2022

Effect of the Freezing Rate on the Quality of Frozen Strawberries

Diogo L. Da Silva

Alexsandro Silveira

Adriano Ronzoni

Christian Hermes

Da Silva, Diogo L.; Silveira, Alexsandro; Ronzoni, Adriano; and Hermes, Christian, "Effect of the Freezing Rate on the Quality of Frozen Strawberries" (2022). *International Refrigeration and Air Conditioning Conference.* Paper 2297.
https://docs.lib.purdue.edu/iracc/2297

Effect of the Freezing Rate on the Quality of Frozen Strawberries

Diogo L. DA SILVA [1,*], Alexsandro S. SILVEIRA [2], Adriano F. RONZONI [3], Christian J. L. HERMES [2]

[1] Laboratory of Vehicular Refrigeration, Department of Mobility Engineering, Federal University of Santa Catarina
Joinville, SC, Brazil

[2] POLO Laboratories, Department of Mechanical Engineering, Federal University of Santa Catarina
Florianopolis, SC, Brazil

[3] Nidec Global Appliance, Joinville, SC, Brazil

[*] Corresponding Author: diogo.londero@ufsc.br

ABSTRACT

Usage of blast freezing to increase the shelf life of food has increased steadily over the years, initially on industrial grounds but recently reaching the households appliances. Albeit being a preservation method that does not require the addition of chemical preservatives, it is known that low freezing rates damage the cellular structure of the food due the formation of large ice crystals. To assess the effect of freezing rate on the quality of food, an experimental apparatus able to control the air temperature and velocity was designed and constructed. The freezing time was measured on strawberry samples (*Fragaria x ananassa*) that were frozen under different air temperature and velocities. The quality of the samples was evaluated based on drip loss and hardness measurements carried out after the thawing process, and then correlated with the freezing rate. Moreover, a mathematical model was implemented to predict the freezing time as a function of operating conditions and thermophysical properties of the food samples. The trade-off between the external and internal thermal resistances was identified and related to the freezing time. Finally, the results showed an increase of 73% on the samples hardness and a reduction in the drip loss by 7 times when the operating condition is changed from -20°C / 0.4 m/s (ordinary household freezer) to -53°C / 6.5 m/s (blast freezer).

1. INTRODUCTION

Among the different methods of food preservation, the freezing process stands out due to its ability to inhibit microbiological growth and undesired chemical reactions, even without the application of chemical preservatives, by reducing the availability of liquid water. Freezing allows the consumption of large amounts of food in regions far from the production centers and outside the harvest season, being a key element in the modern society. As the final quality of frozen food depends on the freezing rate, different freezing methods have been used and developed in the past decades. Dempsey and Bansal (2012) show that the blast freezing method, in which cold air is forced at high speeds over the food to be frozen, is extensively used because it results in relatively uniform freezing rates, even on foods with irregular shapes. In general, blast freezing systems use air velocities between 1.5 and 8.0 m/s, and air temperatures below -35°C (Salvadori and Mascheroni, 2002). Many studies available in the literature show that the blast freezing method achieves fast freezing rates that reduce the transfer of liquid water to the external side of food cells, resulting in relatively small ice crystals, which reduce damage on the cellular structure and, consequently, the loss of water and nutrients during the thawing process, also known as drip loss (Li and Sun, 2002; Kaale et al., 2013; Delgado and Rubiolo 2005; Schudel et al., 2021). Such desirable characteristics not only increase the shelf life, but also bring the quality of the frozen food closer to that observed in the so-called *in natura* counterpart.

Food composition involves different substances like water, carbohydrate, proteins and fibers. Unlike pure substances, the solidification process of foods does not occur at constant temperature. This behavior is explained by the fact that, in food, the freezing of liquid water content causes the increase in the concentration of the solutes in the remaining liquid water, which in turn decreases the freezing point temperature (Damodaran and Parkin, 2017). Another important aspect related to food freezing processes is the accurate prediction of the freezing time, which is a fundamental design criterion for the refrigeration systems. Different simplified models have been proposed based on the pioneering formulation proposed by Plank (1913), originally developed to predict the freezing time of pure liquid water. Such models consider realistic characteristics involved in food freezing process, as the food thermophysical properties, temperature variation during the phase change process, and the sensible heat removal above and below the initial freezing point, which results in a balanced compromise between accuracy and complexity (Pham, 1984).

