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Exergoeconomic model of a central air conditioning system

Эксергоэкономическая модель центральной системы кондиционирования воздуха

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Abstract. The article considers the issues of energy saving in central air conditioning systems by means of their operation parameters optimization, based on the exergoeconomic (thermoeconomic) approach. The necessity of joint consideration thermodynamic and economic factors of system operation is identified. Literature review in the field of study is submitted. There is the schematic diagram of the central air conditioning system provided for which the exergyeconomic model is created. Necessary assumptions are stated. Exergy economic model of central air conditioning system is shown in graphical form. The model is presented as separate zones, connected in-series. Basic expressions of the exergyeconomic model are stated. The expressions allow solving the problem of energy consumption minimization using the Lagrange's method of undetermined multipliers. Expression of a lagrannian for a problem of optimization of parameters of the functioning of the central air conditioning system is received. The performance control laws of separate zones of the air conditioning system providing minimal energy consumption during its operation are offered in a general view. As a conclusion possibility of considerable energy consumption decreases during operation of the air conditioning system.

Аннотация. В статье рассмотрены вопросы энергосбережения в центральных системах кондиционирования воздуха путем оптимизации параметров их функционирования на основе метода эксергоэкономики (термоэкономики). Выявлена и обоснована необходимость совместного учета и термодинамических, и экономических факторов функционирования систем. Представлен обзор литературы в области исследований. Приведена принципиальная схема центральной системы кондиционирования воздуха, для которой создается эксергоэкономическая модель. Сформулированы необходимые допущения. Разработана эксергоэкономическая модель центральной системы кондиционирования воздуха в графическом виде. Модель представлена в виде отдельных зон, соединенных между собой последовательно. Приведены основные аналитические выражения модели, позволяющие решить задачу минимизации энергопотребления с использованием метода неопределенных множителей Лагранжа. Получено выражение лагранжиана для задачи оптимизации параметров функционирования центральной системы кондиционирования воздуха. Предложены в общем виде законы управления производительностью отдельных элементов системы кондиционирования воздуха, обеспечивающие минимальное значение энергетических затрат при ее функционировании. Сделан вывод о возможности значительного снижения энергетических затрат в процессе работы системы кондиционирования воздуха.

Introduction

Central air conditioning system (ACS) is designed to create and maintain the conditions most favorable for human activity, the normal functioning and safety of technological equipment and materials in public buildings and in the technological areas. Central ACS consists of the following main elements: a central air conditioner, power cooling (chiller, cooling machine with water recycling system, etc.), heating source, the air ducts [1]. Their structure and behavior are defined by a scheme of heat and humidity air treatment.

Central ACS are extremely energy-intensive facilities, their individual elements are connected with each other and with customers processes of energy-mass-transfer. Operating costs of ACS can achieve 60–70 % of the operating costs of the building. Because of the inherent features of the central ACS, there are significant losses of heat and cold during system operation, resulting in increased energy consumption. It should be noted that more and more air cooling is required not only during the warm period but during the transition and cold periods.

Therefore, at present it is necessary to improve both elements of ACS and their operation modes to reduce energy consumption required for their normal operation.

The aim of research is to form an approach to ACS optimization, which let optimize operating parameters and decrease energy consumption during ACS operation. In order to achieve the aim some particular problems were solved. They were choice of research method, formalization of energy consumption processes in ACS and development of laws of performance control of individual elements of ACS, the laws are needed for required parameters maintenance.

Literature review

Energy saving and improvement of energy efficiency of the central ACS can be implemented with [2–5]:

- formation and adoption of a more rational volumetric-planning solutions, construction and design measures to reduce heat exchange of buildings with the environment,
- use of more efficient equipment with ACS and their elements,
- technology and automatic control systems improvement in ACS,
- use of ACS circuit solutions to dispose of waste heat to the needs of air conditioning and ventilation.

