Theoretical and experimental study on cryogenic freezing of berries

Damian Valeriu, Iosifescu C. Cristian, Coman Gelu, Drăgan Marcel, Constantin O. Emilia *

Abstract - This paper presents some aspects concerning raspberries and blueberries freezing using liquid nitrogen: duration of the process, microscopic analysis of frozen and thawed berries, parameters variation along the freezing tunnel, advantages and disadvantages of this modern method. Quick freezing of food products in a cryogenic freezer consist in the use latent heat of evaporation of the liquid nitrogen, as well as of the sensible heat of the vapors, whose temperature increase up to final temperature of the frozen product. Considering the demands for reduction of fuel consumption involved in generation of electrical energy needed for classical refrigeration systems, this method uses for freezing liquid nitrogen obtained as secondary product at oxygen production.

Keywords - freezing, nitrogen, cryogenic, food preservation, raspberries, blueberries.

I. Introduction

FREEZING is the favorite modern mean for best preservation of nutrient and organoleptic properties of a large number of food products, ensuring better quality and long term preservation compared to vapor compression system products. Using cryogenic systems one can avoid the large investment required for a compression refrigeration system, using only liquefied cryogenic fluid delivery from time to time.

Quick freezing of products in a cryogenic freezer consists in the use of evaporation latent heat of the liquid nitrogen, as well as of the sensible heat of the vapors, whose temperature increases up to final temperature of the frozen product; the method has the main advantage of a large increase of the heat transfer coefficient between the product to be frozen and the refrigerant.

The use of cryogenic freezing with liquid nitrogen and carbon-dioxide is regarded as the “century revolution” in the food area. Because today's competition in the food international market concerns more the quality level than the price, quick freezing systems have continuously developed since 1960 in the USA and then in Europe.

II. Cryogenic freezing system

The cryogenic freezer is shown below in , and has the following features: hourly freezing capacity: 110 to 120 kg; dimensions: 5220 x 750 x 1450 mm; weight: 500 kg; the temperature of frozen product: -18 °C; the length of conveyer band: 4.5 m; speed of the band: 1.12 m/min; freezing time: ≈ 4 min. Based on the tests carried out, we found out that the thermal core temperature of the product ($t_C \leq -18$ °C) was achieved depending on the exhausted nitrogen vapors temperature, for constant freezer capacity and sprayed liquid nitrogen flow-rate can influence the operating conditions of the cryogenic freezer in stationary regime are: outside air temperature, fat contents of the product, the distance among products on the band, the blockage of a forced air circulation fan and product thickness.

If the exhausted nitrogen vapors temperature increases, the nitrogen consumption decreases. For a vapors temperature of -30 °C, a -18 °C temperature in the core of product is easily achieved. One considered that the exhausted low temperature nitrogen vapors can be used for cooling a temporary food-bank used for product storage prior shipping.

Tunnel temperature was measured every 30 sec using 6 Pt100 sensors. Product’s center and surface temperatures were measured using NTCs. Values presented in Table III are mean values for 30 sec.

III. Required freezing time - mathematical model

Freezing is the process by which most of the water from the cellular liquid and the water from a product's tissues (capillary vases, intercellular spaces) is turned into ice. Water crystallization temperature ranges between -1…-5 °C, at which 60…75 % of the whole water content turns into solid.

The process must be continued afterwards by subcooling the product to a final temperature of -18 to -25 °C, at which 90 to 95 % of the water content turns into solid. Thermal core temperature is a main indicator of the end of the freezing process as it can be with maximum 3 to 5 °C higher than the products' storage temperature.

International Institute of Refrigeration established the following conditions: final temperature of the products thermal core ≤ -15 ºC, average final temperature ≤ -18 ºC. Freezing process of a food product is a typically transient heat and mass transfer process. Transfer phenomenon is complex due to the phase change of the solidifying water and of the transport properties of the product (thermal conductivity, specific heat, etc.).

Computing methods use some simplifying assumptions which allow establishing some simple calculus relations for the freezing duration (according to Plank):

- all the heat is drawn from the product at the freezing point temperature,
- the products are homogenous and isotropic,

* Manuscript received October 15, 2010. This work was supported by CNCSIS UEFISCSU, project number 501-PNII IDEI/2010.

