Online ice crystal size measurements during sorbet freezing by means of the focused beam reflectance measurement (FBRM) technology. Influence of operating conditions

Marcela Arellano a,c,d, Hayat Benkhelifa b,c,d, Denis Flick b,c,d, Graciela Alvarez a,*

1. Introduction

In the manufacturing process of frozen desserts such as sorbet and ice cream, three main steps can be distinguished: preparation of the mix, initial freezing, and hardening of the product. The first step includes the blending of all the ingredients, its pasteurization and homogenization, as well as the cooling and ripening of the mix at 5 °C. During the initial freezing step, the mix is pumped through a scraped surface heat exchanger (SSHE) or freezer. The evaporation of the refrigerant fluid in the jacket of the freezer cools down the temperature of the mix below its freezing point, and causes formation of an ice layer at the wall of the freezer barrel (Cook and Hartel, 2010). Subsequently, the scraper blades of the rotating dasher remove the ice layer from the freezer wall. The small ice crystals contained in the ice layer are dispersed into the centre of the freezer barrel, where they grow and become disc-shaped ice crystals that exit the freezer with a mean size of 15–27 μm (Drewett and Hartel, 2007; Marshall et al., 2003; Russell et al., 1999; Sofjan and Hartel, 2004). At this stage, roughly half of the total amount of water is frozen (Hartel, 1996). Depending on the operating conditions of the process, the draw (exit) temperature of the product varies from −4 to −6 °C, having an adequately low viscosity to be pumped for moulding and packaging. Further on, in the hardening step, the product is introduced into a blast freezer to attain a core temperature of −18 °C (Cook and Hartel, 2010), where roughly 80% of the amount of water is frozen (Marshall et al., 2003). Since the subcooling rate during hardening is not high enough to form new nuclei, the increase in the amount of ice formed with the decrease in temperature follows the equilibrium freezing point curve and leads to the increase in size of the existing
ice crystals (Marshall et al., 2003). Hence, the final ice crystal size of the product will be dictated to a large extent by the evolution during the hardening step of the ice crystals that were formed during the initial freezing. Consequently, the initial freezing process is the most critical step in ice cream and sorbet manufacturing.

The mechanism of ice crystallization within a freezer is affected mainly by the operating conditions of the freezing process, such as the evaporation temperature of the refrigerant fluid, the dasher rotational speed and the mix flow rate. The temperature of the refrigerant fluid provides the driving force that triggers ice nucleation and it determines the heat removal rate of the system. During freezing, ice nucleation occurs at the freezer wall, where there is enough subcooling (roughly −30 °C) between the refrigerant fluid and the mix to form ice nuclei (Hartel, 1996). On the basis of dendritic growth observations in quiescently-frozen sucrose solutions on a chilled surface, Schwartzberg and Liu (1990) suggested that due to the high rate of subcooling at the heat exchange cylinder wall, dendrites are likely to grow there, then are cut off and dispersed into the bulk flow by the scraper blades of the dasher. Subsequently, ice nuclei ripen and become disc-shaped ice crystals in the bulk warm region of the freezer (Cook and Hartel, 2010). Schwartzberg (1990) reported that the space between dendrites was proportional to the freezing rate to the −1/2 power, which means that high subcooling rates lead to a faster growth of more dendrites, with closely spaced branches and a thinner structure. More recently, on the basis of thermal conductivity measurements of a sucrose solution in a flowcell equipped with a scraper blade and a chilled surface, Zheng (2006) concluded that the ice layer formed at the freezer wall was in fact a slush layer composed of both ice and concentrated sucrose solution. Zheng (2006) also found that after each scrape of the blade, many ice nuclei grew rapidly from the ice debris remaining from previous scrapings, and continued to grow along the chilled surface before merging and growing vertically. Hence, a decrease in temperature of the refrigerant fluid would be expected to enhance the cooling rate, causing the faster formation of more ice crystals from the ice debris left behind from previous scrapings, which will grow with a thinner structure and lead to smaller ice crystal sizes.

