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REDUCING WORKING EXPENSES OF HEAT EXCHANGERS OF REFRIGERATION INSTALLATION OBTAINED BY METHOD OF HEAT- SAVING ANALYSIS

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The problems of saving different raw materials, electric energy and water resources controlling the economy and industry of any country are also actual for production of an artificial cold.With a scale of the nowadays application of refrigeration technology and equipment at the enterprises of agroindustrial complex taken into account, even an insignificant saving in the capital investment or rising the energy efficiency of refrigeration systems can give a considerable in its absolute value economical effect.The electric energy and cooling water expenses can be reduced by modifying the equipment design and optimizing the operation conditions of a refrigeration installation provided with serial parts.

The working regime parameters of the separate parts of a refrigeration installation are interrelated and that's why on solving the optimization task it is necessary to study the system in complex as a whole (Gogolin, 1981).Since there is a wide range of possiple changes in the temperatures of a cooled substance and surrounding medium, the optimum regime can be obtained by the method of the mathematical modeling of the refrigeration installation processes.

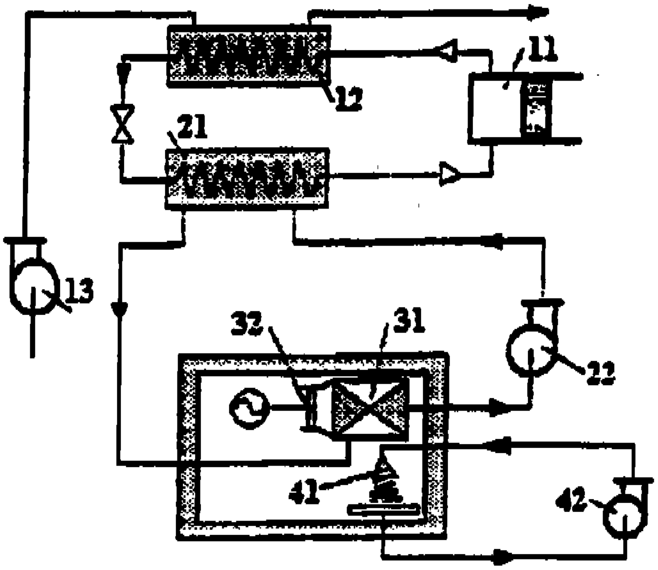

Figure 1 – One-stage refrigeration installation

The heat saving model of a refrigeration installation shows all the changes and transformations of the exergy main flow providing the final effect (Brodnjansky, 1973). If represents any refrigeration installation as some zones connected in series in which a disipation of energy takes place. This idea was successfuly realized by Onosovsky V.V in a number of his research works

(Onosovsky, 1978; Onosovsky, 1980; Onosovsky, 1981; Onosovsky, 1987; Onosovsky, 1966) describing various refrigerating machines and installations operating in their stationary and dynamic regimes. The very these ideas are used for chiosing the optimum working regimes of a refrigeration complex with the peculiar features of its functioning in the process of storing fruits and vegetables taken into consideration. Let's consider this technique of the complex optimization on the basis of the heat saving method (Gogolin, 1981) applied to a typical one-stage refrigeration installation for fruit and vegetable stores (Fig. 1).

A refrigeration installation heat-saving model can be presented in the form of there zones connected in series:
Zone 1 – includes a compressor with electrometer, a condenser, a cooling water pump with electrometer and an expansion valve;
Zone 2 – an evaporator for cooling the intermediate refrigerant and a pump with electrometer which provides its circulation;
Zone 3 – cooling device with a free and forced air flow, a ventilator with electrometer, a humidifying device and a with electrometer (Fig 2).
For each zone there are values of the depreciation and maintenance expenses, z_i, refering to certain part of the inatallation and wich can be defined by means of the following expression:

$$z_i = \frac{\left(k^i_{am} + k^i_{m.e.}\right) \cdot c_i}{\tau_i}, \qquad (1)$$

where k^i_{am} – normative coeeficient of the depreciation expenses for the i-part of an installation;
$k^i_{m.e.}$ – coefficient of the maintence expenses, percent;
c_i – cost of the i-part of an installation, dollars;
τ_{wt} – number of working hours per year for the installation operation, h/year.
For the required depreciation expreciation expenses and cost of repairing the separate parts of an installation, i.e., the values to be defined, the following notation is used:
z_{11} – compressor with electromotor; z_{12} –condenser; z_{13} –pump (ventilator) with electromotor;
z_{21} –evaporator; z_{22} –intermediate refrigerant pump with electromotor;
z_{31} –cooling device; z_{32} –ventilator with electromotor for an air cooler.

