ENERGY ENGINEERING AND CONTROL SYSTEMS

Volume 9, Number 1, 2023

Influence of Transformation Coefficient of Refrigerating Machine on Exergetic Efficiency of Air Conditioning System of Operating Clean Rooms

Volodymyr Labay*, Kyrylo Andreiko

Lviv Polytechnic National University, 12 S. Bandery St., Lviv, 79013, Ukraine

Received: March 28, 2023.   Revised: April 24, 2023.   Accepted: May 04, 2023.

Abstract

Exergetic method is a universal way of thermodynamic research of various processes of energy transformation in energy technological systems, to which air conditioning system for clean room belongs. Implementation of exergetic analysis for energy technological system makes it possible to determine the influence of various elements of its system on its work and because of this to increase the effectiveness of work of energy technological system in general. Performance of any air conditioning system depends on energy effectiveness of refrigeration machine, which serves it and consumes electricity to reduce the heat of supply air which enters the room. And it means that the main purpose of selection of certain refrigeration machine for air conditioning system is to reach the maximum cooling capacity with minimum energy consumption. Innovative mathematical research model of the implemented central straight flow air conditioning system for operating clean rooms was used in this article. The aim of the model is to make computer estimation of exergetic efficiency of existing air conditioning system depending on different factors which have influence on its work, in particular the coefficient of transformation (or energy efficiency rate, EER) of its refrigeration machine. The dependence of the exergetic output-input ratio of implemented air conditioning system for operating clean rooms on coefficient of transformation of its refrigeration machine by different parameters of outdoor and indoor air and the temperature difference between the indoor and supply air were presented. It is shown that the implemented air conditioning system should be preferably used with higher coefficient of transformation of its refrigeration machine and higher difference between temperatures of indoor and supply air by various temperatures of outdoor air that will give the opportunity to gain the highest exergetic output-input ratio, which means gaining the most cost effective option for the exploitation of implemented air conditioning system.

Keywords: exergetic balance; air conditioning systems; clean rooms; exergetic efficiency; coefficient of transformation.

1. Introduction

Currently, during the operation of energy technological systems (ETS), which include air conditioning systems (ACS), to ensure the implementation of a certain technology, the issue of saving fuel and energy resources is of primary importance. Therefore, now the question arises about ETS in which the requirements of technology and energy would not only organically combine, but also complement each other.

In modern technologies related to energy conversion, namely in ACS, an important place is occupied by equipment and processes, the objective assessment of the degree of energy perfection of which can be established only on the basis of their thermodynamic analysis. The simplest method of thermodynamic analysis is energy based on the law of conservation of energy. It allows you to estimate absolute and relative energy losses, identify equipment

---

* Corresponding author. Email address: volodymyr.y.labai@lpnu.ua

This paper should be cited as: V. Labay, K. Andreiko. Influence of transformation coefficient of refrigerating machine on exergetic efficiency of air conditioning system operating clean rooms. *Energy Engineering and Control Systems*, 2023, Vol. 9, No. 1, pp. 9 – 16. https://doi.org/10.23939/jeecs2023.01.009

and processes with the greatest losses. However, this method equates the value of all types of energy to each other, including thermal energy, which is incorrect from the point of view of the second law of thermodynamics, since any type of energy can be completely converted into thermal energy, while the reverse process is accompanied by inevitable losses.

Under the influence of these requirements, a universal exergy analysis method was developed in recent decades. This method was substantiated in the works of R. Clausius, J. Gibbs, G. Guye, A. Stodola, Y. Shargut and R. Petela [6] – [10]. Its main idea is to introduce, along with the general, fundamental concept of energy, an additional indicator – *exergy*, which allows taking into account the fact that energy, depending on external conditions, can have different values for practical using.

Calculations of balances and various characteristics of ETS, in particular ACS, taking into account exergy makes it possible to solve many scientific and technical problems in the easiest and most clear way. They help to remove frequent errors that occur and are associated with ignoring the qualitative side of transformations.

