

ENTROPY-BASED METHODS APPLIED TO THE EVALUATION OF A REAL REFRIGERATION MACHINE

L. Morozyuk

Doctor of Technical Sciences, Professor*

V. Sokolovska-Yefymenko

PhD, Associate Professor*

E-mail: kli24062006@gmail.com

S. Gayduk

PhD, Senior Lecturer*

E-mail: gayduck.sergei@gmail.com

A. Moshkatiuk

Postgraduate student*

E-mail: andrymoshkatyuk@gmail.com

*Department of cryogenic technique

Odessa National Academy of Food Technologies

Kanatna str., 112, Odessa, Ukraine, 65039

Напрямом дослідження є термодинамічний аналіз дійсної холодильної машини за наявності відкладів на теплообмінній поверхні повітряного конденсатора, що здійснюються ентропійними методами, а саме: ентропійно-цикловим, ентропійно-статистичним та методом мінімізації виробництва ентропії. Для аналізу використано експериментальні дані випробувань машини з твердими відкладами у вигляді пилу на зовнішній поверхні повітряного конденсатора.

Ентропійно-цикловим і ентропійно-статистичними методами визначено вплив необоротних втрат в окремих елементах холодильної машини, викликаних наявністю відкладів на зовнішньої теплообмінної поверхні повітряного конденсатора. Ентропійно-цикловий метод оцінив абсолютну величину енергетичних втрат в кожному елементі. Ентропійно-статистичним методом визначено перевитрата роботи в дійсному циклі в порівнянні з теоретичним процесом стиснення в компресорі.

За використанням теорії мінімізації виробництва ентропії оцінено необоротні втрати, пов'язані з аеродинамікою і теплопередаванням під час руху повітря через ребристу поверхню у повітряному апараті. Встановлено вплив зростаючих відкладів на термічний і механічний складові загального виробництва ентропії в теплообмінному апараті, а також визначено масу відкладів, що зумовлює момент його очищення.

Застосування ентропійних методів для аналізу реальної холодильної машини на стадії проектування дає змогу мінімізувати необоротні втрати, пов'язані з умовами експлуатації, і прогнозувати графік техобслуговування, що сприяє енергоощадженню

Ключові слова: ентропійні методи, дійсна холодильна машина, повітряний конденсатор, тверді відклади

1. Introduction

Refrigerating machines and heat pumps with small-scale and medium-scale capacities are referred to the commercial refrigeration equipment. Therefore, energy spending for consumers of these refrigerating machines is the main expense item and, so, it should correspond to those provided in the design project.

Analysis of the processes taking place in the elements of the refrigerating machine or the heat pump should be based on a clear understanding of the criteria of the design process. This will allow constructing an economic model of the machine and evaluating its operation in real conditions.

One of determining factors that adversely affect the operation of commercial refrigerating machines is emersion and growth of various solid fouling on the external surfaces of the elements. Prediction of the rate of fouling deposition on the heat exchange surfaces of refrigerating machines is an unexplored problem. It consists in the presence of a large number of mutually influencing factors associated with the specific conditions of equipment operation.

Thus, it becomes relevant to develop engineering methods for analyzing the real refrigerating machine characteris-

tics to ensure the accounting of the actual operating conditions of the machine while designing. One of such methods is the thermodynamic analysis of real cycles.

Thermodynamics expands the range of applied scientific resources that are able to minimize uncertainties at an early design stage and predict the real operating conditions of the equipment. Therefore, it is relevant to carry out the thermodynamic analysis using the experimental data of real refrigerating machines. Such analysis will make it possible to take into account and predict negative factors arising in the operation process in such conditions. In addition, it can help to identify the weakest elements of the refrigerating machine for the further energy saving issues.

The chosen research topic is relevant due to its prospects for the development of commercial refrigerating equipment.

2. Literature review and problem statement

A lot of information covering various aspects of solid fouling influence has appeared in modern technical literature. In paper [1], the effect of dust deposition on heat exchange surfaces of air conditioner evaporators of various

sizes was investigated. Mathematical models of three types of air conditioners were presented. What's more, it is concluded that the cooling capacity decreases and the power consumption of the refrigerating machine increases with the decrease of the airflow rate through the evaporator.

In [2], the effect of fouling deposition in the form of dust from the air in compact heat exchangers was investigated. It was found that the heat transfer coefficient is reduced by 18 % with sequential artificial deposition of fouling on the heat exchange surface. However, this research does not contain any information about the dimensional characteristics of the heat exchanger.

In paper [3], the heat exchangers with microchannel and plate fins were studied under conditions of fouling. Heat transfer and aerodynamics characteristics for microchannel heat exchangers turned out to be more sensitive to fouling than surfaces with plate fins.

