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THE INFLUENCE OF THERMOPHYSICAL PROPERTIES ON PREDICTED FREEZING TIME OF POTATO

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A b s t r a c t. The aim of this paper was to examine how the value of thermophysical properties of an agricultural product can change its freezing time estimated by the chosen calculation models.

Using the models of Plank, Cleland and de Michelis et al. the effective freezing time of parallelepiped-shaped potato was predicted. The properties included in a prediction were taken from four different sources and the experimental freezing time according these of Ilicali.

In each case of prediction the method of Cleland shows the smallest prediction errors. Besides, the most precise results are obtained by using the properties according to Castaigne. The results of the work prove the significance of the product properties for the accuracy of freezing time prediction.

K e y w o r d s: potato, thermophysical properties, freezing

INTRODUCTION

Potato is one of the most widely cultivated plants in the world owing to its high caloric content of the components like starch, lack of antinutritional substances and the possibility of its growing in the quite diversive climatic zones. Tubers are consumpted mainly in form of french fries, noodles, potatocake as well as an indispensable soup additive. One of the most important processes in the production of fries is their freezing aiming at the preservation so that their long-term storage could be possible in both production conditions and directly at a consumer.

Regarding the maintenance of the best product quality and studying high energy consuming process of thorough freezing, the intention is to obtain the optimum time of its duration. One of the criteria is a proper value selection of thermophysical properties of product that undergoes, the process in the computational program [5,7,13,19,21]. Therefore, it is irrevocable to possess a possibility of the fastest and accurate prediction of freezing time.

The objective of the present paper is to evaluate the influence of thermophysical properties of potatoes to be frozen on the accuracy of freezing time calculation according to the selected models of the process.

MATERIALS AND METHODS

Potato freezing time was analysed using the results of Ilicali's experimental data [10] dealing with freezing time of parallelepiped-shape product with 0.02 x 0.04 x 0.15 m dimensions. In the experiments potato samples were frozen started from the initial temperature (differentiated from 9.8 °C to 23.6 °C), till the temperature of -10 °C was obtained in the thermal centre of a product.

To state the influence of product properties on calculation accuracy of the effective freezing time [11], the three following widely used models for time determination were applied:

Plank's method [18]:

$$t = \frac{\rho\,(d/2)^2 \Delta H}{(T_{kr}-T_o)\lambda}\left(\frac{1}{Bi}+\frac{1}{2}\right)$$

$$[1+0.0053(T_p-T_{kr})]+\frac{1.866(d/2)^2 n\rho c_p}{\lambda}$$

$$\left[\log\left(\frac{T_{kr}-T_o}{T_c-T_o}\right)-0.0913\right]\left[\frac{1}{Bi}+\frac{1}{2}\right],$$

Cleland's [3,4]:

$$t = \frac{\Delta H}{T_{kr}-T_o}\left(P\frac{d}{h}+R\frac{d^2}{\lambda_z}\right),$$

and the analytic-graphical model of de Michelis and Calvelo [6]

$$t=\frac{\rho_n M L_o \omega_1 d^2}{(T_{kr}-T_o)\lambda_4}\left(\frac{P}{Bi}+R\right)+$$

$$\frac{\tau_{1/2} N d^2}{4\alpha_n EHTD}+\frac{\tau_{1/2} N d^2}{4\alpha_z EHTD}.$$

They enable the determination of effective freezing time and combine the features of most calculation methods of analytic-empirical origin, being highly precise at the same time.

Applying each of the above mentioned methods, the thermophysical properties of potato were used after four various sources [1,9,14-16]. The following potato properties were used in the calculations: latent heat of freezing L, cryoscopic temperature T_{kr}, and for both unfrozen and frozen product state: thermal conductivity α, heat capacivity c_p and density ρ (Table 1).

In order to estimate and characterize the accuracy of freezing time calculation, relative prediction error was determined:

$$e = \frac{t_{rz}-t}{t}\,100\,\%.$$

The obtained predicted results of freezing time t and relative errors values of the prediction were analysed at the application of statistical package Statgraphics 5.0 [22]. The errors of freezing time prediction were estimated performing a general statistical analysis. Moreover, there were studies on regression of the experimental freezing time t_{rz} in relation to the time calculated after each of the models and Kolmogorov-Smirnov's test application fitting the distribution of the results into the experimental values distribution [8].