The exergy balance for this ETS, that is, the air conditioning system of operating clean rooms implemented by the authors, has the following form:

$$E_{\mathrm{in}} = E_{\mathrm{out}} + \sum_{i=1}^{n} D_i \text{ , W,} \tag{1}$$

or

$$\sum_{i=1}^{n} D_i = E_{\mathrm{in}} - E_{\mathrm{out}} \text{ , W,} \tag{2}$$

where E_{in} is the exergy of the ACS drive, which is spent on maintaining the process, W; E_{out} is increase in air exergy in air-conditioned rooms, W; $\sum_{i=1}^{n} D_i$ is sum of exergy losses of ETS, W.

The exergy balance of this ETS was compiled on the basis of its principle scheme (Fig. 1).

Obviously, the higher the exergetic efficiency, the higher is the perfection of the ETS and its elements, which was determined from the exergetic balance, namely [6] – [10], [12], [13], [15] – [20]:

$$\eta_{\mathrm{e}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}} \cdot 100 \text{, \%.} \tag{3}$$

The calculation of the exergetic efficiency of the ETS creates conditions for solving the issue of saving fuel and energy resources [7], [8], [11] – [13], [16], [18] – [20].

So, the exergetic efficiency of the ETS was calculated according to the formula (3), in which the numerator is the useful exergetic effect, and the denominator is the exergy costs, and therefore the exergetic efficiency was determined by the formula:

$$\eta_{\mathrm{e}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{out}} + \sum_{i=1}^{n} D_i} \cdot 100 = \frac{E_{\mathrm{effect}}}{E_{\mathrm{costs}}} \cdot 100 \text{, \%.} \tag{4}$$

The efficiency of any air conditioning system depends on the energy efficiency of the refrigerating machine that serves it and consumes electrical energy to reduce the heat of the air entering the room. And this means that the main goal of choosing a certain refrigerating machine for ACS is to achieve maximum cooling capacity with minimum energy consumption. Therefore, to evaluate the energy efficiency of refrigerating machines, the energy efficiency coefficient *EER* (Energy Efficiency Rate), or the transformation coefficient, is introduced, which is equal to the ratio of cooling efficiency to the total consumed power under calculated (standard) operating conditions:

$$EER = \frac{Q_{\text{cool}}}{N_{\text{consum}}}, \tag{5}$$

where Q_{cool} is the cooling capacity of refrigerating machine (RM), W; N_{consum} is power consumption of RM, W.

Currently, the *EER* for RM can be from 1.8 to 5. To indicate the energy efficiency of RM, there are seven categories, which are denoted by letters from "A" (best) to "G" (worst). RM category "A" $EER \geq 3.2$, and category "G" $EER < 2.2$.

Therefore, the purpose of this work was to investigate the influence of the *EER* RM transformation coefficient on the exergetic efficiency of the implemented central direct-flow ACS of operating clean rooms.

2. Description of the object of analysis and the innovative research model

The purpose of air conditioning is to maintain certain air parameters in a limited space (in this case, in clean operating rooms). Usually, the temperature and relative humidity of the air are subject to regulation, and in clean operating rooms it is also the concentration of particles in the air [1] – [5].

Let's consider the direct-flow central ACS for operating clean rooms implemented by the authors, schematically depicted in Fig.1. The operation of such a system depends on the conditions prevailing in the external environment, that is, on the temperature and moisture content of the external air. Therefore, in the warm period of the year (WPY), the outside air is taken in by the central air conditioner through the valve 11, cleaned in the filter 10, then it passes through the air heater 9, is cooled and dried by the polytrope in the air cooler 8, separated in the drip catcher 7, and then supplied by the fan unit 6 through air conditioning filter 5 and filters 3 at the entrance to clean operating rooms. Spent air is removed from the operating clean rooms from the upper and lower zones by the exhaust system through its valve 17 by the exhaust fan 18.