In [4], the nine air-cooled condensers decommissioned at the end of their service life were considered. After testing in the contaminated state, these heat exchange surfaces were cleaned and experiments were performed again. As a result, it was concluded that in some cases fouling improves heat transfer or does not have a significant effect on it. After cleaning the surface, the aerodynamic characteristics are improved. The authors express the opinion that it is necessary to revise the terms of maintenance.

Experimental researches of the air-cooled condenser with plate fins were carried out in [5]. The results of the experiment showed that at the first stage of fouling deposition there is a deterioration of heat transfer and aerodynamics. Then these processes are stabilized and after that, there is further deterioration again.

All works [1–5] aimed at studying the fouling deposition process are experimental. The authors' conclusions are controversial regarding the effect of fouling on heat transfer and aerodynamic characteristics and, furthermore, do not contain a common scientific basis for describing physical processes taking place in the heat exchange elements.

In any case, the real processes of heat transfer and flow movement are irreversible and accompanied by entropy increase.

It is most appropriate to apply entropy methods of the thermodynamic analysis to estimate irreversible losses in energy conversion processes and machines. Such methods allow, along with efficiency assessment, obtaining the distribution of losses by the elements of the refrigeration cycle. So, it becomes easy to determine the “weak” place of the refrigerating system that requires improvement, as well as, finding the most effective ways to reduce energy consumption [6].

The “entropy method” for calculating the “losses” is based on the Clausius subtraction method [7]. This method makes it possible to quantitatively take into account the transition of input energy to the system into the consumption for entropy generation in each separate node of the system.

The entropy-cyclic method [8] consists in calculation and element-by-element analysis of changes (increasing) in the entropy of all objects involved in the process. These objects can either be the parts of the system or not, but they definitely interact with it during its operation. In addition, the entropy-cyclic method includes the total entropy change calculation of the whole system.

The methodology of the thermodynamic analysis using the entropy-cycle method is described in details on an example of the real thermodynamic cycle of the simplest mechan-

ical vapor compression refrigerating machine in [9]. This methodology allows performing a qualitative description of the real processes of any energy conversion system.

The analysis of processes in heat exchangers with increased hydraulic losses on the working fluid side by the entropy-cycle method is described in [10]. In this paper, a real reverse thermodynamic cycle was considered as an example. Thermodynamic analysis is based on the transformation of internally irreversible losses in heat exchangers into equivalent external losses. As a result, these losses were quantified.

The entropy-statistical method combines the classical method of the entropy analysis together with the statistical-probabilistic method [11]. The entropy-statistical method allows determining the necessary energy consumption for the compensation of entropy generation due to irreversibility of working processes in various elements (components) of energy conversion systems. Moreover, this method indicates ways of improvement of such systems [12].

Cycles of mechanical vapor compression refrigerating machines were investigated with the help of the entropy-statistical method in [13]. The elements of the refrigerating machine that require improvements were identified as a result of the calculation. The effects of the thermodynamic properties of the working fluid on the distribution of compression work losses in the refrigerating machine were also determined. The concept of “entropy generation” was introduced in [14]. The entropy generation minimization method was developed in the 70–80° in [15, 16].

A generalized approach of this method with application to any heat exchanger was described in [17]. The researches of entropy generation by the fluid flow in microchannels of an open heat-transfer surface are presented in [18]. Moreover, the optimization of compact finned microchannel coolers by minimizing entropy generation was considered in [19]. Researches in [20] are devoted to the implementation of the abovementioned method in the design process of heat exchangers. A horizontal shell tube condenser was investigated as an example.

The studies [10–20] concern the thermodynamic analysis of the energy-transforming system's elements and are devoted to the study of the stationary modes without taking into account the real operating conditions.

As a result of the literature review, it can be stated that the research topic is an unexplored area. Its studying will later allow solving energy saving problems for real refrigeration machines at the design stage.

3. The aim and objectives of the study

The aim of the research is the search for engineering methods of analysis that could provide an accounting of the external fouling influence on the operation of the real commercial refrigeration machine at the design stage.

To achieve this aim, it is necessary to accomplish the following objectives:

- to apply entropy methods of the thermodynamic analysis to the evaluation of the characteristics of the real refrigerating machine taking into account fouling on the heat exchange surface of the air condenser;
- to establish the limits of each method application in the process of analysis;
- to outline the directions of methods' development for studying various heat exchange surfaces taking into account fouling.

4. Application of entropy methods of the thermodynamic analysis for evaluation of the real refrigerating machine operation

The results of experimental studies of the real small-scale commercial refrigerating machine were used to perform the thermodynamic analysis using entropy methods [5]. The refrigerating machine operates according to the single-stage mechanical compression cycle. The machine includes a BITZER compression-condensing unit LH32E/2KES-0.5.