The scraping action of the dasher improves the heat transfer rate between the freezer wall and the product (Ben Lakhdar et al., 2005). Higher dasher speeds would thus be expected to give lower draw temperatures and smaller ice crystals. However, an increase in dasher speed would also increase the amount of frictional heat generated by the blades, which could dissipate into the product, producing warmer draw temperatures, the melting of the small ice nuclei, and consequently, a reduction in the effective ice nucleation rate. Also, by increasing dasher speed, we increase the movement of the fluid within the freezer, which leads to the enhancement of ice recrystallization phenomena (Cebula and Russell, 1998). Furthermore, an increase in dasher speed may also lead to the attrition of the larger ice crystals (Haddad, 2009; Windhab and Bolliger, 1995), the remaining ice debris of which can lead to the formation of new ice nuclei through secondary nucleation. Sodawala and Garside (1997) used video microscopy to examine the freezing of a 10% sucrose solution on a cold surface with a rotating scraper blade. They observed the formation of ice flocs which grew parallel to the surface after each scrape, then merged and grew vertically. They also observed that an increase in the scraping frequency of the blade led to more frictional heat and to smaller flocs being cut off from the surface. Hence, increasing dasher speed would also be expected to produce new smaller ice nuclei formed from the remaining smaller ice flocs at the surface of the freezer wall.

The mix flow rate dictates the residence time of the product within the freezer, affecting the time available to remove heat from the product, and consequently, the ice nucleation and growth mechanisms of ice crystals. A number of studies in the literature have observed that high mix flow rates (short residence times) for a given draw temperature (by adjusting the temperature of the refrigerant fluid) and dasher speed produced smaller ice crystals due to the reduction in recrystallization phenomena in the bulk region of the product (Drewett and Hartel, 2007; Koxholt et al., 2000; Russell et al., 1999). For a given refrigerant fluid temperature (varying exit temperature) and dasher speed, Russell et al. (1999) also found smaller ice crystals produced at higher mix flow rates, the effect of which was attributed to the reduction in ice crystal coarsening. During the freezing of 30% sucrose/water solutions in an SSHE, Ben Lakhdar et al. (2005) reported that low product flow rates (long residence times) led to a reduction in the exit temperature of the product, and therefore to an increase of the ice mass fraction in the product.

Several studies have highlighted the importance of producing a narrow ice crystal size distribution (CSD) with a small mean size (<50 μm) so as to confer a smooth texture to the final product and enhance consumer acceptance (Cook and Hartel, 2010; Drewett and Hartel, 2007; Hartel, 1996; Russell et al., 1999). It is therefore important to identify the operating conditions of the freezing process that most directly affect ice crystal size so as to improve the quality of the final product.

In order to characterize the ice CSD, many methods have been used. However, some of these methods partially destroy the ice crystal structure during sample preparation, and none of them have been able to directly measure the ice crystal size in the exit stream of the product during the freezing process. Recently, online techniques such as the focused beam reflectance measurement (FBRM) have been developed for in situ monitoring of CSD in the crystallization processes of chemical and pharmaceutical products (Barrett and Glennon, 2002; Negro et al., 2006). In the case of ice crystallization, Haddad et al. (2010) have successfully used the FBRM technique to follow the evolution of ice crystal size during batch freezing of sucrose/water solutions. The FBRM technique is based on the principle of a laser beam that is focused at the window of the tip of the measurement probe. The rotating optics inside the probe allows the laser beam to scan a circular path in

<table>
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<th>Nomenclature</th>
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<tbody>
<tr>
<td>$\hat{Y}_i$</td>
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the region near the window of the probe. When the laser beam intersects a particle, it traces a chord length across the particle. A chord length is defined as a straight line between any two points on the edge of a particle, regardless of how the particle is presented to the probe. The sensor detects the light reflected by the particle, registers the time period of reflection and deduces the length of the chord. The FBRM probe measures thousands of chord lengths per second, sorted into 100 logarithmic size classes and represented as a chord length distribution (CLD). One of the main advantages of this technique is its suitability for in situ measurements of particles at high solid concentrations. However, the FBRM technique gives no information about the morphology of the particles and it measures a CLD rather than a CSD. Still, this measurement can be useful for following the evolution of the ice crystal size.

The present work aimed at studying the influence of operating conditions on the ice crystal chord length monitored online by the FBRM probe, as well as on the draw temperature measured online by a Pt100 probe. The work was carried out during the freezing of lemon sorbet.