In many studies the determination of optimal operation parameters of the energy conversion systems is done with the use of exergy approach [6–13]. In the majority of articles the ACS improvement is done on the exergy efficiency basis [14–16]. However, not always the system which is optimal in thermodynamic terms is optimal in economic terms. Thermoeconomic approach allows taking into consideration simultaneously both thermodynamic and economic factors of ACS operation when optimizing the system [17, 18]. The term "exergoeconomic" is used more often than "thermoeconomic" nowadays [19–24].

The main thing in exergoeconomic approach is application of thermodynamic function of exergy, which defines is the goal of system operation achieved or not, for assessment of changes occurring in the energy conversion system [25–28].

Description of the research

When using the method of exergoeconomic the author describes the changes with the main flow of exergy for the operation of the system with a given capacity. In case of ACS system operation with a given capacity is to obtain the necessary exergy of conditioned air. In the course of this analysis not only the exergy losses, which are occurring in transmission and transformation of energy in individual elements of ACS, but also economic costs which are associated with elements of ACS operation are reviewed and considered.

Both exergy losses and economic costs lead to the increase in the unit cost of flow exergy as it moves from the point of input of exergy in the energy conversion system to the flow output from the system. Taking into consideration that the value of exergy of conditioned air for the analyzed ACS is known, therefore, conditions ensuring minimum exergy price of conditioned air have to be determined to optimize the operation parameters of ACS.

On a substantial level the optimization problem can be formulated as follows: find the minimum energy operational cost of the ACS producing certain amount of conditioned air of a given quality. To solve this problem exergoeconomic model of ACS is developed in the article.

Exergoeconomic approach analysis of changes of the main exergy flow which provides system operation with a given capacity allows us to represent exergoeconomic model of the central ACS as several separate zones. These zones are connected in series. Each zone includes a group of elements of ACS with relative autonomy within the system. Such linearization of the technological scheme of ACS simplifies further calculations due to the taking out of consideration of individual technological ties, without affecting the system power consumption.

Schematic diagram of central ACS for which the exergy model is developed is shown in Figure 1. Figure 1 shows the following elements of ACS: 11 – compressor with an electric motor, 12 – condenser, 13 – pump with an electric motor for supplying cooling water to the condenser, 14 – fan motor on the cooling tower, RV – regulating valve, R – regenerator, 21 – evaporator, 22, 23, 24 – respectively, pumps with electric motors for supplying coolant from the tank of warm water into the evaporator, from the spray chamber into the tank of warm water, from the tank to the chilled water into the spray chamber, 31 – spray chamber, 41 – after heater, 42 – fan with an electric motor to supply air to the consumers.

