THE NEW POSSIBILITIES OF HEAT PIPES APPLICATIONS IN FOOD TECHNOLOGIES

O. Burdo, V. Terziev, E. Kovalenko, S. Milinchuk
Odessa State Academy of Food Technologies, Odessa, Ukraine

Abstract

In a paper the possibility of use of heat pipes (HP) in low-temperature technologies of a dehydration of food liquids is shown. The mathematical model of a conjugate heat-mass-transfer is represented at a block freezing of solutions. The results of experimental researches of processes a cryoseparation of model solutions, juices, extracts, whey and also results of generalization of obtained datas are reduced. Is shown that the application HP reduces to decrease of power consumption in a technology of low-temperature separation of food liquids.

KEYWORDS:

Food technologies, heat pipes, method of block freezing, modeling, power consumption.

INTRODUCTION

The development of modern food industry is characterized introduction power consumption and maximum saving a bioactive complex of raw material of technologies. From this point of view, perspective the low-temperature technologies of separation of food solutions are represented. The technologies of a cryconcentration ensure to production of high quality foodstuffs and require smaller specific power consumption on a comparison with traditional thermal technologies of dehydration. So, the modern equipment of "Philips", "Grenko", "Strayser" firm and etc. spends for removal 1 ton of water from a solution 5,22 $, thus 2,73 $ it is necessary on power consumption. In too time, in modern two-stage evaporators, on evaporation 1 ton the water are necessary for expending 6,45 $, thus the power consumption make 4,96 $ [1, 2]. An essential virtue of technologies of low-temperature separation of solutions is the presence of a reserve of an energy saving (table 1).

Table 1 Analysis of energy consumption of equipment for dehydration of food liquids

№	Process	Specific power consumption, MJ/kg			Potential of an energy saving	
		Real	Physically necessary	Engineering minimum	MJ/kg	%
1.	Single-stage evaporation	2,7…3	2,5	2,6	0,25	11
2.	Two-stage evaporation	1,4…1,6	2,5	1,35	0,15	10
3.	Five-graduated evaporation	0,7…0,8	2,5	0,65	0,05	7
4.	Cryconcentration	0,3…0,5	0,33	0,22	0,1	30
5.	Block freezing, I generations	0,36…0,54	0,33	0,35	0,2	50
6.	Block freezing, with recycling of ice, II generations	0,21…0,22	0,33	0,19	0,01	5

At the same time, the further development of refrigerating technologies is connected to searching of untraditional engineering solutions and development of scientific bases of an energy saving. One of ways of perfecting of low-temperature technologies is use in them of heat pipes (HP).

Perspective the low-temperature technology of a dehydration of food solutions by a method of a block freezing is represented. The originality of this technology consists that the block of ice is formed on the evaporator of HP during a crystallization of a solution, instead of on a stage of a separation. The low power consumption and high quality of obtained concentrates is characteristic for a technology. The new concept of organization of a heat transfer is putted in a basis of a technology at a low-temperature crystallization from solutions formulated as a result of study and the analysis of modern technologies of a freezing [4].

MODELING OF PROCESSES

The process of separation of liquid foodstuff by a method of a block freezing assumes a directed crystallization of molecules of water from a solution on the evaporator of HP.

Let's lead modeling at the following assumptions:

- The heat-mass-transfer is realized out on a surface in limited space between impenetrable walls. The crystallization in volume is absent.
- The process happens in conditions of a natural convection called by a temperature gradient.
- All dry substances of a solution are considered as one of components with known thermalphysic properties.
- The task is considered for a defined interval of time $\Delta\tau$, in which the mean value of temperatures and concentration operate.
- The solution in an initial moment is at temperature of change of phase;

$$t_{Ж} = t_S \text{ at } \tau = \tau_0 . \tag{1}$$

- Temperature on a surface of the block of ice is determined by cryoscopical conditions.

$$t_\Lambda = t_S . \tag{2}$$

- The modification of an enthalpy of a solid phase is low on a comparison with a hidden heat of crystallization.

$$C_{P_\Lambda}\left(t_S - t_\infty\right) << \Omega . \tag{3}$$

In view of reduced assumptions power balance of the process is possible to present as:

$$-Q = \rho_\Lambda \Omega \frac{dV_\Lambda}{dr_\Lambda}\frac{dr_\Lambda}{d\tau} . \tag{4}$$

The conditions of crystallization on the evaporator of HP are caused by thermal conditions of the process, which are determined from a system of equations of thermal balances and equations of a heat transfer.