Let us show the operation of this ACS in the WPY when the temperature $t_{\text{in}} < t_{\text{out}} = t_{\text{O}}$. Fig.2 shows in the coordinate system *I*, *d* the sequence of changes in air parameters, which passes through different equipment of the implemented central direct-flow air conditioning system for operating clean rooms in WPY under different outdoor air parameters. In the studies, the mass productivity of the ACS, calculated according to the required air exchange rate, was accepted as G = 4300 kg/h, the parameters of the outside air varied within the following limits: temperature t_{out} = 30 – 40 °C; relative humidity φ_{out} = 44 – 36 % (moisture content and specific enthalpy, respectively d_{out} = 11.7 – 16.8 g/kg; I_{out} = 60.1 – 83.4 kJ/kg), barometric pressure p_{out} = 1010 hPa; indoor air parameters, respectively are t_{in} = 25 – 29 °C; φ_{in} = 54 – 64 % (respectively, d_{in} = 10.8 – 16.3 g/kg; I_{in} = 52.6 – 70.8 kJ/kg); temperature difference between the internal and supply air depending on the excess heat in the clean room, as well as the temperature of the external air $\Delta t_{\text{S}} = t_{\text{in}} - t_{\text{S}}$ = 9.0 – 4.0 °C; angular coefficient of the process of assimilation of excess heat and moisture in clean rooms by supply air from the air conditioner ε = 27058 – 9711 kJ/kg; the initial temperature of the coolant (40 % propylene glycol solution) for the air cooler: t_{WI} = 9.5 – 15.5°C.

The sequences of changes that occur with moist air passing through various equipment of the implemented air conditioning system are shown in Fig. 2. The construction on the *I*, *d* diagram is made according to [11]. Air parameters at characteristic points of the process (Fig. 2) were set according to the values of the corresponding parameters for outdoor air and were calculated according to known analytical dependencies for moist air.

The authors created an innovative research mathematical model of the implemented air conditioning system for computer evaluation of its exergetic efficiency depending on the *EER* transformation coefficient of the refrigerating machine of the central air conditioner under various parameters of external and internal air and the temperature difference between internal and supply air. Thanks to this model, the results of research were obtained, which are summarized in Table 1.