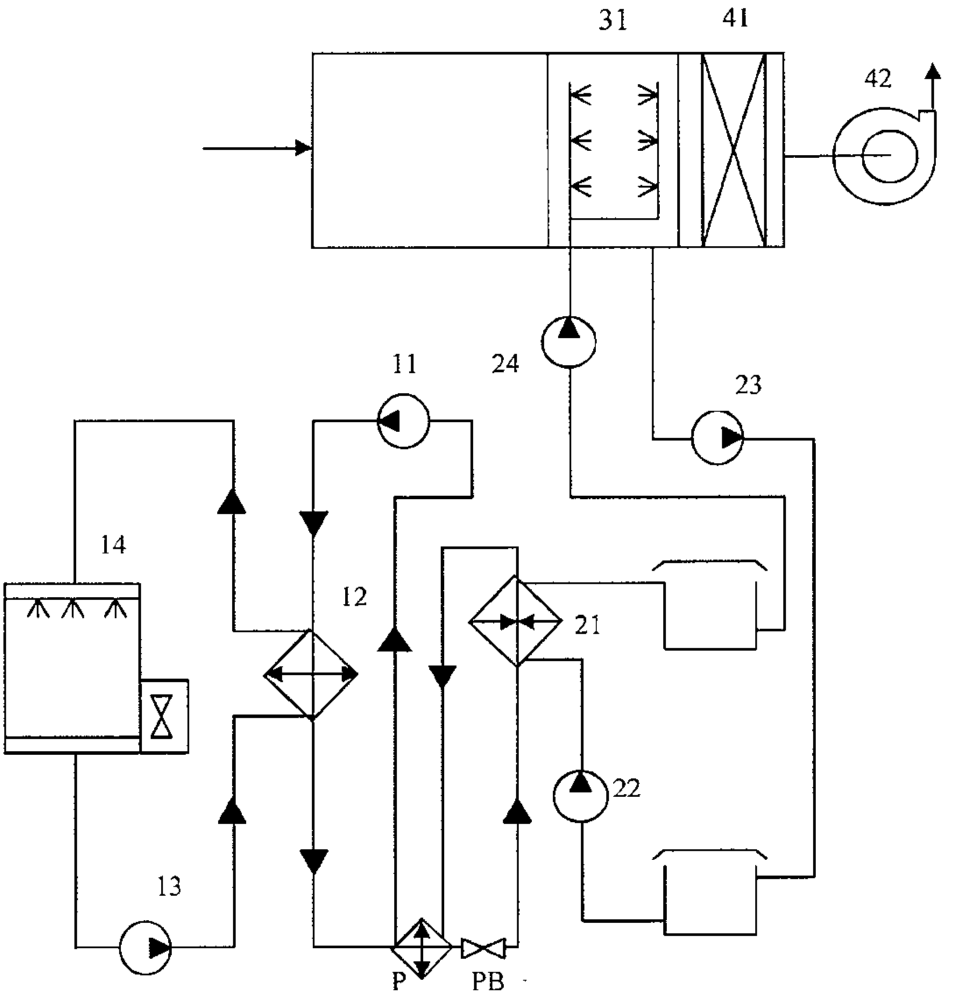

Figure 1. Schematic diagram of the considered central ACS

Taking into consideration necessity of energy consumption decrease, energy costs of ACS operation are used as target function while developing exergoeconomic model. This is due to the fact that energy costs which are directly related to the thermodynamic characteristics of the system include costs of all matter and energy flows that go to the considered ACS through exergy.

To simplify the resulting expressions exergoeconomic model of ACS formulated the following assumptions:

1) change of pressure loss in pipelines and air ducts during transportation of the heat transfer agent, air is not taken into account. Pressure losses in pipelines, ducts and heat exchangers ACS are considered constant and do not dependent on mode of operation;
2) exergy losses occurring in pipelines and ducts because of the heat exchange with the environment, are considered constant, independent of the mode of operation of the ACS;

3) heat exchange between working fluid of the refrigeration machines (the refrigerant) and environment occurring in the compressor and heat exchanger via their external surface, washed by the air is not taken into consideration;
4) overheat of absorbable vapor in the compressor and subcooling of the liquid working fluid (refrigerant) flowing to the expansion valve are not optimized. It is believed that steam superheating is caused by the rules of safe operation of refrigerating machines;
5) heating of the air in the fan and the heating pumped water in the pumps is not taken into consideration;
6) the optimum parameter of the air in the air-conditioned rooms are characterized by the point on the I-D diagram;
7) characteristics of air in the working area of the premises and settings of the outgoing air are the same.

Formulated assumptions have almost no influence on the accuracy of definition of the energy consumption rate. Their impact is estimated at a rate of 1–1.5 %.

Taking into consideration the starting positions and assumptions made exergoeconomic model of ACS is presented in the form of four series-connected zones, shown in Figure 2.

