Розроблена термоекономічна модель холодильної установки, що працює по надкритичному циклу CO_2 у якості холодагенту. Модель побудована для установки типу "повітря – повітря" і дозволяє при оптимізації конструкції і виборі економічних режимів роботи одночасно враховувати як термодинамічні, так і економічні параметри. Приведені результати оптимізації, що забезпечують умови досягнення мінімального рівня приведених витрат

Ключові слова: термоекономічна модель, надкритичний цикл, ексергія, приведені витрати

Разработана термоэкономическая модель холодильной установки, работающей по сверхкритическому циклу CO_2 в качестве хладагента. Модель построена для установки типа «воздух – воздух» и позволяет при оптимизации конструкции и выборе экономичных режимов работы одновременно учитывать как термодинамические, так и экономические параметры. Приведены результаты оптимизации, обеспечивающие условия достижения минимального уровня приведенных затрат

Ключевые слова: термоэкономическая модель, сверхкритический цикл, эксергия, приведенные затраты

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THERMOECONOMIC OPTIMIZATION OF SUPERCRITICAL REFRIGERATION SYSTEM WITH THE REFRIGERANT R744 (CO_2)

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1. Introduction

In recent years, there has been a trend towards phasing out ecologically unsafe substances and their replacement by the natural work substances. In connection with this, interest in the application of natural refrigerating media in refrigeration engineering grew considerably. Among the known natural refrigerating media, carbon dioxide (R744) occupies a special position. This substance, safe for the environment, is nontoxic and incombustible, which is its unquestionable advantage in comparison with other natural refrigerating media, such, as hydrocarbons and ammonia [1]. It possesses high heat-transfer properties and is characterized by low losses of pressure in the cycle, which makes it promising to introduce cooling plants with CO_2 as refrigerating medium in the systems of refrigeration supply at the enterprises of food industry in Ukraine, as well as in different climatic systems for solving vital problems of energy, economic and ecological nature. The number of cooling plants with CO_2 in the world has been growing constantly. In 2007, there were only three refrigeration systems for supermarkets while in 2010 there were already more than 500 [1]. This is connected with the fact that equipment of the secondary circuit (pumps) for the systems with CO_2 makes it possible to save to 90 % of driving energy; in this case, length of cooling line can be considerable.

The progress of world refrigeration industry sets new goals and tasks for designers. Today certain elements of refrigeration system possess a fairly high quality level while some structures already reached their limit of technical perfection. In connection with this, there is a new task of designing cooling plants with the optimum set of equipment and developing rational conditions for their operation, capable of decreasing financial costs while maintaining amount and quality of produced cold.

2. Literature review and problem statement

At present, studies addressing the optimization of supercritical thermotransformers with CO_2 as coolant mostly deal with questions of optimization of their operating cycle with the purpose of achieving maximum coefficient of performance (COP) without regard to the influence of processes of heat transfer in the heat exchangers and economic factors that determine price of the system. Even if heat exchanging processes in the system are considered, then, as a rule, optimization is conducted only for the individual system elements without taking into account their impact on the system as a whole. In any case, the purpose of optimization is the decrease of operational component of the resulting expenses through increasing COP of the plant, while their capital component is not considered. This may lead to irrational rise in price of the system and prevent its widespread implementation, which is relevant for such countries as Ukraine that experience serious economic difficulties.

Thus, authors of paper [2] carried out optimization of a supercritical cycle of CO_2 of heat pump and obtained expressions for the calculation of its optimum parameters. However, ignoring heat exchanging processes in the heat exchangers did not make it possible to estimate the influence of dimensions of these devices on the functions of their capital cost and, accordingly, on the price of an optimized plant.

Authors of article [3] received, as a result of optimization of different supercritical CO_2 refrigeration systems of a supermarket, graphs of dependence of their COP on the values of ambient temperature. Based on this, they selected the system that possesses the largest COP in the examined temperature range of surrounding air. In this case, capital cost of the analyzed refrigeration systems was not considered either.

Authors of paper [4] examined influence of the length of pipes of regenerative intermediate heat exchanger on the parameters of supercritical cycle of CO_2 and COP of heat pump for the purpose of reaching its optimum value. At the same time, the influence of optimum parameters of regenerative heat exchanger on the remaining system elements was not explored, and the optimization of the system as a whole was not carried out.

The same concerns article [5], which presented results of the studies on determining optimum parameters of basic heat exchangers (gas cooler and vaporizer) in the scheme of heat pumps that work on CO_2. Optimization here was based on conducting traditional technical and economic calculations, which imply individual approach to each particularly considered plant and do not provide for obtaining general (analytical) solutions.

Article [6] is devoted to the simulation of the cycle of a heat-pumping supercritical CO_2 plant, intended for the joint production of cold and heat. Taking into account the influence of heat exchanging processes in the system, the authors obtained dependences of optimum COP on the speed of shaft rotation of compressor, temperatures of heat-carriers at the input to vaporizer and gas cooler, CO_2 pressure after compressor, as well as ratio of fixed values of the heat exchanging surfaces of gas cooler and vaporizer. However, when simulating energy processes, the authors used a method of energy analysis only, which does not make it possible to consider energy losses from the external and internal irreversibility in separate units of the plant, which is insufficient for reliable estimation of the system [7, 8]. For a more full analysis of the plant, it is expedient to use the exergetic analysis, based on the calculation of exergy losses in particular processes and in the cycle of a thermodynamic system.