From the external power source the system is sipplied with energy (exergy) the price of which is Pr_{el}, (dollars/kW·h), the compressor electromotor is driven with the energy evaluated as ε_{11}, in a cooling substance pump the electromotor is energized with an amount of energy costing ε_{13}, for the electromotor of the intermediate refrigerant pump it is evaluated as e, in the electromotor of an air cooler it is ε_{32}. A certain quantity of a cooling substance V_{12}, m^3/year, Pr_w, dollars/m^3 is also supplied from the external source. When the air-cooled condensers are used the price of water is Pr_w=0. Inside the system the exergy transferred from zone 1 to zone 2 is designated with symbol ε_2, and from zone2 to zone 3 as ε_3.

As the results of the system operation a total cooling capacity ε_0 can be obtained. The temperature loads in heat-exchange units play a role of the optimized variables; Θ_{con} – between a working agent and a cooling substance (water or air) in a condenser; Θ_{ev} – between the intermediate refrigerant and a working agent in a evaporator; $\Theta_{c.d}$ – between the air and refrigerant in cooling devices and a change of temperature, °°C, in a cooling or cooled substance: Δt_w – water being cooled and $\Delta t_{a.c.}$ – air in condenser, Δt_s – intermediate refrigerant in an evaporator, Δt_{air} – air in an air cooler.

As an optimization criterion (a purpose function) there was chosen a value of the reduced expenses (RE) which for the case under study can be written as follows:

$$RE = \left[Pr_{el}\left(e_{11} + e_{13} + e_{22} + e_{32}\right) + Pr_w \cdot v_{12} + z_{11} \ldots z_{32}\right]\tau_{op}. \tag{2}$$

The values in the forward part of relation eq. (2) can be presented as a function of the chosen variables and a final effect. Hence, a value of the reduced expenses is a function of many variables, the extreme (minimum) values of which can be obtained under the following conditions:

$$\frac{\partial RE}{\partial \Theta_{con}} = \frac{\partial RE}{\partial \Delta_w} = \frac{\partial RE}{\partial \Theta_{ev}} = \frac{\partial RE}{\partial \Delta t_s} = \frac{\partial RE}{\partial \Theta_{c.d.}} = \frac{\partial RE}{\partial \Delta t_a} = 0. \tag{3}$$

The required minimum value as a function of many variables with the measurement of an equation type can be determined by means of the Lagrangian factors. For the heat saving model under study it is useful to consider for each zone the specific values of the amortization and maintenance expenses as well as exergy and cooling substance supplied from the external source as a function of the exergy flow leaving the zone and the optimization variables. In this case the following set of relations can be written:

$$\begin{aligned}
z_{11} &= Z_{11}(\varepsilon_2, \Theta_{con}, \Delta t_w); & z_{21} &= Z_{21}(\varepsilon_3, \Theta_{ev}, \Delta t_s); \\
z_{12} &= Z_{12}(\varepsilon_2, \Theta_{con}, \Delta t_w); & z_{22} &= Z_{22}(\varepsilon_2, \Delta t_s); \\
z_{13} &= Z_{13}(\varepsilon_2, \Theta_{con}, \Delta t_w); & \varepsilon_{22} &= E_{22}(\varepsilon_3, \Delta t_s); \\
\varepsilon_{11} &= E_{11}(\varepsilon_2, \Theta_{con}, \Delta t_w); & z_{31} &= Z_{31}(\varepsilon_2, \Theta_{c.d}, \Delta t_{air}); \\
\varepsilon_{13} &= E_{13}(\varepsilon_2, \Theta_{con}, \Delta t_w); & z_{32} &= Z_{32}(\varepsilon_{c.d}, \Delta t_{air}); \\
v_{12} &= V_{12}(\varepsilon_2, \Theta_{con}, \Delta t_w); & \varepsilon_{22} &= E_{32}(\varepsilon_{c.d}, \Delta t_{air});
\end{aligned} \tag{4}$$

By analogy with it, the values an exergy flow in respect to the separate zones can be expressed as follows:

$$\begin{aligned}
\varepsilon_2 &= E_2(\varepsilon_3, \Theta_{ev}, \Delta t_s); \\
\varepsilon_3 &= E_3(\varepsilon_{c.d}, \Theta_{c.d}, \Delta t_{air}); \\
\varepsilon_{c.d} &= E_{c.d}(Q_{c.d}, t_{c.s.}, t_{s.m}),
\end{aligned} \tag{5}$$

where $t_{c.s.}$ – temperature of a cooled substance, °C; $t_{s.m}$ – surrounding medium temperature, °C.