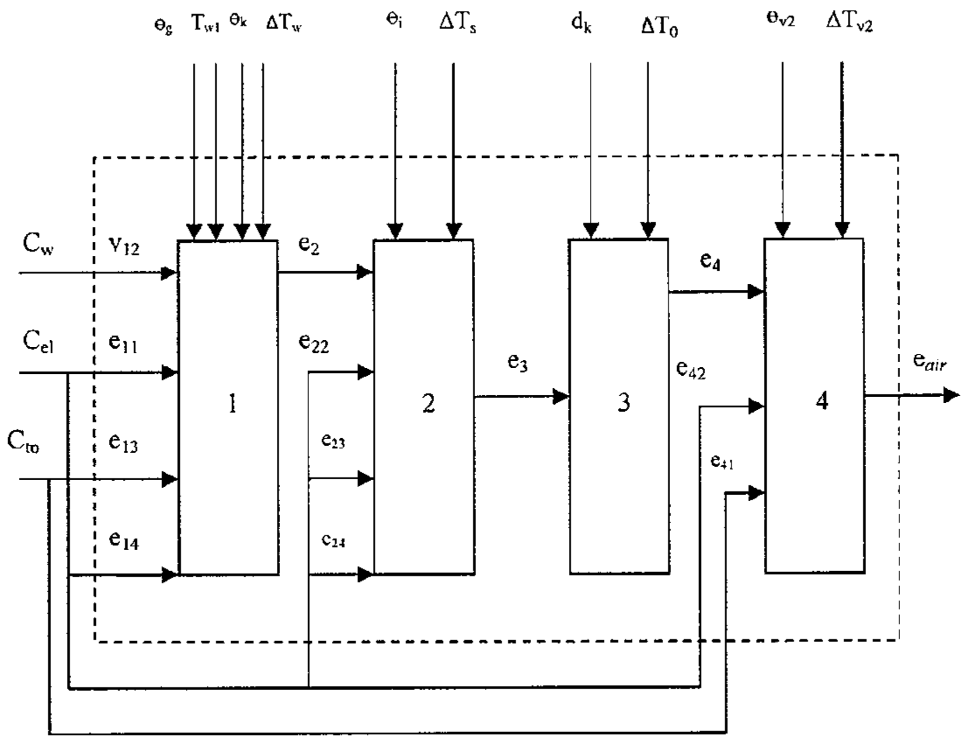

Figure 2. Exergoeconomic model of ACS

Exergy is supplied through the control surface of the model from an external source to various areas: e_{11}, e_{13}, e_{14}, e_{22}, e_{23}, e_{24}, e_{42} – to drive motors of compressor, pump cooling water, cooling tower fan, pumps of intermediate heat transfer medium, the air conditioner fan. The price of exergy supplied from an external source of electrical energy, is known and equals C_{el}. Cooling water is supplied from an external source, flow rate of which equals v_{12}, price – C_{w},. Exergy for heating air in after heater (thermal energy) e_{41} is supplied from an external source with the price of C_{tp}.

Thermal processes are essential in the operation of ACS. Therefore, the optimized variables are the variables that allow developing exergoeconomic model and relatively easy determining the temperature conditions of technological processes in ACS. These variables are following: temperature difference in the cooling tower Θ_g, condenser Θ_k, evaporator Θ_i, after heater Θ_{v2}, the water temperature at the inlet of the condenser T_{w1}, and changes the temperature of cooling water in the condenser $_{\Delta}T_w$, intermediate refrigerant in the evaporator $_{\Delta}T_s$after heater $_{\Delta}T_{v2}$, process air temperature difference and outdoor air $_{\Delta}T_o$, the moisture content of the air treated in the chamber irrigation d_k.

Taking into consideration the assumptions made and the adopted notation the value of the energy cost, including costs for electric and thermal energy, as well as costs for water circuit with a cooling tower is determined by the dependencies:

$$S_{en} = \left[\mathrm{C}_{el} \cdot (\mathrm{e}_{11} + \mathrm{e}_{13} + \mathrm{e}_{22} + \mathrm{e}_{23} + \mathrm{e}_{24} + \mathrm{e}_{42}) + C_w \cdot v_{12} + C_{tp} \cdot \mathrm{e}_{41}\right]\tau, \tag{1}$$

where: τ – the time work of ACS.