2. Materials and methods

2.1. Sorbet freezing

The mix used in these experiments was an ultra high temperature pasteurized lemon sorbet mix (14.6% w/w sucrose, 8% w/w fructose, 0.09% w/w dextrose, 3% w/w lemon juice concentrate 60 Brix, 0.5% w/w locust bean gum/guar gum/hypromellose stabiliser blend). The mix was stored at 5 °C for 24 h prior to use. Freezing of the mix was carried out in a laboratory scale continuous pilot freezer (WCB Model MF 50), a schematic representation of which is shown in Fig. 1. The inner diameter of the heat exchange cylinder was 0.05 m and the length was 0.40 m. The rotor of the freezer was equipped with two rows of scraper blades and occupied roughly 46% of the freezer barrel volume. The freezer had a variable capacity of 0.007–0.021 kg s⁻¹. The evaporation temperature of the refrigerant fluid. The exterior of the freezer jacket was adjusted within the range of −10 to −20 °C as established by the experimental design described in the following section. A calibrated type T (copper – constantan) thermocouple with an accuracy of ±0.2 °C was fixed with conductive aluminium tape on the external surface wall of the freezer jacket, so as to measure the evaporation temperature of the refrigerant fluid. The exterior of the freezer jacket was isolated with foam of 2 cm thickness in order to reduce heat loss. No aeration was employed for any of the experiments.

2.2. Experimental design and statistical analysis

A central composite experimental design was used to assess the influence of three operating conditions – mix flow rate (MFR), dasher rotational speed (DRS) and evaporation temperature of r22 (TR22) – on the response variables: mean ice crystal chord length (MCL) and draw temperature (DT) of the sorbet. The central composite experimental design was composed of three sets of experimental runs, a 2³ set with experimental points at ±1, a 2 × 3 set with points at the extremes of the experimental region (±zα, with α = 1.68) and a central point at zero (Sablani et al., 2007). The experimental design was performed twice and five replicates of the central point were performed in order to provide enough information to estimate experimental error. Table 1 shows the coded values of the experimental design and the real freezing operating conditions. Experimental data were analysed using the response surface methodology. The second-order polynomial model used to predict the experimental behaviour was the following:

\[ \hat{Y} = b_0 + \sum_{i=1}^{3} b_i X_i + \sum_{i=1}^{3} \sum_{j<i}^{3} b_{ij} X_i X_j \]  

where \( \hat{Y} \) is the predicted value of the response; \( b_0, b_i, b_{ij} \) and \( \beta_i \) are the regression coefficients for interception, linear, quadratic and interaction effects, respectively, and \( X_i, X_j \) are the coded levels of the experimental conditions.

The adequacy of each model was assessed by a lack-of-fit test, which assumes \( c \) experimental points with \( d_i \) replicates. Subsequently, it decomposes the residual sum of squares (SS) into one component due to the variation of the replication around their mean value (pure error sum of squares) and into another component due to the variation of the mean values around the model prediction (Lack-of-fit error sum of squares), as shown in the following equation:

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**Fig. 1.** Schematic diagram of pilot Freezer WCB MF 50: (1) Inlet connection for sorbet mix; (2) Inlet cover bowl. (3) Rotor. (4) Scraper blades. (5) Freezer jacket with vaporizing r22. (6) Heat exchange cylinder. (7) Outlet cover bowl. (8) Outlet pipe for sorbet.
The null hypothesis for the lack-of-fit test is that the proposed model predicts the response correctly. The statistical significance is assessed by the F ratio, given by the following equation:

$$ F = \frac{\sum_{i=1}^{c} \sum_{j=1}^{d} (Y_{ij} - \hat{Y}_{ij})^2 / (c - 2)}{\sum_{i=1}^{c} \sum_{j=1}^{d} (Y_{ij} - \bar{Y}_{i})^2 / (d - c)} $$

This F ratio is compared to the F-distribution for the associated degrees of freedom and provides a p-value. If the p-value for the F-test of lack-of-fit is non significant (p > 0.05), we do not reject the null hypothesis, i.e. the model is assumed to be correct.

### 2.3. Draw temperature measurements and ice mass fraction calculations

The draw (exit) temperature determines the ice mass fraction in sorbet $X_{m,i}$. A decrease in the draw temperature will result in an increase of the ice mass fraction, as well as an increase of the apparent viscosity of the product (Cereceró, 2003; Goff et al., 1995). The relationship between the draw temperature of sorbet and its ice mass fraction is established by the equilibrium freezing point curve of sorbet. This curve had been previously determined in our laboratory using differential scanning calorimetric (DSC) measurements. Furthermore, the calculation of the ice mass fraction $X_{m,i}$ is based on a balance of solute (sugar content), considering a thermodynamic equilibrium between the two phases (ice and concentrated solute solution) and taking into account the fact that ice crystals are constituted exclusively of water (Cereceró, 2003).