Although blast freezing has its main applications in industrial and commercial refrigeration niches, in recent years such a technique also began to be used in household refrigerating appliances. However, the relation between food quality and household appliances design parameters, which in turn are ruled by the freezing rate, is not yet fully understood (Ergün et al., 2020; Hoffmann et al., 2021). In addition, the cooling capacity of domestic freezers is generally specified to preserve food that is already frozen, not to freeze fresh goods at high rates (Pearson, 2020). Therefore, the present work is aimed at investigating the effect of the refrigeration system operating conditions, such as air temperature and velocity, on freezing rate and the quality of food. To this end, samples of *Fragaria x ananassa* strawberries were adopted.

2. EXPERIMENTAL APPARATUS

Figure 1 shows a cross sectional view of the experimental apparatus, which is essentially a closed-loop wind tunnel designed to provide a strict control the air temperature and velocity upstream of the test section. The former is adjusted using an evaporator (a) and an electric heater (b) ruled by a PI controller, whilst the latter is set by a variable-speed fan (c) based on the volumetric air flow rate measured at the nozzle (d). The airflow at the desired setpoint is then directed to the test section (e), where the samples are frozen. The experimental uncertainties of air velocity and temperature measurements are ±10% and ±0.5°C, respectively. The structure itself is made of 200-mm thick EPS walls to ensure proper thermal insulation, which is particularly needed for tests at air temperatures as low as -53°C.

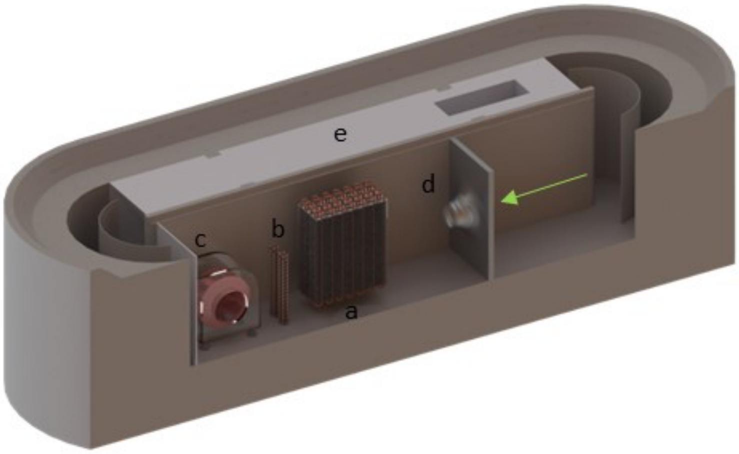
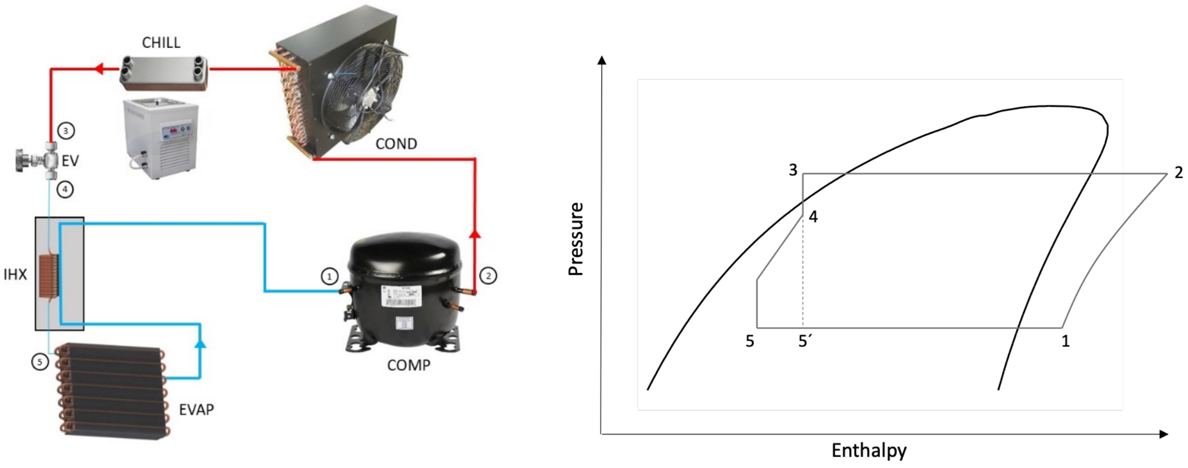