The thermal stream in a system "working body HP - wall - ice - solution " can be presented as:

$$Q = \frac{F\left(t_P - t_X\right)}{R_\Sigma} , \tag{5}$$

where F - summary surface of heat transfer; t_P, t_x - temperature of a solution and working body of HP; R_Σ - summary thermal resistance of a system.

The summary thermal resistance of a system depends on thermal resistances of various sectors:

$$R_\Sigma = \frac{1}{\alpha_X d_k} + \frac{\ln\left(r_K / r_T\right)}{\lambda_X} + \frac{\ln\left(r_\Lambda / r_K\right)}{\lambda_\Lambda} + \frac{1}{\alpha_p d_\Lambda} . \tag{6}$$

Here first component - thermal resistance originating at a heat transfer from a wall of the evaporator of HP to a working body; second - thermal resistance of a wall of HP; third - thermal resistance of the block of ice, fourth - thermal resistance originating at a heat transfer from a solution to the block of ice.

Growth in due course τ radius of the block of ice r_Λ and boundary surfaces of phases "block of ice - solution" F_Λ determines a flowing resistance of a system $R_\Sigma(\tau)$. At a defined combination of a radius of the evaporator of HP r_Λ and coefficient of a heat transfer from a solution to a surface of ice α_P at the expense of considerable growth F_Λ fourth component can be decrease faster, than to increase third component the equations (6). As a modification of thermal resistances at boiling a working body and the wall of HP are insignificant, it is possible to mark, that at a block freezing of solutions with increase of an boundary surface of phases a summary thermal resistance of a system " working body of HP - wall - block of ice - solution" can be decrease. A condition of such conditions will be $Bi = \alpha_P r_\Lambda / \lambda_\Lambda \leq 1$. Thus the critical diameter of the block of ice d_{kp} corresponds to an extremum of function $R_\Sigma = f(d_\Lambda)$. If $d_\Lambda < d_{kp}$, and d_Λ is increased, the thermal stream Q is increased also, which maximal will be at $d_\Lambda < d_{kp}$.

Summary equation of a thermal balance provided that $r_K < r_\Lambda < r_e$ is noted as:

$$Q = c_{p_P} V_p \rho_p \frac{\partial t_p}{\partial \tau} + \Omega F_\Lambda \frac{\partial r_\Lambda}{\partial \tau} + Q_{nom}. \tag{7}$$

Duration of the process of a freezing τ for ideal conditions (in a solution are no soluble components) it is possible to calculate on expression:

$$\tau = \frac{Fo \rho_\Lambda C_{p_\Lambda} (r_\Lambda - r_K)^2}{\lambda_\Lambda}, \tag{8}$$

where $\rho_\Lambda, c_{p_\Lambda}, \lambda_\Lambda$ - denseness, thermal capacity and thermal conduction of ice;

Fo - number the Fourier describing dimensionless time of a crystallization.

In view of reduced assumptions (equation 1 - 4) for a dimensionless coordinate $x = \frac{r_e - r_\Lambda}{r_e - r_K}$ the number Fo is determined:

$$Fo = \frac{Ph}{2(n+1)}\left(1 + \frac{2}{Bi}\right), \tag{9}$$

where Bi - number of a Bio, determinate under the equation of the form:

$$Bi = \alpha_x r_T \left(\frac{\ln r_K / r_T}{\lambda_K} + \frac{\ln r_\Lambda / r_K}{\lambda_\Lambda} \right). \tag{10}$$

Here Ph - the number of change of phase is calculated on a relation:

$$Ph = \frac{\rho_P \Omega}{\rho_\Lambda c_{P_\Lambda} (t_K - t_H)}. \tag{11}$$

n - constant describing the form of the block of ice. For a slice - n = 0, for the cylinder - n = 1.

