# A novel technique to control ice cream freezing by electrical characteristics analysis

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7

8    **Abstract**

9    The freezing process is very important in ice cream production affecting quality, taste and yield of

10   the finished product. Batch freezer machines use different control techniques to tightly control the

11   freezing process, based on monitoring of the temperature and/or the viscosity (i.e. consistency) of

12   the product. Temperature control, however, features low sensitivity and need calibration for

13   different product compositions, while product viscosity is essentially inferred from dasher motor

14   load, sensitive to power line fluctuations, volume of product and dasher motor characteristics.  In

15   this context, this paper presents a novel technique based on measurements of the product electrical

16   characteristics, tightly linked to temperature and viscosity. The experimental results presented in

17   this work clearly indicate that the proposed technique provides a suitable, non destructive tool to

18   monitor ice cream quality product that overcomes the drawbacks of the standard methods, thus

19   representing an advance in the state of the art for freezing control.

20

21   *Keywords*: ice cream, freezing, dasher motor, impedance measurements.

22

23   **1. Introduction**

24   Ice cream has been appreciated in the western world since the 13th century, when Marco Polo

25   returned from the Far East Asia with water ice recipes. Over time, these water ices have evolved

26   into today's popular frozen desserts (Marshall et al., 2003)(Quinzio, 2009).

Nowadays the international ice-cream market has significant dimensions and faces prospects of continuous further growth worldwide (www.dairymark.com, 2008).

Within ice cream production process, freezing is a very important operation strongly affecting the quality, taste, and yield of the product (Marshall et al., 2003). While being frozen, the ice cream mix is agitated in order to incorporate air and to limit the size of ice crystals that are formed, as required to give smoothness in body and texture and satisfactory overrun in the ice cream (Marshall et al., 2003) (Caillet et al., 2003) (Chang and Hartel, 2002) (Goff et al., 1999).

Typically, ice cream is produced fresh using a batch freezer and is then immediately extruded. The finished product is then held and served at a temperature suitable for a highly viscous semi-frozen state (Marshall et al., 2003).

Conventional batch freezer consists of a scraped-surface tubular heat exchanger, jacketed with boiling refrigerants (such as hydrofluorocarbons) and containing a rotating dasher scraping the ice off the inner surface and whipping the mix to incorporate air.

The mixture is frozen at a variable temperature (generally within the range -11 < T (°C) < -5), according to type of process and composition, and very rapidly in order to obtain an even distribution of the solid and aerated phases throughout the entire structure of the product, avoiding separation of the solutes.

Batch freezers use different control techniques to ensure a tight control of the process, generally based on monitoring of the temperature and/or the viscosity (consistency) of the product, this latter being normally inferred from the current drawn by the dasher motor ($I_{motor}$).

Since the product temperature decreases very slowly during the final phase of the freezing process, temperature monitoring, used in the past since the advent of viscosity control, normally provides low sensitivity, leading to high dispersion in product softness. Moreover, the temperature at the end of the process strongly depends on ice cream composition and recipe as well as the actual performance of the temperature sensor, that is placed at the bottom of the cylinder and can have bad contact with the product.

53  Product viscosity control, normally carried out by monitoring $I_{motor}$, solves many of these problems.

54  During the freezing process the product viscosity increases, and so does $I_{motor}$. Low values for this

55  current indicates that the product is too soft or warm, while values higher than suitable threshold

56  indicate that the product is too stiff or cold. This type of control too, however, has significant

57  drawbacks, since measurements of $I_{motor}$ are influenced by power line fluctuations, quantity of

58  mixture in the freezing cylinder and dasher motor characteristics (thus, in practice, different stop

59  process thresholds must be set for different type of electric motors).

60  In this context, then, a reliable technique directly monitoring the product characteristics would be

61  highly desirable and good candidates for the task are techniques based on measurements of the ice-

62  cream electrical characteristics, known to be interesting indicators of product status, although only

63  at macroscopic level, and to be function of product temperature and viscosity (Georges and Chen,

64  1986)(Hori et al., 1982). Moreover, these measurements can be performed with electronic circuits

65  with stable power supply not influenced by motor type and power line fluctuation.

66  Recently, electrochemical impedance spectroscopy has been used for non destructive monitoring in

67  different areas of food processing and analysis, such as, for instance: determination of water and

68  lipid content in meat (Chanet et al., 1999); determination of pH acidity and hardness in yogurt

69  (Kitamuna et al., 2000); detection of mastitis in raw milk samples (Norberg et al., 2004) (Ferrero et

70  al., 2002); measurement of microbial concentration in milk (Felice et al., 1999) (Piton and Dasen,

71  1988) (Piton and Rongvaux-Gaida, 1990), yogurt (Pirovano et al., 1995) and ice cream (Grossi et

72  al., 2008) (Grossi et al., 2009) (Grossi et al., 2010); detection of protein concentration in label free

73  immunosensors (Lin et al., 2010).

74  Electrochemical Impedance Spectroscopy (EIS) essentially works as follows (Barsoukov and

75  MacDonald, 2005): the analyzed sample is stimulated with a sinusoidal test signal of fixed

76  amplitude (usually ranging from 10mV to few hundreds mV) and the sample impedance Z is

77  measured in a definite range of frequencies. The acquired spectra can be represented using various

78  graph types including Bode plots, where |Z| and Arg(Z) are plotted as function of frequency, or

79 Nyquist plots where the imaginary component of Z is plotted versus the real one for different values

80 of frequency. Data from different samples characterized by different parameters are compared to

81 test the correlation between product properties and electrical parameters.

82 In this paper EIS has been used to demonstrate that electrical parameters can provide information

83 about the ice cream status during freezing in a conventional batch freezer. To this purpose, data

84 acquired from EIS measurements have been compared to the freezer process parameters. In

85 particular, the correlation with the current drawn by the dasher motor has been studied.

86 In section 2 the measurement set up as well as the tested products are presented. Results are

87 discussed in section 3 while conclusions are drawn in section 4.

88

89 **2. Materials and methods**

90 A conventional batch freezer (Fig. 1a) has been used with standard vanilla flavored ice cream mix

91 to test the correlation between the measured electrical parameters and the current drawn by the

92 dasher motor. The product temperature has been also monitored during the freezing process with a

93 PT100 thermistor placed within the cylinder in direct contact with the product.

94 The freezer (Coldelite Compacta Top 3002 RTX, Carpigiani Group) essentially represents a scraped

95 surface heat exchanger. The dasher (d=264 mm, L=255 mm) with the attached scraper blades

96 rotates within a cylindrical barrel, cooled by an evaporating agent (i.e. R-404A). Air is incorporated

97 and dispersed in the mix by the dasher. The mix is frozen and simultaneously scraped from the

98 cylindrical freezer wall by the scraper blades. The rotational speed of the dasher is 120 rpm.

99 When not differently specified, the experiments have been performed pre-cleaning the barrel with

100 hot water and completely filling the freezing chamber (with 7 liters of ice-cream mix).

101 In general, in batch freezers the process ends when $I_{motor}$ reaches a threshold value $I_{motor,TH}$

102 dependent on the type of motor: for the freezer used in the work the default factory $I_{motor,TH}$ value is

103 6.5 A. The user can also vary the values of $I_{motor,TH}$ suggested by machine producer (within about ±

104  10%) to achieve the desired product softness with specific mix compositions: higher values of

105  $I_{motor,TH}$ are used for products featuring high concentrations for sugar and/or total solids.

106

107  *2.1 Experimental set up*

108  The front door of the batch freezer (Fig. 1 b) has been modified so as to use two adjacent stainless

109  steel cylinders as a couple of electrodes for the electrochemical measures. Such electrodes have

110  been connected to the input port of the impedance analyzer Agilent E4980A, capable of measuring

111  the electrical characteristics of the sample on a range of frequencies from 20 Hz to 2 MHz. A PC

112  laptop acquires the measured data from the impedance analyzer via a USB interface and from the

113  batch freezer via a serial RS232 port. All programs for data acquisition, graphing and data filing

114  have been realized with National Instruments LabVIEW software. A schematic representation of

115  the experimental set up is shown in Fig. 1 (c).

116  Preliminary measurements have been carried out to investigate the optimal experimental

117  parameters, namely values for amplitude and frequencies of the input test voltage. In general, in EIS

118  measurements the amplitude of the input voltage ($V_{in}$) is kept at the lowest value compatible with

119  the need of measurement reliability, as lower voltages produce lower perturbations to the sample

120  under test and quasi linear responses (Darowicki, 1995). In our case, preliminary measurements

121  suggested to use  an amplitude of 100 mV for the test signal: lower values resulted inadequate

122  signal-noise ratios (due to the strong electromagnetic noise produced by the motor), while higher

123  values resulted in stronger sample alterations with no improvements in measurement reliability.

124  As for frequency of the test signal, measurements have been carried out with values logarithmically

125  spaced in the range 20 Hz  - 10 KHz.

126  Fig. 2 (a) and (b) show plots of |Z| and Arg(Z) vs. time for different frequencies. Since, however,

127  the different assays are strongly influenced by the dynamics of the refrigerating system (see

128  Supplementary Material for more details), the time origin for each assay has been set at the

129  beginning of the product temperature decrease. As can be seen the |Z| curve is almost independent

130    of the frequency for the test signal. On the contrary, Arg(Z) exhibits high sensitivity to such a

131    parameter: in particular, the signal to noise ratio decreases with frequency and for values higher

132    than 100 Hz  measurements become substantially unreliable. Moreover, as reported in the

133    Supplementary Material, Nyquist plots indicate that higher frequencies lead to high noise levels and

134    poor measurement reproducibility. Thus, in our experiments test signal frequency  has been set at

135    20 Hz.