Figure 1: Schematic view of the experimental setup

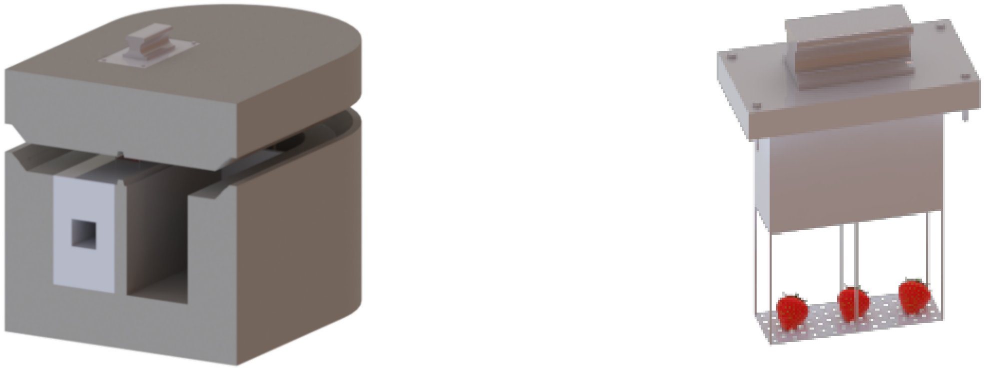
Figure 2 depicts a schematic representation of the single-stage compression refrigeration loop (Fig. 2a) and the correspondent thermodynamic state description by means of a pressure-enthalpy diagram (Fig. 2b). The compression process (1-2) is carried out by a variable-speed reciprocating compressor (COMP) with a volumetric displacement of 15 cm^3. The condensation process (2-3) is carried out by an air condenser (COND) connected in series with a plate-type heat exchanger (CHILL) cooled by a brine solution that allows the reduction of condensing pressure to increase the cooling capacity, particularly at low evaporating temperatures. An expansion valve (EV) is connected in series with a capillary tube to control the refrigerant flow and the evaporating temperature according to the required operating conditions. The testing facility is equipped with an internal heat exchanger (IHX) between the capillary tube and the suction line not only to protect the compressor against slugging but also to increase the evaporator (EVAP) cooling capacity by shifting the thermodynamic state 5´to 5, as illustrated in Fig. 2b.



(a) (b)

Figure 2: Schematic representation of the refrigeration loop (a), and its thermodynamic states in a *p-h* diagram (b)

Figure 3 illustrates the test section (Fig. 3a) and the so-called drawer (Fig. 3b), where the food samples (eight strawberries) are placed. The drawer allows the samples preparation and instrumentation at the room temperature, while the air temperature and velocity at the test section are reaching the steady-state conditions. The strawberry samples were select beforehand based on mass, external dimensions and ripening criteria. The average mass, soluble solids content, and distance between the head and the apex points were 21.0 g, 6.4° brix and 4.5 cm, respectively. Three out of eight samples are instrumented with thermocouples placed near its thermal center. The freezing time, freezing rate, drip loss and hardness of the samples were measured, as described below.



(a) (b)

Figure 3: Detailed views of the test section (a) and the food samples drawer (b)

2.1 Freezing time and freezing rate

The freezing time was defined as the time required to the thermal center sample temperature be cooled down from the initial freezing point to -18°C. The freezing rate was calculated as the ratio between half of the sample diameter and the freezing time.

2.2 Thawing process

After the freezing process has been completed, the thawing process was carried out moving the samples out from the test section and placing them inside a defrost chamber previously set at 15°C. The thawing process was finished when the temperature of the center of the food samples reaches 4°C.

2.3 Drip loss and hardness measurements

The impact of the freezing process on the quality of the samples was assessed by means of drip loss and hardness measurements. The former was evaluated by means of the difference between the initial and final mases, as follows:

$$DL = 100(1 - m_c/m_i) \tag{1}$$

where m_i represents the total sample mass before the freezing and m_c is the total sample mass after the thawing. In addition, the hardness of the samples was quantified by means of the so-called texture analyzer equipped with a 35-mm probe. The maximum drip loss and hardness measurement uncertainties are ±0.5% and ±15%, respectively.

2.4 Testing conditions

Experiments were performed considering air temperatures ranging from -20°C down to -53°C, and air velocities ranging from 0.4 up to 6.5 m/s. These values were chosen to cover the conditions typically observed in applications spanning from ordinary domestic appliances to stand-alone blast freezers. The experimental conditions used in this work are presented in Table 1, where Test #1 represents a central point of the experimental domain, test #10 employs the coldest air temperature at maximum velocity, and test #7 represents a typical domestic freezer operating condition.