As is known, when designing thermotransformers, for increasing energy effectiveness in their performance, it is necessary to strive for a decrease in losses from irreversibility of thermodynamic processes. However, in practice this frequently leads to the rise in price of the plant [9]. Therefore, in the course of selection of optimum operating conditions of refrigeration systems, it is necessary to consider a number of economic factors. Here of help are the thermoeconomic methods, based on exergy analysis, of simultaneous account of thermodynamic and economic factors when conducting optimization calculations. Each element of the system is considered here to be an energy conversion apparatus, the conversion of energy in it is accompanied by economic expenses. Any material flows, entering the system, and results of their interactions, are expressed through changes in exergies of these flows. This makes it possible to optimize internal energy processes in the refrigeration plant and to conduct purposeful selection of those compromise solutions, which would provide obtaining minimum level of the resulting expenditures for its creation and operation.

In the 1960s, an autonomous method of thermoeconomic optimization was developed and verified in connection with optimum design of desalination plants [10, 11]. These papers were for many years an example of successful application of the thermoeconomic method in the search for the optimum regime-structural characteristics of a thermotechnical system. Subsequently, autonomous method was adapted for solving optimization problems of the regime parameters of operation of the refrigeration plants [12–14].

An application of the autonomous method of thermoeconomic optimization when designing or deep modernizing supercritical thermotransformers with CO_2 as refrigerating medium will make it possible to thoroughly consider influence of the entire totality of thermodynamic and economic factors on the parameters of optimum system, which cannot be taken into account by standard engineering methods.

3. The aim and tasks of research

The purpose of research is the development of procedure for the thermoeconomic optimization of air-air supercritical refrigeration CO_2 systems, based on autonomous method, and its application for the optimization of the mode parameters of operation of conditioner that works by the supercritical CO_2 cycle.

To achieve this aim, the following tasks are to be solved:

– to build a thermoeconomic model of supercritical refrigeration plant of the type "air – air" with the coolant R744 (CO_2);

– to calculate, based on the constructed thermoeconomic model, extreme values of optimizing parameters of a conditioner that works by the supercritical CO_2 cycle, given a variability of electric power tariff.

4. Thermoeconomic model of refrigeration plant of the "air – air" type that works by the supercritical CO_2 cycle as a refrigerant

A thermoeconomic model of the refrigeration machine (RM) in question includes a schematic of installation with designation of all its basic elements, combined by conditional control boundary. This schematic corresponds to a real technological scheme of RM. Entry to the system is conducted through the conditional control boundary, as well as exergy and thermal fluxes exit via it (Fig. 1).

In Fig. 1: CM – compressor, GC – gas cooler, FGC – fans of gas cooler, ThV – throttle valve, FV – fans of vaporizer, V – vaporizer, Q_v – refrigerating capacity of V, Q_{GC} – heat productivity of GC, e^{V}_{cool} – exergy, which the airflow in the vaporizer must possess, taking into account the heat, supplied by FV, e^{V}_{ref} – exergy, which must be supplied to the vaporizer by refrigerant, e^{GS}_{ref} – exergy, supplied by refrigerant to the gas cooler.

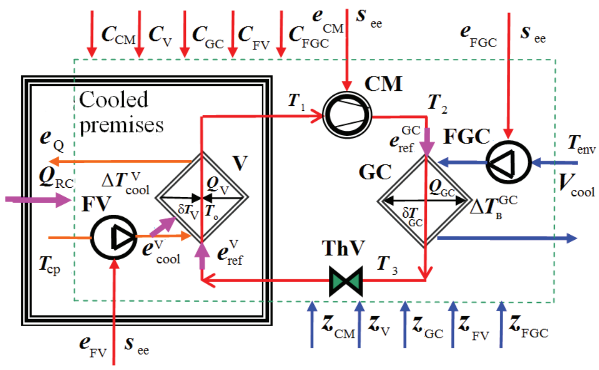

Fig. 1. Thermoeconomic model of refrigeration plant of the "air – air" type with CO_2 as refrigerant that works in the supercritical region

Flows of exergy e_{CM}, e_{FV} and e_{FGS} for the drive of compressor, as well as of ther fans of vaporizer and gas cooler are supplied through conditional control boundary of the thermoeconomic model. The price of these exergies, delivered from the external electrical source, is numerically equal to the price of the used electric power by tariff $s_{ээ}$ s_{ee} due to the equality of electrical energy and exergy of this energy [8, 15]. Cooling air at rate V_{cool} and temperature T_{env}, which has corresponding exergy whose cost equals zero, is also supplied through the conditional control boundary from the environment.

In the course of analysis of the thermoeconomic model, the losses of exergy are examined and considered, which appear during transfer and conversion of energy in separate elements of the plant, as well as economic expenses due to the creation and operation of these elements, – their cost, annual summary deductions from this cost and tariffs on heat carriers. The losses of exergy and economic expenses lead to an increase in the price of the unit of exergy with the motion of the main flow of exergy through key elements of the plant from the point of introduction of exergy to the system to obtaining final performance efficiency by the user, which is evaluated by the set resulting exergetic productivity of refrigeration plant e_Q, that is, by the exergy of obtained cold [14].

Numerical value of the resulting exergetic productivity of refrigeration plant e_Q is determined by the set values Q_{RC}, T_{cp} and T_{env} from expression

$$e_Q = Q_{RC}\left(\frac{T_{env}}{T_{cp}} - 1\right),$$

where Q_{RC} is the refrigerating capacity of RM, that is, amount of heat, taken away from the cooled object per time unit, W; T_{cp} is the temperature in the cooled premises, K.