136    The current drawn by the dasher motor  and the product temperature during freezing are represented

137    as function of time in Fig. 2 (c) and Fig. 2 (d), respectively. As can be seen, product temperature

138    decreases at the beginning of the freezing process and saturates at a value ranging from -9°C to -

139    5°C, clearly indicating that temperature measurement can only provide approximate results and is

140    unsuitable for accurate process control.

141

142    *2.2 Ice cream mix*

143    A standard vanilla ice cream mix (Mondi nel Mondo, Rome, Italy, www.mondinelmondo.it) has

144    been used for the experiments. The ingredients of the mix are sugar, coconut oil, dextrose, glucose

145    powder, milk proteins, stabilizers (E412, E410, E466), emulsifiers (E471, E473), flavoring in the

146    composition of 17.5 Kg by powder and 30 liters by water. The ice cream recipe is as follows: fat

147    content 11%, milk solids-not-fat 11%, sugar 10%, corn syrup solids 5%, stabilizers/emulsifiers

148    0.5%, total solids 37.5%.

149    The ice cream mix production has been carried out using a Carpigiani Pastomaster RTL machine to

150    prepare, pasteurize and age ice cream mixes. The basic steps in the manufacturing are as follows:

151    - mixing of ingredients (i.e. mixing powder with water in the tank of the pasteurizer);

152    - pasteurization at 65 °C for 30 minute (automatically managed by the pasteurizer);

153    - cooling to 4 °C (automatically managed by the pasteurizer);

154    - ageing at 4 °C for 10 hours (automatically managed by the pasteurizer).

155    Small batches of mix were taken from the pasteurizer and put into the batch freezer; then, the dasher

156    was started and the refrigerant system turned on.

157    Finally, at the end of the freezing process, the ice cream was extracted from the freezer and the

158    machine was cleaned.

159

160    *2.3 Statistical analysis*

161    The obtained data have been analyzed using Microsoft EXCEL statistical tools. Measured values of

162    $|Z|$, Arg(Z) and $\Delta$Arg(Z) (difference between two consecutive measurements of Arg(Z)) have been

163    represented as function of the corresponding values of $I_{motor}$ and correlation between the variables

164    has been studied by means of linear regression analysis (Mason et al., 2003). Multiple regression

165    analysis has been carried out with Microsoft EXCEL add-on Prentice Hall PhSTAT v 1.4.

166

167    **3. Results and discussion**

168    The correlation between electrical parameters and $I_{motor}$ in the experiments described in the previous

169    Section has been intensively investigated.

170    Fig. 3 (a) shows the experimental data $|Z|$ vs. $I_{motor}$ clearly exhibiting a linear relationship between

171    the two variables. The linear regression line equation as well as the determination factor $R^2$ have

172    been calculated. The dispersion among the predicted value is not uniform on the entire range of

173    $I_{motor}$, in particular it increases when $I_{motor} > 5$ A.

174    Fig. 3 (b) shows the experimental data Arg(Z) vs. $I_{motor}$. At the beginning of the freezing process,

175    when temperature is not very low and mix is still in the liquid state, Arg(Z) increases rapidly. Later,

176    the mix density increases, producing first a slower increase and later a saturation of Arg(Z). For

177    $I_{motor} > 4$ A (when freezing has already started) the relation Arg(Z) vs. $I_{motor}$ is essentially linear, as

178    clearly indicated in Fig. 3 (c) representing data obtained for $I_{motor}$ values in the range 3.5 - 7.5 A.

179    The linear regression line equation for the measured data as well as the determination factor $R^2$ are

180   also presented. From Fig. 3 (b) it is also evident that dispersion on the estimated value of Arg(Z) is

181   lower at the end of the freezing process.

182   The values of $\Delta$Arg(Z) increase rapidly at the beginning of the freezing process (low $I_{motor}$ values),

183   reach a maximum at $I_{motor} \approx 2.5$ A, then decreases as freezing continues. In Fig. 3 (d) values of

184   $\Delta$Arg(Z) are plotted against $I_{motor}$ in the range 3 - 7.5 A. The linear regression line equation as well

185   as the determination factor $R^2$ are presented too. As can be seen, data dispersion is initially higher

186   and decreases as the freezing process continues.

187   As for the correlation between product temperature and $I_{motor}$, the results in the Supplementary

188   Material show that it is very poor.

189   From the scatter plots of Fig. 3 the threshold value for the electrical parameters to stop the freezing

190   process ($|Z|_{TH}$, Arg(Z)$_{TH}$ and $\Delta$Arg(Z)$_{TH}$) can be estimated from the regression line equation as

191   function of the threshold $I_{motor,TH}$. Since, for the batch freezer used in the experiments, the producer

192   suggested $I_{motor,TH} = 6.5$A, the corresponding thresholds for the electrical parameters are $|Z|_{TH} =$

193   755.3$\Omega$, Arg(Z)$_{TH} = -13.58°$ and $\Delta$Arg(Z)$_{TH} = 2.26°$.

194   The repeatability of the experiments has been tested by means of 8 freezing assays performed under

195   the same conditions and the results, as well as statistics for the time to reach the stop process

196   threshold, are shown in Fig. 4. As can be seen, the freezing control using $|Z|$ leads to more

197   repeatable curves and minimum dispersion on the stopping time ($\Delta$time = 1.85 minutes), than those

198   exploiting measurements of Arg(Z) ($\Delta$time = 3.6 minutes) and $\Delta$Arg(Z) ($\Delta$time = 3.1 minutes).

199   These latter methods, however, exhibit smaller dispersion than straightforward $I_{motor}$ control ($\Delta$time

200   = 3.88 minutes).

201   Multivariate regression analysis has been carried out using best-subset procedure to investigate if

202   expressing $I_{motor}$ as linear function of more than a single electrical parameter significantly increases

203   data correlation. To this purpose, it is found that using both $|Z|$ and Arg(Z) significantly improves

204   the correlation ($R^2$=0.79 instead of $R^2$=0.69),  while adding $\Delta$Arg(Z) produces only a negligible

205   increase. Thus, in the following, only measurements of $|Z|$ and Arg(Z) are considered.

206 The experiments described above were performed by cleaning the freezer with hot water before the

207 start of the process (so as to eliminate residuals of ice cream from previous assays and making the

208 initial temperature as homogeneous as possible) and filling the barrel always with the same quantity

209 of mix (corresponding to the maximum capacity of 7 liters). Since this is not the case during the

210 normal operation of a batch freezer, the effects of consecutive freezing processes without cleaning

211 as well as loading the freezer with different mix quantities have been studied.

212 To this purpose, three freezing procedures have been carried out in a row without cleaning the

213 machine barrel between consecutive assay and the results are presented in Fig. 5. As can be seen,

214 values of $|Z|$ are not significantly affected by the absence of barrel cleaning between different

215 freezing processes. On the contrary, $Arg(Z)$ exhibits significantly higher values only at the

216 beginning of the freezing process when the machine barrel is not cleaned from the previous

217 operation (possibly because of the presence of residuals of frozen ice cream between electrodes). As

218 freezing proceeds, however, these differences disappear and the data are no longer dependent on

219 repeated machine cleaning. Therefore, lack of cleaning between different freezings in practice does

220 not affect the reliability of electrical parameter measurements to determine the end of the freezing

221 process.

222 A typical situation where the freezing process fails to control the product stiffness is when the ice

223 cream freezes on the blades of the dasher motor, a problem more likely to occur when the cylinder

224 is fully loaded and the temperature is very low at the beginning of the process. To investigate the

225 capability of the type of control proposed in this work to overcome this problem, $|Z|$, $Arg(Z)$ and

226 $I_{motor}$ have been monitored during freezing assays featuring ice cream freezing on the blades of the

227 dasher motor. The curves shown in Fig. 6 (a), (b) and (c) indicate that the values of $I_{motor}$ remain

228 always lower than the threshold of 6.5 A, while $|Z|$ and $Arg(Z)$ reach their stop process thresholds

229 essentially at the same times than in the "standard" freezing experiments of Fig. 4. Therefore, the

230 combined monitor of both electrical parameters and $I_{motor}$ can be used to detect the occurrence of the

231      problem of ice-cream freezing on the scraping blades (see Supplementary Material for |Z| and

232      Arg(Z) plotted vs. $I_{motor}$), allowing the user to promptly take countermeasures.

233      Fig. 7 (a), (b) and (c) show the time evolution of |Z|, Arg(Z) and $I_{motor}$ in the case of the freezer

234      filled with four different volumes of ice cream mix: 3 liters (minimum value of freezing capacity), 4

235      liters, 5 liters and 7 liters (maximum value of freezing capacity). Both |Z| and $I_{motor}$ do not reach the

236      corresponding stop process thresholds for the 3 liters case, while Arg(Z) is almost not influenced by

237      mix volume and provides good control also at lowest load. As can be seen, the |Z| vs. time curve

238      depends on the mix volume.

239      In particular, in the case of 3 liters, |Z| initially increases (for the first 4 minutes), then slightly

240      decreases (from 4 to 6 minutes) while later increases again. This irregular behavior could be

241      explained as follows. When the ice-cream volume is low, electrodes are only partially covered by

242      the ice-cream mix, thus resulting in less conductivity and higher |Z|. When freezing begins, the

243      product temperature lowers producing an increase in both mix volume and electrodes coverage: |Z|

244      decreases. When, instead, ice-cream volume increases no more |Z| is bound to increase with

245      decreasing temperature. Thus the irregular behavior of |Z| can be the results of the opposite events

246      of increasing electrodes coverage and product freezing (decreasing and increasing |Z|, respectively).

247      Even if measurements of neither |Z| nor $I_{motor}$ provide reliable control for the freezing process in the

248      case of the minimum volume (3 liters), the former type of monitor is preferable. In fact, on the

249      contrary of motor stress and $I_{motor}$ that depend on product volume, the problem of |Z| is related to

250      electrode area coverage and can be solved by suitable placing of the electrodes so as they are

251      entirely covered by product even in the case of minimum mix volume.