Damian Valeriu, Iosifescu C. Cristian, Coman Gelu, Drăgan Marcel are with the Department of Thermal Systems & Environmental Engineering, "Dunarea de Jos" University of Galati, ROMANIA, 111 Domnească St., G Bldg, 800201 Galati ROMANIA (phone: 0040-236-314463, e-mail: valeriu.damian@ugal.ro)

Constantin O. Emilia is with the Department of Bioengineering in Food Industry

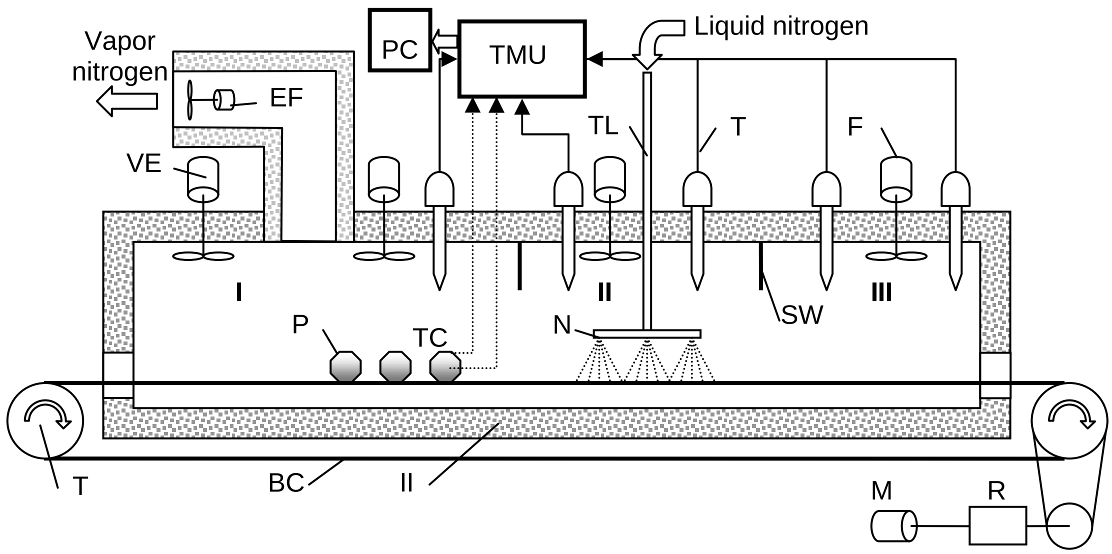


Fig. 1. Cryogenic freezer.
M - electric motor; P - product; BC - belt conveyor; R - worm reducer; F - fan; EF - vapor exhaust fan; N - nozzle; SW - separating wall; TL - nitrogen transfer line; D - drum; T -thermo resistance; TC - thermocouple; TMU - temperature measuring unit; PC - computer; I - pre-cooling area; II - freezing area; III - sub-cooling area

- the cooling surroundings has a constant temperature,
- the product has already been cooled down to the freezing temperature.

Total duration of the freezing process is [1]:

$$\tau_c = \tau_r + \tau_{cg} + \tau_{sr} \quad [\mathrm{s}] \tag{1}$$

where: τ_r [s] - primary refrigeration duration; τ_{cg} [s] - freezing duration; τ_{sr} [s] - product duration subcooling;

Primary refrigeration duration can be computed from the following relation:

$$\tau_r = \frac{m \cdot c}{\alpha \cdot s} \cdot \ln \frac{t_i - t_{mI}}{t_f - t_{mI}} \quad [\mathrm{s}] \tag{2}$$

$$m = \rho \cdot V \; [\mathrm{kg}] \tag{3}$$

$$V = \frac{4 \cdot \pi \cdot r_0^3}{3} \quad [\mathrm{m}^3] \tag{4}$$

where: m - product mass; ρ - density; c - specific heat; α - convection coefficient; s - product's external area; t_I - initial temperature; t_f - final temperature; t_{mI} - cooling surrounding temperature (zone I);

For a spherical shape product, freezing duration can be determined using Plank's formula [4]:

$$\tau_{cg} = \frac{\rho \cdot l_{cg}}{t_{cg} - t_{mII}} \cdot \left(\frac{r_0^2}{6 \cdot \lambda} + \frac{r_0}{3 \cdot \alpha} \right) \tag{5}$$

where: t_{cg} - freezing temperature; t_{mII} - cooling surrounding temperature (zone II); α - convection coefficient; r_0 - sphere radius; l_{cg} - freezing latent heat; ρ - density; λ - thermal conductivity;