Since the value of refrigerating capacity for the examined refrigeration plant is assigned quantitatively, then for the optimization of the system it is necessary to define conditions that ensure obtaining minimum price of the unit of refrigerating capacity of the system. Therefore, for analysis of the thermoeconomic model, as objective function, we accepted the resulting expenses PZ, which are a sum of both operational and capital expenses for the introduction and operation of refrigerating plant during certain specific service life.

It is extremely important here to consider the ratio between the values of tariff for electric power and the costs of equipment. At the relatively low tariff, especially with the high price of equipment, for the minimization of resulting expenses, it becomes more beneficial to try to decrease price of the most expensive elements of system (for example, to use heat exchangers of smaller area). In this case, in spite of the increased irreversible losses that lead to decrease in COP of the plant and increase in operational expenses, an economic effect is present due to reduced capital investments in basic equipment. With an increase in tariff for electric power, it becomes on the contrary more beneficial to increase capital investments in the plant. An economic effect in this case is observed due to an increase in the degree of thermodynamic perfection of the system, increase in its COP and, therefore, reduction in operational expenses.

Thus, it becomes obvious that maximum COP is not always optimum from an economic point of view. This technique implies search for such values of parameters of the cycle of refrigeration palnt (Fig. 2) that would provide for the optimum value of COP of the plant from a position of the minimization of resulting expenses. This concerns, in particular, the value of CO_2 pressure in gas cooler P_2, which, as rule, when designing supercritical refrigeration systems that work on CO_2, is calculated based on the consideration of providing maximum COP by the known dependence [16].

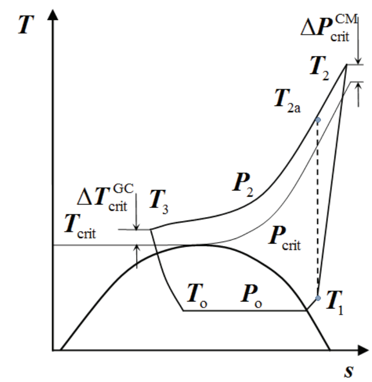

Fig. 2. Supercritical cycle of RM performance in the T-s diagram

In this technique, optimum value P_2 and optimum value of temperature at the output from gas cooler T_3 are the required values. It should be noted that at the input to the throttle valve, CO_2 temperature is equal to T_3 since the examined scheme of refrigeration plant lacks an additional heat exchanger-aftercooler.

Therefore, when constructing a thermoeconomic model of the given refrigeration machine, it is necessary to ensure conditions, which do not allow calculated values of pressure P_2, as well as temperature T_3, to decrease below critical values, that is, the conditions $P_2>P_{crit}$ and $T_3>T_{crit}$ must be observed.

In order to solve optimization problem, the following were accepted as the optimizing variables: excess CO_2 pressure at the output of compressor P_2 above critical value ΔP_{crit}^{CM}, excess CO_2 temperature at the output of gas cooler T_3 above critical value ΔT_{crit}^{GC} (Fig. 2) and the mean logarithmic temperature head between the heat carriers that exchange energy in vaporizer δT_V.

Mean logarithmic temperature head in gas cooler δT_V was calculated analytically as function of the selected optimizing variables.

At present, price of the heat exchanging equipment, which works on CO_2, is extremely high since it is operated under conditions of considerably higher pressure (4–5 times higher) in comparison with the heat exchangers that work on freons. That is why at relatively low tariffs for electric power, from the thermoeconomic positions, it is necessary to strive for a decrease in dimensions of the "air – CO_2" heat exchangers through the intensification of heat emission from the air by a considerable increase in the speed of blowout of its external heat exchanging surface. This has an essential effect on the increase in heat transfer in the plant, since heat emission from the air is considerably less than from CO_2.

At a certain ratio of tariff for electric power and the price of heat exchanging equipment, this can prove to be economically beneficial despite the fact that it leads to a significant increase in hydraulic resistance and energy consumption by fans. However, a considerable increase in the air speed is unacceptable for conditioning systems since it is connected with an increase in the level of noise and it can create cold draft in the cooled premises, which will unfavorably affect health of the consumers of cold. Furthermore, a notable increase in the consumption of electric power by the fans contradicts the very idea of energy-efficiency and introduction of ecologically clean climatic systems as it will lead to an increase in the electric energy generation at power stations and, thus, to an increase in harmful emissions to the environment.

That is why, when solving this problem, values of magnitudes of change in air temperature in vaporizer ΔT^{V}_{cool} and gas cooler ΔT^{GC}_{cool} were not optimized, that is, ΔT^{V}_{cool}=const and ΔT^{GC}_{cool}=const. It was accepted that their values correspond to the levels of air speed in the heat exchangers of conditioning systems that are acceptable from a sanitary point of view.

Since refrigerating capacity of refrigeration plant Q_{RC} and temperature in the cooled premises T_{cp} by the condition of optimization problem remain constant, and $\Delta T^{V}_{cool}=\text{const}$, then the value of magnitude of the exergy flow e_{FV} for the fan drive of vaporizer, their price C_{FV} and annual summary deductions from this price z_{FV} were accepted as constant and not influencing solution of the optimization problem. In this case, on the contrary, value of heating capacity of gas cooler Q_{GC} changes a little as a result of change in the values of exergy losses in the system, which at $\Delta T^{GC}_{cool}=\text{const}$ leads to insignificant change in the air rate through the gas cooler, power of its fans and their cost indices.