Table 1: Summary of testing conditions

Test #	Air velocity [m/s]	Air temperature [°C]
1	3.5	-30
2	6.5	-40
3	6.5	-20
4	6.5	-30
5	3.5	-20
6	3.5	-40
7	0.4	-20
8	0.4	-30
9	0.4	-40
10	6.5	-53

3. PREDICTION MODEL

The mathematical model proposed by Cleland and Earl (1984) was used in this work for predicting the freezing time of the samples. Such an approach was selected due to its good accuracy while keeping a low computational cost. Also, the model considers aspects such as temperature variation during the phase change process and sensible heat removal above and below the freezing point, being both key phenomena affecting the freezing rate. Basically, the freezing time is calculated from:

$$\theta = \frac{\Delta H}{\Delta T}\left(\frac{PD}{h} + \frac{RD^2}{k_s}\right)\left[1 - \frac{1.65\, Ste}{k_s} ln\left(\frac{T_c - T_m}{T_{ref} - T_m}\right)\right] \tag{2}$$

where ΔH is the sample volumetric enthalpy change between T_f and final center temperature T_c, whereas T_{ref} (-18°C) is the reference temperature, and ΔT is the weighted average temperature difference defined as follows:

$$\Delta T = \left(T_f - T_m\right) + \frac{\left(T_i - T_f\right)^2 C_l - \left(T_f - T_c\right)^2 C_s}{2\Delta H} \tag{3}$$

where C_l represents the volumetric specific heat of the unfrozen phase, C_s is the volumetric specific heat of the frozen phase, T_i and T_f are the initial and the initial freezing food temperatures, T_m is the cold air temperature. Approximating the samples geometry by spheres, the shape factors P and R can be calculated from:

$$P = 0.1084 + 0.0924Pk + Ste(0.231Pk - 0.3114/Bi + 0.6739) \tag{4}$$

$$R = 0.0784 + Ste(0.0386Pk - 0.1694) \tag{5}$$

where *Pk, Ste* and *Bi* are the Plank, Stefan and Biot numbers, defined as follows:

$$Pk = \frac{C_l\left(T_i - T_f\right)}{\Delta H} \tag{6}$$

$$Ste = \frac{C_s\left(T_f - T_m\right)}{\Delta H} \tag{7}$$

$$Bi = \frac{hD}{k_s} \tag{8}$$

where D is twice the shortest distance between the thermal center and the sample surface, k_s is the solid phase heat transfer conduction coefficient and h is the coefficient of convective heat transfer, calculated from (Whitaker, 1972):

$$Nu = 2 + \left[0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right] Pr^{0.4} \left(\frac{\mu_m}{\mu_s}\right)^{\frac{1}{4}} \tag{9}$$

where Re is the Reynolds number and Pr is the Prandtl number, while μ_m and μ_s are the air viscosities evaluated at T_m and at the average food temperature, respectively.

4. RESULTS AND DISCUSSION

The cooling-freezing curve of test #10, obtained for an air temperature of -53.0°C and velocity of 6.5 m/s, is depicted in Fig. 4. Based on the stopping criterion previously defined, the freezing time for this experimental condition was measured as 7.3 minutes. Three stages can be seen during the freezing process, defined as precooling, phase change and subcooling. The first stage begins at the initial temperature (T_i) of 20°C and is completed when the initial freezing point (T_f) is reached. The first slope change observed at 7.8 minutes for -1.9ºC reveals the beginning of the phase change, which takes 5.5 minutes to be completed. During the phase change, it is observed that the temperature is not constant due to the increase of the solute concentration in the remaining liquid water, which is known as constitutional supercooling (Porter *et al.*, 2009). Ultimately, the beginning of the subcooling stage is identified by the second slope change, which takes place at 13.3 minutes for -4.5°C.

