this work, useful charts for designing a low temperature freezing process and apprising the trade-off between the various design parameters (freezing time, cooling capacity, medium temperature, food production rate and type of food product) were determined. The developed methodology and the charts can be assists during the design of new industrial food freezers plants, being also a profitable aid in choosing between batch processes, where foods are frozen by lots in a closed and insulated room, or in-line ones, in which food is processed in freezing tunnel on a conveyor belt. Moreover, the thermal model adopted can be applied to all type of food products.

References

[1] Biglia A, Fabrizio E, Ferrara M, Gay P, Ricauda Aimonino D. Performance assessment of a multi-energy system in a food industry. *Energy Procedia* 2015;82:540-45.

[2] Castro-Giráldez M, Balaguer N, Hinarejos E, Fito PJ. Thermodynamic approach of meat freezing process. *Innov Food Sci Emerg* 2014;23:138-45.

[3] Dempsey P, Bansal P. The art of air blast freezing: Design and efficiency considerations. *Appl Therm Eng* 2012;47:71-83.

[4] ASHRAE. *Refrigeration ASHRAE Handbook*. 2010; ISBN 978 1 933742 82 3.

[5] Kim BYH, Liesse C, Kemp R, Balan P. Evaluation of combined effects of ageing period and freezing rate on quality attributes of loins. *Meat Sci* 2015;110:40-5.

[6] Agnelli ME, Mascheroni RH. Cryomechanical freezing. A model for the heat trasnfer process. *J Food Eng* 2001;47:263-70.

[7] Rodezno ELA, Sundararajan S, Mis Solvan K, Chotiko A, Li J, Zhang J, Alfaro L et al. Cryogenic and air blast freezing techniques and their effect on the quality of catfish fillets. *LWT- Food Sci Technol* 2013;54:377-82.

[8] Salvadori VO, Mascheroni RH. Analysis of impingement freezers performance. *J Food Eng* 2002;54:133-40.

[9] Foster AM, Brown T, Gigiel AJ, Alford A, Evans JA. Air cycle combined heating and cooling for the food industry. *Int J Refrig* 2011;34:1296-304.

[10] Pham QT. An extension to Plank's equation for predicting freezing times for foodstuffs of simple shape. *Int J Refrig* 1984;7:377-83.

[11] USDA. *Nutrient database for standard reference*. 1996, release 11. U.S. Department of Agriculture, Washington D.C.

[12] Choi Y, Okos MR. 1986. Effects of temperature and composition on the thermal properties of foods. In Food Engineering and Process Applications 1986;1:93-101. LeMaguer M, Jelen P; eds. Elsevier Applied Science, London.

[13] NIST *Reference Fluid Thermodynamic and Transport Properties Database*: Version 9.1. National Institute of Standards and Technology (Standard Reference Data). United States Department of Commerce. Gaithersburg, Maryland.

[14] Holman JP. *Heat Transfer*. 10th ed. New York: McGraw-Hill Series in Mechanical Engineering; 2010.

[15] Pham QT. Freezing time formulas for foods with low moisture content, low freezing point and for cryogenic freezing. *J Food Eng* 2014;127:85-92.