252      The reason because |Z| is sensitive to electrode coverage while Arg(Z) is not, can be understood

253      considering the electrical circuit for a couple of electrodes of length L partially covered by a

254      conductive media, up to a length $l < L$ (Fig. 7 (d)).

255      Denoting $R_{AIR}$ and $R_{MIX}$ the resistances of the air and the media, respectively, since $R_{AIR} \gg R_{MIX}$

256      the system impedance can be described as:

257  $$Z = R_{MIX} + \frac{1}{j\omega C_{MIX}} \quad,$$  (1)

258  thus:

259  $$|Z| = \sqrt{R^2_{MIX} + \left(\frac{1}{\omega C_{MIX}}\right)^2} \quad,$$  (2)

260  $$Arg(Z) = -Arctg\left(\frac{1}{\omega R_{MIX} C_{MIX}}\right) \quad.$$  (3)

261  Denoting as $R^*_{MIX}$ and $C^*_{MIX}$ the resistance and capacitance for the electrodes covered with unit

262  length of conductive media, $R^*_{MIX}$ and $C^*_{MIX}$ are independent on the electrodes coverage level and

263  thus on the mix volume. It is $R_{MIX} = \dfrac{R^*_{MIX}}{l}$ and $C_{MIX} = l \cdot C^*_{MIX}$ , hence:

264  $$|Z| = \frac{1}{l} \cdot \sqrt{R^*_{MIX} + \left(\frac{1}{\omega C^*_{MIX}}\right)^2} \quad,$$  (4)

265  $$Arg(Z) = -Arctg\left(\frac{1}{\omega R^*_{MIX} C^*_{MIX}}\right) \quad.$$  (5)

266  Eq. 4 and 5 indicate that |Z| decreases as l increase, while Arg(Z) is independent of l.

267  To support this interpretation, |Z| and Arg(Z) have been measured in the frequency range 20 Hz - 10

268  KHz in experiments featuring the machine filled with different volumes of ice cream mix and  with

269  the dasher motor turned off to guarantee a constant level of electrode coverage. The results

270  (presented in the Supplementary Material), fully confirm the electrical model of Fig 7 (d).

271  Preliminary measurements have also been carried out on other three ice cream mixes, different for

272  composition and producers, and the results (presented in the Supplementary Material) are in good

273  agreement with those described above in this paper, clearly indicating that the technique proposed

274  in this paper can be successfully applied to different mixes without the need of individual

275  calibration.

276

277  **5. Conclusions**

278 In this paper a novel technique to control the freezing process of ice creams in conventional batch

279 freezer has been presented. The new method, based on the measurement of the product electrical

280 parameters, $|Z|$ and $\text{Arg}(Z)$, by a couple of stainless steel electrodes (for instance placed on the

281 front door of the machine), presents significant advantages compared with the current technique

282 based on monitoring of the current drawn by the dasher motor. This, in essence, because the

283 electrical parameters are an indicators of product status, although only at macroscopic level, hence,

284 contrary to the current drawn by the dasher motor, are insensitive to power line fluctuations and

285 electric motor characteristics, as well as independent of the volume of ice-cream within the machine

286 (provided suitable placing of the electrodes so as they are completely covered with product even in

287 the case of minimum mix volume).

288 The experimental data presented in the paper show a good linear correlation of both $|Z|$ and $\text{Arg}(Z)$

289 with the current drawn by the dasher motor, with $|Z|$ being the best choice as parameter to be

290 monitored because of higher data correlation and repeatability.

291 On the whole, the control of ice cream freezing process by electrical parameters monitoring

292 represents an economical and reliable technique advancing the state of the art in the field.

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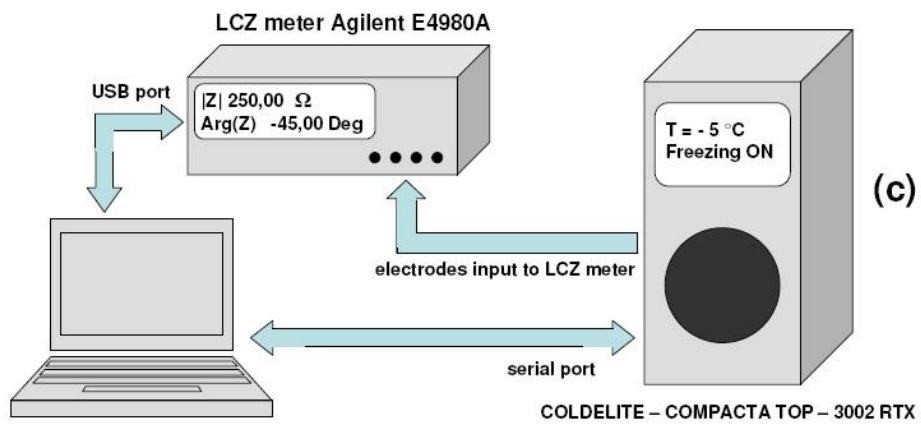
**Fig. 1** Industrial batch freezer used in the experiments (a), frontal grid of the machine (b) and a
scheme representing the set-up used in the experimental.

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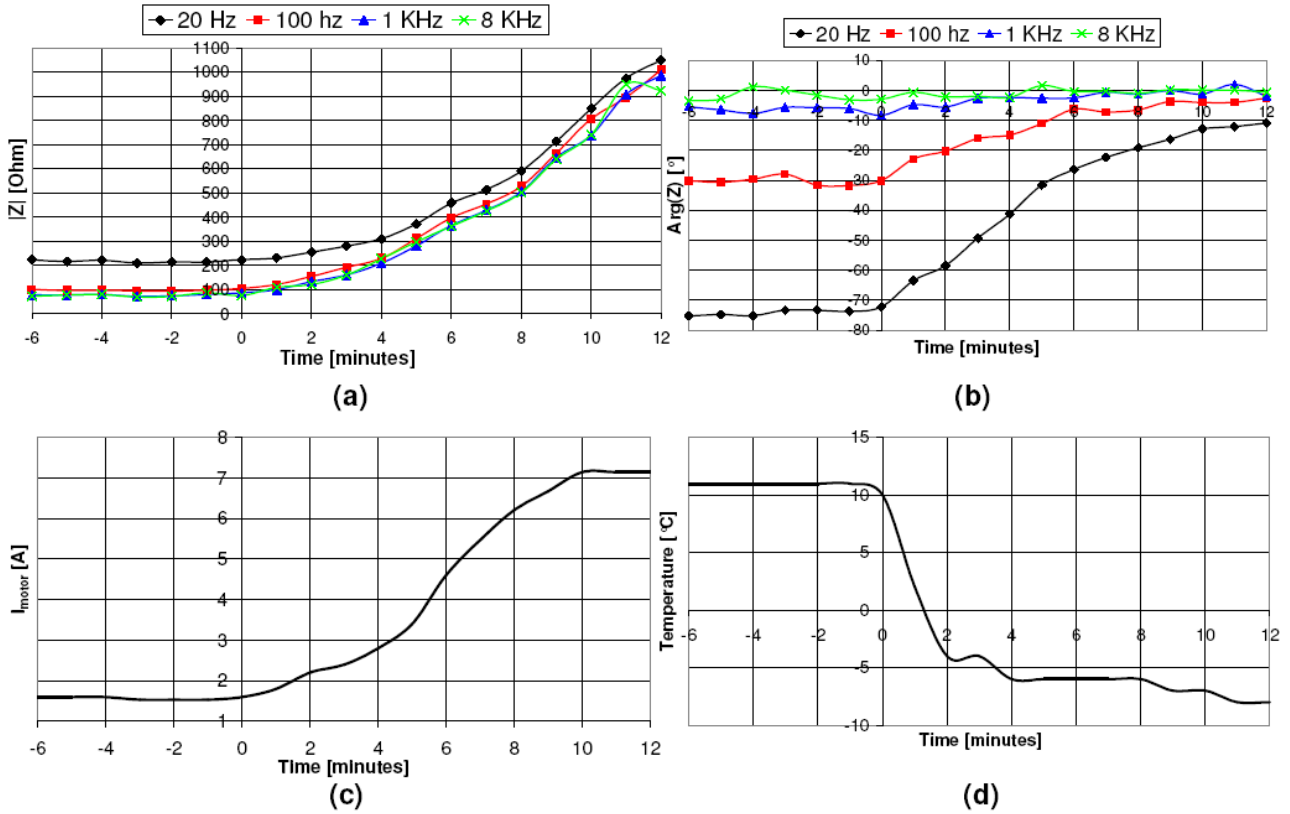


**Fig. 2** Curves of |Z| and Arg(Z) vs. time measured for different frequencies of the test signal (Fig. a

and b, respectively). Current drawn by the dasher motor (c) and product temperature (d) as function

of time during the freezing process for a vanilla flavored ice cream mix.