If by a modification of an enthalpy of a solid phase during a freezing to neglect, from the equation (9) it is possible to determine minimum time of a crystallization of a solution $\tau_{\min}$. The real time of an ice formation τ_∂ is more $\tau_{\min}$. It can be calculated, using a correction $\psi_1 = f(Ph, Bi, n)$. For calculate ψ_1 the equation of the form [5] is used:

$$\psi = 1 + \frac{1}{2}\left(\frac{Bi}{Bi+1}\right)^{2/3}\left(\sqrt{1 + 2\frac{F_\Lambda r_\Lambda / V_\Lambda}{Ph}} - 1\right). \tag{12}$$

Then a relation determines the real time of crystallization:

$$\tau_\partial = \tau_{\min} \psi_1. \tag{13}$$

The above given equations reflect a character only of thermal processes. Specifity of mass transfer processes happening at a block freezing of food solutions describes represented in [3] diffusion model.

The diffusion model is represented in cylindrical coordinates and describes a velocity of driving of the boundary of phases " block of ice - solution", character of a modification of concentration of a solution, material balance of a system and character of a modification of temperature of an boundary surfaces of phases in relation to a surface of the evaporator of HP. The solution of the task of a mass transfer at a block freezing is connected to a determination of coefficient of a mass transfer β.

Now in view of the above-stated peculiarities of a conjugate heat-mass-transfer the real time of crystallization from food solutions can be presented in the form:

$$\tau_{\partial} = \tau_{\min}\psi_1\psi_2 , \tag{14}$$

where ψ_2- coefficient which is taking into account mass transfer processes and determined as $\psi_2 = \left(Bi_{\partial}\right)^k$; here Bi_{∂} - number of a Bio diffusion - $Bi_{\partial} = \beta r_{\Lambda}/D$. k - exponent, determined experimentally.

EXPERIMENTAL RESEARCHES AND GENERALIZATION OF RESULTS

For a solution of the task of a conjugate heat-mass-transfer at a low-temperature crystallization from a solution and the confirmations of adequacy to a represented model are spent the following experimental researches.

The influence of temperature of boiling of a working body of HP, concentration of a solution, thermalphysic properties of a solution, diameter of the evaporator of HP, diameter of a capacity for a solution and height of the block of ice on a kinetics of formation of the block of ice (modification of a radius of the block of ice and it of a mass in time), on a character of a modification of structural characteristic of the block of ice and solution (porosity of the block of ice, concentration of dry substances in the block of ice and solution) was studied. The researches were spent on juices, extracts, and whey [6].

The results of a research of processes of a cryconcentration of apricot juice are represented in a figure 1. The kinetics of formation of the block of ice is determined by complex influence of temperature conditions of the process, height of the block of ice flowing, concentration of a solution and diameter of the evaporator of HP (figure 1a). Here, with increase of a radius of the block of ice, the velocity of its growth decreases. At the same time, the increase of a surface of the block of ice is accompanied by prompt increase of a mass (figure 1b). The character of a modification of a radius of the block of ice and it of a mass also depends on flowing concentration of a solution and temperature on a surface of the evaporator of HP. With a diminution of concentration of a liquid and temperature of a surface of the evaporator of HP the intensification of a heat-mass-transfer is observed, the growth rate of the block of ice and efficiency of HP is increased. Thus, the specific power consumption the are less, than less diameter of the evaporator of HP. However, taking into account a ratio of volume of ice to volume of a capacity with a solution, it is necessary to mark, that on magnitude of specific expenditures the greater influence render concentration of a solution and temperature regime of operations of a refrigerating plant (figure 1 c, d).

During experiment the character of distribution of concentration on a radius of the block of ice and in pores of the block of ice was studied. It has allowed to research a structure of the block of ice, in particular it a porosity.