Costs of equipment components C_i, annual summary deductions from these costs z_i, as well as the exergy, applied to each element e_i from external source, were expressed in the form of functional dependences on the assigned resulting exergetic productivity of refrigeration plant e_Q and on the optimizing variables that affect the element in question

$$e_{CM}, C_{CM}, z_{CM}, C_V, z_V, e_{FGC}, C_{FGC}, z_{FGC}, C_{GC}, z_{GC} = \\ = f\left(e_Q, \delta T_V, \Delta T^{GC}_{crit}, \Delta P^{CM}_{crit}\right). \tag{1}$$

Symbols C_{CM}, C_V, C_{GS} and C_{FGS} represented in expression (1) denote the cost, respectively, of compressor CM, vaporizer V, gas cooler GC, fans of cooling air in gas cooler FGC, and z_{CM}, z_V, z_{GC} and z_{FGC} – annual summary deductions from this cost.

Annual summary deductions from the cost of elements of a refrigeration plant are normalized by the time interval of work of the system and are determined from expression [12, 14]

$$z_i = \frac{\left(k_i^{norm} + k_i^{ren}\right) C_i}{\Delta\tau},$$

where k_i^{norm} and k_i^{ren} are, respectively, the normative coefficient of deductions and coefficient of deductions for renovation and repair from the cost of the i-th element, $\Delta\tau$ is the analyzed duration of work of the system per year, h.

Objective function of resulting expenses PZ was calculated by formula

$$PZ = \left[s_{ee}\left(e_{CM} + e_{FV} + e_{FGC}\right) + z_{CM} + z_V + z_{FV} + z_{GC} + z_{FGC}\right] \times \\ \times \Delta\tau \cdot n_{seas} + C_{CM} + C_V + C_{FV} + C_{GC} + C_{FGC}, \tag{2}$$

where n_{seas} is the analyzed number of seasons of work of the refrigeration machine.

In order to solve the optimization problem, functional expressions (1) that are present in objective function of the resulting expenses (2) were represented in the form of expanded analytical dependences, which describe energy processes that take place in separate elements of the examined system of refrigeration supply. These dependences are quite cumbersome and, because of limitations of the article, are given below by only some expressions, which are used for their construction, in the non-expanded form.

Nusselt criterion from CO_2 in a gas cooler was calculated by formula [17, 18]

$$Nu^{GC}_{ref} = Nu_{sub}\phi,$$

where Nu_{sub} is the Nusselt criterion at the weakly-varying properties of heat carrier in the subcritical region; ϕ is the correction of Krasnoshchekov-Protopopov to account for the gradient of temperature in the near-wall layer under conditions of CO_2 cooling in the supercritical region.

For determining value Nu_{sub}, we used Petukhov-Kirilov dependence [17, 19–21]

$$Nu_{sub} = \frac{\frac{\xi}{8} Re_w Pr_w}{12{,}7\sqrt{\frac{\xi}{8}}\left(Pr_w^{2/3} - 1\right) + 1{,}07}, \tag{3}$$

where Re_w and Re_w are the Reynolds and Prandtl criteria from CO_2 at temperature of the inner wall of the pipe of gas cooler T_w [17]; ξ is the coefficient of hydraulic resistance of heat carrier at constant properties.

The Reynolds criterion was calculated by formula [17, 21]

$$Re_{wall} = \frac{4G_{ref}}{\pi d \mu_w}, \tag{4}$$

where G_{reff} is the mass flow rate of cold carrier, kg/s; d is the diameter of pipes for the passage of cold carrier, m; μ_w is the coefficient of dynamic viscosity of cold carrier at temperature of the inner wall of the pipe of gas cooler T_w [17].

Coefficient of hydraulic resistance ξ that is present in dependence (3) was calculated by the Filonenko formula [17–22]

$$\xi = \left(1{,}82 \lg Re_c - 1{,}64\right)^{-2}.$$

The correction of Krasnoshchekov-Protopopov ϕ to account for the gradient of temperature in the near-wall layer, which considers influence on heat exchange of the change in the physical properties of CO_2 by the cross-section of flow under cooling conditions in the supercritical region, was calculated as [17, 18]

$$\phi=\left(\frac{\rho_w}{\rho_{ref}}\right)^n\left(\frac{\overline{c}_p}{c_{pw}}\right)^m, \qquad (5)$$

where $\overline{c}_p=(i_{ref}-i_w)/(T_{ref}-T_w)$ is the mean integral heat capacity of CO_2 in the range of temperatures T_w–T_{ref}, kJ/(kg·K); T_{ref} is the temperature in the flow of vapor of CO_2 in gas cooler, K; i_w, c_{pw} and ρ_w are, respectively, enthalpy, kJ/kg, mass heat capacity and density, kg/m^3, CO_2 at T_w; i_{ref} and ρ_{ref} are the enthalpy and density of CO_2 at T_{ref}; n is the function of pressure P_2; m is the function of pressure P_2 and ratio $\overline{c}_p/c_{pw}$. Values of n and m are represented in Tables [17].

Isentropic performance efficiency of compressor that works on CO_2 was determined from expression [23]

$$\eta_{is}=0{,}00476\left(\frac{P_2}{P_o}\right)^2-0{,}09238\frac{P_2}{P_o}+0{,}89810, \qquad (6)$$

where P_o is the boiling pressure of refrigerant, bar.

