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EVALUATION OF BLAST FREEZING PROCESS ON THE QUALITY OF FROZEN STRAWBERRIES (*FRAGARIA X ANANASSA*)

Diogo Lôndero da Silva
ReVe - Vehicular Refrigeration Lab, Mobility Engineering Deptartment, Federal University of Santa Catarina, Joinville, SC, Brazil
diogo.londero@ufsc.br

Alexsandro S. Silveira
Christian J. L. Hermes
POLO Laboratories, Mechanical Engineering Department, Federal University of Santa Catarina, Florianópolis, SC, Brazil

Adriano F. Ronzoni
Nidec Global Appliance, Joinville, SC, Brazil

Abstract. *Domestic freezers are widely used to store food for long periods. In addition to preserving the properties of food, low temperatures inhibit the growth of microorganisms without the need for chemical additives. Freezing food with conventional domestic freezers produces large ice crystals, which in turn destroy the food cellular structure. To minimize these drawbacks, domestic blast freezers are being developed to achieve fast freezing rates in compact units. However, the relationship between the refrigeration system parameters and the food quality are not completely established. In this context, the present work is aimed at investigating the effect of the refrigeration system operating conditions on the food freezing time and quality. For this end, an experimental apparatus capable of controlling the air temperature and velocity was designed and assembled. Freezing time and drip loss were measured on strawberry samples (Fragaria x ananassa) under different air temperature and velocities. Moreover, a mathematical model was implemented to predict the freezing time. The model takes into account the food temperature variation during the phase change processes and the sensible heat removal above and below the food initial freezing point. The mathematical model was validated against the experimental results, showing errors within ±20% thresholds. The results also reveal how the operating conditions affect the balance between the convective and conductive thermal resistances, and their impacts on the freezing time. Furthermore, it is also explored how the operating conditions can be combined to improve the quality of frozen food based on drip loss measurements.*

Keywords: *blast freezing, freezing time, food preservation, drip loss*

1. INTRODUCTION

The freezing of food allows its preservation for long periods, increasing its offer in regions far from the production centers and even outside the harvest and production period. Food freezing can be performed by different methods, among them the so-called air blast freezing process which is largely used in commercial and industrial applications. In air blast freezing, fans are employed to enhance the heat transfer coefficient and to reduce air temperature gradients throughout the freezer (Dempsey and Bansal, 2012). According to Salvadori and Mascheroni (2002), typical blast freezing operations consider air velocities spanning from 1.5 to 8.0 m/s and air temperatures below -35°C. Different researchers show that fast freezing rates obtained with blast freezers lead to the formation of small ice crystals, which are critical to minimize cellular structure damage and drip loss during thawing (Li and Sun, 2002; Kaale et al., 2013; Delgado and Rubiolo 2005). Fast freezing is therefore able to keep the organoleptic properties of the frozen food closer to the *in natura* counterparts. However, it is hypothesized that there does exist a threshold beyond that an increase in freezing rate did not impact overall product quality during storage (Farouk, 2003). Recent developments in the realm of blast freezers for domestic applications have heightened the need for a better understanding of the relationship among the refrigeration system design parameters and the food quality (Hoffmann et al, 2021; Ergün et. al 2020). In general, domestic freezers are designed to preserve food that is already frozen, not to freeze fresh goods (Pearson, 2020). For these reasons, the present work is aimed at advancing the studies on the effects of the refrigeration system operating conditions as air stream velocity and temperature on the frozen food quality, using samples of *Fragaria x ananassa* strawberries for the analysis.

2. EXPERIMENTAL WORK

An experimental apparatus was designed and constructed to carry out the experiments under strictly controlled conditions. This characteristic is particularly useful in studying food samples, which naturally presents considerable