As a result of mathematical handling of experimental datas on the computer the criteria equations for account of coefficient of a mass transfer β are obtained at a block freezing [6]:

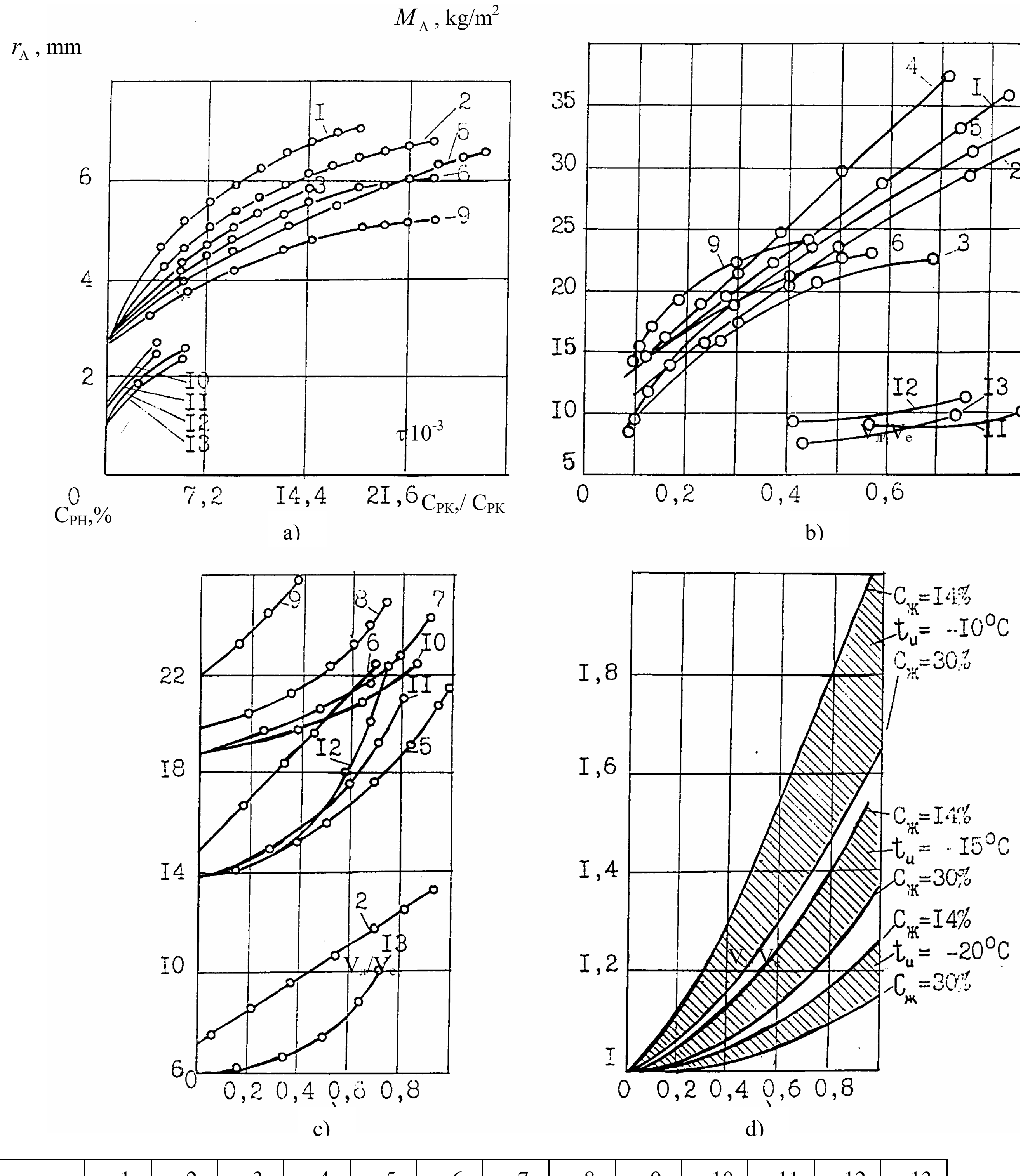
- whey:

$$Sh = 3{,}39 Ra^{0{,}8}\left[\frac{Sc}{\Pr}\right]^{1/3}\left[\frac{d_K}{h}\right]^{1{,}51}. \tag{15}$$

- fruit juices:

$$Sh = 3{,}39 Ra^{0{,}41}\left[\frac{Sc}{\Pr}\right]^{1/3}\left[\frac{d_K}{h}\right]^{0{,}4}. \tag{16}$$

Coefficient of a mass transfer β, determined of the equations (15-16), takes into account a mass transfer both on an exterior surface of the block of ice, and in it pores.