The compression-condensing unit consists of: semi-hermetic piston compressor, air-cooled condenser, oil separator, receiver and liquid separator. The compression-condensing unit is placed on a single frame. Low temperature in the cooled chamber is controlled by the air cooler. An electric heater carries out a heat load to the chamber.

The experiment involved the refrigerating machine testing with the presence of solid fouling in the form of dust on the external surface of the air-cooled condenser. Dust was collected from 4 active air-cooled condensers of commercial refrigerating machines that are similar to the experimental one. Experimental researches were separated into several stages. At the first experimental stage, the refrigerating machine was tested under conditions of the clean surface of an air-cooled condenser. Then dust was sprayed in portions as a finely dispersed substance mixed with water. Moreover, an additional amount of fouling was added at different stages of the experiment.

4.1. The entropy-cycle method in the analysis of the real refrigerating machine operation

The analysis was done according to the computational and graphic method by means of $T - s$ state diagram (Fig. 1, 2).

Irreversibility in the real refrigerating machine cycle is estimated by means of the empirical method that is based on the Gouy-Stodola equation:

$$L_{\Sigma} = T_{amb} \cdot \Delta S_{\Sigma} \tag{1}$$

The real cycle of the refrigerating machine is based on experimental data [5] (Fig. 1) for the clean surface of the condenser and taking into account dust deposition on the external heat-exchange surface (Fig. 2).

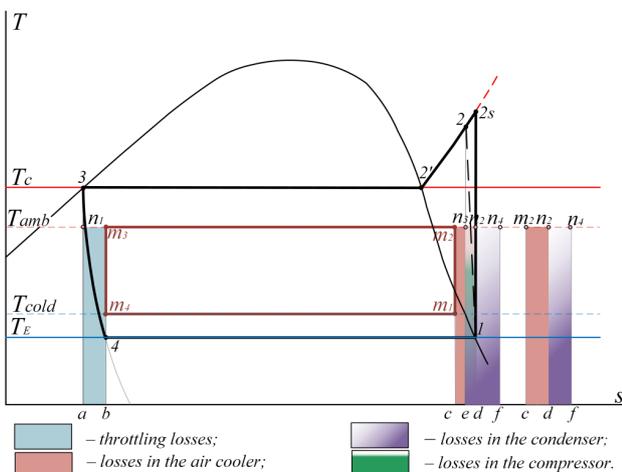


Fig. 1. Determination of irreversible losses in the real cycle with the clean surface of the air-cooled condenser

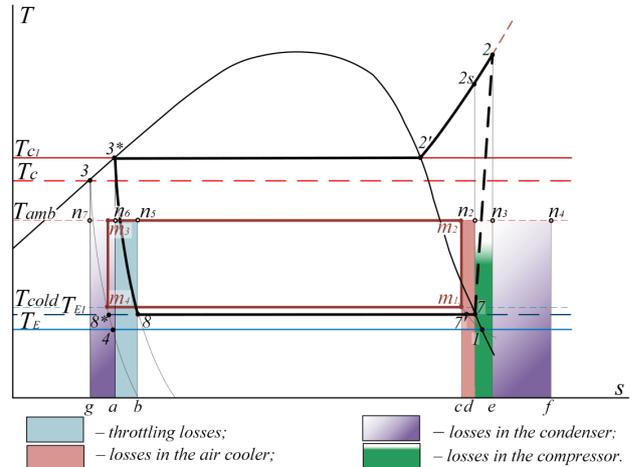


Fig. 2. Determination of irreversible losses in the real cycle taking into account dust deposition on the external surface of the air-cooled condenser

This interpretation of the cycle takes into account external irreversibility in the processes of heat rejection and heat supply, as well as internal irreversibility in the compression processes in the compressor and throttling in the thermostatic expansion valve (TEV).

Fig. 1 shows the real compression process (1)–(2) with heat rejection. This process takes place with the presence of forced air blowing on the compressor; entropy in the process decreases. Fig. 2 corresponds to the experiment conditions – when the maximum amount of fouling (300 g of dust) is deposited to the external surface of the air-cooled condenser. In this case, the heat-exchange surface of the air-cooled condenser is completely contaminated. Therefore, the air passage is absent and the compressor is not cooled. The compression process in the compressor is accompanied by an increase in entropy. Fouling causes an increase in the condensing temperature $T_{c1} > T_c$ and an increase in the evaporating temperature $T_{E1} > T_E$.

The corresponding Carnot cycle is constructed for carrying out the analysis at real temperatures of the experiment: ambient temperature T_{amb} , cooled chamber temperature T_{cold} , condensing temperature T_c and evaporating temperature T_E . Conditions of equality between the cooling capacities of the Carnot cycle and the real cycle are presented in Fig. 1 (area $cm_1m_4b = \text{area } d14b \Rightarrow q_E = h_1 - h_4 = T_{cold} \cdot (s_c - s_b)$).