RESULTS AND DISCUSSION

The results of statistical estimation of freezing time prediction errors after particular

Table 1. Thermophysical properties of potato used in the analysis of prediction models

Properties	According to			
	Lacroix [14]	ASHRAE [1]	Hung [9]	Leblanc [15,16]
Density, unfrozen - m^3/kg	1100	1040	1093.82	1069
frozen - m^3/kg	980	988	1035.5	1012
Conductivity, unfrozen - W/mK	0.45	0.49	0.53	0.50
frozen - W/mK	1.7	1.09	1.9	1.00
Latent heat - J/kg	284742.27	270467.3	240625.65	246888.8
Moisture content - %	85	81	71.85	73.7
Heat capacity, unfrozen - J/kgK	3800	3558.8	3346.07	3420
frozen - J/kgK	1800	1842.2	1883.15	1870
Cryoscopic temperature - ^oC	-0.8	-0.6	-0.6	-0.8
Thermal diffusivity, unfrozen - m^2/s	1.077E-7	1.33E-7	1.202E-7	1.14E-7
frozen - m^2/s	9.63E-7	5.99E-7	9.74E-7	5.28E-7

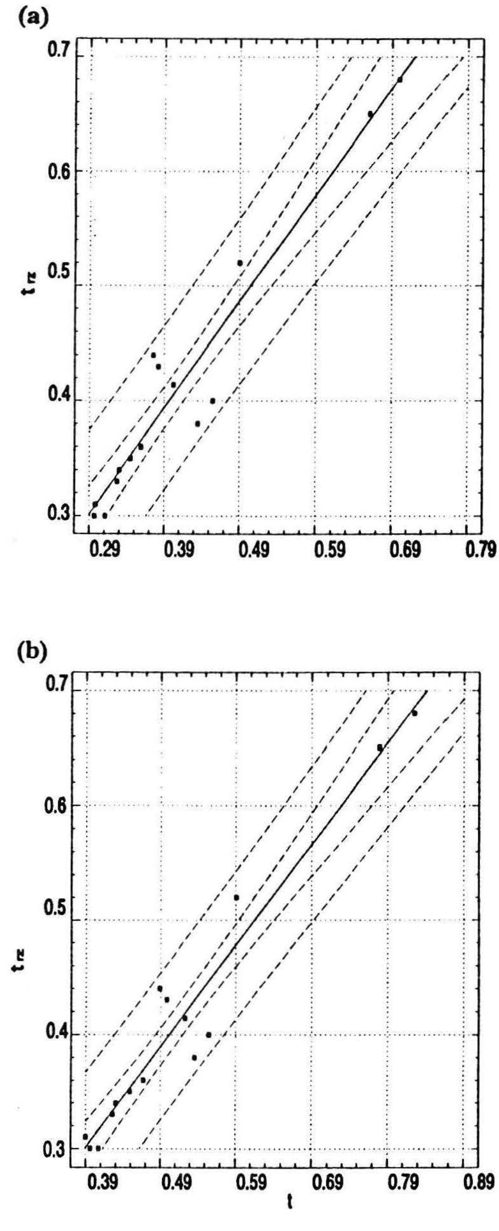

Fig. 1. Regression of experimental freezing time (t_{rz}) of potato in relation to time (t) calculated under Cleland's model; properties acc. to [14] (a) and [1] (b).

method with every use of thermophysical properties of potato according to Table 1 were demonstrated in Table 2. Due to the analysis of the evaluation it has been found out that the most accurate results are obtained according to Cleland's method accepting potato properties after Lacroix [14] (Fig. 1), while the poorest were also obtained at Cleland's model application, however with the product properties according to ASHRAE [1], (Fig. 2, Table 3).

The regression analysis of the experimental freezing time t_{rz} in relation to time calculated after the models confirm the mentioned statements. The times received according to Cleland's model combining the properties after Lacroix [14] (Fig. 1) demonstrate the best regression analysis (Table 3), including the findings of Table 2, naturally. However, the worst regression of the experimental time related to calculated freezing time was also acquired from the results after Cleland's method while the properties according to ASHRAE [1], (Fig. 2, Table 3).

Considering all the calculated data it should be stated, that the application of Plank model [17] gives the best results by using potato properties according to Leblanc *et al.* [16] whereas using de Michelis model [6], the properties after ASHRAE [1], (Tables 1,2 and 3) should be accepted. That gives evidence of differentiated quality of each properties group as well as value of methods applied to freezing time calculation [2,12].

The above mentioned conclusions have been confirmed by Kolmogorov-Smirnov two sample test [22], used to examine the distribution compatibility of the obtained results after each particular model and the values of experimental freezing time. The most favourable compatibility of distributions was proved for the results after Cleland's model together with the properties according to Lacroix [14] (Fig. 2a), whereas the poorest agreement of results in relation to the experimental values was noted for those also obtained after Cleland's method but at application of potato thermophysical properties after ASHRAE [1] (Fig. 2b).

Although the statistical tests suggest explicitness of the results, still, the problem requires some broad investigations.