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**(a)**

**(b)**

**(c)**

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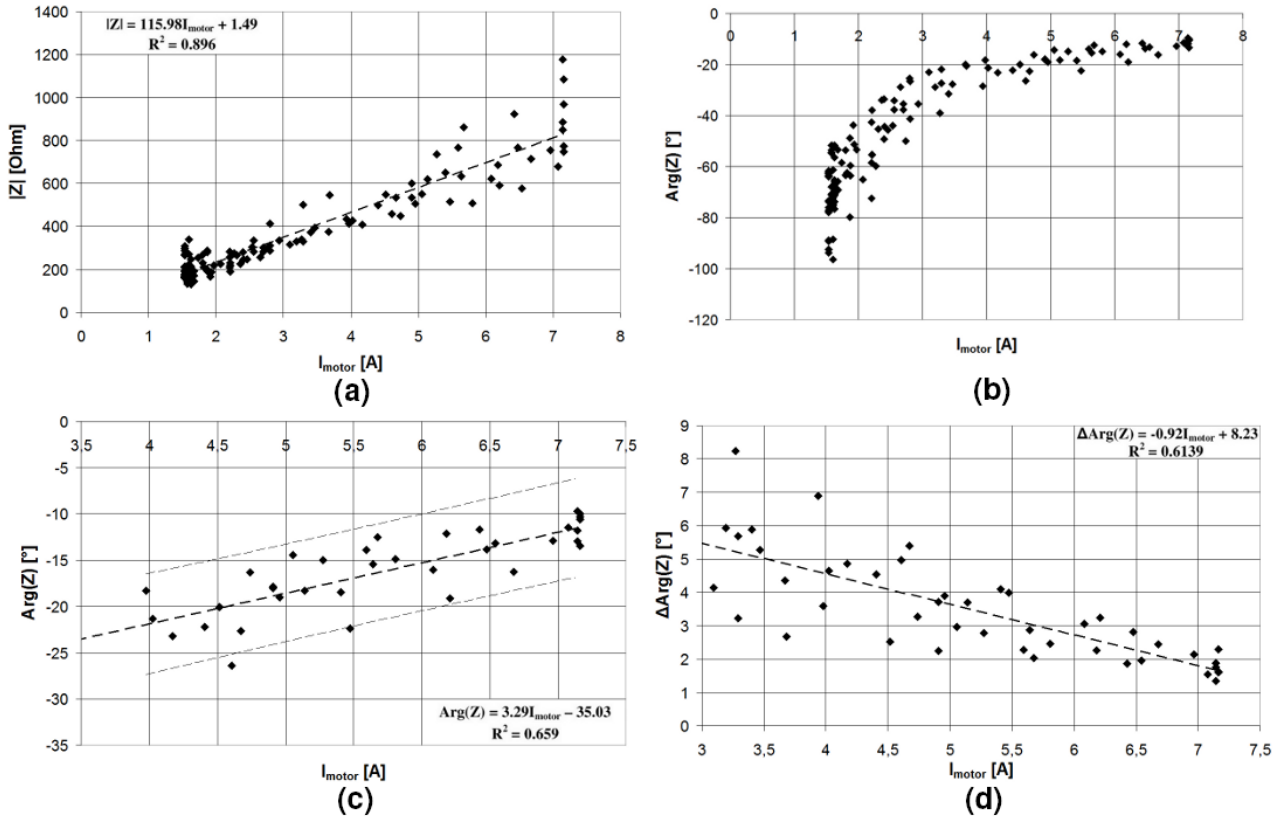
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439 **Fig. 3** Curves of |Z| (a), Arg(Z)  and ΔArg(Z) (d) vs. $I_{motor}$. Two curves Arg(Z)  vs. $I_{motor}$ are

440 presented for the entire range values of $I_{motor}$ (b) and for values in the range 3.5A to 7.5A (c).

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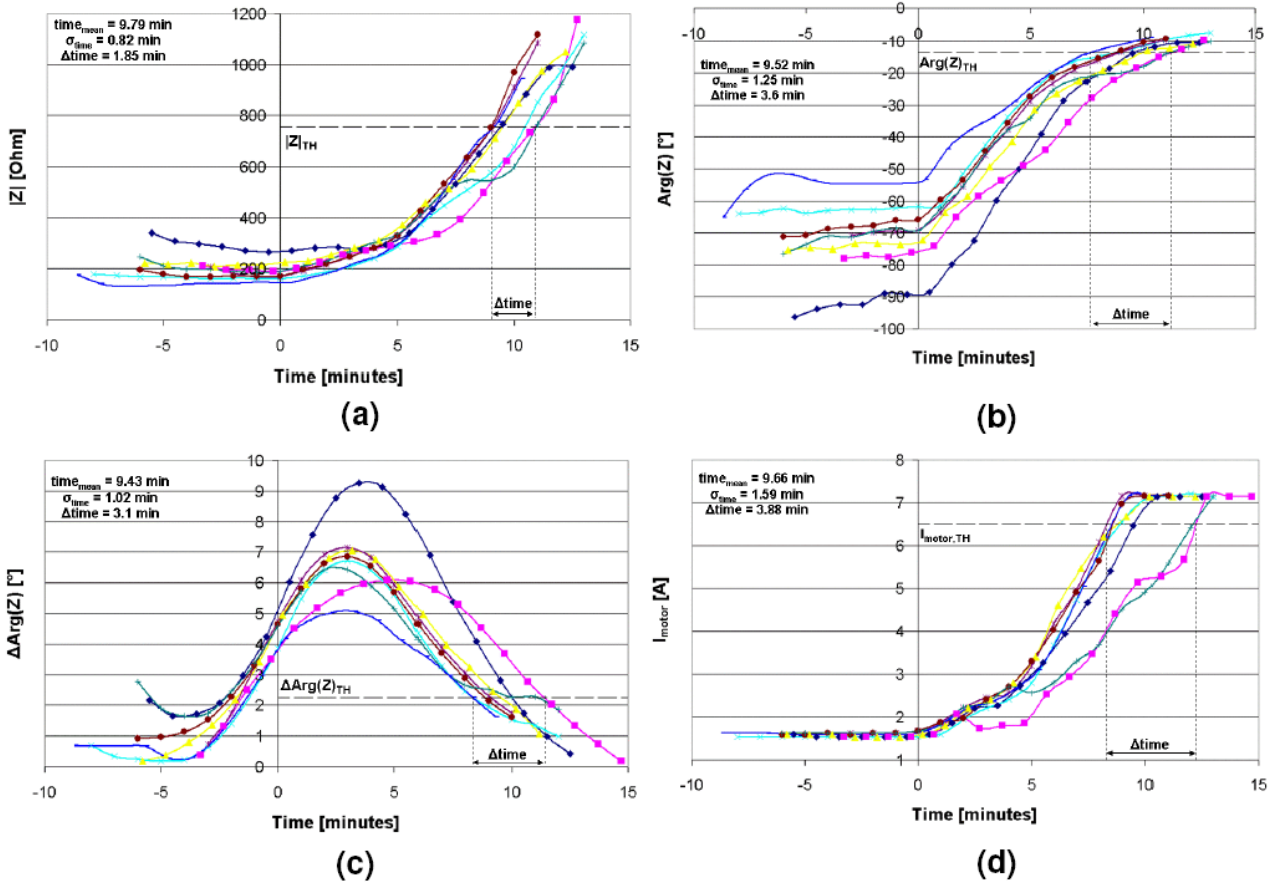
**Fig. 4** Repetition trials for the ice cream freezing process. The values of |Z|, Arg(Z), $\Delta$Arg(Z) and $I_{motor}$ are plotted vs. time, while statistics for the stop process time are presented. The legend for the trial number is as follows: $1^{st}$ ($\blacklozenge$, dark blue), $2^{nd}$ ($\blacksquare$, pink), $3^{rd}$ ($\blacktriangle$, yellow), $4^{th}$ (**x**, light blue), $5^{th}$ ($\ast$, purple), $6^{th}$ ($\bullet$, brown), $7^{th}$ (I, dark green), $8^{th}$ (−, blue).

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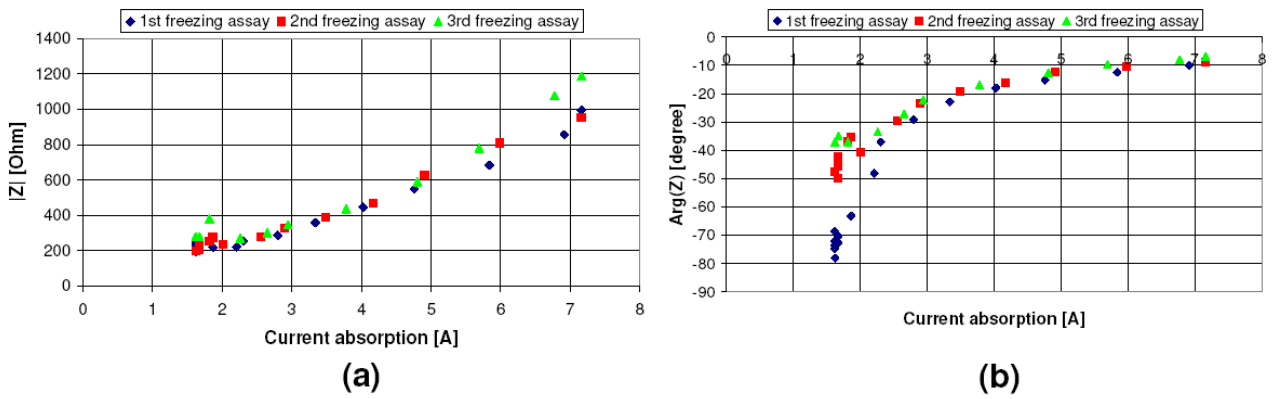
**Fig. 5** |Z| and Arg(Z) vs. $I_{motor}$ for freezing processes carried out without cleaning the machine barrel between consecutive assays.