variability among its properties. As can be seen in Figure 1, the experimental apparatus is comprised of a close loop air circuit, which is used to control the temperature and the velocity of the air stream at inlet of the test section (TS). After flowing through the evaporator (EVP), the air temperature is adjusted to the set point by means of an electric heater (EH) driven by a PI controller. In its turn, the variable velocity fan (FAN) controls the air velocity based on the volumetric air flow rate measured at the nozzle (NZ). The maximum experimental uncertainties of temperature measurements and air velocities are ±0.5°C and ±10%, respectively. Figure 1 also depicts the positions where the temperatures were measured. Temperatures T1-T3 were measured inside the food samples, while T4-T8 were used to monitor and control the air temperatures at different locations in the experimental apparatus during the tests.
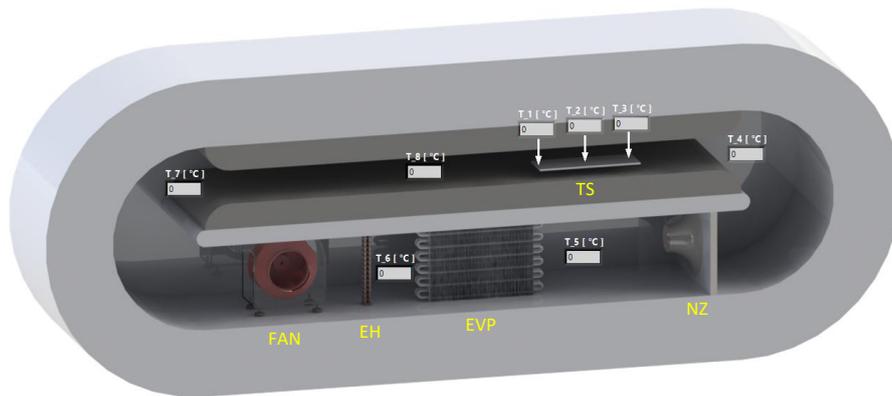

Figure 1. Schematic representation of the experimental setup

Figure 2 illustrates a schematic representation of the refrigeration circuit installed in the experimental setup. It is comprised by a single-stage compression cycle with an internal heat exchanger employed to increase the evaporator cooling capacity and to protect the compressor against liquid slugging. The refrigeration system is equipped with a 15-cm^3 variable capacity compressor running with the propane (R-290) as refrigerant.
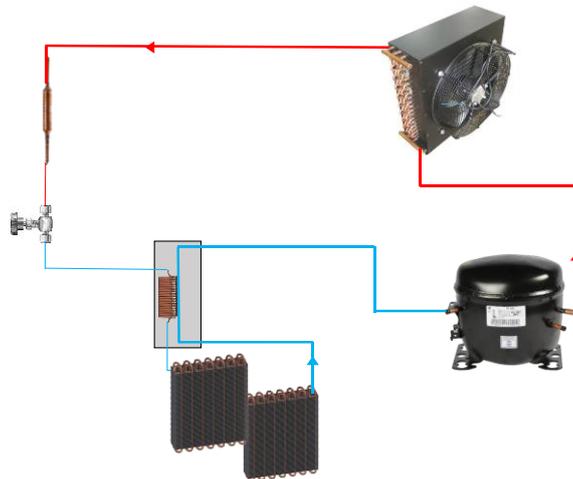

Figure 2. Schematic representation of the refrigeration circuit

A detailed view of the test section is depicted in Fig. 3a. The test section has a drawer (see Fig. 3b) where the food samples are placed at ambient conditions outside the wind-tunnel (20°C), whereas the test section reaches steady-state conditions inside the wind-tunnel. The drawer with eight samples is inserted into the test section and so the test starts. Three out of eight samples are instrumented with thermocouples placed near the center. The strawberry samples were select beforehand based on a similar mass, external dimensions and ripe criteria. The average mass, soluble solids content and distance between the head point and apex point were 21.0 g, 6.4° brix and 4.5 cm, respectively. The freezing time and drip loss of the samples were measured in each experiment, as described below.

(a)   (b)

Figure 3. Detailed view of the test section and the food samples drawer

2.1 Freezing time

The freezing time was defined as the time required for pulling down the food sample from the initial freezing point until -18°C.

2.2 Thawing process

The thawing process was carried out immediately after the freezing process was completed. The samples were removed from the test section and placed in a defrost chamber, previously set at 15°C. The thawing process is completed when the food sample temperature reaches 4°C.

2.3 Drip loss

The drip loss was measured by evaluating the relative difference between the initial and final mass of the samples, as follows:

$$Drip\ loss = \frac{m_i - m_f}{m_i} \tag{1}$$

where m_i represents the total sample mass before the freezing process while m_f is the total mass sample after the thawing process.

2.4 Experimental plan

In order to emulate different operating conditions, ranging from ordinary domestic freezers up to forced convection blast freezers, the experiments were performed considering air velocities ranging from 0.4 up to 6.5 m/s, and air temperatures spanning from -20°C down to -40°C. Table 1 shows the test conditions used in this work. Test #1 is a central point of the experimental domain, while test #7 represents an ordinary domestic freezer operating condition.