Consumption of electric energy to drive the compressor, pumps, fans, water consumption and thermal energy depend on the operation mode of the ACS, and therefore, on the temperature pressures in heat exchangers, intervals of change of heat carrier temperature and moisture content processed in the spray chamber. Therefore, the right side of expression (1) is a function of the selected optimization variables. Hence, energy consumption is a function of several variables, its extreme value is determined by the condition of equality to zero of partial derivatives of an energy consumption function of optimized variables.

$$\begin{aligned}
&\partial S_{en}/\partial\theta_q = 0; && \partial S_{en}/\partial\Delta\mathrm{T}_w = 0;\\
&\partial S_{en}/\partial\theta_\text{к} = 0; && \partial S_{en}/\partial\Delta\mathrm{T}_s = 0;\\
&\partial S_{en}/\partial\theta_i = 0; && \partial S_{en}/\partial\Delta\mathrm{T}_{v2} = 0;\\
&\partial S_{en}/\partial\theta_{v2} = 0; && \partial S_{en}/\partial\Delta\mathrm{T}_0 = 0;\\
&\partial S_{en}/\partial\theta_{w1} = 0; && \partial S_{en}/\partial\Delta d_k = 0.
\end{aligned} \tag{2}$$

It can be applied in case when all the optimized variables are independent and the problem is reduced to the determination of the absolute extremum. In practice, these variables are linked, which makes analytical description of the relationships between all the optimized variables extremely difficult. Exergoeconomic method simplifies this task.

The idea of the exergoeconomic model of ACS as a number of series-connected zones allows expressing the exergy, supplied to each of the zones, in the form of functional dependencies from the flow exergy, leaving the reporting zone, and affecting this zone of optimized variables.

Then the amount of exergy, supplied to the various elements of ACS from an external source e_j (Figure 2), and volumetric flow rate of the cooling medium (water), used for discharging the heat of condensation v_{12}, in general terms are described as follows:

$$\begin{aligned}
e_{11} &= E_{11}\left(\mathrm{e}_2, \theta_q, \mathrm{T}_{w1}, \theta_\text{к}, \Delta\mathrm{T}_w\right),\\
e_{13} &= E_{13}\left(\mathrm{e}_2, \theta_q, \mathrm{T}_{w1}, \theta_\text{к}, \Delta\mathrm{T}_w\right),\\
e_{12} &= E_{12}\left(\mathrm{e}_2, \theta_q, \mathrm{T}_{w1}, \theta_\text{к}, \Delta\mathrm{T}_w\right),\\
e_{22} &= E_{22}\,(\mathrm{e}_3, \theta_i, \Delta\mathrm{T}_s),\\
e_{23} &= E_{23}\,(\mathrm{e}_3, \theta_i, \Delta\mathrm{T}_s),\\
e_{24} &= E_{24}\,(\mathrm{e}_3, \theta_i, \Delta\mathrm{T}_s),\\
e_{41} &= E_{41}\,(\mathrm{e}_{air}, \theta_{v2}, \Delta\mathrm{T}_{v2}),\\
e_{42} &= E_{42}\,(\mathrm{e}_{air}, \theta_{v2}, \Delta\mathrm{T}_{v2}),
\end{aligned} \tag{3}$$

where: e_j – the amount of exergy, E_j – the function describing its variation.