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**Fig. 6** Monitored values of |Z| (a), Arg(Z) (b) and $I_{motor}$ (c) for a freezing process when the mix freezes on the blades of the dasher motor.
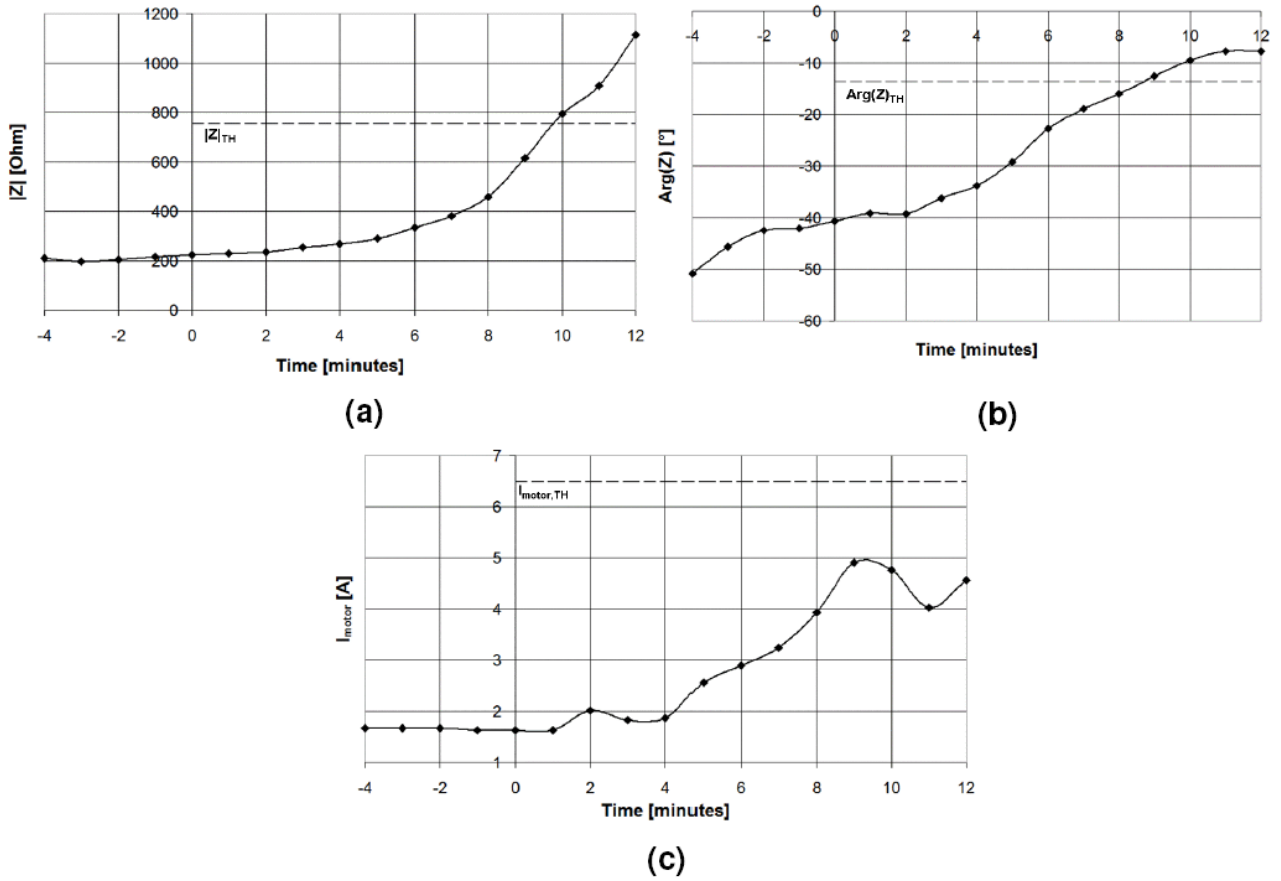
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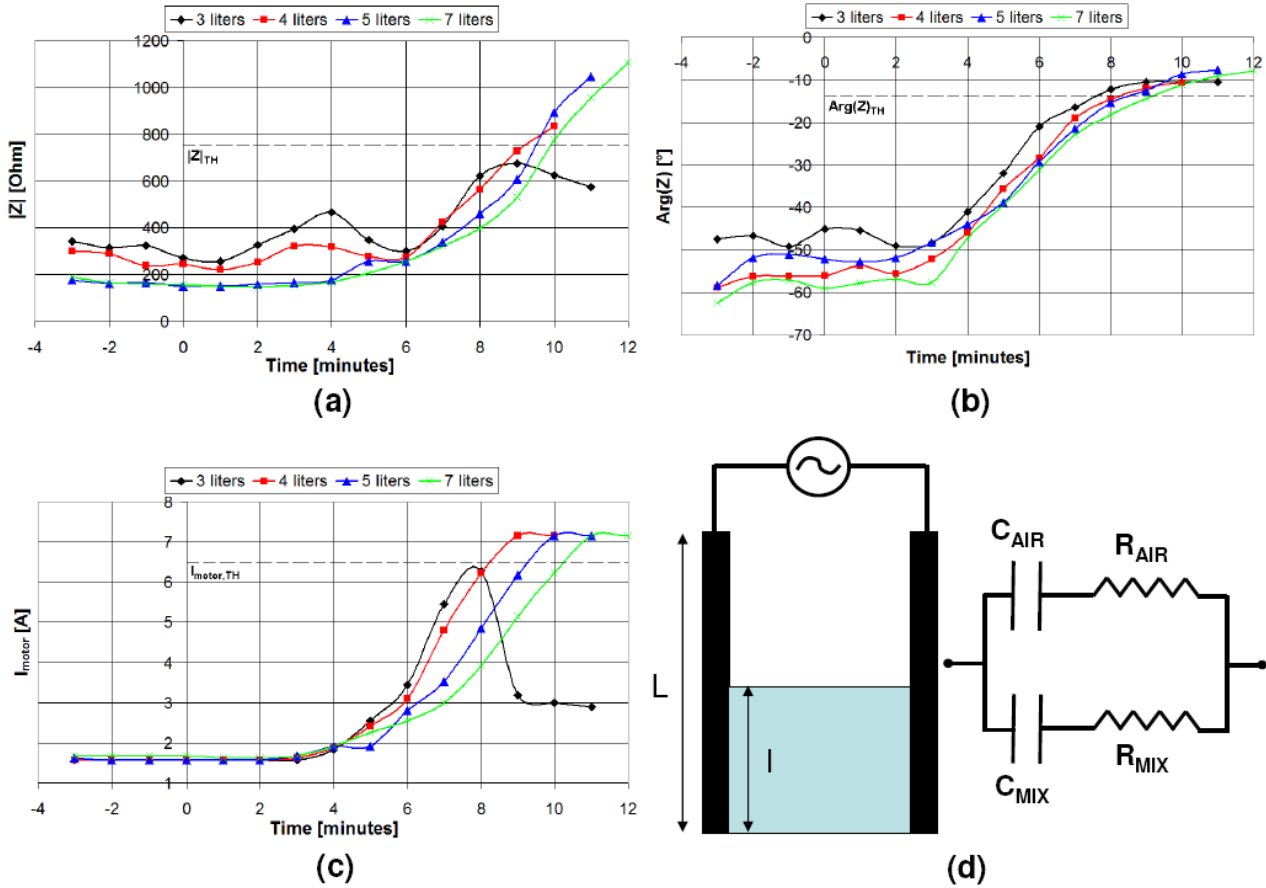


**Fig. 7** Curves of |Z|,  Arg(Z) and $I_{motor}$ vs. time for freezing processes carried out filling the machine barrel with different volumes of ice cream mix (Fig. a, b and c, respectively). Electrical model for the system formed by a couple of electrodes only partially covered by conductive media (d).

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# Supplementary Material

# A novel technique to control ice cream freezing by electrical characteristics analysis

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*EIS monitoring of the freezing process*. The ice cream mix has been subjected to freezing process and the electrical parameters $|Z|$ and $\text{Arg}(Z)$ have been measured for the frequency range 20Hz - 10KHz at time intervals of 1 minute. In Fig. S1 the Nyquist plot for EIS measurements are shown for different acquisition times. As can be seen, higher frequency measurements result in lower signal-to-noise ratio, poor reproducibility and, in general, higher dispersion than the corresponding low frequency measurements (due to the electromagnetic noise generated by the dasher motor). This, in particular, affects the last phase of the freezing process when the measurements dispersion at high frequency is significantly higher than at the beginning of the process.

The Nyquist plot of Fig. S1 can be also used to validate the electrical model for the system product-electrodes. A model composed of the series of a resistance $R_{MIX}$ (accounting for the product conductivity) and a capacitance $C_{MIX}$ (essentially due to the capacitive product-electrode interface) has been used. Thus:

$$Z = R_{MIX} + \frac{1}{j\omega C_{MIX}} \qquad\qquad \text{Re}(Z) = R_{MIX} \qquad\qquad \text{Im}(Z) = -\frac{1}{\omega C_{MIX}}$$

This is consistent with Fig. S1 where $\text{Re}(Z)$ is essentially frequency independent and $\text{Im}(Z)$ decreases as the frequency increases.
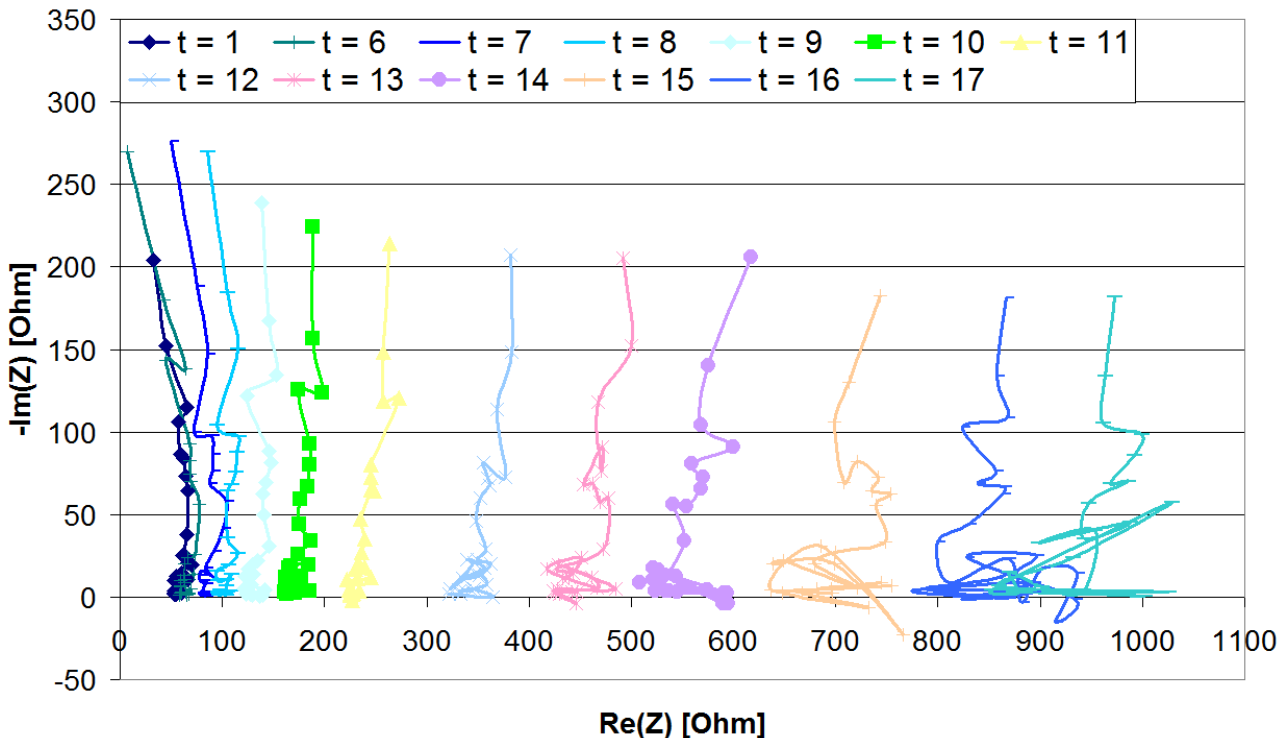