The analysis sequence demonstrates the comparison of two cycles (the real and corresponding Carnot cycles) through gradual replacing of the growing irreversibility by upbuilding the corresponding Carnot cycle width.

Minimum specific work in the Carnot cycle is defined as follows:

$$w_{min}^C = w_{comp}^C - w_{exp}^C, \tag{2}$$

where $w_{comp}^C = h_{m_2} - h_{m_1}$ is specific compressor work; where $w_{exp}^C = h_{m_3} - h_{m_4}$ is work obtained by expansion of vapor in the expander.

Real specific compression work in the cycle is determined as:

$$w_{real} = q_C - q_E, \text{ kJ} \cdot \text{kg}^{-1}. \tag{3}$$

Excessive consumption of specific work in the real cycle can be specified from Eq. (2) and (3) as:

$$L = w_{real} - w_{min}^c, \text{ kJ}\cdot\text{kg}^{-1}. \tag{4}$$

Losses in separate cycle processes for the clean surface of the air-cooled condenser are determined by Eq. (5)–(8).

Internal losses due to the throttling process are determined as follows:

$$L_{thr} = T_{amb} \cdot (s_b - s_a) \Leftrightarrow b4m3n1a. \tag{5}$$

External losses in the heat supply process in the air cooler:

$$L_{ac} = T_{amb} \cdot (s_d - s_c) \Leftrightarrow cn3n2d. \tag{6}$$

Internal losses due to irreversible compression in the compressor are determined as:

$$L_{comp} = T_{amb} \cdot (s_e - s_d) \Leftrightarrow dn2n3e. \tag{7}$$

External losses in the heat rejection process in the air-cooled condenser are defined as:

$$L_c = (h_2 - h_3) = T_{amb} \cdot (s_f - s_e) \Leftrightarrow, \tag{8}$$

where

$$s_f = \frac{h_2 - h_3}{T_{amb}} + s_a. \tag{9}$$

The results of losses calculations in separate elements of the refrigerating machine taking into account fouling are presented in Table 1.

Table 1

Summary table of losses in separate processes of the real cycle

Losses in each process kJ/kg	Condenser surface condition	
	Clean surface	Surface with 300 g of dust
L	13.70	31.00
L_{thr}	2.06	9.42
L_{ac}	7.07	5.30
L_{comp}	-4.70	6.77
L_c	7.66	13.88

Analysis shows that losses in the air-cooled condenser have the greatest influence on the energy efficiency in the considered real cycles. In addition, fouling aggravates the effect of these losses.

Thus, it can be concluded that the entropy-cyclic method ensures the real cycle analysis and does not require complex analytical and numerical methods of calculation. However, this method does not quantify irreversibility, only illustrating it visually.

4. 2. The entropy-statistical method in the analysis of the real refrigerating machine operation

The study of the real refrigerating machine by the entropy-statistical method is based on research materials [11].

Refrigerating machine cycles are shown in Fig. 1, 2. Adiabatic coefficient of the compressor efficiency η_{is} is 0.8.

The sequence of the main elements analysis is as follows.

Real specific refrigerating capacity of the refrigerating machine is determined as:

$$q_E^{real} = q_E, \text{ kJ}\cdot\text{kg}^{-1}. \tag{10}$$

Minimum specific work is defined by Eq. (11):

$$w_{min} = q_E^{real} \cdot \frac{T_{amb} - T_{cool}}{T_{cold}}, \text{ kJ}\cdot\text{kg}^{-1}. \tag{11}$$

Specific isentropic compression work is determined as follows:

$$w_{is} = h_{2s} - h_1, \text{ kJ}\cdot\text{kg}^{-1}. \tag{12}$$

Thermodynamic efficiency of the cycle can be expressed as:

$$\eta_{th} = \frac{w_{is}}{w_{real}}. \tag{13}$$

Real coefficient of performance can be defined from Eq. (14)

$$COP_{real} = \frac{q_E^{real}}{w_{real}}. \tag{14}$$

Minimum required specific consumption of compression work to compensate entropy generation in the air-cooled condenser:

$$\Delta w_c^{min} = T_{amb} \cdot (h_2 - h_3) \cdot \left(\frac{1}{T_{amb}} - \frac{1}{T_c} \right), \text{ kJ}\cdot\text{kg}^{-1}. \tag{15}$$

Minimum required specific consumption of compression work to compensate entropy generation while throttling in the thermostatic expansion valve:

$$\Delta w_{thr}^{min} = T_{amb} \cdot (s_4 - s_3), \text{ kJ}\cdot\text{kg}^{-1}. \tag{16}$$

Minimum required specific consumption of compression work to compensate entropy generation in the air-cooler

$$\Delta w_{ac}^{min} = T_{amb} \cdot q_E^{real} \cdot \left(\frac{1}{T_E} - \frac{1}{T_{cold}} \right), \text{ kJ}\cdot\text{kg}^{-1}. \tag{17}$$

Total value of minimum work to compensate entropy generation in all elements of the refrigerating machine determines the calculated isentropic compression work:

$$w_{is}' = w_{min} + \Delta w_c^{min} + \Delta w_{thr}^{min} + \Delta w_{ac}^{min}, \text{ kJ}\cdot\text{kg}^{-1}. \tag{18}$$

Energy losses in the compressor are defined as follows:

$$\Delta w_{comp}' = w_{exp} - w_{is}, \text{ kJ}\cdot\text{kg}^{-1}. \tag{19}$$

Calculation results of minimum required work to compensate entropy generation of the cycles are presented in Table 2.