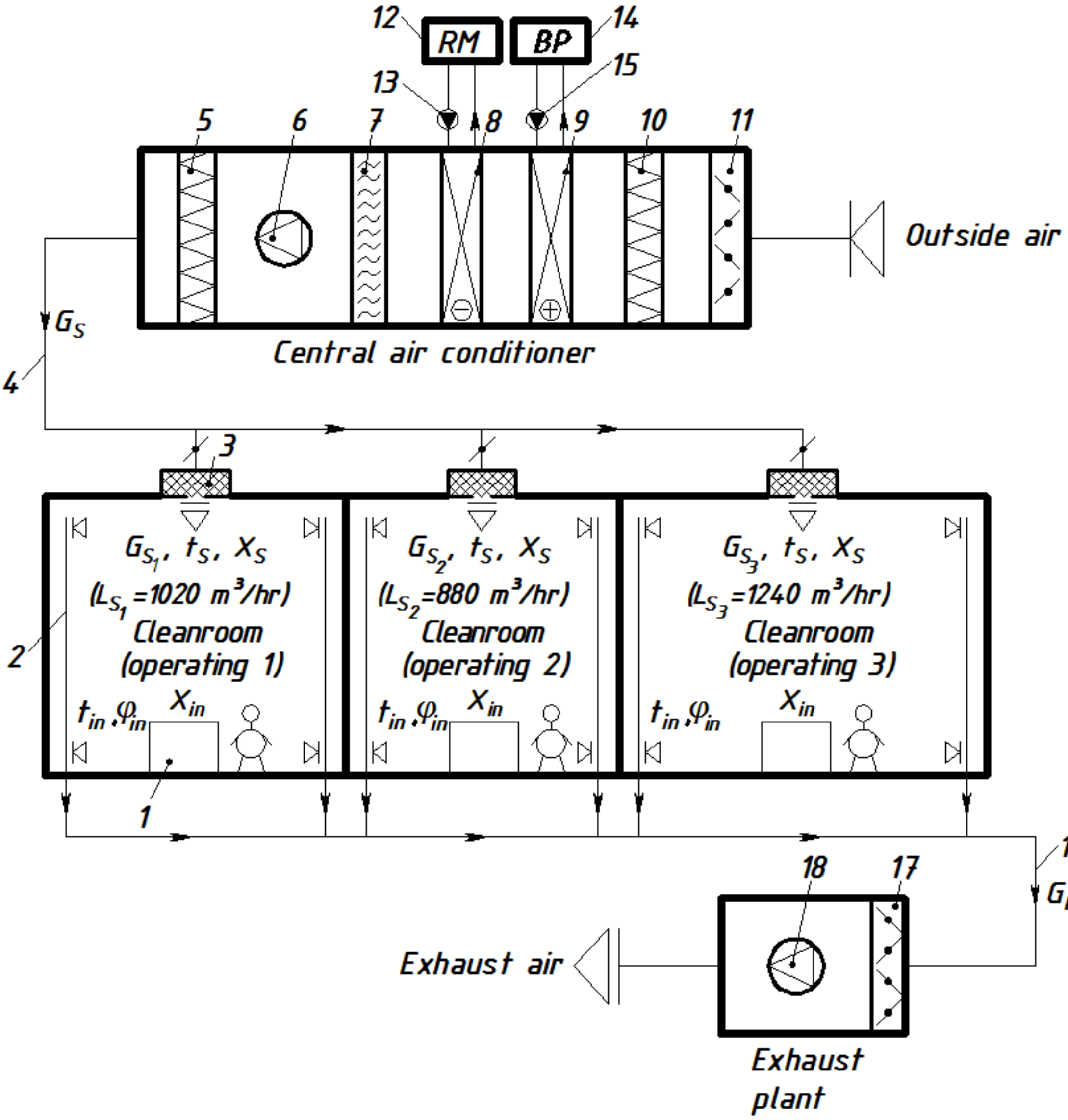

Fig.1. Basic scheme of the implemented central straight flow air conditioning system for operating clean rooms: 1 – technological equipment; 2 – air exhaust channels in clean rooms; 3 – filters of supplied air to the room; 4 – supplied air duct; 5 – filter of supplied air in a conditioner; 6 – fan unit of conditioner; 7 – drop catcher of conditioner; 8 – air cooler of conditioner; 9 – air heater of conditioner; 10 – filter of outside air in conditioner; 11 – valve of outdoor air in conditioner; 12 – refrigerating machine (RM); 13 – pump of cold water of RM; 14 – boiler plant (BP); 15 – pump of warm water; 16 – exhaust air duct; 17 – valve of exhaust air; 18 – fan unit of the exhaust plant.

Exergetic input-output ratio, which characterizes the efficiency of the implemented central direct-flow air conditioning system of operating clean rooms in WPY, was determined by formula (4), in which $E_{\text{out}} = E_{\text{S}} - E_{\text{I}}$ is reduction of the exergy of conditioned air in the clean rooms of cardiology operating rooms (utilized exergy), W; E_{S} and E_{I} are accordingly, the exergy of supply air and internal air in clean rooms, W; $D_{\text{SO}} = E_{\text{S1}} - E_{\text{O}}$ is air exergy loss in the air conditioner cooler, W; E_{S1} and E_{O} are accordingly, the exergy of the treated air at the exit and entrance (external air) to the air conditioner air cooler, W; $D_{\text{S1S}} = E_{\text{S1}} - E_{\text{S}}$ are losses of air exergy during its transportation in supply air ducts and fan of ACS, W; E_{S1} and E_{S} are accordingly, the exergy of the air at the inlet of the supply fan of the air conditioner and at the outlet of the supply air ducts in the clean rooms, W; $D_{\text{out}} = E_{\text{I}} - E_{\text{O}}$ are exergy losses with exhaust conditioned air from clean rooms, W; $D_{\text{sup.fan}}$ are exergy losses with the supply fan of the air conditioner, W; $D_{\text{exh.fan}}$ are exergy losses with the exhaust fan, W; D_{RM} are exergy losses with the refrigerating machine of the central air conditioner, W. Therefore, the total exergy losses in the operating ACS were determined as follows:

$$\sum_{i=1}^{n} D_i = D_{\mathrm{SO}} + D_{\mathrm{S_1S}} + D_{\mathrm{out}} + D_{\mathrm{sup.fan}} + D_{\mathrm{exh.fan}} + D_{\mathrm{RM}},\ \mathrm{W}. \qquad (6)$$