The duration [h] for subcooling of the frozen product to the final average temperature (t_{mf}) can be calculated using Plank's relation:

$$\tau_{sr} = 933 \cdot c_m \cdot n \cdot \left| \lg \frac{t_{cg} - t_{mIII}}{t_{III} - t_{mII}} - 0{,}0913 \right| \cdot \left(\frac{2 \cdot r_0}{\alpha} + \frac{r_0^2}{\lambda} \right) \cdot \frac{1}{3{,}6} \tag{6}$$

where: c_m - frozen product average specific heat; n - dimensionless coefficient, whose values depends on the Biot dimensionless group, defined by:

$$Bi = \frac{\alpha \cdot \delta}{\lambda} \tag{7}$$

where $\delta = r_0$.

Table I. Values for the dimensionless coefficient n vs. Bi [2]

Bi	0.25	0.5	1.0	2.0	4.0	10	∞
n	1.21	1.188	1.156	1.112	1.06	1.02	1.00

t_{cg} - freezing final temperature; t_{mII} - cooling surrounding temperature (zone III); t_{mIII} - thermal core final temperature of the product;

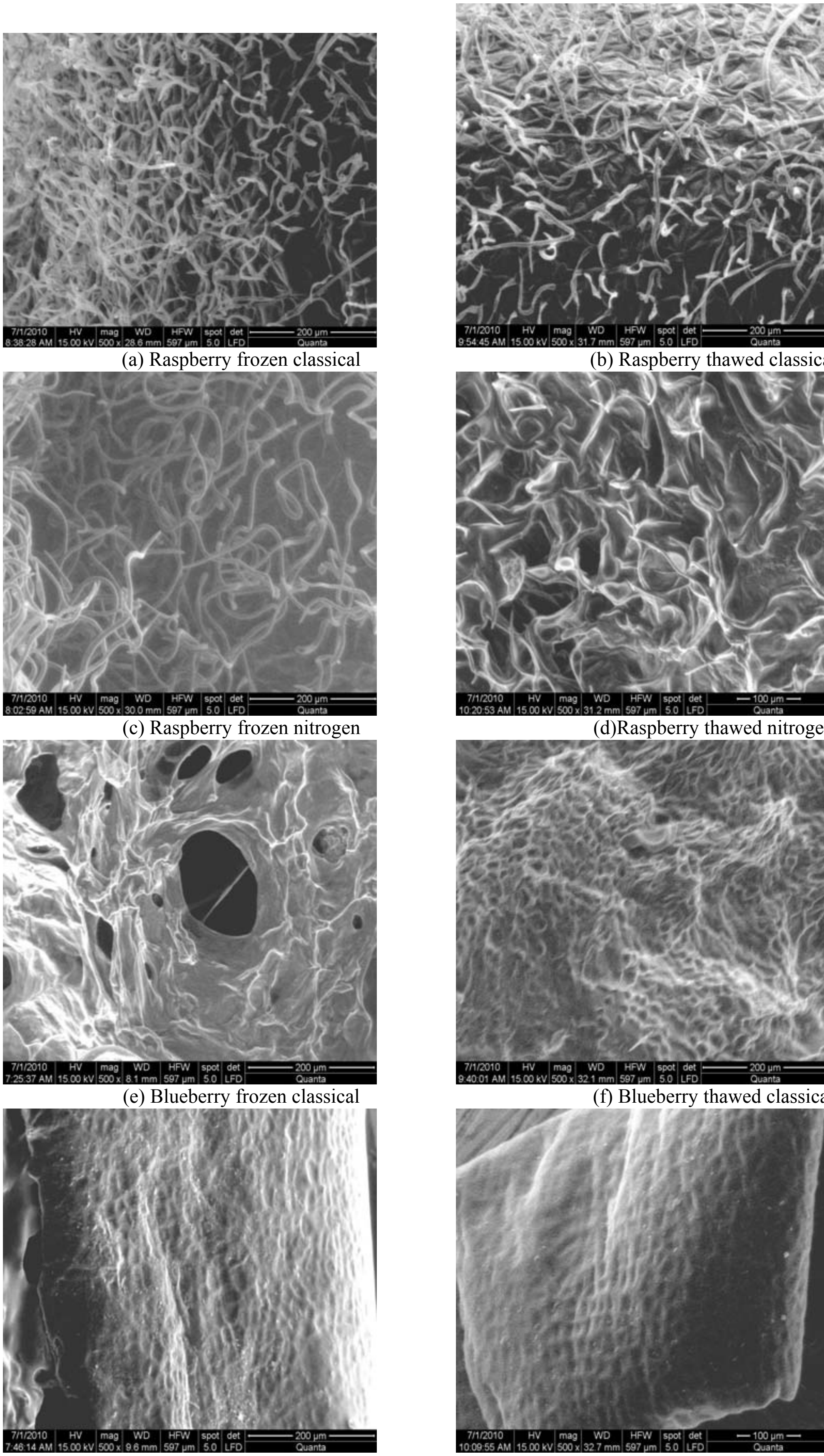
Various properties of the considered products are presented in the following table.