Table 1. Operating 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

3. MATHEMATICAL MODEL

The freezing time was evaluated considering the strawberries as spheres and using the mathematical model proposed by Cleland and Earl (1984). The model takes into account the food temperature variation during the phase change process, and the sensible heat removal above and below the datum freezing point. Based on these considerations, 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 D is twice the shortest distance between the thermal center and the strawberry surface, h is the coefficient of convective heat transfer, k_s is solid phase coefficient of conduction heat transfer, T_m is the cold air temperature, T_c is the final center temperature, T_{ref} (-18°C) is the reference temperature for ΔH, while the P and R are parameters that consider the food geometry expressed as

$$P = 0.1084 + 0.0924Pk + Ste\left(0.231Pk - \frac{0.3114}{Bi} + 0.6739\right) \tag{3}$$

$$R = 0.0784 + Ste(0.0386Pk - 0.1694) \tag{4}$$

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

$$Bi = \frac{hD}{k} \tag{5}$$

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

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

Also, ΔT is the weighted average temperature difference expressed as

$$\Delta T = (T_f - T_m) + \frac{(T_i - T_f)^2 C_l - (T_f - T_c)^2 C_s}{2\Delta H} \tag{8}$$

where T_i is the initial food temperature, C_l is the volumetric specific heat of the unfrozen phase, C_s is the volumetric specific heat of the frozen phase, ΔH is the sample volumetric enthalpy change between T_f and final center temperature T_c. As the geometry of the food samples was similar to spheres, the convective heat transfer coefficient were evaluated based on the correlation recommended by Whitaker (1995), as follows:

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

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

4. RESULTS

Figure 4 shows the cooling-freezing curve for test #2, obtained with air temperature and velocity of -40.0°C and 6.5 m/s, respectively. The cooling-freezing curve profile reveals that the freezing process is divided in three stages, defined as precooling, phase change and subcooling. The precooling stage starts at the initial temperature (T_i) and is completed when the initial freezing point temperature (T_f) is reached, deflagrating the phase change stage. As can be seen, the beginning of the phase change is identified by the first inflection on the cooling-freezing curve, approximately at 5.5 minutes and -2.0°C in Fig. 4. Later, the second curve inflection identifies the beginning of the subcooling stage, approximately at 13.5 minutes and -5.0°C. Furthermore, it is observed that the phase change does not occur at a constant temperature. This is explained by the fact that the sample is comprised by different substances like water, carbohydrate, proteins and fibers. As part of the liquid water content is frozen, the concentration of the solutes increases in the remaining liquid water, which in turn decreases the freezing point temperature. For this particular condition, the freezing time was measured as 9.2 minutes.
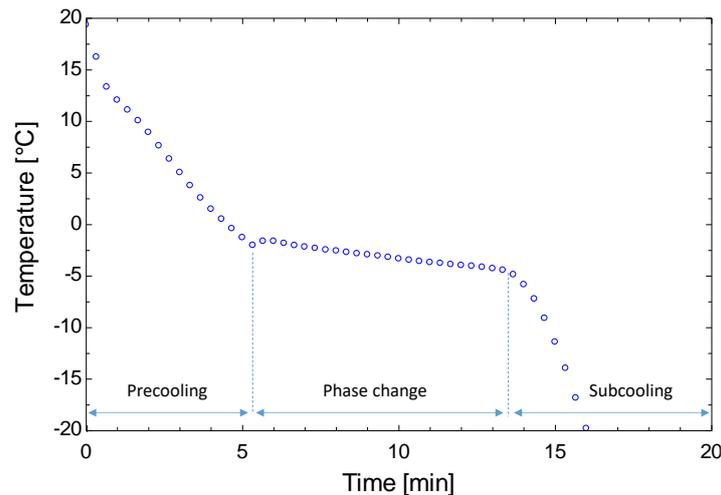
Figure 4. Sample of an experimental cooling-freezing curve

Figure 5 compares the effect of air velocity on freezing time for air temperatures of -20°C and -40°C. The largest freezing time of 120 minutes was achieved at -20°C and 0.4 m/s, which represents operating conditions similar to those observed in ordinary domestic freezers. As can be seen, the freezing time is reduced by increasing the air velocity and reducing the air temperature. For instance, at -40°C and 6.5 m/s, the observed freezing time is only 9.2 minutes. The considerable difference between freezing times of this two operating conditions is justified by the fact that higher air velocities increase the heat transfer coefficient between the air and the food, while lower air temperatures increase the temperature difference, which in turn increases the heat transfer rate.