Table 2

Specific values of minimum required work to compensate entropy generation

Specific values of minimum required work, $\text{kJ}\cdot\text{kg}^{-1}$	Air-cooled condenser surface condition	
	Clean surface	Surface with 300 g of dust
w_{\min}	9.68	9.17
Δw_c^{\min}	7.09	10.29
Δw_{thr}^{\min}	2.35	4.71
Δw_{ac}^{\min}	5.075	3.588
$\Delta w'_{comp}$	-3.90	6.20
w'_{is}	24.19	27.75
w_{is}	24.80	28.20
w_{exp}	20.88	34.42

Fig. 3, 4 present the calculated distribution of specific losses, $\text{kJ}\cdot\text{kg}^{-1}$.

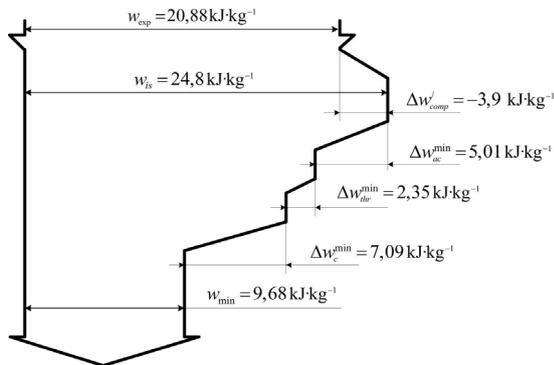


Fig. 3. The calculated distribution of specific losses on the main elements of the refrigerating machine with the clean surface of the air-cooled condenser, $\text{kJ}\cdot\text{kg}^{-1}$

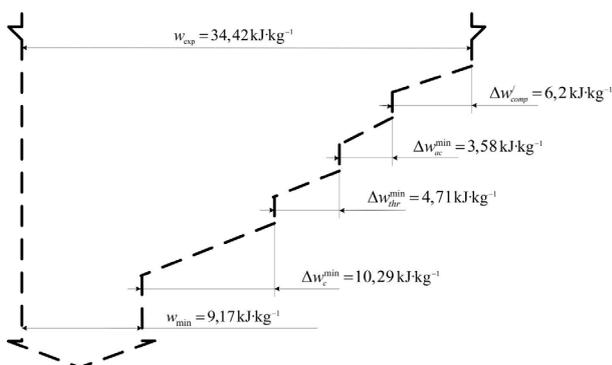


Fig. 4. The calculated distribution of specific losses on the main elements of the refrigerating machine with 300 g of dust on the external surface of the air-cooled condenser

Discrepancy between the calculated values of isentropic compression work w'_{is} according to the equation (18) and

w_{is} according to the $T-s$ diagram for the refrigerating cycle with the clean surface of the air-cooled condenser does not exceed 2.4 %. At the same time, discrepancy does not exceed 1.6 % for the refrigerating cycle with the air-cooled condenser with 300 g of dust on the external surface. The obtained result indicates the real distribution of losses on the elements of the refrigerating machine.

The analysis of the entropy-statistical method shows changes of losses by elements depending on the state of the air-cooled condenser surface. This allows focusing on the need of forehanded cleaning of heat exchangers in the refrigerating machine.

4. 3. “Entropy generation minimization” method in the analysis of the air-cooled condenser operation in the real refrigerating machine

The “entropy generation minimization” method is based on the thermodynamics of non-equilibrium irreversible processes.

The essence of the method is to establish minimum entropy generation in the studied element of the energy conversion system. This makes it possible to determine its optimal operation mode that, in turn, allows saving energy. The “entropy generation minimization” method is used for the analysis of irreversible stationary processes.

The operating conditions adjust the basic characteristics of the energy conversion system’s elements. Hence, the processes in the elements should be considered as non-equilibrium and non-stationary. One of the sources of the thermodynamic transformation of these processes is emersion and growth of solid fouling on the heat-exchange surface of the heat exchangers. Wherein, the values of solid fouling growth vary with time and the conditions for heat exchange are unknown. In this case, entropy generation is a function of time that cannot be optimized. Under such conditions, it would be correct to determine the rate of entropy generation depending on operating time of the refrigerating machine.