Equations included in the system (3) belong to different zones of exergoeconomic model, zones are connected with the main exergy flow. Exergy flow connecting separate zones is presented as functional dependence on exergy flow leaving the zone and optimized variables affecting the considered zone:

$$\begin{aligned}
e_2 &= E_2\,(\mathrm{e}_3, \theta_i, \Delta\mathrm{T}_s),\\
e_3 &= E_3\,(\mathrm{e}_4, d_k, \Delta\mathrm{T}_0),\\
e_4 &= E_4\,(\mathrm{e}_{air}, \theta_{v2}, \Delta\mathrm{T}_{v2}).
\end{aligned} \tag{4}$$

The links between optimized variables leads to a consideration of the problem of minimization of the energy consumption as the optimization problem of several variables function in the presence of equality constraints (equations), i.e. as the problem of finding a conditional extremum. One of the most effective ways to solve problems associated with finding the conditional extremum is Lagrange's method of undetermined multipliers. The application of Lagrange's method of undetermined multipliers allows to transform and reduce the problem of finding the conditional extremum of the original function of energy consumption (1) to the problem of finding the unconditional extremum (a minimum) a new function – the Lagrangian [17].

The Lagrangian expression for the problem of optimization of operation parameters of ACS, given the systems of equations (3) and (4) is written as follows:

$$\begin{aligned} L = \{ & C_{el}\big[E_{11}\big(e_2,\theta_q,\mathrm{T}_{w1},\theta_{\text{к}},\Delta\mathrm{T}_w\big) + E_{13}\big(e_2,\theta_q,\mathrm{T}_{w1},\theta_{\text{к}},\Delta\mathrm{T}_w\big) + E_{22}\,(e_3,\theta_i,\Delta\mathrm{T}_s) \\ & + E_{23}\,(e_3,\theta_i,\Delta\mathrm{T}_s) + E_{24}\,(e_3,\theta_i,\Delta\mathrm{T}_s) + E_{42}\,(e_{\text{air}},\theta_{v2},\Delta\mathrm{T}_{v2})\big] \\ & + C_w\,V_{12}\big(e_2,\theta_q,\mathrm{T}_{w1},\theta_{\text{к}},\Delta\mathrm{T}_w\big) + C_w\,E_{41}\,(e_{\text{air}},\theta_{v2},\Delta\mathrm{T}_{v2}) \\ & + \lambda_2\,[E_2\,(e_3,\theta_i,\Delta\mathrm{T}_s) - e_2] + \lambda_3\,[E_3\,(e_4,d_k,\Delta\mathrm{T}_0) - e_3] \\ & + \lambda_4\,[E_4\,(e_{air},\theta_{v2},\Delta\mathrm{T}_{v2}) - e_4]\big\}\,\tau. \end{aligned} \quad (5)$$

To find the conditions of the extremum partial derivatives from the Lagrangian (5) over all the variables (as optimized and additional equations imposed by communication) should be taken and set equal to zero. Partial derivatives for the exergy flows connecting separate zones of exergoeconomic model e_j, allow determining values of the Lagrange multipliers λ_j. For example, Partial derivative to e_2 has the following form:

$$\partial L/\partial e_2 = \tau\partial/\partial e_2\,[C_{el}(E_{11} + E_{13}) + C_w\,V_{12} - \lambda_2 e_2] = 0\,; \quad (6)$$

because $\tau \neq 0$, then the value of the derivative is zero. Whence it follows that:

$$\lambda_2 = \partial/\partial \mathrm{e}_2\,[C_{el}\,(\mathrm{E}_{11} + \mathrm{E}_{13}) + \mathrm{C}_w\,V_{12}]. \quad (7)$$

Similarly the expressions for the multipliers λ_3 and λ_4 can be obtained.

The derivative of (5) to the optimized variables allows us to obtain the expression represented by the system (8).