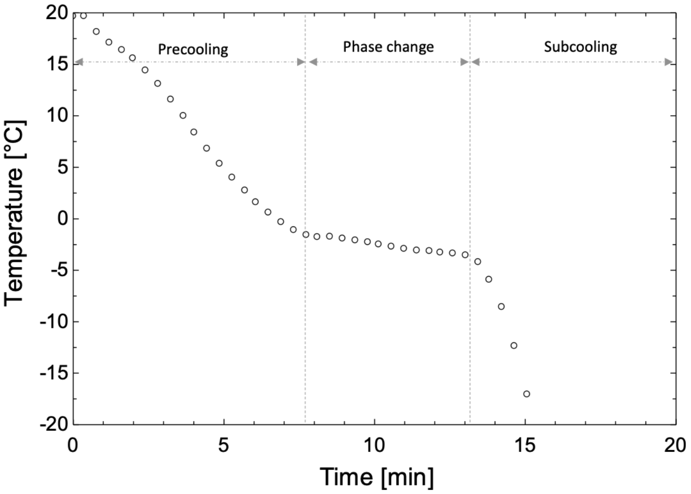
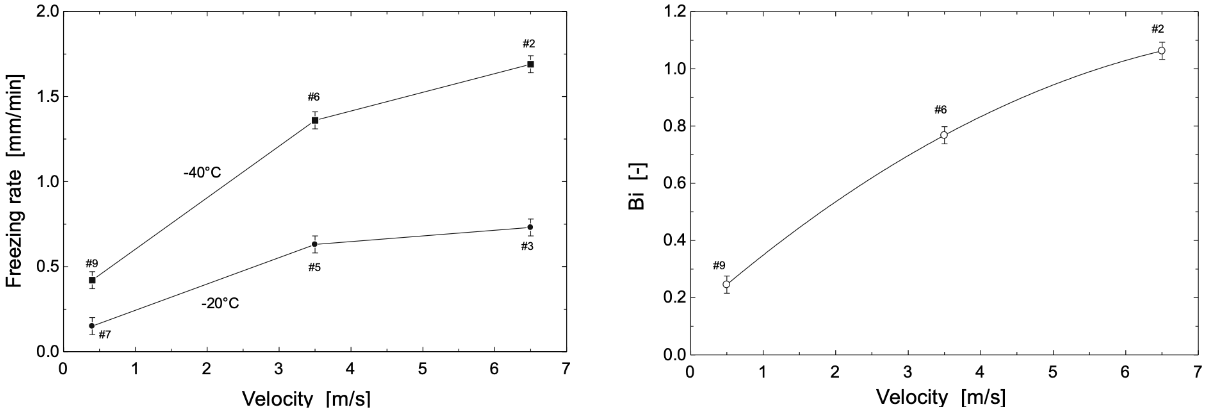


Figure 4: Experimental cooling-freezing curve for the conditions of test #10

Figure 5a presents the results of six experimental conditions of Tab. 1, showing that the freezing rate is enhanced when the air velocity is increased and/or the air temperature is reduced. A significant contrast is observed when comparing tests #2 and #7, being the latter performed with a condition similar to those observed in ordinary household appliances. Such a change in experimental conditions increases the freezing rate from 0.15 mm/min to 1.69 mm/min, an eleven times augmentation as higher air velocities reduce the convective thermal resistance between the air and the food sample, while lower air temperatures increase the temperature difference, thus intensifying the heat transfer rate.

The results also show that the effect of air velocity on the freezing rate is not linear, and depends on the air temperature. For example, a decrease of the air velocity from 3.5 m/s to 0.4 m/s at -40°C results in a freezing rate reduction of approximately 3.2 times. On the other hand, a reduction of just 1.2 times in the freezing rate is observed when the air velocity is reduced from 6.5 m/s to 3.5 m/s at the same temperature (-40°C). Such behavior is due to the effect of the air velocity on the ratio between the internal thermal conduction and the external convective resistance of the samples, evaluated by means of the Biot number, defined as in Eq. (8). Fig. 5b shows the Biot number as a function of the air velocity, where Eq. (7) was adopted to calculate the heat transfer coefficient. The asymptotic behavior in Fig. 5b shows that the effect of air velocity on the total thermal resistance is gradually reduced: as the air velocity is increased, the convective resistance is reduced so that the conduction resistance inside the samples rules the heat transfer.



(a) (b)

Figure 5: Experimental freezing time (a) and Biot number (b) for different testing conditions

Figure 6 compares experimental and simulated results for the freezing rate according to testing conditions #1 to #6. The tests carried out at 0.4 m/s were not included in the analysis as their operating conditions are out of the validity range of Eq. (2). As can be seen, all the results lie within a ±20% error band, while a small tendency for the model to underestimate the results for freezing rates greater than 1.25 mm/min can also be observed. However, such results are satisfactory if one takes into account the model assumptions and the experimental uncertainties.