Application of the entropy generation minimization theory to determine irreversibility in the heat exchanger using the example of the air-cooled condenser is considered below. The experimental results and analysis of the air-cooled condenser characteristics taking into account fouling on the external surface of heat exchange are presented in [5]. A discrete increase in the dust mass is used under the experimental conditions. Wherein, the dust mass is a function of time in real conditions.

A model of the air-cooled condenser with fouling on the external surface is shown in Fig. 5.

The compressor provides the circulation of the condensing “hot” flow of the working fluid. The fan provides the circulation of “cold” air.

The finite temperature difference in the heat exchanger is conditionally divided into two parts: $(T_c - T_{wall})$ and $(T_{wall} - T_{av}^{air})$. Thus, entropy generation is carried out by each flow in isolation from the heat exchanger as a whole.

Analysis for moving airflow is as follows.

For this analysis, the approach described in [17] is used. The flow in the heat exchanger participates in entropy generation, which is conditionally divided into thermal s^T and mechanical s^M components. These components are the result of two processes occurring with the flow:

- heat transfer at a finite temperature difference;
- flow movement with friction.

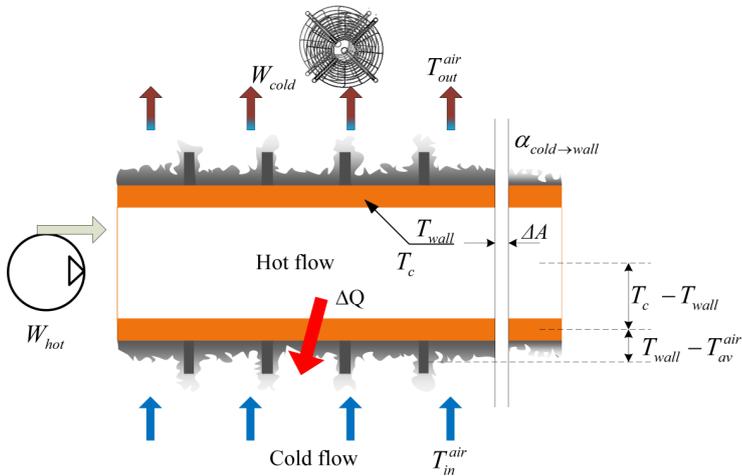


Fig. 5. Generalized model of the air-cooled condenser with fouling on the external surface

The reduced value of the thermal component of entropy generation by airflow can be expressed as:

$$\bar{s}_{air}^T = \frac{Q_c}{A_{ext} \cdot T_{av}^{air} \cdot \alpha_{ext}^{air}}, \tag{20}$$

where Q_c – heat load on the condenser; A_{ext} – the external surface area of the condenser; α_{ext}^{air} – the coefficient of heat transfer from air reduced to the external surface of the finned element; T_{av}^{air} – average air temperature in the condenser.

The reduced value of the mechanical component of entropy generation by airflow is defined as follows:

$$\bar{s}_{air}^M = \frac{N_{fm} \cdot T_{wall}}{T_{av}^{air} \cdot Q_c}, \tag{21}$$

where N_{fm} – power consumption of the fan motor; T_{wall} – wall temperature of the condenser tube.

Total entropy generation by airflow is determined as:

$$\bar{s}_{air} = \bar{s}_{air}^T + \bar{s}_{air}^M. \tag{22}$$

The results of calculations are presented in Tables 3, 4.

Fig. 6 shows entropy generation by airflow in graphic form in the coordinate system “entropy generation – fouling mass”.

As can be seen from Fig. 6, the reduced value of the thermal component of entropy generation by airflow \bar{s}_{air}^T up to a certain point (dust mass 200 g) does not significantly affect total thermal resistance to heat transfer with fouling increase on the external surface of the air-cooled condenser. Further fouling increase is accompanied by intensive entropy generation. Wherein, the reduced value of the mechanical component of entropy generation \bar{s}_{air}^M having reached its maximum value at 200 g of dust mass begins to decrease. This effect is explained by the fact that with full contamination of the air-cooled condenser cross-section (300 g of dust), main airflow does not pass through it, but ejects end airflow of the environment.

As a result, total entropy generation by airflow \bar{s}_{air} tends to increase the ordinate, and the separate components are comparable with each other.

Thus, the performed thermodynamic analysis allows fixing the time of air-cooled condenser operation until its cleaning.