In eq. (4) and (5) ε_j and E_j characterize one and the same thing but ε_j is the amount of exergy and E_j is its functional dependence. The same refers to z_j and Z_j as well as to v_{12} and V_{12}.

By means of a system of eq. (4) and (5), with relation eq. (2) taken into consideration, a Lagrangian equation can be developed and for the said case written as follows:

$$
\begin{aligned}
L = \{ & Pr_{el}\left[E_{11}(\varepsilon_2,\Theta_{con},\Delta t_w)+E_{13}(\varepsilon_2,\Theta_{con},\Delta t_w)+E_{22}(\varepsilon_3,\Delta t_s)+E_{32}(\varepsilon_{c.s},\Delta t_{air})\right]+\\
& + Pr_w \cdot V_{12}(\varepsilon_2,\Theta_{con},\Delta t_w)+Z_{11}(\varepsilon_2,\Theta_{con},\Delta t_w)+Z_{12}(\varepsilon_2,\Theta_{con},\Delta t_w)+\\
& + Z_{13}(\varepsilon_2,\Theta_{con},\Delta t_w)+Z_{21}(\varepsilon_2,\Theta_{ev},\Delta t_s)+Z_{22}(\varepsilon_2,\Delta t_w)+Z_{31}(\varepsilon_{c.s},\Theta_{c.s},\Delta t_{air})+\\
& Z_{32}(\varepsilon_{c.s},\Delta t_{ev})+\lambda_2\left[E_2(\varepsilon_3,\Theta_{ev},\Delta t_s)-\varepsilon_2\right]+\lambda_3\left[E_3(\varepsilon_{c.s},\Theta_{c.s},\Delta t_{air})-\varepsilon_3\right]+\\
& \lambda_0\left[E_0(Q_{c.s},t_{c.s},\Delta t_{s,m})-\varepsilon_0\right]\}\tau_i
\end{aligned}
\qquad (6)
$$

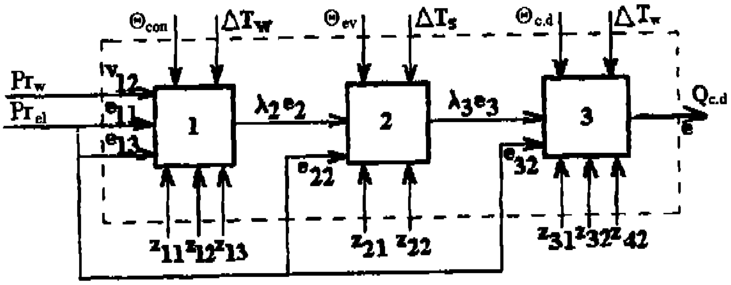

Figure 2 – Heat-saving model of a one-stage refrigeration installation

where L – Lagrangian; λ_2, λ_3, λ_0 – Lagrangian factors.

The required minimum is determined on the condition that the partial variables taken from the Lagrangian equation for all the variables, both the values being optimized and developed by means of eq. (4) considered for this case to be independent are equal to zero.

$$
\frac{\partial L}{\partial \Theta_{con}}=\frac{\partial L}{\partial \Delta t_w}=\frac{\partial L}{\partial \Theta_{ev}}=\frac{\partial L}{\partial \Delta t_s}=\frac{\partial L}{\partial \Theta_{c.d}}=\frac{\partial L}{\partial \Delta t_{ev}}=\frac{\partial L}{\partial \varepsilon_2}=\frac{\partial L}{\partial \varepsilon_3}=\frac{\partial L}{\partial \varepsilon_0}=0 \qquad (7)
$$

On the basis of the derivative values of ε_j the Lagrangian factors can be determined:

$$
\begin{aligned}
\lambda_2 &= (\partial/\partial\varepsilon_2)(Pr_{el}E_{11}+Pr_{el}E_{13}+Pr_w V_{12}+Z_{11}+Z_{12}+Z_{13}),\\
\lambda_2 &= (\partial/\partial\varepsilon_3)(Pr_{el}E_{22}+Z_{21}+Z_{22}+\lambda_2 E_2),\\
\lambda_2 &= (\partial/\partial\varepsilon_0)(Pr_{el}E_{32}+Z_{31}+Z_{32}+\lambda_3 E_3)
\end{aligned}
\qquad (8)
$$