The cost of elements of refrigeration machine that works on CO_2, was represented in the form of functional dependences, built on the basis of cost functions, given in [23]:

$$C_{CM}=10167{,}5(e_{CM}\eta_{CM})^{0{,}46};$$

$$C_{FV}=629{,}05(e_{FV}\eta_{FV})^{0{,}76};$$

$$C_{FGC}=629{,}05(e_{FGC}\eta_{FGC})^{0{,}76};$$

$$C_V=1397\ F_V^{\ 0{,}89};$$

$$C_{GC}=1397\,F_{GC}^{\ 0{,}89}, \qquad (7)$$

where η_{CM}, η_{FV}, η_{FGC} are the performance efficiency of electric motor of compressor, fans of vaporizer and capacitor (taking into account performance efficiency of transfer); F_v and F_{GC} are the area of outside heat exchanging surface of vaporizer and gas cooler (that are of identical design in the considered plant). The cost of elements of refrigeration machine in expressions (7) is described in USD and was converted into Ukrainian hryvnas by the current exchange rate.

Magnitudes G_{ref}, T_{ref}, P_o and P_2 that are present in expressions (4)–(6), as well as other in the thermoeconomic model, not described above, were in turn represented in the form of expanded analytical dependences. For example, coefficients of heat transfer of heat exchangers that are ncluded in expressions C_V, C_{GC} and z_V, z_{GC} (1), and isentropic efficiency of compressor were presented in the form of functional dependences k_V, k_{GC}, η_{is}=f (e_Q, δT_V, ΔT^{GC}_{crit}, ΔP^{CM}_{crit}) with the help of the known calculation formulas, described in [21, 24–26].

Minimum of objective function (2) corresponds to the optimum system characteristics from the position of minimization of the resulting expenses. At present, due to a considerable increase in computational capacities of computer technology, it is possible, upon describing an entire system as a whole by analytical expressions, which take into account interrelation between all optimizing parameters, to represent these parameters as independent variables in equation (PZ=f (δT_V, ΔT^{GC}_{crit}, ΔP^{CM}_{crit}) and to solve the problem of thermoeconomic optimization by searching for unconditional extremum of function of the resulting expenses PZ. For this purpose, partial derivatives from objective function PZ (2) by all optimizing variables are leveled to zero:

$$\frac{\partial PZ}{\partial \delta T_V}=0;\quad \frac{\partial PZ}{\partial \Delta T^{GC}_{crit}}=0;\quad \frac{\partial PZ}{\partial \Delta P^{CM}_{crit}}=0. \qquad (8)$$

Received system (8) consists of transcendental nonlinear equations whose solution formulates the required conditions of the minimum of function of the resulting expenses. Analytical solution of the optimization problem in the form of system of equations (8) is applicable for any refrigeration machine that works according to the examined scheme (with the same aet and type of equipment).

5. Results of calculating extreme values of optimizing parameters of conditioner given a variability of tariff for electric power

Let us examine results of the thermoeconomic optimization of refrigeration plant of the "air – air" type (conditioner) whose schematic is analogous to the one represented in Fig. 1. The system is equipped with a piston compressor, plate evaporator and gas cooler of identical geometry with the stamped out pipes for the CO_2 passage and axial fans.

We accepted as the initial data: refrigerating capacity Q_{RC}=16,8 kW; duration of work of the system per year $\Delta\tau$=8000 h; analyzed number of seasons of work of the plant n_{seas}=30 years; normative coefficient of deductions from the cost of equipment k_i^{norm}=0,15; air temperature in the cooled premises T_{cp}=18 °C; ambient temperature T_{env}=32 °C, accepted equal to air temperature at the input of the gas cooler; tariff for electric power varied from s_{ee}=1,68 UAH/(kW·h) and larger.

In this case, in order to solve a system of equations (8), preliminary values of optimizing variables for the identification of thermophysical properties of CO_2 and air in different elements of the system were assigned. In addition, we assigned preliminary values of heat flows densities in the vaporizer and gas cooler, related to their inner surface, and temperature of the inner wall of the pipe of gas cooler in a particular section.

These preliminary values, as a rule, correspond to characteristics of the yet not optimized actually existing system. However, as shown in [27], whose authors investigated "convergence" of the thermoeconomic model of a chiller, constructed according to the analogous principle, when they assigned different values of the initial optimizing parameters for the purpose of estimatation of divergences in the values of parameters of optimum variant, characteristics of the selected optimum RM always proved to be identical, but with a positive effect from the optimization, different in magnitude. Thus, at any initial values of optimizing variables and other above-mentioned parameters, at invariable assigned geometry of heat exchangers, at the same assigned price indices and calculated period of operation, there is one and the same optimum result obtained.

By the values of optimizing variables, obtained as a result of solution, we evaluated divergences in the values of thermophysical properties of heat carriers and in the values of other, preliminarily assigned, parameters of the system. Then they were refined and the calculation was repeated until they matched the calculated values.

If, in the examined region, objective function has only one extreme point and, furthermore, objective function does not have gaps while the existence of extremum is predetermined by physical prerequisites, then the conducted analysis and the obtained necessary conditions for the existence of extremum are sufficient [14]. The obtained results completely satisfy these conditions. Fig. 3 demonstrates graphs of dependence of objective function of the resulting expenses PZ (2) on each of the optimizing variables when substituting the obtained optimum values of the remaining optimizing variables into it.