Table 3

Calculation of air-cooled condenser characteristics

Air-cooled condenser characteristics	Air-cooled condenser surface condition			
	Clean surface	Surface with 100 g of dust	Surface with 200 g of dust	Surface with 300 g of dust
A_{ext} , m ²	9.77	9.77	9.77	9.77
Q_c , kW	3.81	2.84	2.31	3.67
T_{av}^{air} , K	297.60	297.90	298.20	296.80
α_{ext}^{air} , W·m ⁻² ·K ⁻¹	67.89	44.03	35.86	26.42
T_{wall} , K	298.30	298.30	298.70	297.00
N_{fm} , kW	0.1034	0.1056	0.1067	0.1144

Table 4

Entropy generation by airflow

Entropy generation by air flow	Air-cooled condenser surface condition			
	Clean surface	Surface with 100 g of dust	Surface with 200 g of dust	Surface with 300 g of dust
$\bar{s}_{air}^T \times 10^3$	19.3	22.2	22.2	47.2
$\bar{s}_{air}^M \times 10^3$	27.2	37.2	46.2	31.3
$\bar{s}_{air} \times 10^3$	46.5	59.2	68.2	78.8

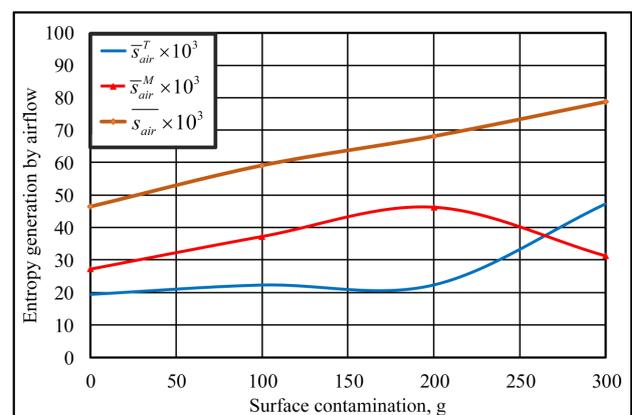


Fig. 6. Variation of entropy generation by airflow depending on the fouling mass of dust on the external surface of the condenser

5. Discussion of analysis results by the entropy methods

The study was conducted according to three different methods of thermodynamic analysis: the entropy-cycle

method, the entropy-statistical method and the “entropy generation minimization” method. The main function in all methods is entropy.

In the entropy-cycle method, the entropy value estimates the energy loss in the cycle and indicates the element of the greatest influence on the energy efficiency reduction. According to the results of the research, this element turned out to be the condenser. And, what's more, growth of fouling deposition on its external surface increases the effect of these losses. The analysis according to the entropy-cycle method is accompanied by the graphical construction in the T-s coordinate system, and so can clearly illustrate possible irreversible losses.

In the entropy-statistical method, compressor work and its changes associated with the real processes in all other elements of the refrigerating machine are used along with entropy. It is this function that determines the maintenance terms of the refrigerating machine.

In the “entropy generation minimization” method entropy is a function of optimization, with the help of which any heat exchanger is examined and optimized in isolation from the entire refrigerating machine. In this study, the single flow in the air-cooled condenser, which is the source of fouling and is of primary interest, is examined. Determining the rate of entropy generation by airflow in the presence of fouling makes it possible to predict time intervals between the maintenance of the heat exchanger. This ensures energy saving and long-term operation of the refrigerating machine.

It is seen that the considered methods need to be applied combined for analyzing the real refrigerating machine.

The alternative method of such research is the construction of a mathematical model based on the results of experimental data [1–5]. The mathematical modelling is currently

considered as the only one possible way for studying the dynamics of fouling formation in the real refrigerating machines. However, it is worth noting that conduction of the experiment requires time and material costs and cannot be used to analyze the real cycle at the design stage.

The advantage of this study is that its results are capable of giving important practical forecasts as early as at the design stage when the expected real cycle is being studied. This approach will contribute to energy saving.

6. Conclusions

1. The entropy-based methods are elements of the logical method that is the base for the optimization program. This method makes it possible to eliminate the area of unrealistic solutions, such as the operation mode of the air-cooled condenser with 300 g of dust fouling.

2. The entropy-cyclic and entropy-statistical methods are identical. They solve the same problems and quantitatively give the same approximate values of irreversibility in the separate processes. These values differ by no more than 3 %.

3. It is necessary to use the theoretical principles of thermodynamics of non-equilibrium processes for the thermodynamic assessment of fouling influence on heat transfer and aerodynamics in the heat exchanger. The reason of this is that the fouling process is the function of time.

4. The thermal and mechanical components of entropy generation are quantitatively comparable ($1 \leq \bar{s}_{ar}^M / \bar{s}_{ar}^T \leq 2$) when fouling is on the heat exchange surface. Accounting for both components must be present when assessing the total irreversible losses in the heat exchanger.