	1	2	3	4	5	6	7	8	9	10	11	12	13
d_u, mm	47	47	47	47	47	47	23	47	47	23	23	18	18
t_u, ^{0}C	-20	-15	-10	-20	-15	-10	-20	-15	-10	-9	-9	-14	-14
C_{PH}, %	7	7	8	14	14	15	19	20	22	20	14	14	6

Fig. 1. Kinetics of processes of a block freezing of apricot juice

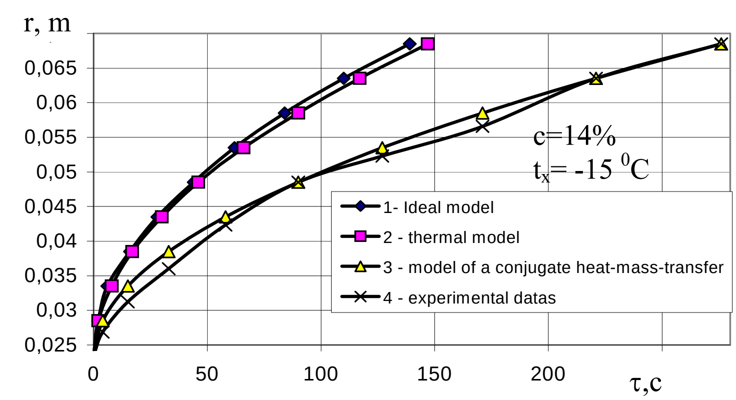


Fig. 2. Comparison of analytical and experimental researches

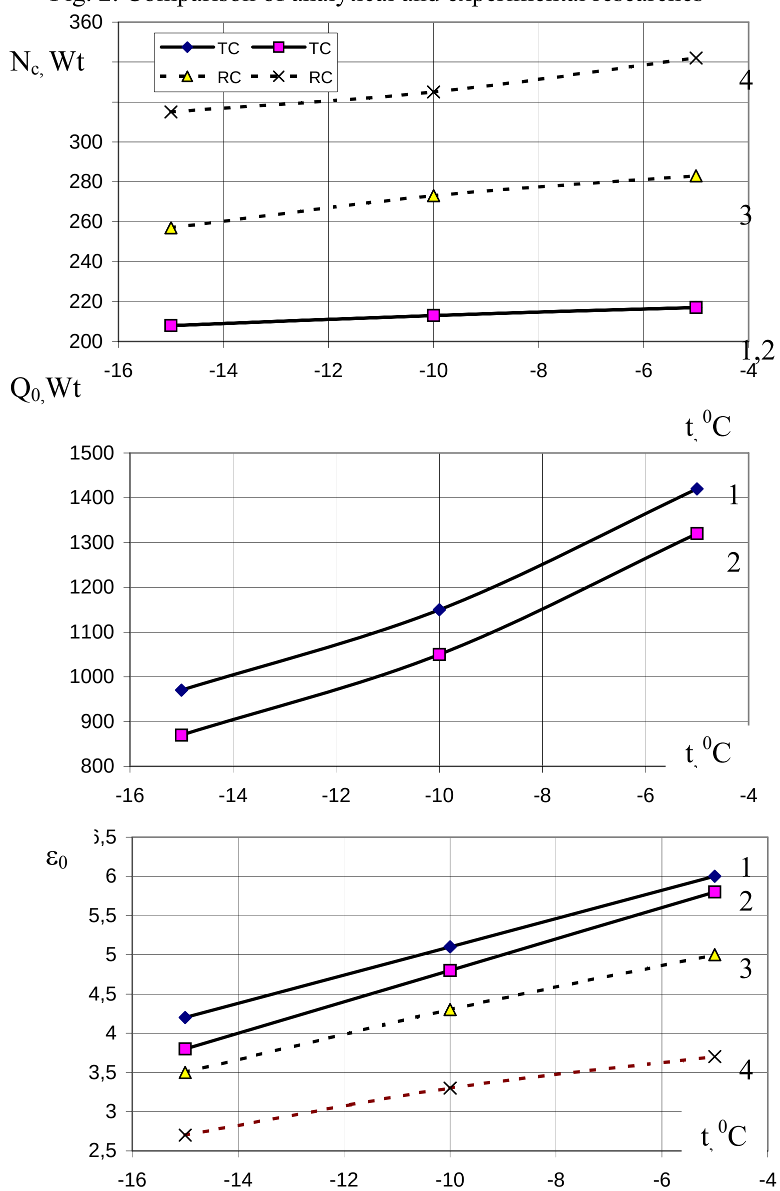


Fig. 3. Experimental researches of parameters and power characteristic of a refrigerating cycle with regeneration of ice (temperature an environment: 1,3 - 10 ^{0}C, 2,4 - 20 ^{0}C)

The determination from the equations (15-16) coefficient of a mass transfer has allowed to calculate diffusion number of Bio and exponent in the ratio $\psi_2 = \left(Bi_\partial\right)^k$. Is established, that k =0,1.

The results of calculate of duration of the process of a crystallization on a represented model were compared to experimental datas. In a figure 2 is shown, as far as adequately reflect the real process a cryoseparation of whey an ideal model (8), model which is taking into account only a singularities of a heat transfer (13) and models of a conjugate heat-mass-transfer (14). Analyzing represented curves it is possible to mark, that the greatest divergence with experimental datas is characteristic for an ideal and thermal model. A mean error of calculation of duration of the process o freezing on a model conjugate heat-mass-transfer does not exceed 14%. It speaks that the represented model conjugate heat-mass-transfer is fair for practical calculation of a low-temperature crystallization from food solutions on the evaporators of HP. For an operating evaluation of complex influence technological, regime and design data on characteristics of the process of a block freezing, and also for calculate of these processes the engineering nomograms are developed [7].