Table II. Various properties of the considered products

Property\ Product	t_c [C]	c_{pI} [kJ/kgK]	c_{pIII} [kJ/kgK]	l_{cg} [kJ/kg]	u [%]	λ [W/m-K]	ρ [kg/m^3]
Blueberries	-2.6	3770	1930	288.4	87.4	0.54	1000
Raspberries	-1.1	3520	1840	283.8	82	0.49	998

The cooling environment zonal average temperatures (t_{mI}, t_{mII}, t_{mIII}) as well as the product temperatures (t_{cg}, t_{mIII}) were measured using NTCs connected to a computer.

As one can notice in Fig. 3, increased size of products radius r_0 in the range of 1 … 10 mm leads, as expected, to increased partial durations, and therefore an increased total duration for the entire freezing process. For the same product size, due to the different properties, blueberries have a slightly longer process time than raspberries (for the reference case with r_0 = 0.005 m: $\tau_{tot\ blueberries}$ = 3.59 min, and $\tau_{tot\ raspberry}$ = 3.02 min).



(a) Raspberry frozen classical
(b) Raspberry thawed classical
(c) Raspberry frozen nitrogen
(d)Raspberry thawed nitrogen
(e) Blueberry frozen classical
(f) Blueberry thawed classical
(g) Blueberry frozen nitrogen
(h) Blueberry thawed nitrogen

Fig. 2 Cell structure for nitrogen and classical frozen and thawed blueberries and raspberries

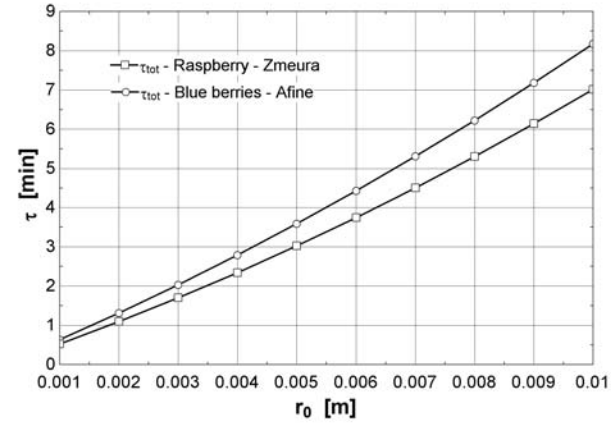


Fig. 3 Total freezing time vs. product radius

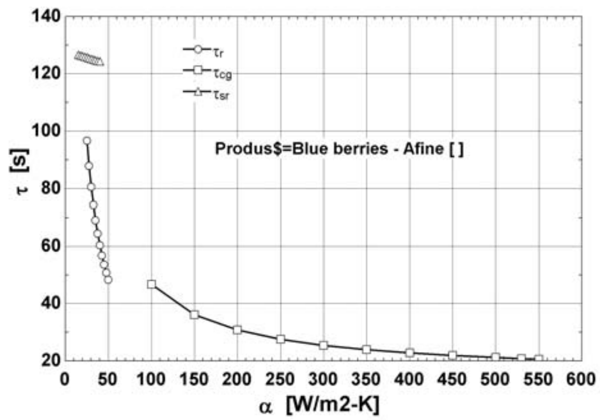


Fig. 4 Influence of convection coefficients on corresponding times

Fig. 4 shows the influence on convection coefficients $\alpha_{1,2,3}$ on corresponding process times. As it can be seen, the most powerful influence is the one of the cooling coefficient. Reference average values were [3]:

Table III. Tunnel average Parameters

Parameter	Symbol	Unit	I	II	III
Average temperature	t_m	°C	-75	-150	-60
Heat transfer coefficient	α	W/m^2-K	25	175	60

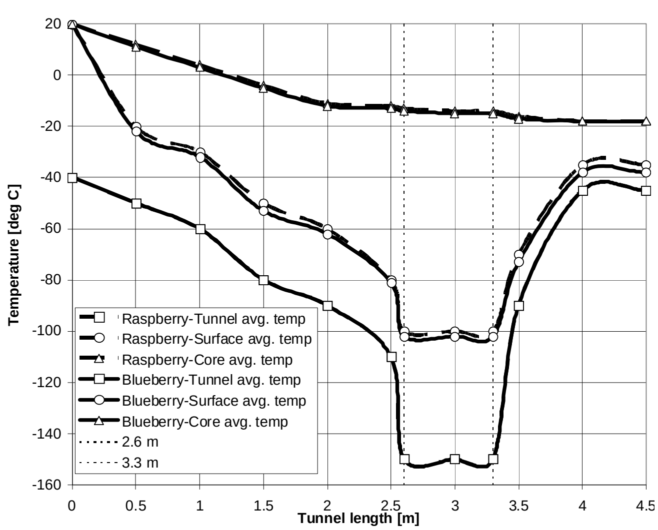


Fig. 5 Measured ambient (average) and product's (surface and core) temperature variation along the freezing tunnel

From Fig. 5 it can be noticed that:

- after approximately 3 minutes, product core temperature reaches -15 °C, but temperature leveling in the product will continue (condition for proper freezing is that $t_c \leq$ -18 °C), and the measured final temperature was t_c = -26 °C;
- heat flow q_s and average heat transfer coefficient α_m are maxim in the liquid nitrogen spraying area;
- after passing the spraying area, the heat flow is still high because there still are liquid nitrogen evaporating drops;
- nitrogen vapor exhaust temperature is approx. -35 to -40 °C and can be determined by adjusting the vapor exhaust fan speed.

IV. Microscopic Analysis of the Products and Freezing Process Parameters Variation

It can be noticed in Fig. 2 that using (fast) liquid nitrogen cryogenic freezing, the berries keep their initial fiber shape, because ice crystals are smaller than cells, and therefore do not break them. Using (slow) freezing by mechanical refrigeration, berries fiber are deformed due to the ice crystals that pierce the cells wall.

V. Conclusions

The main **advantages** of liquid nitrogen freezing (used mainly on expensive products as fish fillet, seafood, pastry, berries, etc.) are:

- simple design, small space required and easy cleaning;
- short startup and freezing times, movable freezers ;
- reduced weight losses;
- the system can be used for various food products with no modifications;
- fully automation is possible, no defrost necessary (there are no evaporators);
- due to the high freezing speed, the formed ice crystals are very small and they do not damage the frozen products cells, thus keeping the initial color and taste; no preliminary product cooling is required;
- liquid nitrogen is obtained almost “for free” as an auxiliary product in oxygen production.

The main **disadvantage** of this freezing method is the high cost of liquid nitrogen, but considering that freezing cost accounts only for 13,3 % of the product's price, one may disregard this disadvantage.

References

[1] Damian V., Vasilescu C., *Congelarea criogenică a produselor din carne*, Ed. Evrika, Brăila, 1997
[2] Porneală S., *Tehnica frigului şi climatizării în Industria Alimentară*. Ed. Fundaţiei Universitare "Dunărea de Jos", Galaţi, 2000.
[3] Dinglinger, G., *Probleme du transfer de chaleur au cours de la congelation par pulverization d'azot liquide*. Aliments congeles, IIIF, 1969
[4] Brennan, James G., *Food Processing Handbook*, WILEY-VCH Verlag GmbH & Co. KGaA, 2006.
[5] Fellows, P., *Food Processing Technology - Principles and Practice, 2nd Edition*, Woodhead Publishing Limited and CRC Press LLC, 2000.
[6] Hui, *Handbook Of Fruits And Fruit Processing* - Blackwell, 2006.
[7] Jongen, Wim, *Fruit and Vegetable Processing, Improving Quality* - CRC Press, 2002.
[8] Sun, *Handbook Of Frozen Food Processing And Packaging*, CRC Press, 2006.