ТЕРМОДИНАМІЧНИЙ АНАЛІЗ ТА МОДЕЛЮВАННЯ

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Thermodynamic analyses of heat exchangers in cryogenic systems

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The problems of thermodynamic analysis associated with the heat exchangers that used in cryogenic technology are discussed. Heat exchangers of high and medium pressure air separation and fluidizing plants operating at different temperature levels were selected for modelling. There are many features according to which the classification of heat exchangers is made. These features include such facts as the number of flows of the working fluid, the relative direction of the flows of working substances, the purpose of the apparatus, and others. These features are also associated with the design of heat exchangers and the software for the design, which contains thermodynamic calculations. The general thermodynamic approach is based on the equation for the values of the thermodynamic efficiency characteristics and the restrictions imposed on them At the exergy method of analysis, the corresponding balance is based on the energy balance equation. On the basis of this balance, the losses from irreversibility of the selected object and its exergy (thermodynamic) efficiency can be directly determined In a heat exchanger, both types of losses exist, but it is not possible to reveal the contribution of each type to total losses using only the exergy balance. This is due to the fact that this balance is drawn up for a closed control surface that reflects a physical object and not logical reasons associated with this object. Meanwhile, the determination of technical losses is an urgent tasks since the change in the thermodynamic parameters that regulate these losses are the basis for increasing the coefficient of the thermodynamic efficiency of the analyzed system A method and an algorithm for calculating the components of losses from irreversibility in these heat exchangers are proposed. The exergy method of thermodynamic analysis was used to calculate the components of these losses for some two-flow heat exchangers. The investigation of the obtained calculation results is presented.

Keywords*: Cryogenic technology; Heat exchanger; Equation of state; Exergy method; Losses from irreversibility of processes*

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1. Introduction

Heat exchanger is a unique object of thermodynamic analysis because of some reasons. First, it is the most common element of cryogenic plants [1-3]. Secondly, it contains practically all the problems and tasks of thermodynamic analysis. The peculiarity of the heat exchanger as an object of this analysis should be explained by the fact that under certain conditions [4-6], it can be formally attributed, like an expander and a compressor, to an ideal unit of an installation, in which there are no losses from irreversibility of processes.

At the same time, at the logical level of the considered apparatus, it is enough to simply set the tasks of thermodynamic analysis, which is explained by the similarity of its design and its constituent parts. For instance, in a piston expander, it is necessary to analyse individual gas processes, such as intake, expansion and expulsion [7]. In this case, it is required to create and analyse a thermodynamic model of each of these processes.

For a part of the heat exchanger, the same processes are characteristic for the entire apparatus, while its thermodynamic model is qualitatively preserved. This feature, in particular, is used to determine the thermodynamic performance of two-flow and multi-flow heat exchangers [8].

Despite the simplicity of the formulation of the problem of thermodynamic analysis of a heat exchanger, its very solution in some cases cannot be carried out directly by either exergy or entropy methods. Therefore, it is necessary to create and test additional approaches for solving such problems in these situations. In this case, there is a need to create a classification of thermodynamic analysis problems based on possible methods for their solution.

Currently, there are a large number of articles and monographs on various aspects related to heat exchangers. Among the sources covering their thermodynamic analysis are monographs [9-11]. The designs of heat exchangers and the existing methods for their calculation are described in [12-15]. However, there are not enough publications summarizing the accumulated research results when analysing the thermodynamic efficiency of heat exchangers. The purpose of this work is to fill this deficit of corresponding information to some extent

2. Problems of thermodynamic analysis of heat exchangers

There are many features according to which the classification of heat exchangers is made. These features include such facts as the number of flows of the working fluid, the relative direction of the flows of working substances, the purpose of the apparatus, and others. These features are also associated with the design of heat exchangers and the software for the design, which contains thermodynamic calculations [16-18]. The thermodynamic analysis carry out after thermodynamic calculations of the system, so its impact on the designs of the apparatus is not essential. For this reason, thermodynamic analysis is weakly associated with the above characteristics. Therefore, as noted in the introduction to this work, it makes sense to divide the analysis problems on two groups. The first group uses only general thermodynamic statements. The second group requires additional physical assumptions.