Initially, the solute is present in sorbet mix at a certain initial mass fraction ($X_{m,i}$). Then, the solute is concentrated as freezing of the sorbet occurs, until it reaches a final mass fraction ($X_{m,f}$) in the liquid phase that is related to the temperature by the equilibrium freezing point curve. Since the final liquid phase represents only a fraction ($1 - X_{m,i}$) of the sorbet, the ice mass fraction can be calculated by the following equation:

$$ X_{m,i} = X_{m,i} \cdot X_{m,f}(T) \Leftrightarrow X_{m,i} = 1 - \frac{X_{m,i}}{X_{m,f}(T)}. $$(4)

Once the experimental conditions of the freezer were set and the steady state of the system was attained, the draw temperature of the product was measured online by means of a calibrated Pt100 probe (Baumer, 2000, accuracy of ±0.1°C). The Pt100 probe was inserted into the outlet pipe of the freezer before the exit of the product as shown in Fig. 2. Draw temperature and ice mass fraction data were recorded and calculated every 5 s for a period of 10 min by using a program written in LabVIEW®.

### 2.4. Ice crystal CLD measurements by the FBRM probe

The ice crystal CLD was measured online using a Mettler-Toledo Lasentec® FBRM probe (Model S400A-8). This device is composed of stainless steel body 8 mm in diameter. At the tip of the probe there is a sapphire window through which a 780 nm laser beam is transmitted to the sample. A set of rotating optics, inside the probe, focuses the laser beam into a small spot, creating a scanning circular path at the interface between the window of the probe and the particles in suspension (cf. Fig. 3A). When a particle is intersected by the laser beam, it reflects the laser light throughout the time it is being scanned (cf. Fig 3B). Simultaneously, the time period of reflection is detected by the FBRM probe and then multiplied by the tangential speed of the laser beam, yielding a distance across the particle, which is a chord length (Greaves et al., 2008; Wynn, 2003). The tangential speed of 2 m/s of the laser beam is typically much faster than that of the particles, which makes it possible to consider that the particles are fixed with respect to the laser scanning path. The effect of particle motion is therefore considered negligible for the measurements (Abbas et al., 2002). The signals produced by the FBRM probe can be processed in two different modes: the ‘fine’ mode and the ‘coarse’ mode. When the ‘fine’ mode is used, the particles measured are counted individually. The ‘coarse’ mode considers the individual particles that constitute an aggregate as a whole (cf. Fig 4). Therefore, throughout our experiments the ‘fine’ mode was used in order to enhance the FBRM probe sensitivity to measure each ice crystal in the product individually. The FBRM probe measures thousands of chords per second, providing a CLD i.e. the number of counts per second sorted by chord length into 100 logarithmic size classes. Starting from the FBRM CLD data, the samples were classified using the LASER xcel program. The cumulative size distribution was chosen as the most suitable approach for the classification of the CLD data (Baumer, 2002).
with this information, the mean chord length of the ice crystals is obtained by the following equation:

\[
MCL = \frac{\sum_{i=1}^{100} n_i c_i}{\sum_{i=1}^{100} n_i}
\]

(2)

where \(n_i\) is the number of particles for each of the size classes \(i\) of chord length \(c_i\).

2.4.1. Relationship between CLD and PSD

Wynn (2003) established the relationship between the moments of CLD and PSD, and determined that the mean chord length of a sphere is \(\pi/4 \approx 0.785\) times smaller than its diameter. Hence, the mean ice crystal chord length can be considered to be roughly 22% smaller than the mean size of the ice crystals, if we assume that they are spherical in shape. However, sometimes the mean chord length can be smaller than the mean particle size by a factor of less than 0.785 (Wynn, 2003). In order to illustrate this relationship, a simultaneous measurement of a known particle size suspension was performed using the FBRM probe and a video microscopy sensor probe, the EZ Probe D12\(^*\) (developed by the ESCPE in Lyon, France), the measurement principle of which is explained elsewhere (Presles et al., 2009). The suspension was composed of polyamid seeding particles (PSP) with a mean size of 27.5 \(\mu\)m suspended at a concentration of 0.25\% w/w in ethanol. The images generated by the EZ Probe D12\(^*\) sensor were processed by image analysis, so as to determine the PSD of the suspension (based on a sample of 3000 particles). Starting with this PSD data, the CLD was calculated by a conversion algorithm that follows the same mathematical approach as the one reported by Haddad (2009). Fig. 5 shows the comparison of the CLD calculated from the EZ Probe D12\(^*\) PSD data and the CLD directly measured by the FBRM probe. It can be observed from Fig. 5 that there is good agreement overall between the FBRM measurements and the calculated CLD, although the FBRM probe tends to overestimate the number of small particles. For these results, the calculated CLD has a mean chord length of 21.6 \(\mu\)m, while the CLD measured directly by the FBRM probe has a mean chord length of 20.5 \(\mu\)m. This means that there is roughly a 5\% difference between the calculated CLD and the CLD measured by the FBRM probe.