Figure 5 also shows that low air velocities as 0.4 m/s significantly increase the freezing time. For instance, at -20°C, the reduction of air velocity from 3.5 m/s to 0.4 m/s increases the freezing time by approximately 4 times. However, the results show that the freezing time variation is not so drastic when the air velocity is reduced from 6.5 m/s to 3.5 m/s at the same temperature (-40°C), increasing the freezing time by only 1.2 times. This result is explained by the relative magnitude of the internal conduction resistance and the external convection resistance of the samples, represented by the Biot Number, $Bi = (hD)/k$.
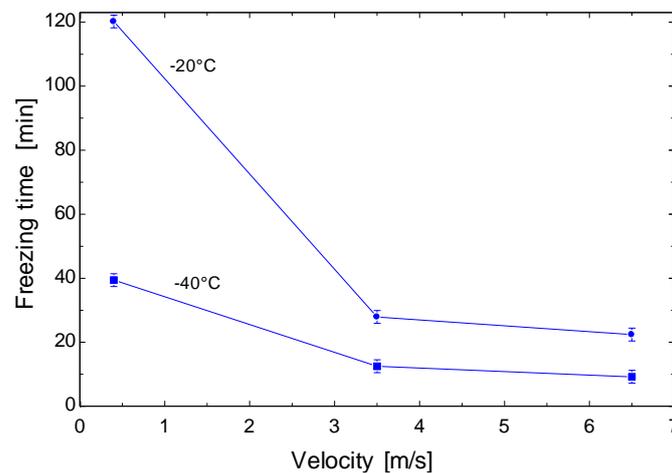

Figure 5. Freezing time comparison for different operating conditions

Figure 6 shows an asymptotic growth of the average Biot number, evaluated for different air velocities. The error bands are due to the difference between samples diameter (D). Based on the curvature of this chart, it is possible to conclude that the air velocity has a stronger effect on the Biot number at low air velocities. Consequently, the effect of the air velocity in the heat transfer process is higher at lower air velocities as 0.4 m/s. Moreover, the higher freezing times observed at 0.4 m/s (see Fig. 5) show that the freezing rate is governed by the convective thermal resistance at this condition. As the air velocity is increased, the convective air resistance is reduced so that the conduction resistance inside the samples becomes more important on the heat transfer process.
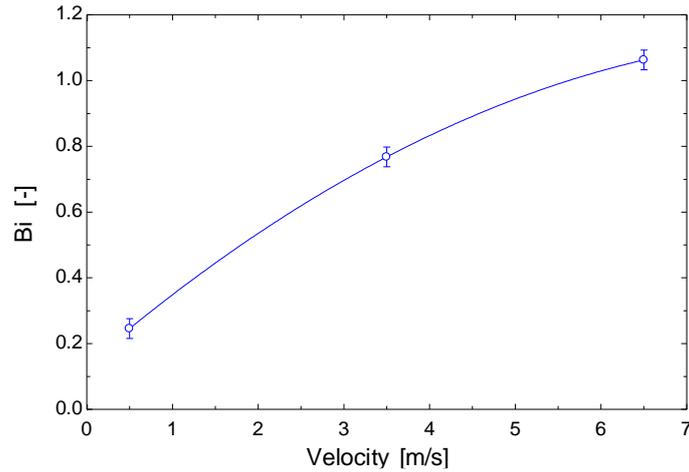
Figure 6. Biot number for different air velocities