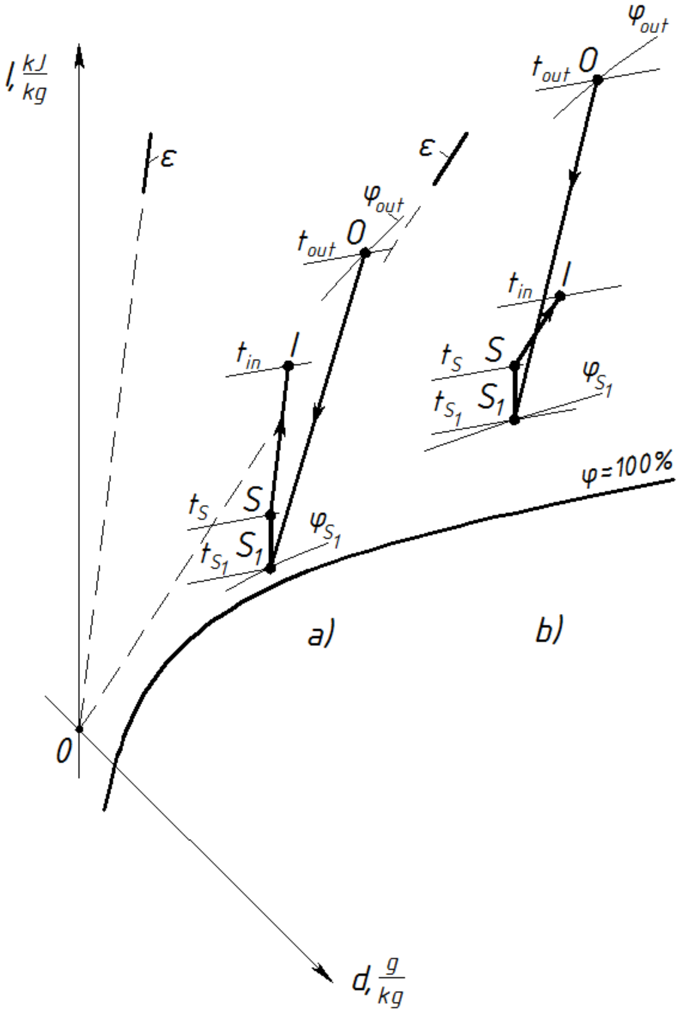

Fig.2. The image of the process of changing the state of moist air in the implemented central straight flow air conditioning system in a warm period of year on the *I-d* – diagram: a) for conditions of the research – t_{out} = 30; 32°C; t_{in} = 25; 26°C; Δt_{S} = 9; 7°C; b) for conditions of the research – t_{out} = 35; 38; 40°C; t_{in} = 27; 28; 29°C; Δt_{S} = 6; 5; 4°C: $\mathrm{OS_1}$ – the process of polytropic treatment (cooling and drying) of air $G_{\mathrm{out}} = G_{\mathrm{S}}$ in the air cooler; $\mathrm{S_1S}$ – the process of supplied air G_{S} heating by 1°C in a fan and duct; SI – the process of excess heat and moisture assimilation in a cleanroom by supplied air G_{S} via the conditioner.

Definition of values included in formula (4) is given in [19], [20].