POWER ANALYSIS OF TECHNOLOGY OF BLOCK FREEZING

It is known, that the physical minimum of power consumption on a freezing makes 0,33 MJ on 1 kg of a removed moisture. At the same time in industrial freezing peanuts the real power consumptions of a make about 0,8 MJ on 1 kg of removed moisture. Thus the most essential power consumptions of energy arise at the expense of work of concentrators of a machine type, in pumps, tanks for growth of crystals, recirculation and etc. [1, 2].

The passage to a technology of a block freezing allows reducing specific power consumptions of energy at the expense of shaping the block of ice not by a stage of a separation and on the evaporator of HP in the process of crystallization. Thus, scheme of a concentration, instead of machine concentrators - hardware considerably becomes simpler, the necessity in those elements of the scheme, where the greatest losses of a cold happen.

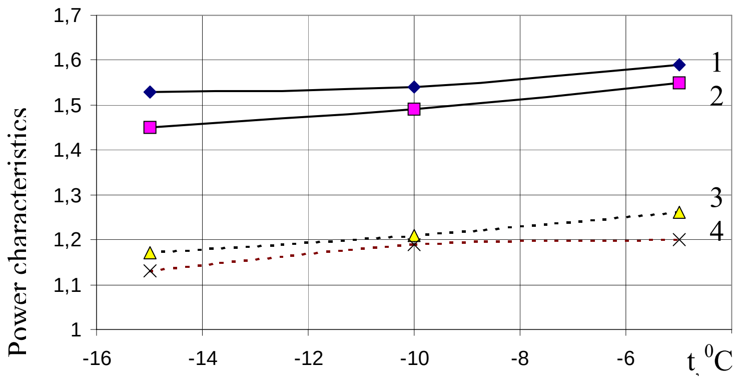


Fig. 4. Comparison of power characteristic of a typical refrigerating cycle (TC) and cycle with regeneration of ice (RC) 1,2 - $t_{\text{of an environment}} = 10\ ^0$C; 3,4 - $t_{\text{of an environment}} = 20\ ^0$C

As the basic energy is expended in a refrigerating cycle, the further improvement of a technology is offered to realize by organization of return in a refrigerating cycle of energy of a melting of ice. It is offered energy melting of the block of ice to use for partial condensation and supercooling of the refrigerating agent before a throttling. It will allow not only to approximate specific power consumption to a physical minimum but also to finish them up to a main less physical minimum (table 1).