2.4.2. CLD measurements at the freezer outlet

When performing the freezing experiments, the FBRM probe was inserted into the outlet pipe of the freezer at a 45\(^\circ\) angle relative to the flow (cf. Fig. 2), making it possible to continuously renew the sorbet flow that was being measured. In this way, it was possible to measure the CLD of the ice crystals contained in the exit stream of the product directly, without any sample preparation, thus preserving the ice crystal structure. In order to avoid condensation at the inside surface of the FBRM probe window, a purge was carried out with nitrogen at 1 bar with a flow rate of 5 l/min. Once the steady state of the freezer was established, the chord length acquisition data were synchronized with draw temperature measurements and recorded every 5 s for a period of 10 min.

3. Results and discussion

3.1. Freezer operating conditions and global ANOVA analysis

Table 1 presents the operating conditions under which measurements were taken and the mean values of the responses
The results show that using the FBRM sensor makes it possible to directly monitor online the evolution of the CLD of the ice crystals contained in the exit stream of the product during the freezing of sorbets containing up to 40% of ice (without sample preparation), which was one of the objectives of this research.

The global ANOVA analysis in Table 2 shows that the mean chord length (MCL) response model is significant ($p < 0.0001$, $R^2 = 0.94$), with a non significant lack-of-fit ($p = 0.6$). Hence, we can consider that the second order polynomial model is adequate to predict the experimental behaviour of MCL. The model for the draw temperature of sorbet (DT) is also significant ($p < 0.0001$, $R^2 = 0.99$) and does not show lack-of-fit ($p = 0.8$). Therefore, the DT response can be adequately represented by the model. It is important to remind the reader that the use of these models should be limited to the range of experimental conditions used in this work.

3.2. Influence of the refrigerant fluid temperature and mix flow rate on draw temperature

According to the ANOVA analysis of the response variables in Table 3, the mix flow rate and the evaporation temperature of the refrigerant fluid had the most significant effect on the draw temperature (DT) at a 95% confidence interval. This effect concerned both their linear and quadratic terms ($p < 0.0001$ for $\beta_1$, $p < 0.0001$ for $\beta_2$, $p = 0.0002$ for $\beta_{11}$ and $p = 0.0336$ for $\beta_{22}$), as well as their interaction effect ($p = 0.0284$ for $\beta_{12}$). Fig. 6 shows the surface plot of the draw temperature behaviour as a function of the evaporation temperature and mix flow rate at DRS = 78.5 rad s$^{-1}$.

The results show that a decrease in refrigerant fluid temperature leads to a reduction in the sorbet draw temperature as well as to an increase in the ice mass fraction (cf. Table 1, runs 10, 13 and 14) since more heat is removed from the product.

In Fig. 6 we can also observe that when the freezer operates at lower mix flow rates, the draw temperature of sorbet decreases, and inversely the ice mass fraction increases (cf. Table 1, runs 9, 10 and 11). This effect is explained by the increase in the residence time of the product with the decrease in the mix flow rate, since the product remains in contact with the freezer wall longer, so that more heat is removed from the product. Likewise, Ben Lakhdar et al. (2005) obtained higher ice mass fractions (lower product exit temperature) by reducing the product flow rate during the freezing of 30% sucrose/water solutions. For a given refrigerant fluid temperature (varying exit temperature) and dasher speed, Russell et al. (1999) also found lower draw temperatures produced at lower mix flow rates due to the longer residence time available for heat removal.

3.3. Influence of refrigerant fluid temperature and mix flow rate on mean chord length

The ANOVA analysis in Table 3 shows that the mean chord length response was significantly affected at a 95% confidence interval by the evaporation temperature, for its linear and
The mix flow rate did not show a significant effect ($p = 0.1636$ for $b_1$).