Turning now to the mathematical model, Fig. 7 compares simulated and experimental results of freezing time related to tests number 1 to 6 of Tab. 1. The tests carried out at 0.4 m/s were not considered, because they represent operating conditions out of the validity of Eq. (2). It is observed that the mathematical model predictions are within ±20% error bands. The largest errors were obtained under operating conditions associated with the highest freezing rates. This observation shows that the mathematical model tends to slightly overestimate the freezing time when used in this region of the experimental domain. Despite this observation, the results are very satisfactory considering the simplicity of the semi-empirical analytical model.
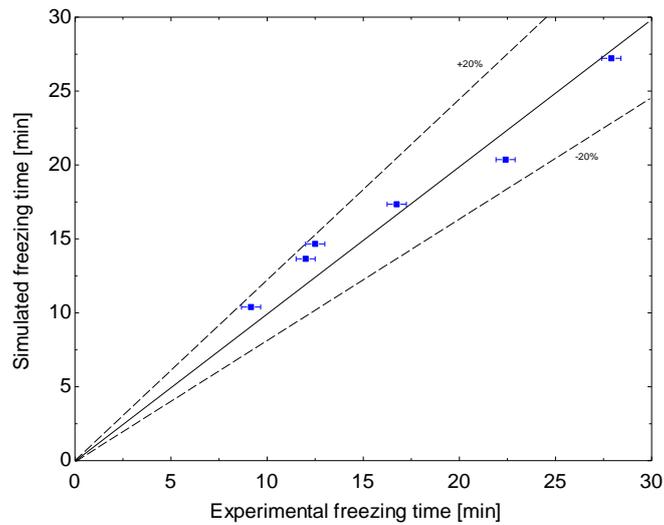

Figure 7. Comparison between experimental and simulated freezing time results

Figure 8 depicts the effect of the air temperature on the freezing time calculated by the mathematical model, for different Biot number values. For this simulation, the geometry and thermal properties of the strawberry were kept constant. Thus, the increase of Biot number (Eq. 5) represents the increase of the heat transfer coefficient due to the air velocity increase. As can be seen, the freezing time is reduced with the air temperature decrease for different Biot numbers. Moreover, it is observed the effect of the Biot number on the curvature of the lines. For instance, as the Biot number is reduced the curvature is increased, mainly at higher air temperatures. These results show 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. The understanding of these non-linearities may be useful when designing blast freezers parameters such as the evaporator temperature and fan performance.
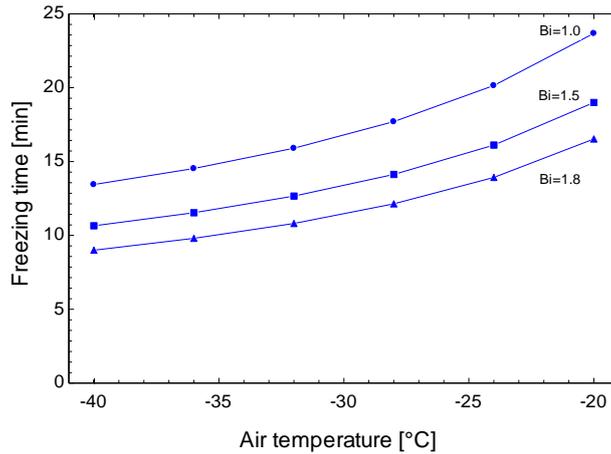
Figure 8. Simulated freezing time as function of Biot and air temperature

The effect of the freezing process on the quality of the food samples was evaluated based on the drip loss test, which indirectly quantifies the food cell structure damage caused by the freezing process. Figure 9 compares the average drip loss experimental results for the different operating conditions of Tab. 1. It is observed that the drip loss of strawberry samples is affected by the freezing process operating conditions. For instance, an average drip loss value of 3.5% is observed at 0.4 m/s and -20°C, which represents the performance of an ordinary domestic freezer. This amount is reduced to 0.5% at 6.5 m/s and -40°C, which represents a reduction of 7 times on the drip loss of the samples. Based on these results it is observed that the effect of operating conditions on the drip loss and freezing time are similar, confirming that a reduction on the freezing time has positive effect on the frozen strawberry quality. To corroborate this graphical observation, an analysis of variance (ANOVA) was conducted. Based on the F = 7.25 and p-value = 0.02 statistics, it was obtained enough evidence to support that the drip loss is affected by the air temperature and air velocity within the experimental range. Figure 9 also shows that at -40°C there is no significant benefits on the drip loss by increasing the air velocity further that 3.5 m/s. This result is important in order to select the proper fan for a specific air temperature in a blast freezer.
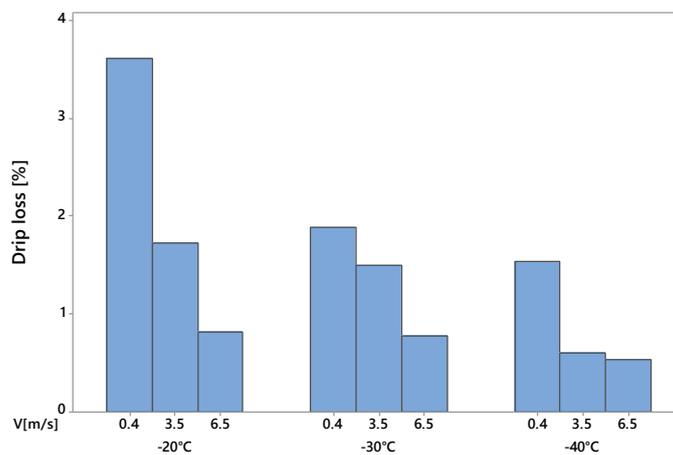