3. Results of research work

On the basis of the research conducted by us on the innovative mathematical model for the specified SCP, the dependence of the exergetic efficiency η_{e} on the *EER* transformation coefficient of its refrigerating machine under various parameters of the external (t_{out} , φ_{out}) and internal (t_{in} , φ_{in}) air and the temperature difference Δt_{S} between the internal and supply air was obtained, which are given in Fig. 3 and Table 1.

Analyzing the received research data in Fig. 3 and Table 1, the following conclusions can be reached. The overall increase in the *EER* transformation coefficient from 2.6 to 4.0, i.e. 1.54 times, leads to an increase in the value of exergetic efficiency η_e under various research conditions from 1.29 to 1.30 times or by 29 – 30%. It is also worth noting (Fig. 3 and Table 1) that at the largest temperature difference between the internal and supply air Δt_S = 9.0°C, there are the highest values of exergetic efficiency η_e. And this means that at a certain temperature of the outside air t_{out}, the temperature difference between the internal t_{in} and supply t_S air Δt_S should be taken as maximum as possible. Therefore, it is desirable to use the selected air conditioning system with a higher transformation coefficient *EER* of its refrigerating machine and a higher temperature difference between the internal and supply air at different temperatures of the external air, which will make it possible to obtain the highest exergetic efficiency η_e, which means to obtain the most cost effective option for using the implemented air conditioning system.

The dependencies shown in Fig. 3 and Table 1 were obtained by us in the form of an analytical formula for the temperature difference between the external and internal air Δt_S = 4.0 – 9.0°C and the transformation coefficient *EER* = 2.6 – 4.0:

$$\begin{aligned}\eta_e = 0.1456 \cdot EER + 0.0328 \cdot \Delta t_S +\\ + 0.0195 \cdot EER \cdot \Delta t_S + 0.3206,\ \%.\end{aligned} \tag{7}$$

The maximum error of calculations according to formula (7) is 6.0%.

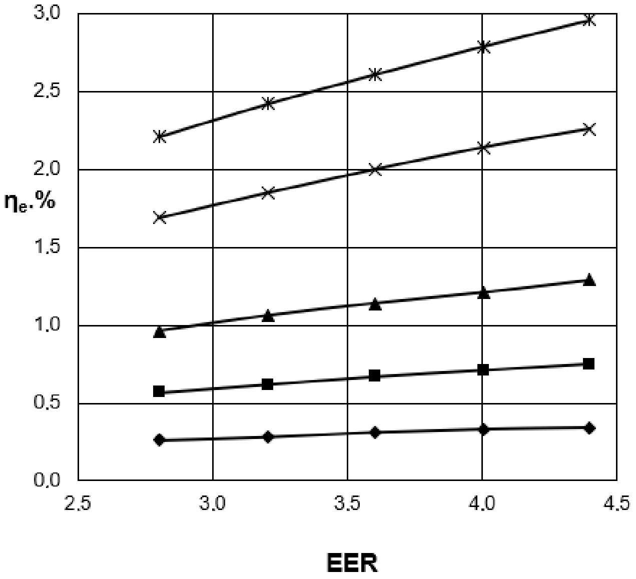

Fig.3. Dependence of the exergetic efficiency η_e of the implemented central direct-flow ACS of operating clean rooms on the *EER* RM transformation coefficient and research conditions:
1 row ♦ are t_{out} =40°C; φ_{out} =36%; t_{in} =29°C; φ_{in} =64%; Δt_S =4.0°C; t_S =79%;
2 row ■ are 38; 38; 28; 64; 5.0; 84;
3 row ▲ are 35; 40; 27; 60; 6.0; 84;
4 row x are 32; 42; 26; 55; 7.0; 82;
5 row * are 30; 44; 25; 54; 9.0; 92.

Table 1. Dependence of the exergetic efficiency η_e of the implemented central direct-flow ACS of operating clean rooms on the *EER* transformation coefficient of the refrigerating machine of the air conditioner.