**Fig. S1** Nyquist plots for different acquisition times (in minutes) during the freezing process.

540    *Repetition of the freezing assays*. Different freezing assays has been carried out using the same ice-
541    cream mix (described in the Section "Materials and Methods") and conditions (cylinder washed
542    with hot water between assays and filled with 7 liters of mix). Nevertheless, the curves of both the
543    electrical parameters and current drawn by the dasher motor vs acquisition time presented poor
544    repeatability. This must be ascribed to the dynamics of the freezing system. As can be seen in Fig.
545    S2, where the temperature of the product is plotted as function of the acquisition time, the time t*
546    when the product temperature begins to decrease presents an high dispersion (with values of t*
547    ranging from 2.7 minutes to 8.8 minutes). Thus, to eliminate the dispersion due to the freezing
548    system dynamics, the time origin has been set to the instant the product temperature begins to
549    decrease.
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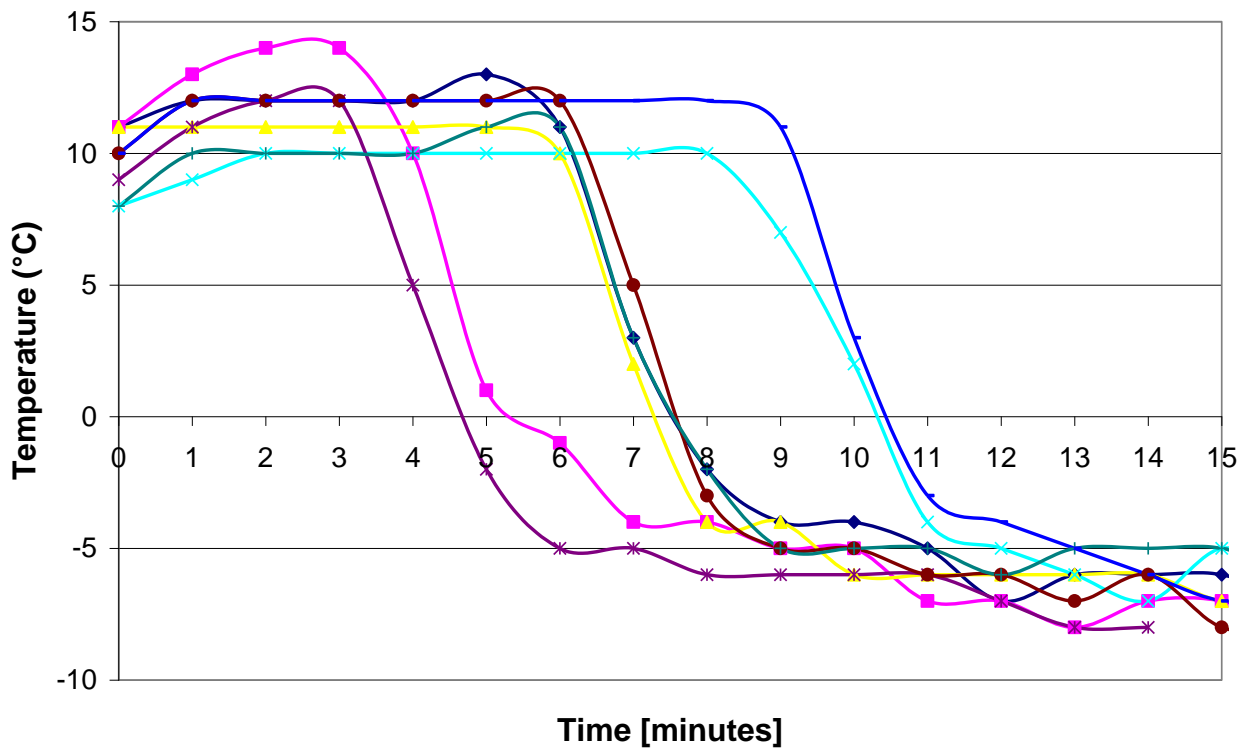


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552    **Fig. S2** Product temperature vs. acquisition time for different freezing assays.
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572  *Correlation between product temperature and current drawn by the dasher motor*. The product

573  temperature is monitored during the freezing assay by the sensor temperature PT100, placed in

574  direct contact with the product. In Fig. S3 the product temperature is plotted versus the current

575  drawn by the dasher motor $I_{motor}$. As can be seen, very poor correlation exists between the two

576  parameters. The product temperature decrease at the beginning of the freezing process and then

577  saturates at a value ranging from -9°C to -5°C.

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580  **Fig. S3** Scatter plot for the product temperature vs. the current drawn by the dasher motor.
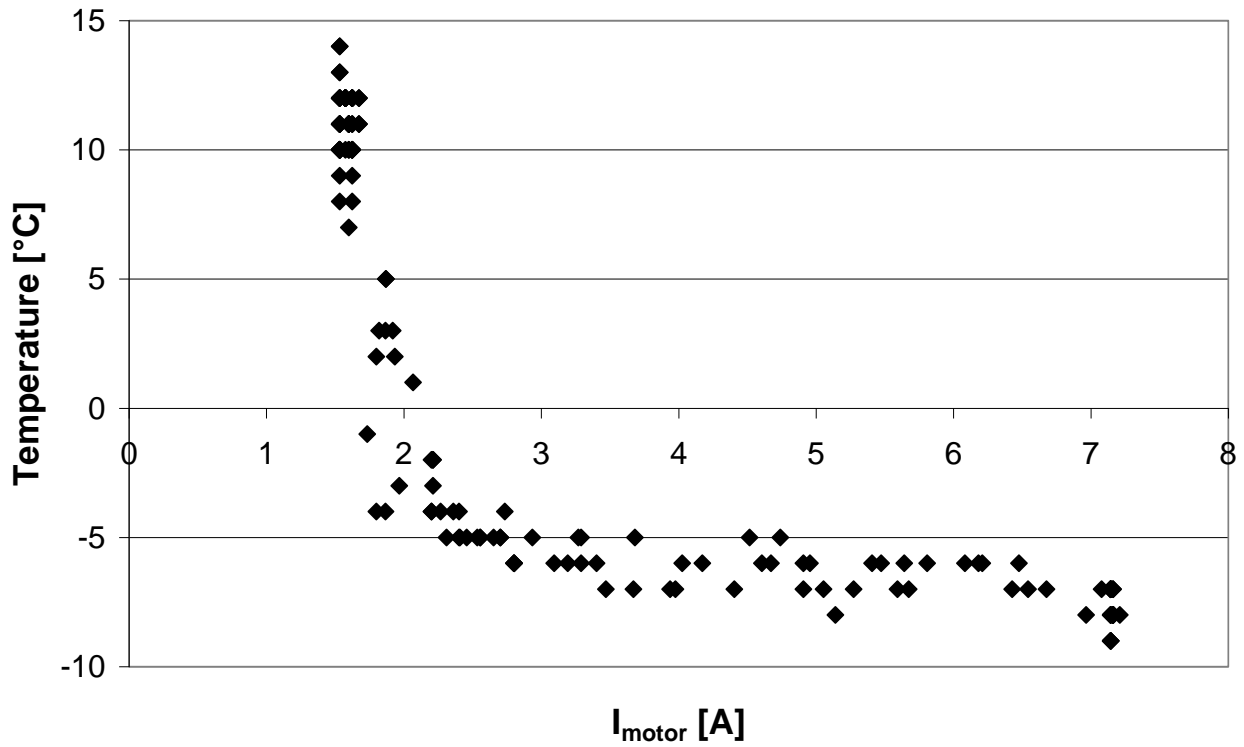
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601 *Detection of ice cream mix freezing on the blades of the dasher motor by combined monitoring of*
602 *electrical characteristics and current drawn by the dasher motor*. This problem can happen during
603 the freezing assay in particular when the freezer cylinder is loaded with maximum mix volume (7
604 liters) and the chamber temperature is very low already at the beginning of the process. This event
605 must be promptly detected since under this condition the proper control of product stiffness is
606 compromised. In Fig. S4 the monitored values for |Z| and Arg(Z) are plotted versus the
607 corresponding $I_{motor}$ values for a freezing assay featuring this particular problem. Lower and higher
608 bounds from repeatability tests are also shown. As can be seen, as the mix freezes on the blades of
609 the dasher motor, values of $I_{motor}$ decreases while |Z| and Arg(Z) increases. This causes the
610 measured data to fall off the safe working area represented by dashed lines in Fig. S4. Thus,
611 combined monitoring of |Z|, Arg(Z) and $I_{motor}$ can promptly detect this problem.