Table 2. Statistical evaluation of relative errors of freezing time prediction

Model	Plank [18]				Cleland [3,4]				de Michelis [6]			
Properties after:	Lacroix [14]	ASHRAE [1]	Leblanc [15,16]	Hung [9]	Lacroix [14]	ASHRAE [1]	Leblanc [15,16]	Hung [9]	Lacroix [14]	ASHRAE [1]	Leblanc [15,16]	Hung [9]
Sample size	15	15	15	15	15	15	15	15	15	15	15	15
Mean %	-6.985	13.507	9.25	-12.1	-0.59	27.14	26.29	-1.29	-17.86	-3.658	-2.2086	-17.53
Stand. dev.	8.139	7.808	7.316	7.949	7.70	8.586	8.786	7.64	8.570	6.537	9.234	8.053
Error range												
minimum	-17.88	1.28	-1.81	-22.9	-14.85	11.75	11.06	-15.3	-30.01	-15.35	-16.54	-30.8
maximum	7.11	26.23	20.52	1.67	14.55	42.06	40.99	13.54	-0.19	8.52	13.78	-1.53
95% conf. int. for mean %												
from	-11.49	9.18	5.19	-16.47	-4.86	22.39	21.43	-5.529	-22.6	-7.279	-7.323	-21.779
to	-2.48	17.83	13.299	-7.666	3.67	31.9	31.16	2.939	-13.11	-0.037	2.906	-12.858

Table 3. The results of regression analysis of experimental freezing time in relation to time predicted after studied models

Model	Plank [18]				Cleland [3,4]				de Michelis [6]			
Properties after:	Lacroix [14]	ASHRAE [1]	Leblanc [15,16]	Hung [9]	Lacroix [14]	ASHRAE [1]	Leblanc [15,16]	Hung [9]	Lacroix [14]	ASHRAE [1]	Leblanc [15,16]	Hung [9]
Intercept	0.094	0.054	0.051	0.092	0.033	-0.028	-0.043	0.037	0.076	-0.004	0.054	0.079
Slope	0.808	0.762	0.800	0.874	0.926	0.847	0.883	0.922	0.999	1.054	0.888	0.973
Correl. coef.	0.981	0.975	0.976	0.973	0.966	0.973	0.972	0.966	0.952	0.970	0.975	0.959

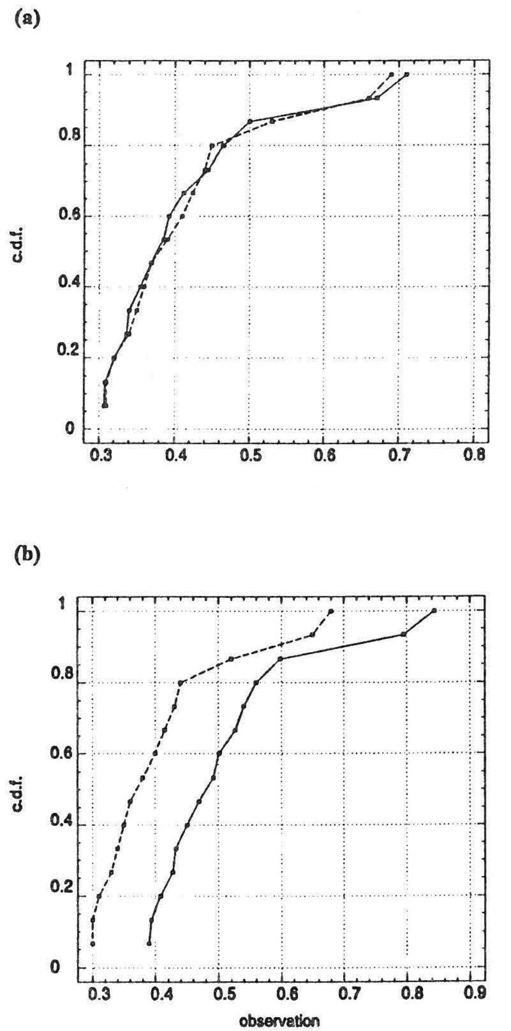

Fig. 2. Cdf plot of experimental freezing time (t_{rz}) of potato and time (t) predicted after Cleland's model; properties acc. to [14] (a) and [1] (b). t_{rz} - solid line, t - dashed line.

CONCLUSIONS

The models for freezing time calculations arise from procedures that are imposed with numerous simplifications [2,20]. The thermophysical properties of potato are determined by various methods and, regarding a full range of temperatures, with specified accuracy. Moreover, there are some additional factors that decrease accuracy of freezing time calculation [2]. Therefore, there have existed grounds to reach at quite unexpected conclusion out of performed investigations.

It is well known that Cleland's models [2] belong to the most precise analytic-empirical solution of the problem of freezing time prediction. Then, there are some proofs confirming the divergence among the results after the calculating models in case a product has not been a test substance [12,16]. In such situation it is evident that the model gives extreme results.

To obtain a more complete picture of the studied problem, it would be advisable to widen the experiment scope and the process conditions (*Bi, Fo*), too. It does not impair the significant influence of thermophysical properties of the product upon the accuracy of freezing time prediction, in general.

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