EER	Research conditions				
	t_{out} = 30°C; φ_{out} = 44%; t_{in} = 25°C; φ_{in} = 54%; Δt_S = 9.0°C; φ_S = 92%	t_{out} = 32°C; φ_{out} = 42%; t_{in} = 26°C; φ_{in} = 55%; Δt_S = 7.0°C; φ_S = 82%	t_{out} = 35°C; φ_{out} = 40%; t_{in} = 27°C; φ_{in} = 60%; Δt_S = 6.0°C; φ_S = 84%	t_{out} = 38°C; φ_{out} = 38%; t_{in} = 28°C; φ_{in} = 64%; Δt_S = 5.0°C; φ_S = 84%	t_{out} = 40°C; φ_{out} = 36%; t_{in} = 29°C; φ_{in} = 64%; Δt_S = 4.0°C; φ_S = 79%
	η_e , %	η_e , %	η_e , %	η_e , %	η_e , %
2.6	2.56	2.01	1.93	1.78	1.48
2.8	2.70	2.12	2.03	1.88	1.56
3.2	2.93	2.30	2.20	2.03	1.69
3.6	3.13	2.46	2.36	2.17	1.81
4.0	3.31	2.61	2.49	2.30	1.92

This means that the exergy analysis of the implemented central direct-flow air conditioning system of operating clean rooms, performed on the innovative mathematical research model created by the authors, made it possible to thoroughly evaluate the dependence of the exergy efficiency η_e of this system on the EER transformation coefficient of the air conditioner refrigerating machine for various parameters of external (t_{out}, φ_{out}) and internal (t_{in}, φ_{in}) air and temperature difference Δt_S between internal and supply air.

4. Conclusion

An innovative mathematical research model created by the authors of the implemented central direct-flow air conditioning system of operating clean rooms was used, which enables a computer evaluation of its energy efficiency based on exergetic efficiency depending on various factors affecting its operation, in particular the EER transformation coefficient of its refrigerating machine [19], [20]. The dependence of the exergetic efficiency η_e of the implemented central direct-flow air conditioning system of operating clean rooms on the *EER* transformation coefficient of the refrigerating machine of the air conditioner for various parameters of external (t_{out}, φ_{out}) and internal (t_{in}, φ_{in}) air and the temperature difference Δt_S between internal and supply air is given. It is demonstrated that it is desirable to use the selected air conditioning system with a higher transformation coefficient *EER* of the air conditioning refrigerating machine and a higher temperature difference Δt_S between the internal and supply air at different temperatures of the external air t_{out}, which will make it possible to obtain the highest exergetic efficiency η_e, which means that we obtain the most cost effective option for using the implemented air conditioning system air.

References

[1] Fedotov A.E. (2003) Clean rooms. Moscow, ASINKOM. (in Russian)

[2] Hayakawa I. (1990) Clean rooms. Moscow, Mir. (in Russian)

[3] White V. (2010) Cleanroom Technology: Fundamentals of Design, Testing and Operation. Willey.

[4] White V. (2004) Projection of clean rooms. Moscow, Klinrum. (in Russian)

[5] ISO 14644-1:2015. Clean Rooms and Associated Controlled Environments. Part 1: Classification of Air Cleanliness by Particle Concentration

[6] Sokolov, E. Ya., Brodyansky, V. M. (1981) Energetic foundations of heat transformation and cooling processes. Energoizdat, Moscow. (in Russian)

[7] Shargut, Ya., Petela, R. (1968) Exergy. Energy, Moscow. (in Russian)

[8] Brodyansky, V. M., Verkhivker. G. P., Karchev, Ya. Ya. and others (1991) Exergetic calculations of technical systems. Kyiv, Nauk. Dumka. (in Russian)

[9] Brodyansky V. M. (1973) Exergetic method of thermodynamic analysis. Moscow, Energy. (in Russian)

[10] Ber G. D. (1977) Technical thermodynamics. Moscow, Mir. (in Russian)

[11] Bogoslovsky, V. N., Kokorin, O. Ya., Petrov, L. V. (1985) Air conditioning and refrigeration. Moscow, Stroyizdat. (in Russian)

[12] Prokhorov, V. I., Shilkloper, S. M. (1981) A method for calculating the exergy of a moist air flow. Refrigeration equipment. 9, 37–41. (in Russian)