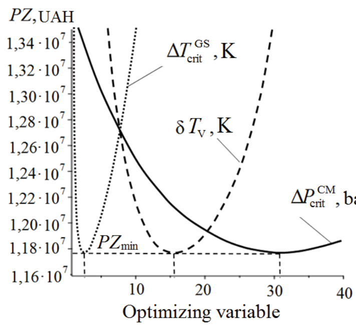

Fig. 3. Dependence of the resulting expenses on the values of optimizing parameters at s_{ee}=1,68 UAH/(kW·h)

The graphs clearly outline the minimums of function of the resulting expenses PZ whose coordinates correspond along the Y-axis to the minimum of function of the resulting expenses, and along the X-axis – to the optimum value of given optimizing variable.

Calculations were conducted for the tariff for electric power s_{ee}=1,68 UAH/(kW·h), planned to take effect as of 1 March 2017 in Ukraine. An analysis of results revealed that, even at this tariff, taking into account high price of basic equipment of refrigeration machine, from the point of view of minimization of the resulting expenses, it is expedient to strive for the decrease in their capital component through an increase in operating costs, which, along with a general financial benefit, leads to the decrease in COP of the examined plant.

We searched for such a value of tariff for electric power at which, taking into account cost functions (7), COP of the plant, optimum from the point of view of minimization of the resulting expenses, would practically equal its initial value. The calculations demonstrated that this is reached at the tariff for electric power s_{ee}=2,58 UAH/(kW·h), while, with an increase in the tariff above this value, COP of the optimized system continues to grow. To analyze causes for such a change in COP of the optimized system depending on the values of tariffs for electric power, this problem was solved also at conditional values of tariffs for electric power s_{ee}=2,58 UAH/(kW·h) and s_{ee}=3,48 UAH/(kW·h). Results of calculations are presented in Tables 1, 2.

Data represented in Tables 1 and 2 demonstrate that at the tariff for electric power s_{ee}=1,68 UAH/(kW·h), values of the optimizing variables change as follows: ΔP^{CM}_{crit} and, accordingly, pressure after compressor P_2 grows, as well as mean logarithmic temperature head in vaporizer δT_v, while ΔT^{GC}_{crit} and, respectively, T_3 are reduced. A considerable increase in value δT_v leads to significant reduction in the area of heat exchanging surface of the vaporizer and its cost, which exerts main influence on the decrease in the level of capital costs. At the same time, this increase δT_v at a fixed mean temperature of air in the vaporizer is connected with the reduction in the boiling point T_o and notable increase in the exergy losses from the external irreversibility.

Table 1

Results of RM optimization at different conditional values of tariffs for electric power

Parameter	RM initial variant (Init)	Optimal RM (Opt)		
		1	2	3
Conditional value of tariff for electric power, UAH/(kW·h)	1,68–3,48	1,68	2,58	3,48
Boiling temperature T_o, °C	6,34	–1,82	0,45	1,89
CO_2 boiling pressure P_o, bar	41,18	33,61	35,72	37,05
CO_2 temperature at the input to compressor T_1, °C	11,34	3,18	5,45	6,89
CO_2 pressure after compressor P_2, bar	101,83	104,74	102,00	100,07
Degree of refrigerant compression in compressor	2,47	3,12	2,86	2,70
Isentropic efficiency of compressor	0,699	0,656	0,673	0,683
CO_2 temperature after compressor T_2, °C	114,24	140,00	128,89	121,96
CO_2 temperature after gas cooler T_3, °C	37,06	33,58	33,34	33,17
Mean logarithmic CO_2 temperature in gas cooler, °C	74,22	84,15	78,95	75,68
Specific mass cold capacity of vaporizer, kJ/kg	122,15	155,6	151,3	148,1
CO_2 mass flow rate, kg/s	0,1391	0,1092	0,1123	0,1147
Coefficient of compressor delivery	0,805	0,759	0,777	0,788
Exergy losses in compressor mechanism, kW	0,093	0,097	0,091	0,089
Exergy losses in throttling, kW	1,949	1,596	1,542	1,507
Exergy losses in vaporizer, kW	0,500	1,059	0,900	0,801
Exergy losses in gas cooler, kW	2,812	3,164	2,823	2,605
Total exergy losses, kW	5,354	5,916	5,356	5,002
Power consumption of electric motor of CM from the network, kW	8,608	9,363	8,611	8,135
Effective power of compressor (on shaft), kW	6,41	6,98	6,42	6,06
Change in air temperature in vaporizer, K	8,000	8,000	8,000	8,000
Air mass flow rate through vaporizer, kg/s	2,11	2,11	2,11	2,11
Total power used by electric motor of vaporizer fans from the network, kW	0,189	0,189	0,189	0,189
Coefficient of heat transfer of vaporizer, $W/m^2 \cdot K$	80,4	85,1	84,3	83,7
Mean logarithmic head in vaporizer, K	7,000	15,573	13,243	11,752
Area of outer surface of vaporizer, m^2	30,2	12,8	15,2	17,3
Heat capacity of gas cooler, kW	23,31	23,87	23,31	22,96
Change in air temperature in gas cooler, K	10,0	10,0	10,0	10,0
Air mass flow rate through gas cooler, kg/s	2,29	2,34	2,29	2,25
Total power used by electric motor of gas cooler fans from the network, kW	0,279	0,296	0,279	0,267
Coefficient of heat transfer of gas cooler, $W/m^2 \cdot K$	99,8	100,1	98,7	97,9
Mean logarithmic head in gas cooler, K	25,059	22,898	20,050	18,203
Area of outer surface of gas cooler, m^2	9,3	10,4	11,8	12,9
Total power used by RM from the network, kW	9,075	9,847	9,078	8,591
Coefficient of conversion (COP) of RM	1,851	1,706	1,851	1,956