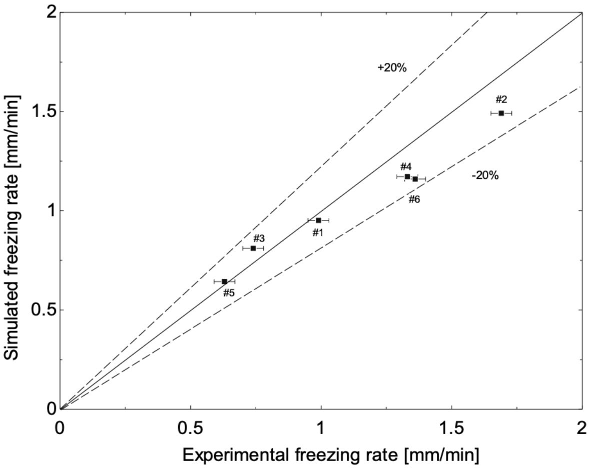


Figure 6: Comparison between experimental and simulated freezing rates

After the validation exercise, the model was used to assess the relation between the freezing time and air velocities and temperatures outside the experimental range, when air temperatures as low as -60°C and air velocities up to 12 m/s were considered in the calculations. The continuous lines represent the conditions inside the experimental domain, while the dashed lines are related to the model extrapolations. Obviously, the freezing time is reduced by decreasing the air temperature or increasing the Biot number. Nonetheless, a closer look at the curves reveals that a decrease in the Biot number increases the slopes, mainly at higher air temperatures (>-30°C), thus revealing that air temperature reductions at relative low air velocities or air velocities increase at relative higher air temperatures have a stronger effect on the reduction of the freezing time. Understanding of such non-linearity is quite useful when selecting compressors, evaporators and fans for blast freezing applications.

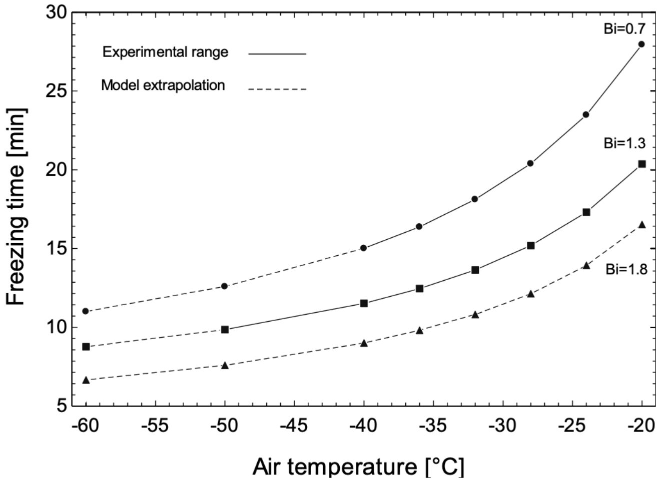
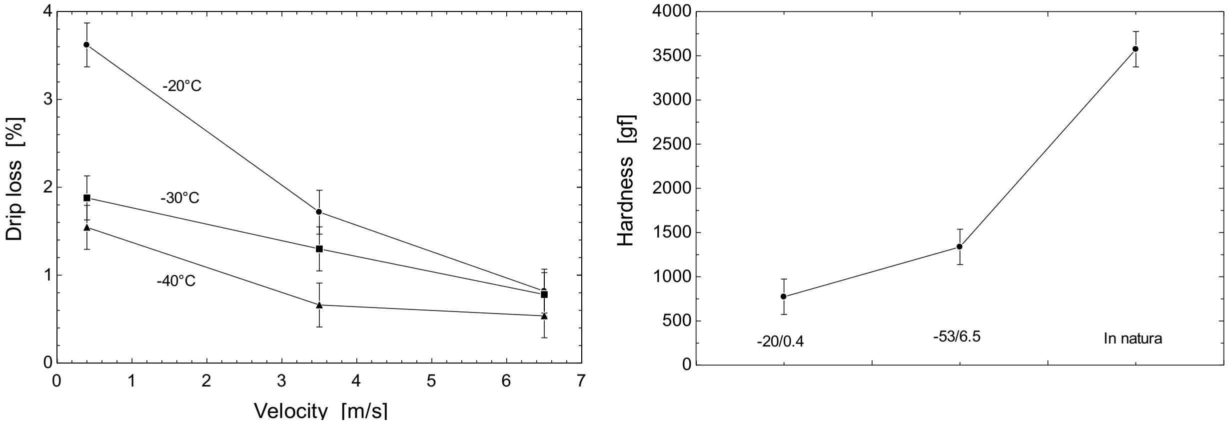


Figure 7: Simulated freezing time as function of Biot number and air temperature

To evaluate the relation between the food quality and the freezing conditions, drip loss and hardness measurements were carried out after thawing the samples. Figure 8a shows that the drip loss is reduced by increasing the air velocity and/or reducing the air temperature, both key parameters in increasing the freezing rate. In addition, an average drip loss figure of 3.5% is observed at 0.4 m/s and -20°C, which represents the performance of an ordinary domestic freezer. On the other hand, for 6.5 m/s and -40°C, the drip loss is reduced to 0.5%, a 7 times reduction. The statistical significance of the drip loss measurements was assessed by means of an analysis of variance (ANOVA), showing a p-value of 0.02 (<0.05), thus corroborating the conclusions.