The general thermodynamic approach is based on the equation for the values of the thermodynamic efficiency characteristics and the restrictions imposed on them. Below are the tasks with the corresponding comments using this approach.

Calculation of the thermodynamic efficiency. At the exergy method of analysis, the corresponding balance is based on the energy balance equation. On the basis of this balance, the losses from irreversibility of the selected object D and its exergy (thermodynamic) efficiency η_e can be directly determined. At the same time, there is some uncertainty in calculating the value of η_e, due to the transfer of terms from one part of the exergy balance to another its part. This takes place, for instance, when it is necessary to take into account transit exergy. If there are no chemical reactions in the substance flow, then the exergy function [19, 20] can be used to calculate the change in exergy in this flow.

The exergy calculation made it possible to calculate only the value D. In this case, for a heat exchanger that operates at temperatures below the temperature of surroundings T_{sur}, it is necessary to change the sign of heat leakage to the opposite [21].This sign reversal operation is described in detail in the monograph [10].

When evaluating the two methods of thermodynamic analysis, it should be noted that the exergy method is much easier to formalize than the entropy method [22-26].

Checking the correctness of calculations. The criteria of the thermodynamic efficiency of a power plant, the following inequalities may be written as

$$0 \le D \le E. \tag{1}$$

$$0 \le \eta_e \le 1. \tag{2}$$

In inequalities (1), symbol E is the total exergy of the obtained products. For a heat exchanger, the value E is equal to the sum of the exergy of the flows of working substances, that leaving the apparatus.

If any of the inequalities (1) or (2) is violated, it is necessary to check the previously performed thermodynamic calculations. Errors, for instance, occur at $\eta_e \to 1$, when negative values of D are possible for heat exchangers because of calculating error.

Checking the thermodynamic availability for work of heat exchangers. Thermodynamic availability for work is the simultaneous satisfaction of the analyzed object with the requirements of I and II laws of thermodynamics. For a two-flow heat exchanger, this problem is relevant if the flow rates significantly differ, or phase transformations in working substances takes place in them. In these cases, this check is reduced to an analysis of the feasibility of the second law under conditions corresponding to the first law. Requirements of the second law are given in the form of an inequality corresponding to its definite formulation. For a two-flow apparatus, it is sufficient to use the formulation given by Clausius [9, 27, 28], according to which heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.

When solving this problem, it is necessary to check the feasibility of the energy balance of the heat exchanger. Some aspects of the problem under consideration are described in [29, 30].

Determination of the minimum energy consumption for obtaining products in a low-temperature unit. The solution to this problem is based on a formally compiled exergy balance equation. In this case, formalization assumes that all exergy flows included in the selected contour are on the left side of this equation. Also exergy flows and losses from irreversibility emerging from it are on the its right side. Then the exergy of each of the flows in the right-hand side is the minimum energy consumption to obtain a product corresponding to this flow. This condition applies to any power plant. Thus, using the formal exergy balance equation, it is possible to obtain the division of the total minimum energy costs between similar costs for products. If useful energy is generated in a cryogenic plant, in the circuit of which there is an expander, then this energy in the form of work should be considered as the product of this installation.

To solve a different kind of the problem, it is not enough to use only the exergy balance equations. A number of assumptions are additionally required. The basis for their appearance can be considered from the classification of losses from irreversibility on the basis of the reasons for their occurrence [19], according to which they are divided into technical and own. The main difference between these types of losses is that, at the logical level, technical losses are completely removable, while own ones are not.

In a heat exchanger, both types of losses exist, but it is not possible to reveal the contribution of each type to total losses using only the exergy balance. This is due to the fact that this balance is drawn up for a closed control surface that reflects a physical object and not logical reasons associated with this object. Meanwhile, the determination of technical losses is an urgent tasks since the change in the thermodynamic parameters that regulate these losses are the basis for increasing the coefficient of the thermodynamic efficiency of the analyzed system.