Figure 9. Drip loss results comparison for different operating conditions

In order to provide a simple expression to relate the frozen food quality with operating conditions of a blast freezer, the drip loss experimental result were correlated as

$$Drip\ Loss = e^{(2.14-0.18V+0.04T)} \tag{10}$$

with $R^2 = 0.92$, where V is air velocity expressed in m/s and T is the air temperature expressed in °C. Figure 10 shows the surface obtained from Eq. (10), where it can be seen an asymptotic reduction of the drip loss with the increase of air velocity and the reduction of the air temperature. The average drip loss experimental results used for the regression are represented by the black circles on the surface. The trend indicated by the surface shows that drip loss can be reduced any further by lowering the temperature or increasing the air velocity.
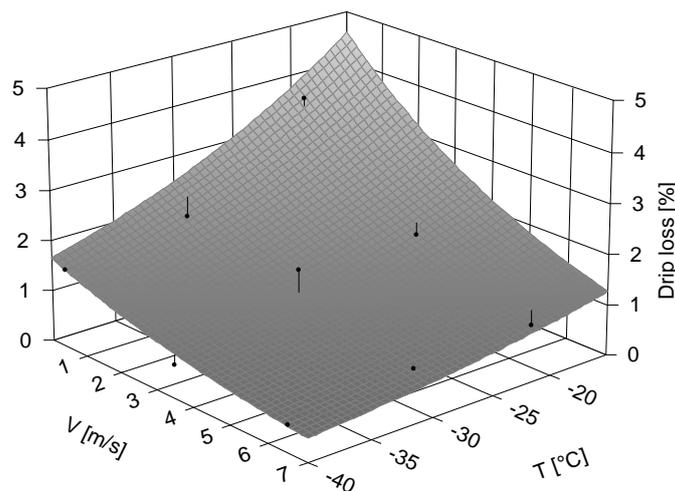
Figure 10. Drip loss dependence with air velocity and temperature

5. CONCLUSIONS

In this work, the effects of the air velocity and air temperature were evaluated on the quality of frozen strawberry (Fragaria x ananassa) samples. An experimental facility was designed and constructed to control the air velocity and air temperature used during the freezing process. The experimental setup is comprised by a wind tunnel equipped with a single stage compression refrigeration system. The test section has a drawer compartment, allowing to start the freezing process only after the operating conditions have been reached inside the wind-tunnel. The experiments were carried out with air velocities between 0.4 and 6.5 m/s and air temperatures between -20 and -40°C. The mathematical model developed by Cleland and Earle (1984) was used to predict the freezing time, considering the strawberries as spheres. The experimental results show the differences between the precooling, phase change and subcooling stages related to the sample freezing process. Moreover, the effect of air velocity and temperature were investigated on the freezing time of the samples. At -20°C and 0.4 m/s, which represents an ordinary domestic freezer operating condition, the measured freezing time was 120 minutes, while at -40°C and 6.5 m/s the freezing time was reduced to 9.2 minutes. The mathematical model was validated against the experimental results, showing predictions within ±20% error bands. The mathematical model was used to carry out an analysis based on the Biot number, showing 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 time. The impact of the freezing process on the quality of the samples were evaluated based on the drip loss analysis, which indirectly quantifies the cellular structure damage caused by the freezing process. The results show a reduction of 7 times on the drip loss, when the operating conditions are changed from -20°C and 0.4 m/s to -40°C and 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). Finally, the experimental results were used to correlate the strawberry drip loss with the operating conditions. The obtained equation can be used to assist the development of more efficient domestic blast freezer systems linking some important operating parameters with the food quality.

6. ACKNOWLEDGEMENTS

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