(a) (b)

Figure 8: Experimental comparisons of drip loss (a) and hardness (b) measurements for different testing conditions

Furthermore, the effect of the operating conditions on the hardness of the samples is presented in Fig. 8b. It is worth noting that texture measurements quantify human sensory experience when chewing the food. Unlike drip loss, texture measurements can be also carried out with fresh (*in natura*) samples that can be used as a reference. As expected for strawberries, the *in natura* sample present the higher hardness figures (3574 gf). In addition, it can be seen that the hardness result for test condition #10 (i.e. -53°C and 6.5 m/s that led to the faster freezing rate) presents higher figures in comparison to test condition #7 (-20°C and 0.4 m/s that led to the slower freezing rate). In summary, the change from condition #7 to condition #10 increases the hardness from 773 gf to 1337 gf, respectively, which is equivalent to a 73% augmentation. These results confirm that increasing the freezing rate brings the quality of the frozen-thawed food closer to that observed in the *in natura* counterpart.

Also, the drip loss was correlated with the air velocity (m/s) and temperature (°C), yielding the following surface:

$$DL = exp(2.14 - 0.18V + 0.04T) \tag{10}$$

The regression analysis presented R^2=0.92, indicating a good mathematical representation of the experimental dataset. Figure 9 shows the surface described by Eq. (10), where it can be seen that the increase of air velocity and the reduction of the air temperature cause an asymptotic reduction of the drip loss. A surface extrapolation suggests that the drip loss of the strawberry samples can be reduced even further.

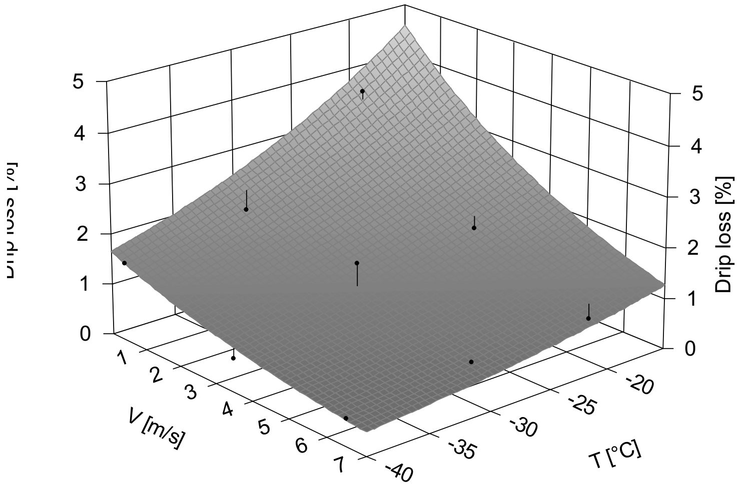


Figure 9. Graphical representation of Eq. (10) (solid points stand for the experimental data)

5. SUMMARY AND CONCLUSIONS

The effects of the air velocity and air temperature, and therefore the freezing rate, were evaluated on the quality of frozen strawberry (*Fragaria x ananassa*) samples. An experimental facility was design and constructed to control the air velocity and air temperature in the test section during the freezing process. Air velocities ranging from 0.4 m/s up to 6.5 m/s, and air temperatures ranging from -20°C down to -53°C were considered. The experimental results show the effect of air velocity and temperature on the freezing rate. For -20°C and 0.4 m/s, which represents the operating condition of an ordinary household freezer, the measured freezing rate was 0.15 mm/min, while 1.69 mm/min was achieved for -40°C and 6.5 m/s. A prediction model was implemented, was validated (showing results within ±20%). and used to predict the samples freezing rates outside the experimental range.

The model revealed that the air temperature reductions at relative low air velocities or air velocities increase at relative higher air temperatures have a stronger effect on the reduction of the freezing rate. In addition, food quality analyses were carried out by means of drip loss and texture measurements to assess the impact of the freezing process on the quality of the samples. The results show a reduction of 7 times on the drip loss, when the operating conditions are changed from -20°C / 0.4 m/s to -40°C / 6.5 m/s. An analysis of variance confirmed the effects of air temperature and velocity on the samples drip loss (p-value=0.02). Also, the result showed an increase of 73% on the samples texture, when the operating condition is changed from -20°C / 0.4 m/s to -53°C / 6.5 m/s. The experimental dataset was used to carry out a regression analysis of the drip loss as a function of the operating conditions, i.e. air temperature and velocity, when an asymptotic behavior was observed as the air velocity is increased whilst the air temperature is reduced. These results confirmed that the quality of frozen-thawed foods is strongly correlated with the freezing rate.