Table 2

Ecomomic indices and effect of RM optimization

Parameter	Init	Opt	Init	Opt	Init	Opt
	1		2		3	
Conditional value of tariff for electric power, UAH/(kW·h)	1,68		2,58		3,48	
Price of compressor, UAH thousand	573,7	596,3	573,7	573,8	573,7	559,0
Price of vaporizer, UAH thousand	695,5	324,6	695,5	378,1	695,5	423,5
Price of gas cooler, UAH thousand	244,6	269,7	244,6	301,1	244,6	326,2
Price of vaporizer fans, UAH thousand	3,8	3,8	3,8	3,8	3,8	3,8
Price of gas cooler fans, UAH thousand	5,1	5,3	5,1	5,1	5,1	4,9
Price of all basic equipment, UAH thousand	1522,6	1199,6	1522,6	1261,8	1522,6	1317,3
Capital costs (Cap_i) incl. deductions over 30 years (8000 h per 1 year), UAH thousand	9897	7798	9897	8202	9897	8563
Operational costs ($Oper_i$) over 30 years (8000 h per 1 year), UAH thousand	3659	3970	5619	5621	7580	7175
Resulting costs (PZ_i) over 30 years (8000 h per 1 year), UAH thousand	13556	11768	15516	13823	17476	15738
Optimization effect, %	**13,19**		**10,91**		**9,95**	

Accordingly, boiling pressure P_o is reduced, which, in conjunction with an increase in value P_2, leads to an increase in compression ratio in compressor, a decrease in its isentropic efficiency and rise in temperature T_2, which increases by a larger magnitude than T_3 is lowered. This, in turn, leads to an increase in the mean logarithmic CO_2 temperature in gas cooler, which, at a fixed mean temperature of air, contributes to an increase in the exergy losses from external irreversibility in gas cooler. Delivery coefficient of compressor also decreases, and the exergy losses in its mechanism grow.

The optimum ratio of values T_3 and P_2, obtained from position of the minimization of the resulting expenses at this tariff, leads to an increase in specific mass refrigerating capacity of vaporizer, reduction in the consumption of refrigerant and losses of exergy in the process of throttling.

However, summary exergy losses in the system grow (Fig. 4), which, in spite of a certain reduction in the consumption of refrigerant, leads to an increase in the energy consumption of compressor and its cost, an increase in operational expenses and decrease of COP of the system. In this case, reduction in temperature T_3 leads to the decrease in the mean logarithmic head in gas cooler, an increase in its dimensions and increase in its price. But, in spite of the increase in the price of gas cooler and compressor, the resulting expenses decrease due to a considerable reduction in the cost of vaporizer (Table 2).

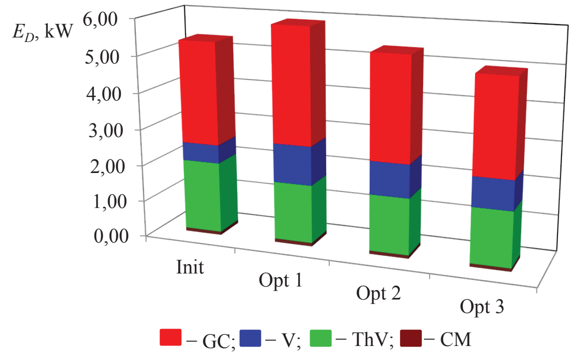

Fig. 4. Losses of exergy in the elements of initial and optimal RM at different conditional values of tariffs for electric power: Opt 1 – optimal RM at s_{ee}=1,68 UAH/(kW·h); Opt 2 – at s_{ee}=2,58 UAH/(kW·h); Opt 3 – at s_{ee}=3,48 UAH/(kW·h)

With an increase in tariff for electric power to s_{ee}= =2,58 UAH/(kW·h), optimum value of optimizing variable ΔP_{crit}^{CM} and, accordingly, pressure after compressor P_2 grows by a lower magnitude in comparison with the original value. This also concerns value of the mean logarithmic temperature head in vaporizer δT_V, while ΔT_{crit}^{GC}, and, respectively, T_3 continues to decrease. The area of heat exchanging surface of vaporizer somewhat increases in comparison with the optimum value, calculated at tariff s_{ee}=1,68 UAH/(kW·h), but remains much less than the original value, as well as the price of vaporizer. Accordingly, in comparison with the variant, calculated at tariff s_{ee}=1,68 UAH/(kW·h), due to reasons described above, the exergy losses in vaporizer and gas cooler decrease but they nevertheless remain above the initial ones. However, this is compensated for by a certain reduction in the exergy losses in the mechanism of compressor and in the process of throttling. Summary losses of exergy become practically equal to its original value (Fig. 4), as well as, respectively, energy consumption of compressor, its price, operational expenses of the system and its COP (Tables 1, 2). At this tariff, with practically constant operational expenses, the resulting expenses decrease because the cost of vaporizer is lowered by a larger value than the price of gas cooler grows (Table 2).