Since E_{11}, E_{13}, V_{12}, Z_{11}, Z_{12}, Z_{13} are the linear functions of ε_2; E_{12}, E_{21}, Z_{22}, E_2 – linear functions of ε_3; E_{32}, Z_{31}, Z_{32}, E_3 – linear functions of ε_0, the Lagrangian functions in the given case determine the cost of an exergy flow unit, the exergy supplied to each consequent zone with an amount of the dissipated energy and the amortization expenses in the previous zone taken into consideration.The Lagrangian derivatives from the independent variables t_j and Δt_j form a system of equations the solution of which on the basis of eq. (8) permits to define the values of variables Θ_{con}, Δt_{air}, Θ_{ev}, Δt_s, $\Theta_{c.d}$, Δt_w corresponding to the optimum working regime of a refrigeration installation

.Fig. 3 presents a saving in the reduced expenses which included a change in depreciation, maintenance and energy expenses.These facts indicate that the optimum values Θ_c, ΔT_w, Θ_o, ΔT_c depend on many factors (electric energy and water prices, temperature of the surrounding medium, a number of working hours for a refrigeration installation per year , etc.).

But practically these factors are not used and not consider in the nowadays existing normative documents due to which the optimum working regime of refrigeration equipment is not secured. A relative saving in a changeable part of the reduced expenses can be presented as follows:

$$\Delta \mathrm{Pr} = \frac{\mathrm{Pr}_{\mathrm{nor}} - \mathrm{Pr}_{*}}{\mathrm{Pr}_{\mathrm{nor}}} \cdot 100\%, \qquad (9)$$

where $\mathrm{Pr}_{\mathrm{nor}}$ – changeable part of the reduced expenses on a refrigeration which is designed and intended for a normative (recommended) temperature load;

Pr_{*} - same at the optimum working regime.

The results of research in a relative saving of the material and financial resources are given in Table 1.

Table 1: Relative saving in material and financial resources, % at the optimization of a refrigeration installation

T_{3c}	Nomination	Temperature of a cooled substance, T_{cool}, °C		
		2	0	-2
20	Electric energy	6.3	6.28	6.2
	Water	46.1	45.2	44.0
	A changeable part of the summarized expenses	17.07	16.14	14.8
10	Electric energy	6.91	6.76	6.22
	Water	48.32	47.74	46.08
	A changeable part of the summarized expenses	19.83	18.59	16.14

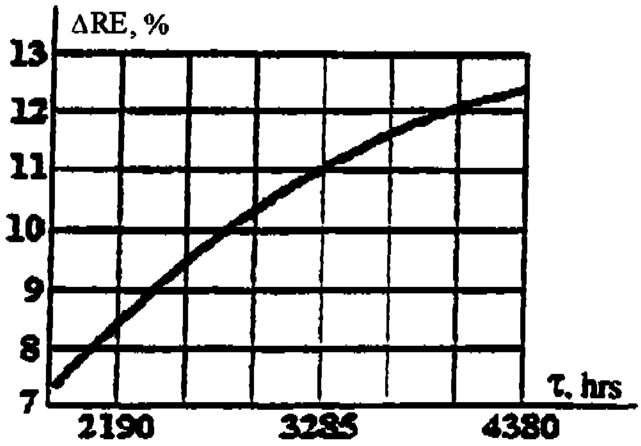

Figure 3 – Dependence of a relative saving of a changeable part of the reduced expenses ΔRE on the installation period of the installation operation

The results of the optimization calculations that it is not reasonable on designing the optimum equipment and refrigeration cycles to rely upon the recommendations for selecting the temperature loads. The results of study indicate that the value of a change in the temperatures of a cooling substance and cooled substance is affected by many factors which depend on a place and operation conditions of a refrigeration installation. The latter permits to draw a conclusion that the optimum working regime of a refrigeration installation is quite individual and should be developed for each concrete case.

Thus the optimization of the refrigeration installation operation intended for each installation individually with the required conditions and the functioning taken into consideration is supposed and is able to reduce considerably the above mentioned expenses to increase the effectively of installation. Besides, it is necessary to take into consideration the fact that many fruit-and-vegetable stores are scheduled to work by seasons and that's why there should be envisaged a change in a number of working hours which in its turn permits to choose the necessary optimum working regime of the refrigeration equipment.

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