NOMENCLATURE

Roman

Bi	Biot number	(-)
C	Volumetric specific heat	(J $m^{-3}K^{-1}$)
D	Thermal diameter	(m)
DL	Drip loss	(%)
H	Volumetric enthalpy	(J m^{-3})
h	Coefficient of convection	(W $m^{-2}K^{-1}$)
k	Coefficient of conduction	(W $m^{-1}K^{-1}$)
m	Mass	(kg)
Nu	Nusselt number	(-)
P	Shape factor	(-)
Pk	Plank number	(-)
Pr	Prandtl number	(-)
Re	Reynolds number	(-)
Ste	Stefan number	(-)
T	Temperature	(K)
V	Velocity	(m s^{-1})

Greek

Δ	Difference	(-)
μ	Viscosity	(kg $m^{-1}s^{-1}$)
θ	Freezing time	(s)

Subscripts

c	final at center
f	initial freezing point
i	initial
l	unfrozen phase
m	cold air
ref	reference
s	frozen phase

REFERENCES

Cleland, A.C, Earle, R.L. (1984). Freezing time predictions for different final product temperatures. *Journal of Food Science, Vol. 49*, No. 4, pp. 1230-1232.

Delgado, A.E., Rubiolo, A.C. (2005). Microstructural changes in strawberry after freezing and thawing processes. *LWT - Food Science and Technology*, *Vol. 38*, No. 2, pp. 135-142.

Dempsey, P., Bansal, P. (2012). The art of air blast freezing: Design and efficiency considerations. *Applied Thermal Engineering*, *Vol. 41*, pp. 71-83.

Damodaran, S, Parkin, K. L. (2017). *Fennema's Food Chemistry*, 5th Edition, CRC Press.

Ergün A.R., Yanat, M., Baysal, T. (2020). The effects of the novel home freezing system on microstructure, color, antioxidant activity, and microbiological properties of strawberries. *International Journal of Refrigeration, Vol. 121*, pp. 228-234.

Farouk, M.M., Wieliczko, K.J., Merts, I. (2003). Ultra-fast freezing and low storage temperatures are not necessary to maintain the functional properties of manufacturing beef. *Meat Science*, *Vol. 66*, pp.171-179.

Hoffmann, T.G., Ronzoni, A.F., Da Silva, D.L., Bertoli, S.L., De Souza, C. K. (2021). Impact of household refrigeration parameters on postharvest quality of fresh food produce. *Journal of Food Engineering*, *Vol. 306*, 110641.

Kaale, L.D., Eikevik, T.M., Bardal, T., Kjorsvik, E., Nordtvedt, T.S. (2013). The effect of cooling rates on the ice crystal growth in air-packed salmon fillets during superchilling and superchilled storage. *International Journal of Food Refrigeration*, *Vol. 36*, pp. 110 – 119.

Li, B., Sun, D.W. (2002). Novel methods for rapid freezing and thawing of foods – a review. *Journal of Food Engineering*. *Vol. 54*, pp 175-182.

Pearson, A. (2020). Refrigeration Applications Column - Working from home, *Ashrae Journal*, pp 70, June.

Pham, Q. T. (1984). An extension to Plank's equation for predicting freezing times for foodstuffs of simple shapes. *International Journal of Refrigeration, Vol. 7*, pp. 377 – 383.

Plank, R. (1913). Die Gerfrierdauer von Eisblocken. *Zeitschrift für die gesamte Kälte Industri*, *Vol. 20*, No. 6, pp. 109-114.

Porter, D.A., Easterling, K.E., Sherif, M.Y. (2009). Phase transformations in metals and alloys, 3rd edition, CRC Press.

Salvadori, V.O., Mascheroni, R.H. (2002). Analysis of Impingement freezers performance. *Journal of Food Engineering, Vol. 54*, No. 2, pp. 133 - 140.

Shudel, S., Prawiranto, K., Defraeye, T. (2021). Comparison of freezing and convective dehydrofreezing of vegetables for reducing cell damage, *Journal of Food Engineering, Vol. 293*, 110376.

Whitaker, S. (1972). Forced convection heat transfer correlations for flow in pipe, past flat plates, single cylinders and for flow in packed beds and tubed bundles. *AIChE Journal*, *Vol. 18*, pp. 361-371.

ACKNOWLEDGEMENTS

The financial support from Nidec Global Appliance and Embrapii, through Grant No. PPOL-1901.0020, and the funding provided by the National Institutes of Science and Technology (INCT) Program (CNPq Grant No. 404023/2019-3; FAPESC Grant No. 2019TR0846) are duly acknowledged. The authors are also thankful to Breno Borges, Eliana Weiss, Jairo Vieira and Pedro Bruggemann, undergrad students at the POLO Labs, for their help with the experiments.