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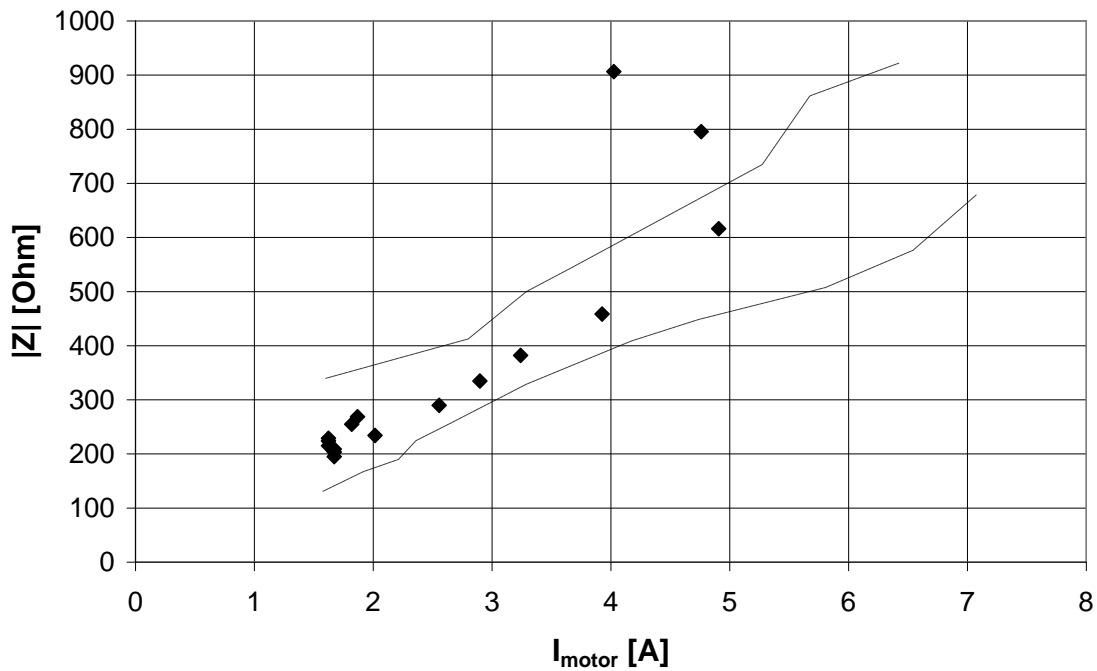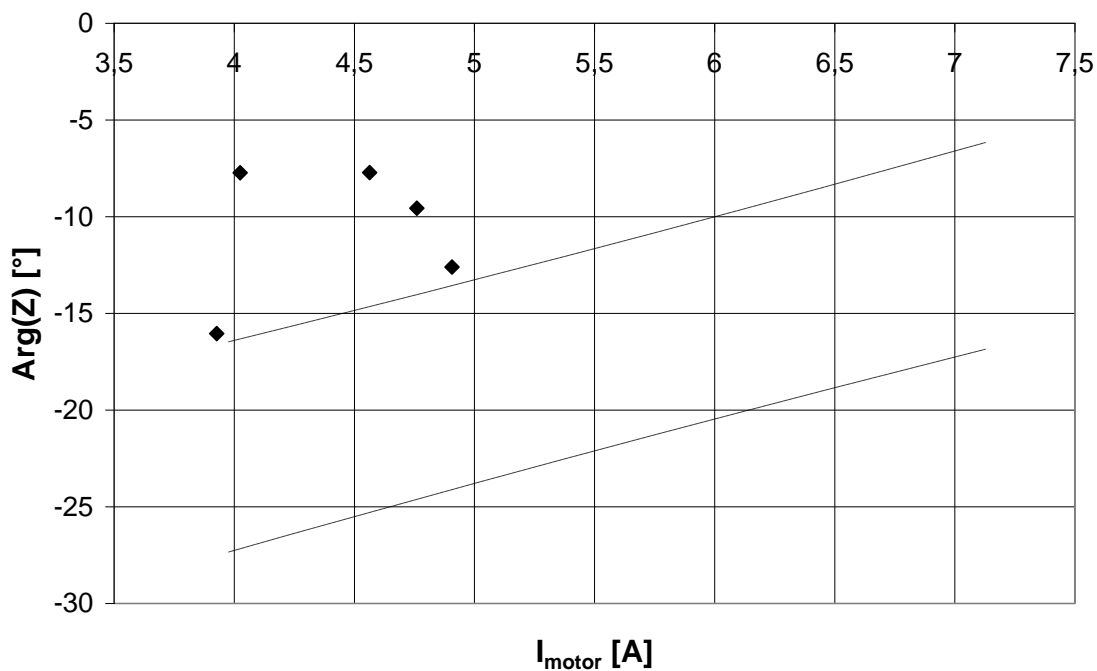
614 **Fig. S4** Plots of |Z| and Arg(Z) vs. $I_{motor}$ for a freezing assay featuring mix freezing on the blades of
615 the dasher motor.
616 *EIS analysis of ice cream mix with different levels of electrodes area coverage*. As a further proof of
617 the dependence of electrical parameters on the electrode area coverage, the machine has been
618 loaded with different volumes of ice cream mix (with the dasher motor turned off to guarantee a
619 constant level of electrode coverage) and |Z|, Arg(Z) measured on the frequency range 20 Hz - 10
620 KHz. The results, presented in Fig. S5, show how while |Z| is a strong function of electrodes area
621 coverage, Arg(Z) is essentially independent.