With an increase in tariff for electric power to s_{ee}= =3,48 UAH/(kW·h), optimum value of optimizing variable ΔP_{crit}^{CM} and, accordingly, pressure after compressor P_2 are reduced in comparison with the original value. Optimum value of the mean logarithmic temperature head in vaporizer δT_V continues to decrease in comparison with its optimum values at the previously examined tariffs, but it remains higher than in the initial variant ΔT_{crit}^{GC} and, respectively, T_3 continues to decrease, similar to the previously examined tariffs. The area of heat exchanging surface of vaporizer somewhat increases in comparison with the optimum value, calculated at tariff s_{ee}=2,58 UAH/(kW·h), but remains much less than the original value, similar to the price of vaporizer. Accordingly, in comparison with the variant, calculated at tariff s_{ee}= =2,58 UAH/(kW·h), due to reasons described above, the losses of exergy in vaporizer decrease, but nevertheless remain above the initial ones. In this case, the exergy losses in gas cooler are reduced in comparison with the initial variant, similar to the exergy losses in the mechanism of compressor and in the process of throttling. The summary exergy losses in the system further decrease (Fig. 4). Energy consumption of compressor and its cost is reduced, respectively, operational expenses of the system decrease and its COP grows (Tables 1, 2). A decrease in operational expenses at this tariff leads to reduction in the resulting expenses, which is also contributed to by the decrease in their capital component, since the cost of vaporizer and compressor is reduced by a larger value than the cost of gas cooler grows (Table 2).

Economic indices of RM and the ratio of capital and operational components in the resulting expenses PZ of RM before and after its optimization at different conditional values of tariffs for electric power are given in Fig. 5.

Capital and operational expenses were determined as

$$\mathrm{Cap} = \left(z_{CM} + z_{V} + z_{FV} + z_{GC} + z_{FGC}\right)\cdot \Delta\tau \cdot n_{seas} + \\ + C_{CM} + C_{v} + C_{FV} + C_{GC} + C_{FGC};$$

$$\mathrm{Oper} = s_{ee}\left(e_{CM} + e_{FV} + e_{FGC}\right)\cdot \Delta\tau \cdot n_{seas}.$$

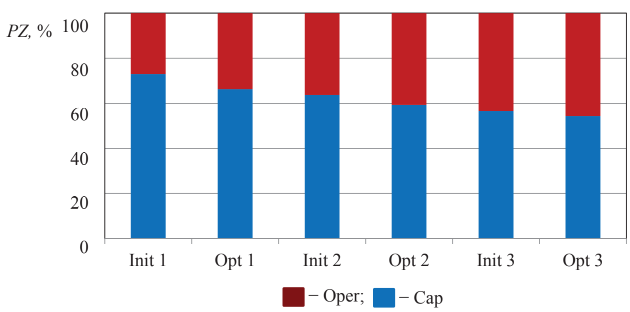

Fig. 5. Percentage ratio of capital and operational components of PZ at different conditional values of tariffs for electric power

Fig. 5 demonstrates that with an increase in tariff for electric power, the share of operational components in the resulting expenses grows in the optimized RM in comparison with the initial one.

6. Discussion of results of the thermoeconomic optimization of supercritical refrigeration plant of the "air – air" type with the refrigerant R744 (CO_2)

Developed technique and software make it possible to solve the optimization problem of regime parameters in the operation of supercritical refrigeration systems that work on R744 (CO_2), taking into account interrelations between parameters of all basic subsystems when providing for a minimum level of the resulting expenses for their creation and operation.

Numerical solution of this problem for the refrigeration plant of the "air – air" type (conditioner) with CO_2 as refrigerating medium, which works in the supercritical region, allowed us to find optimum parameters of the system, which ensures conditions for reaching minimum level of the resulting expenses at different values of tariffs for electric power.

One of the benefits of technique consists in the fact that the obtained unique analytical solution in the form of a system of equations is applicable for the thermoeconomic optimization of any refrigeration system that works according to the considered scheme and with a similar type of equipment.

A shortcoming in the method is the fact that, for simplification of the representation of analytical dependences, the thermoeconomic model did not take into account hydraulic losses of pressure in the connecting pipelines of CO_2 and their influence on COP. However, these losses may in principle be disregarded since their influence on effectiveness of the cycle is not considerable because of the CO_2 thermophysical properties. In this case, the given model can be complemented by the appropriate equations to account for hydraulic losses in the pipelines of the system.

An application of this method in practice should contribute to the reduction in financial expenses for creation and operation of conditioners that work on CO_2, to an increase in their competitiveness compared with traditional freon systems and contribute to the creation of conditions for their large-scale implementation in Ukraine.

In future, the given technique can be adapted for solving problems of the thermoeconomic optimization of regime parameters of operation of thermotransformers of other functional designation that work on CO_2.

7. Conclusions

1. Development of the thermoeconomic model of supercritical refrigeration plant of the "air – air" type with the refrigerant R744 (CO_2) made it possible to represent objective function of the resulting expenses in the form of expanded analytical expressions, which take account of interrelation between all optimizing parameters of the system. An analytical solution of the optimization problem in the form of a system of equations of partial derivatives from objective function of the resulting expenses for all optimizing variables is applicable for any refrigeration machine that works according to the considered scheme.

2. As a result of the thermoeconomic optimization of regime parameters of operation of conditioner that works by the supercritical CO_2 cycle, it was possible to reduce esimated value of the resulting expenses over 30 years of its operation by 10–13 % through more rational distribution of energy flows in it. In this case, the character of optimization of the system is affected by the value of tariff for electric power. At a relatively low tariff, economic effect is present due to the reduction in capital investments into basic equipment, in spite of increased irreversible losses, which lead to a decrease in COP of the plant and increase in operational costs. With an increase in the tariff, it, on the contrary, becomes more beneficial to increase capital investments into the plant for the purpose of reducing the effect of irreversibility in its elements, increasing its COP and, therefore, decreasing operational expenses.

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