Fig. 7 shows the surface response of the mean ice crystal chord length as a function of the evaporation temperature and mix flow rate at $\text{DRS} = 78.54 \text{ rad s}^{-1}$. These results demonstrate that a decrease in the evaporation temperature of the refrigerant fluid leads to a reduction in the MCL. The influence of the refrigerant fluid temperature can be seen more clearly in Fig. 8, where the measured ice crystal CLD are shown at three different evaporation temperatures (cf. Table 1, runs 10, 13 and 14). These results show that there is an increase in the population of small ice crystals with the decrease in the refrigerant fluid temperature. At $-10.6 \text{ C}$, 78% of the ice crystals are in the range of 1–10 $\mu$m, and at $-19.8 \text{ C}$ the population of the ice crystals in the same range increases to 88%. This effect can be explained by the enhancement of the cooling rate that leads to the formation of more ice crystals that grow with a thinner structure from the ice debris of previous scrapings, and therefore lead to the presence of a higher number of small ice crystals in the product. Similarly, Koxholt et al. (2000) as well as Drewett and Hartel (2007) obtained ice creams with smaller ice crystals by using low refrigerant fluid temperatures, the effect of which was attributed to the higher subcooling applied to the product which enhanced the nucleation rate.

It is generally accepted that the mean ice crystal size in ice creams and sorbets at the outlet of the freezer is 15–27 $\mu$m (Drewett and Hartel, 2007; Marshall et al., 2003; Russell et al., 2007).

**Table 2**

<table>
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<tr>
<th>Response</th>
<th>$R^2$</th>
<th>$F$ value (model)</th>
<th>p-value (model)</th>
<th>p-value (Lack-of-Fit test)</th>
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<tr>
<td>MCL</td>
<td>0.94</td>
<td>55</td>
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<tr>
<td>DT</td>
<td>0.99</td>
<td>265</td>
<td>&lt;0.0001</td>
<td>0.8</td>
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*a MCL = mean chord length; DT = draw temperature; $R^2$ = coefficient of determination.

**Table 3**

Regression coefficients of the experimental behavior model and significance levels at 95% ($p$-values) for responses of MCL and DT.

<table>
<thead>
<tr>
<th>Response</th>
<th>Interception</th>
<th>Linear</th>
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<tr>
<td>MCL</td>
<td>17.896</td>
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<td>&lt;0.0001</td>
<td>0.902</td>
<td>&lt;0.0001</td>
<td>0.9571</td>
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<tr>
<td>DT</td>
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<td>0.262</td>
<td>0.031</td>
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<td>-0.902</td>
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</tr>
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</table>

Coefficients ($b$) subindex: 1 = mix flow rate; 2 = evaporation temperature $r_{22}$; 3 = dasher rotational speed.

*a MCL = mean chord length; DT = draw temperature.

Significant influence at 95% confidence interval.
the area of the experimental design of this work the MCL ranged from 5 to 9 μm. This difference between the ice crystal MCL and the ice crystal size can be explained by taking into account the fact that the MCL is often considered to be 0.785 times smaller than the particle size, and also, as previously discussed, the FBRM technique tends to overestimate the number of small particles.

Since the work of Russell et al. (1999), it has been commonly assumed that for a given refrigerant fluid temperature (varying exit temperature) and dasher speed, smaller ice CSD can be obtained by increasing the product flow rate, due to a reduction of crystal coarsening in the freezer. However, as we have just seen in our results (cf. Fig. 7 and Table 1, runs 9–11), the mix flow rate did not have a significant effect on the mean ice crystal chord length (cf. Table 3, linear effect for $\beta_1$ on MCL). On the basis of these results it appears that there is a compensatory effect between two phenomena occurring in the freezer: on the one hand, as previously discussed, when using low mix flow rates, the residence time of the product is longer, leading to a decrease in the temperature of the product, as well as promoting further growth of the ice crystals. On the other hand, this reduction in the draw temperature of sorbet also corresponds to an increase in the ice mass fraction and therefore to an increase in viscosity. This tends to increase shear stress in the product at the freezer barrel, which increases the friction between ice crystals and results in the attrition of the larger ice crystals, the ice debris of which can generate new small ice nuclei by secondary nucleation.