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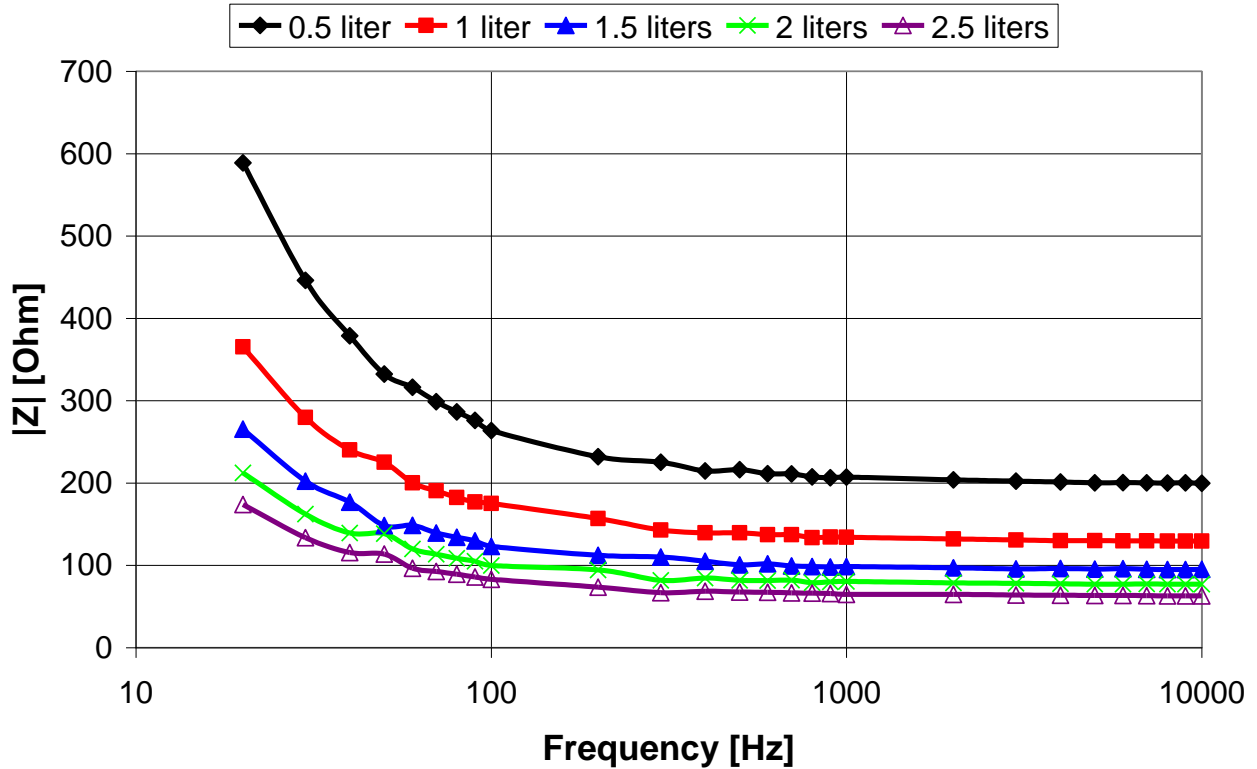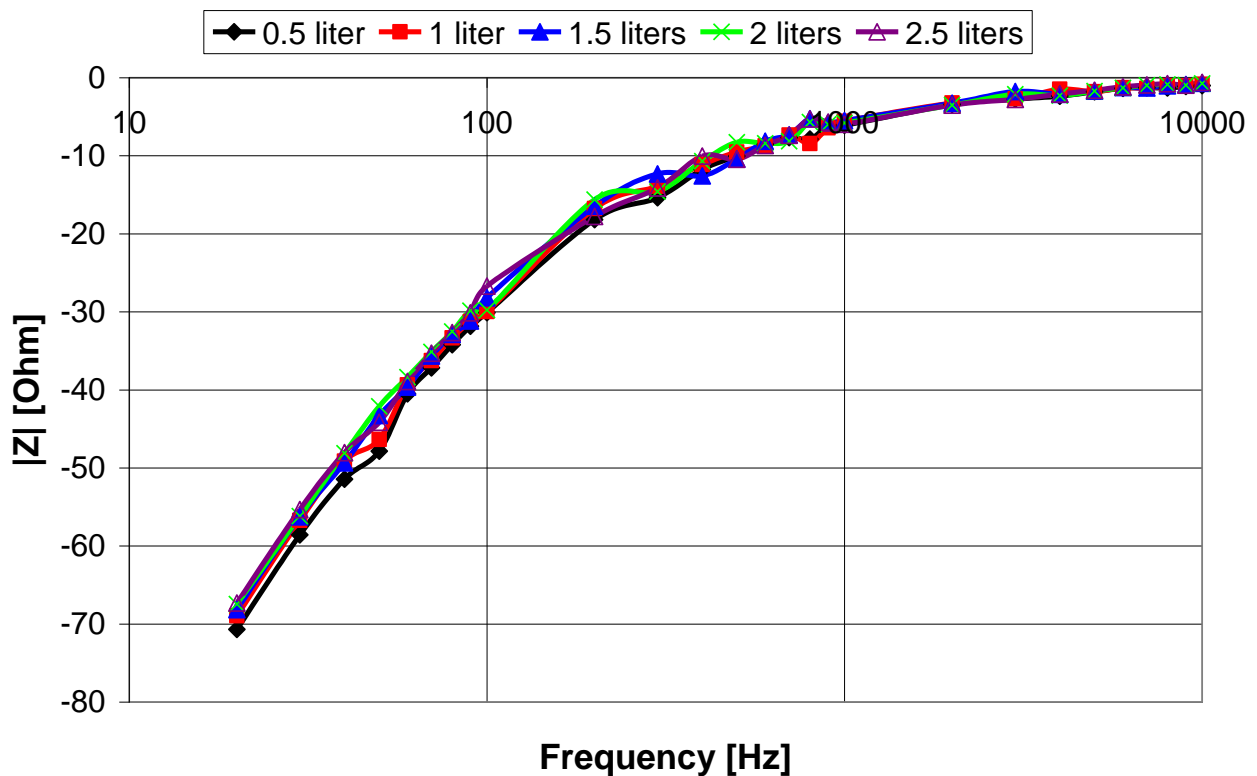
624 **Fig. S5** |Z| and Arg(Z) as function of frequency for different ice cream mix volumes.
625 *Measurements on different ice cream mixes*. Preliminary measurements have been carried out on a
626 limited number of ice cream mix of different compositions and producers to test the correlation of
627 the electrical parameters |Z| and Arg(Z) with the current drawn by the dasher motor and compare
628 the results with those obtained with the test mix described in the Materials and Methods section.
629 The recipes for the three product tested, hereafter named Ice Cream Mix A, B and C, are as follows.
630
631 Ice Cream Mix A: fat content 6%, milk solids-not-fat 12.5%, sugar 12%, corn syrup solids 4%,
632 stabilizers/emulsifiers 0.4%, total solids 34.9%.
633
634 Ice Cream Mix B: fat content 10%, milk solids-not-fat 11%, sugar 12%, corn syrup solids 3%,
635 stabilizers/emulsifiers 0.4%, total solids 36.4%.
636
637 Ice Cream Mix C: fat content 6%, milk solids-not-fat 11%, sugar 11%, corn syrup solids 5%,
638 stabilizers/emulsifiers 0.5%, total solids 33.5%.
639
640 Ice Cream Mix A is produced by Berglandmilch (Austria, www.berglandmilch.at), while Ice Cream
641 Mix B and C by Mondi nel Mondo (Rome, Italy, www.mondinelmondo.it).
642
643 In Fig. S6 the electrical parameters |Z| and Arg(Z) are plotted vs current drawn by the dasher motor.
644 Dashed lines represent the lower and higher bounds for the test mix described in the "Materials and
645 Methods" section resulting from the scatter plots of Fig. 3 in the manuscript. As can be seen,
646 measurements present good agreements with data obtained with the test mix, with only slightly
647 lower values of |Z| at the beginning of the freezing process.
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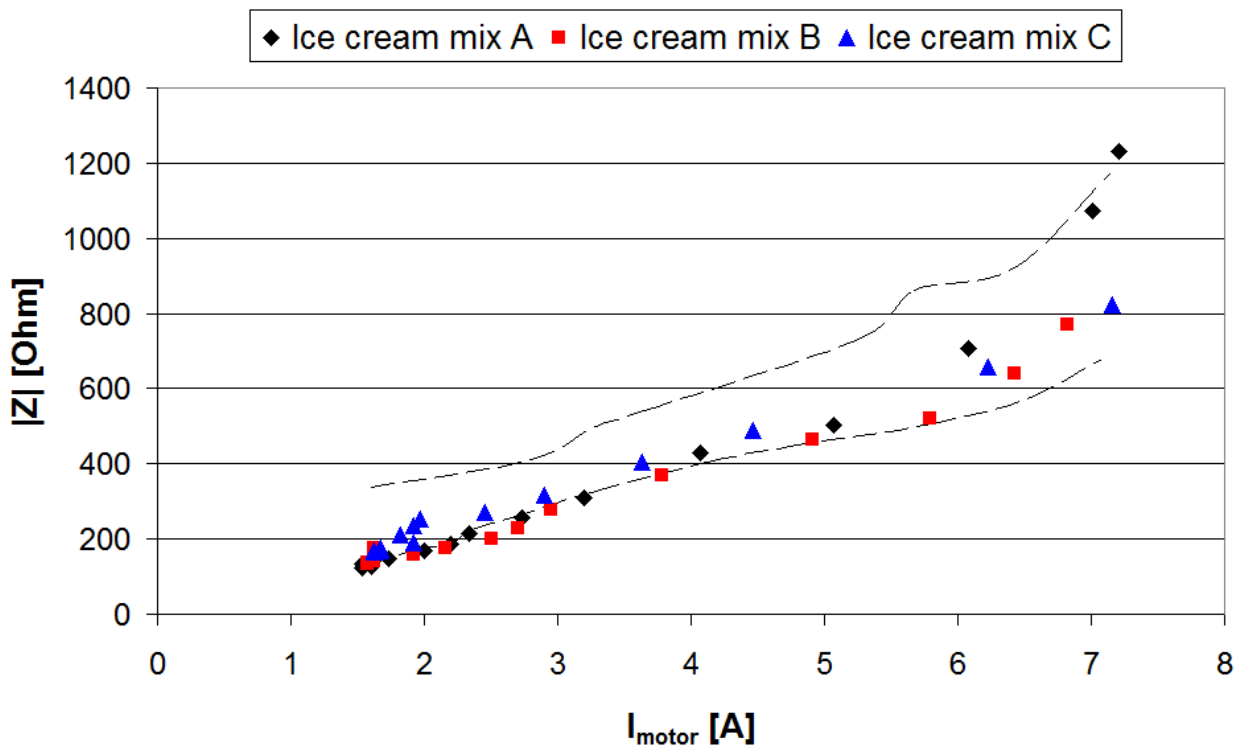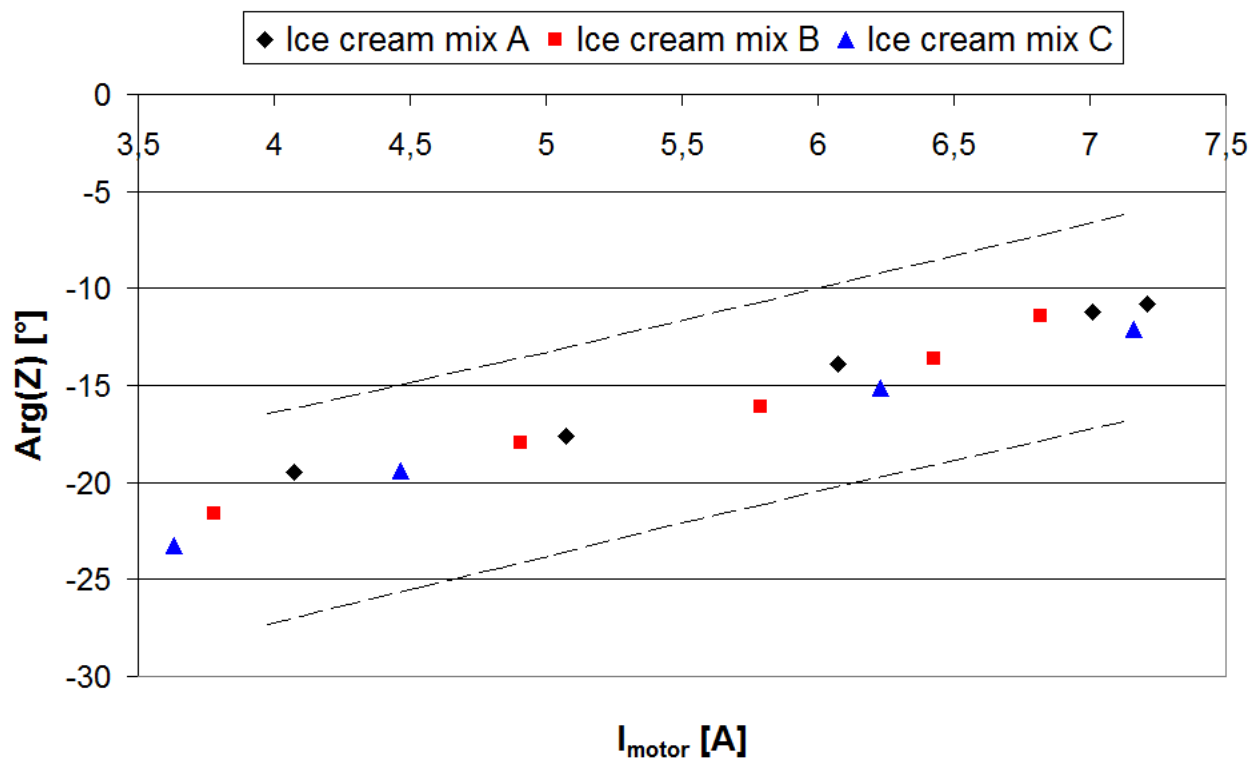
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652 **Fig. S6** Scatter plots for |Z| and Arg(Z) as function of the current drawn by the dasher motor for
653 different ice cream mixes.
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