[13] Shilkloper, S. M., Zhadyn, S. I. (1982) Exergetic analysis of microclimate and energy supply systems. Construction and architecture. 9(4), 18–27. (in Russian)

[14] SNiP 2.04.05–86. (1987) Heating, ventilation and conditioning. Moscow, TSITP Gosstroya USSR. (in Russian)

[15] Yantovsky, E. I. (1988) Flows of energy and exergy. Moscow, Nauka. (in Russian)

[16] Bes, T. (1962) Exergy in heating, air-conditioning and drying processes. Industrial Energy. 10(11), 388–392. (in Polish)

[17] Labay Volodymyr, Omelchuk Oksana. (2002). XIV Conference of heating engineers "Prospects for the development of district heating". Conference materials. Solina, Rzeszow University of Technology, 137–144. (in Polish)

[18] Labay Volodymyr, Ivanukh Taras. (2000) Exergetic efficiency of central air conditioners. 5th Rzeszow-Lviv-Koszyce Scientific Conference "Current problems of construction and environmental engineering". Proceedings of Rzeszow University of Technology "Construction and environmental engineering". 32(2), Environmental Engineering, 229–235. (in Ukrainian)

[19] Labay, V. Y., Garasym, D. I. (2014) Study of exergetic efficiency of air conditioning systems of clean rooms. Scientific and technical journal "Refrigeration technology and technology", 4(150), 47–53. (in Ukrainian)

[20] Labay, V., Harasym, D. (2014) Innovation model for energy efficient investigations of air conditioning systems for cleanrooms, ECONTECHMOD, Lublin-Rzeszow. 3(1), 47–52.

Вплив коефіцієнта трансформації холодильної машини на ексергетичний ККД системи кондиціонування повітря операційних чистих кімнат

Володимир Лабай, Кирило Андрейко

Національний університет «Львівська політехніка», вул. С. Бандери, 12, м. Львів, 79013, Україна

Анотація

Ексергетичний метод є універсальним способом термодинамічного дослідження різноманітних процесів перетворення енергії в енергетичних технологічних системах, до яких відноситься система кондиціювання повітря для чистого приміщення. Здійснення ексергетичного аналізу для енерготехнологічної системи дає можливість визначити вплив різних елементів її системи на її роботу і завдяки цьому підвищити ефективність роботи енерготехнологічної системи в цілому. Ефективність роботи будь-якої системи кондиціонування залежить від енергоефективності холодильної машини, яка її обслуговує і споживає електроенергію для зменшення теплоти припливного повітря, яке надходить у приміщення. А це означає, що основною метою підбору тієї чи іншої холодильної машини для системи кондиціонування є досягнення максимальної холодопродуктивності за мінімального споживання енергії. У статті використана авторська інноваційна математична модель дослідження впровадженої центральної прямотечійної системи кондиціонування повітря для діючих чистих приміщень. Метою моделі є проведення комп'ютерної оцінки ексергетичної ефективності існуючої системи кондиціювання повітря залежно від різних факторів, що впливають на її роботу, зокрема коефіцієнта трансформації *EER* її холодильної машини. Наведено залежність ексергетичного ККД впровадженої системи кондиціонування повітря для діючих чистих приміщень від коефіцієнта трансформації *EER* її холодильної машини за різних параметрів зовнішнього та внутрішнього повітря та різниць температур внутрішнього та припливного повітря. Показано, що впроваджена система кондиціонування повітря має переважно використовуватися з вищим коефіцієнтом трансформації *EER* її холодильної машини та більшою різницею між температурами внутрішнього та припливного повітря за різних температур зовнішнього повітря, що дасть можливість отримати найвищий ексергетичний ККД, що означає отримання найощаднішого економічного варіанту експлуатації впровадженої системи кондиціонування.

Ключові слова: ексергетичний баланс; система кондиціювання повітря; чисте приміщення; ексергетична ефективність; коефіцієнт трансформації *EER*.