3.4. Influence of dasher speed on draw temperature

According to the ANOVA analysis shown in Table 3, dasher speed had a significant influence on the draw temperature for its linear term ($p = 0.0014$ for $\beta_3$) and for its interaction with the mix flow rate ($p = 0.0391$ for $\beta_{13}$). The behaviour of the draw temperature response as a function of the evaporation temperature and the dasher speed at $\text{MFR} = 0.014 \text{ kg s}^{-1}$ is shown in Fig. 9. It can be seen that, although significant, the influence of dasher speed on the draw temperature is very small (cf. Table 1, runs 10, 12 and 15). However, its influence is slightly accentuated when low mix flow rates are used (cf. Table 3 interaction effect $\beta_{13}$ on DT). Hence, we can consider that an increase in dasher speed at low mix flow rates leads to a very slight increase in the exit temperature of the product. In view of these results it is our opinion that this slight warming effect is due to an increase in the amount of frictional energy dissipated into the product, which is partially compensated by the improvement of the heat transfer rate produced by the faster removal of the ice layer at the freezer wall. Russell et al. (1999) also observed an increase in product temperature for a given refrigerant fluid temperature (varying exit temperature) and mix flow rate led by the increase in dasher speed, an effect which was attributed to the increased dissipation of frictional energy. Conversely, experiments performed by Ben Lakhdar et al. (2005) showed that an increase in dasher speed led to an increase in the heat transfer coefficient between the inner wall of the freezer and the product, producing lower draw temperatures.

3.5. Influence of dasher speed on mean chord length

The ANOVA analysis in Table 3 shows that the mean ice crystal chord length was significantly affected by the dasher speed at a 95% confidence interval in its linear term ($p = 0.034$ for $\beta_5$). The influence of the dasher speed and the evaporation temperature at $\text{MFR} = 0.014 \text{ kg s}^{-1}$ is shown in Fig. 10. It can be seen that increasing the scraping action of the dasher slightly reduces the mean ice crystal chord length within sorbet (cf. Table 1, runs 10, 12 and 15). This result suggests that an increase of the dasher speed leads to the generation of new small ice nuclei by secondary nucleation, which are induced from the ice debris that result from either the attrition of the larger ice crystals (result of an increase in the shear rate within the product) or the smaller size of the ice flocs that are detached from the wall (result of an increase in the scraping frequency of the blades). Russell et al. (1999) found ice creams with larger ice crystals, produced by higher dasher speeds, for a given refrigerant fluid temperature (varying exit temperature) and mix flow rate. This effect was attributed to the increase of mechanical dissipation which increased the temperature of the product and led to the melting of the small ice crystals and the increase of ice recrystallization.

4. Conclusions

This study has shown that the FBRM technique is a convenient tool that makes it possible to follow directly online the evolution of the ice crystal CLD in sorbets containing up to 40% of ice. Our results demonstrate that the temperature of the refrigerant fluid has the strongest effect on draw temperature as well as on the mean chord length of sorbet. Low evaporation temperatures led to lower draw temperatures (higher ice mass fractions) because more heat was removed from the product. The ice crystal mean...
chord length was significantly reduced by using lower refrigerant fluid temperatures due to the enhanced cooling rate that led to the growth of more ice crystals with a thinner structure from the ice debris of previous scrapings.

The mix flow rate significantly affected the draw temperature of sorbet. For a given evaporation temperature and dasher speed, lower mix flow rates (longer residence times) result in lower draw temperatures due to the fact that the product remains in the freezer longer, allowing more time for heat removal. No significant influence of the mix flow rate was observed on the mean ice crystal chord length, due to a compensatory effect between two phenomena: at lower mix flow rates, there is more time available for crystal coarsening. However, at lower mix flow rates there is also more time to decrease the draw temperature, which increases the ice mass fraction and therefore the viscosity of the product. The latter effect increases shear stress in the product, leading to the attrition of the larger ice crystals, the ice debris of which can induce the formation of new small ice nuclei by secondary nucleation.

The dasher speed showed a very slight effect on the draw temperature and the ice crystal mean chord length. Higher dasher speeds result in very slightly warmer draw temperatures due to frictional energy that is generated by the scraping action of the dasher. However, this warming effect was moderated by improving the heat transfer between the product and the wall. An increase in dasher speed slightly reduced the ice crystal mean chord length, an effect which can be explained by the generation of new ice nuclei by secondary nucleation induced either by the smaller ice clumps detached from the scraped surface or by the remaining ice debris produced during the attrition of the larger ice crystals.

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References