References

1. Yang L., Braun J. E., Groll E. A. The Role of Filtration in Maintaining Clean Heat Exchanger Coils // Final Report AR-TI-21CR/611-40050-01. Air-Conditioning and Refrigeration Technology Institute (ARTI). 2004. doi: <https://doi.org/10.2172/833362>
2. Lankinen R., Suihkonen J., Sarkomaa P. The effect of air side fouling on thermal-hydraulic characteristics of a compact heat exchanger // International Journal of Energy Research. 2003. Vol. 27, Issue 4. P. 349–361. doi: <https://doi.org/10.1002/er.880>
3. Bell I. H., Groll E. A. Experimental comparison of the impact of air-side particulate fouling on the thermo-hydraulic performance of microchannel and plate-fin heat exchangers // International Refrigeration and Air Conditioning conference. 2010.
4. Mehrabi M., Yuill D. Evaluation the effect of washing on the heat transfer capacity on air-side flow resistance of air cooled condensers // International Refrigeration and Air Conditioning conference. 2018.
5. Method of Experimental Investigation of Air-Cooled Condensers for Small Refrigeration Machines and Heat Pumps / Morosuk L. I., Sokolovska V. V., Gaiduk S. V., Moshkatuk A. V. // Refrigeration Engineering and Technology. 2017. Vol. 53, Issue 3. P. 4–11. doi: <https://doi.org/10.15673/ret.v53i3.674>
6. Metod – termodinamicheskii analiz // Bol'shaya Enciklopediya Nefti i Gaza. URL: <http://www.ngpedia.ru/id145767p2.html>
7. Gohshteyn D. P. Sovremennye metody termodinamicheskogo analiza energeticheskikh ustanovok: na pravah rukopisi / Odesskiy Tekhnologicheskii Institut im. M. V. Lomonosova. Odessa, 1967. 333 p.
8. Eksergeticheskie raschety tekhnicheskikh sistem: sprav. pos. / A. A. Dolinskiy, V. M. Brodyanskiy (Eds.). Kyiv: Naukova dumka, 1991. 360 p.
9. Morosuk T., Nikulshin R., Morosuk L. Entropy-cycle method for analysis of refrigeration machine and heat pump cycles // Thermal Science. 2006. Vol. 10, Issue 1. P. 111–124. doi: <https://doi.org/10.2298/tsci0601111m>
10. Morozyuk L. I., Sokolovskaya V. V., Ol'shevskaya O. V. Termodinamicheskii analiz teploobmennyykh apparatov v sostave energopreobrazuyushchey sistemy entropiyno-tsiklovym metodom // Vestnik Mezhdunarodnoy akademii holoda. 2013. Issue 4. P. 24–27.

11. Arharov A. M. Osnovy kriologii. Entropiyno-statisticheskiy analiz nizkotemperaturnykh sistem: monografiya. Moscow: izd-vo MGTU im. N. E. Baumana, 2014. 507 p.
12. Arharov A. M. O nekotorykh osobennostyakh termodinamicheskogo analiza nizkotemperaturnykh sistem // Vestnik MGTU im. N. E. Baumana. Ser.: Mashinostroenie. 2010. P. 29–40.
13. Arharov A. M., Shishov V. V. Entropiyno-statisticheskiy analiz raspredeleniya zatrat energii na kompensatsiyu neobratimosti rabochnykh processov sistem kondicionirovaniya // Vestnik MGTU im. N. E. Baumana. Ser.: Mashinostroenie. 2013. Issue 2. P. 84–97.
14. Prigozhin I. Vvedenie v termodinamiku neobratimyykh processov: monografiya. Moscow: Izd-vo inostr. lit-ry, 1960. 160 p.
15. Bejan A. Entropy Generation through Heat and Fluid Flow: monograph. New York: John Wiley & Sons, 1982. 264 p.
16. Bejan A., Tsatsaronis G., Moran M. Thermal Design and Optimization: monograph. New York: John Wiley & Sons, 1996. 540 p.
17. Comparison of the entropic exergetic and economic optima of a heat exchanger / Le Goff P., De Olivera S., Schwarzer B., Tondeur D. // Analysis of Thermal and Energy Systems, Proceedings of International Conference Athens. Athens, 1991. P. 105–116.
18. Khan, W. A., Yovanovich M. M., Culham J. R. Optimization of microchannel heat sinks using entropy generation minimization method // Twenty-Second Annual IEEE Semiconductor Thermal Measurement And Management Symposium. 2006. doi: <https://doi.org/10.1109/stherm.2006.1625210>
19. Entropy generation analysis of liquid fluid past embedded open parallel microchannels within the surface / Yazdi M. H., Abdullah S., Hashim I., Sopian K., Zaharim A. // European journal of scientific research. 2009. Vol. 28, Issue 3. P. 462–470.
20. Morozyuk L. I. Optimization of heat exchangers of refrigeration machines by entropy generation minimization method // Eastern-European Journal of Enterprise Technologies. 2015. Vol. 4, Issue 8 (76). P. 42–48. doi: <https://doi.org/10.15587/1729-4061.2015.47753>