Such engineering solution was examined experimentally. At a comparison of power indexes and specific characteristics of a refrigerating cycle with regeneration of an energy of ice and typical refrigerating cycle is visible, that with increase of temperature of an air from 10 up to 20 ^{0}C saving of the electric power (in the graphs the effective powers are reduced) makes from 20 up to 60 % (figure 3). Except for improving power characteristics of a cycle the volumetric characteristics of the compressor are improved as also. It allows using of the compressor with smaller volumetric efficiency.

The comparison of characteristics of a typical cycle (TC) with a cycle with regeneration of ice (RC) is spent on an effective power on the shaft of the compressor $\dfrac{N_e^{TC}}{N_e^{RC}}$ (curves 1,3) and effective refrigerating coefficient $\dfrac{\varepsilon_0^{TC}}{\varepsilon_0^{RC}}$ (curves 2,4) at identical absolute cold-productivity (figure 4).

The obtained characteristics allow making the prognosis of development of energy saving at a dehydration of food liquids. The use of an energy of ice will allow in block freezing plants of the second generation to finish a level of power consumption up to 0,08 kWh on 1 kg of ice, that there correspond 0,22 MJ/kg. On a comparison with evaporators by installations, it in 10 times is less than in single-stage and in 3 times less than in five-stage evaporators.

CONCLUSIONS

1. A perspective technology of production of high-quality liquid concentrates of coffee, milk, juices, extracts is the cryconcentration. However, the existing plants for cryconcentration bulky, reserves of decrease of power consumption in them are exhausted.
2. The use of a HP in plants of cryconcentration allows in a complex to solve a problem of simplification of a construction and decrease of an energy-consumption.

3. The offered model of a kinetics of an ice formation on the evaporators of a HP takes into account as a combination of the processes of a heat-mass-transfer in a system "solution - block of ice - surface of the evaporator of a HP ", and interior processes of a heat transfer at evaporation in itself HP.
4. The application of a block freezing on the evaporator of a HP allows realizing return of energy of ice in a refrigerating cycle. Trials of such systems has shown, that the decrease of power consumption on 20 … 60 % is achieved.

Nomenclature

F - surface of heat exchange; V - volume; M - mass; r - radius; d - diameter; C - concentration; t - temperature; τ - time; ρ - denseness; c_p - thermal capacity; Ω - specific heat of ice formation; Q - thermal stream; R - thermal resistance; α, λ, β, D - coefficient, accordingly, heat transfer, thermal conduction, mass transfer, diffusion; Ph - number change of phase; Fo - number the Fourier; Bi - number of a Bio; Sh - number Shervud; Sc - number Schmidt; Pr - number Prandtl; Ra - number Relay; Λ - ice; e - capacity; x - working body of HP; k - final; н - initial; p, ж - solution; u - evaporator of HP; s - saturation.

Reference

1. Pap L. Concentration by a freezing /under educat. Kochenov O.G., translation of Voronov A.O. /-M.: Light industry, 1982. - 97 p.
2. Plotnikov V.T., Filatkin V.P. Separating freezing plants. -M.: Agropromizdat, 1987. -352 p.
3. Burdo O. G., Gayda S., Kovalenko E.A., Stanevsky O.L. Heat Pipes in the Process and Apparatuses of Food Productions // Proc. 3th International Seminar "Heat Pipes, Heat Pumps, Refrigerators". - Minsk (Belarus).- 1997. pp. 130-134.
4. Patent 1716976 USSR. A method of obtained of the concentrated liquid foodstuff by a freezing /Burdo O. G., Gorikin S.F. Publ. 29.02.92. Bulletin N8.
5. Heat exchangers design handbook /Under educat., Petuchov B.S., translet. with English, 2 vol. -M.: Energoizdat, 1987. -560 p.
6. Burdo O. G., Kovalenko E.A. Kinetics of formation of the ice block at the cryconcentration of food liquids//Scient.work OSAFT. -1996. -number 16. - pp. 248 - 252.
7. Burdo O. G., Kovalenko E.A., Milinchuk S.I. Energy saving in refrigeration technologies // Scient.work OSAFT. -1999. -number 19. – pp. 258 - 263.