$$\begin{aligned} \partial L/\partial\theta_q &= C_{el}\,(E_{11} + E_{13}) + C_w\,V_{12} = 0; \\ \partial L/\partial T_{w1} &= C_{el}\,(E_{11} + E_{13}) + C_w\,V_{12} = 0; \\ \partial L/\partial\theta_k &= C_{el}\,(E_{11} + E_{13}) + C_w\,V_{12} = 0; \\ \partial L/\partial T_w &= C_{el}\,(E_{11} + E_{13}) + C_w\,V_{12} = 0; \\ \partial L/\partial\theta_i &= C_{el}\,(E_{22} + E_{23} + E_{24}) + \lambda_2 E_2 = 0; \\ \partial L/\partial\Delta T_s &= C_{el}\,(E_{22} + E_{23} + E_{24}) + \lambda_2 E_2 = 0; \\ \partial L/\partial d_k &= \lambda_3 E_3 = 0; \\ \partial L/\partial\Delta T_0 &= \lambda_3 E_3 = 0; \\ \partial L/\partial\theta_{v2} &= C_{el}\,E_{42} + C_{tp}\,E_{41} + \lambda_4 E_4 = 0; \\ \partial L/\partial\Delta T_{v2} &= C_{el}\,E_{42} + C_{tp}\,E_{41} + \lambda_4 E_4 = 0. \end{aligned} \quad (8)$$

The system of equations (8) establishes a relationship between the energy dissipation and energy consumption in every zone of exergoeconomic model for certain values of economic indicators C_{el}, C_{tp}, C_w, λ_2, λ_2, λ_4. The Lagrange multipliers λ_2, λ_2, λ_4 in general case represent the price per unit of exergy leaving each zone of exergoeconomic model.

The solution of system (8) taking into consideration equations (7) and similar equations for λ_3 and λ_4 allows determining the necessary conditions for finding the minimum of Lagrangian (5). To solve equations (7) and (8) expressions (3) and (4), written in general form, must be submitted in the form of deployed analytical expressions describing the processes occurring in the separate elements of ACS. In the description of these processes the characteristics of heat and humidity treatment of air, depending on the spray chamber type and the presence of the heat recovery operational peculiarities of the cooling machine depending on the type of the used compressor (piston, rotary, centrifugal or screw) and the applied refrigerant are taken into consideration. For example, the heat load on the condenser of the cooling machine is determined by empirical formulas I.S. Badyl'kes [29]. It also should be considered that the characteristic mode of operation of ACS is the continuous load change due to the influence of external disturbing factors, which are climatic conditions – the outdoor air temperature T_{os} and the moisture content of outdoor air d_{os}.

Obtained by optimizing the mode of operation of ACS values of operating parameters are used in determining the optimal laws of performance control of individual elements of ACS, minimizing energy consumption. The laws of performance control of individual elements of ACS represent the dependence on the values of different medium of temperature and moisture content of outdoor air, for example:

$$v_{12} = V_{12}\,(T_{os}, d_{os}),$$
$$v_{14} = V_{14}\,(T_{os}, d_{os}), \qquad (9)$$
$$v_{22} = V_{22}\,(T_{os}, d_{os}),$$

where: v_{12} – water flow in the system of water recycling, v_{14} – the airflow of cooling tower fans, v_{22} – consumption of intermediate refrigerant through the evaporator of the cooling machine.

Obtained laws of performance control allow to formulate proposals for the development of requirements for the automatic control system based on programmable logic controllers that provides a ACS operation in energy saving modes [30]. Such automatic control system takes into account all the parameters of ACS required for high-speed control and maintainance of energy efficient operation modes. Implementation of the resulting control laws is possible by using variable frequency drives for fans, pumps, valves, which receive control signals from programmable logic controllers.

Approach to exergoeconomic analysis and optimization of the central ACS proposed in the article lets determine the optimal values of operational parameters of ACS and to achieve a reduction of the energy consumption by 5–6 % in the process of their work.

Conclusions

1. The exergoeconomic method is discussed in relation to optimization of the functioning of the central ACS.

2. Expressions allowing to solve the problem of minimizing the energy consumption of the central ACS using the method of uncertain Lagrange multipliers are given in general form.

3. The proposed approach can be used for optimization of ACS with other circuit solutions.

4. The laws of performance control of individual elements of the ACS that allows developing of automatic control system of ACS based on programmable logic controllers are given in general form.

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