Below is considered a problem that requires certain assumptions for its solution.

3. Determination of components of the total exergy losses of a two-flow heat exchanger

In practice, it is usually assumed that the total exergy losses of the heat exchanger D_S include the following components:

- from irreversible heat exchange between flows D_{hf};
- from irreversible heat exchange of the apparatus with the environment D_{hs};
- from hydraulic resistances of each *i*-th material flow D_{pi}.

This list does not include all components of the *DS* value. For instance, there are no losses due to thermal conductivity along the heat exchanger. However, in the method described below, all unaccounted losses are indirectly included in one of the constituent values of D_S, usually in the term D_{hf}.

Due to their additivity, the components of losses are related to the total losses by the equality

$$D_\Sigma = D_{hf} + D_{hs} + \sum_i D_{pi}. \qquad (3)$$

The D_S value is determined by a purely thermodynamic method based on the exergy balance equation.

Fig. 1 shows the calculated thermodynamic diagram of the further considered two-flow heat exchanger for the cryogenic plant, named as HE.

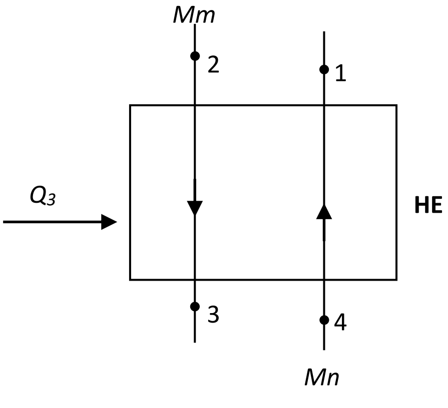

***Figure 1** – Design diagram of a two-flow heat exchanger*

In this diagram, the following names are used: M_m is the flow rate of the warm substance flow of high pressure, M_n is the flow rate of the cold substance flow of low pressure, Q_3 is the heat leakage to the exchanger from the surroundings.

The energy balance equation for the apparatus shown in Fig. 1 takes the form

$$M_m \cdot h_2 + M_n \cdot h_4 + Q_3 = M_m \cdot h_3 + M_n \cdot h_1. \tag{4}$$

In equality (4), the symbol h_k, k= 1,2..4, denotes the enthalpy at the k-th nodal point.

Based on expression (4), an equation for the exergy balance of the heat exchanger HE is

$$M_m \cdot e_2 + M_n \cdot e_4 = M_m \cdot e_3 + M_n \cdot e_1 + D_\Sigma. \tag{5}$$

The exergy function for the k-th nodal point e_k is calculated from the next relation [19]

$$e_k = h_k - T_{env} \cdot s_k, \tag{6}$$

where T_{env} is the ambient temperature, s_k is the entropy at the k-th nodal point.

The exergy analysis of a heat exchanger assumes that one of the quantities (enthalpy, flow rate, heat from surroundings, or another variable) is determined from the energy balance, and the remaining quantities must be known.

The method described below for finding the components of the total losses D_S of a heat exchanger is based on the implementation of the following steps:

1. Consistent exclusion from consideration of certain types of losses, taking into account all other components of D_S.

2. Drawing up exergy and energy balances without excluding losses, based on which a new value of the total losses of the heat exchanger DS' is calculated.

3. Calculation of the contribution of the excluded loss type as a difference ($D_S - D_{S'}$).

The procedure for implementing the first step is ambiguous. It specify the types of excluded losses, assuming the corresponding components of D_S to be equal to zero. To ensure the fulfillment of equality (5), it is necessary to eliminate all types of losses, except one loss, the contribution of which would be calculated from relation (5).

Among the types of losses under consideration, these include the components D_{in}, D_{pi}. The reason for their own losses lies in the nature of the processes. They cannot be reduced to zero without a radical change in these processes. In the general case, the losses D_{hf} are own, since it is impossible to achieve reversible heat transfer between flows with different heat capacities of working bodies. Only in the special case, when the working fluids of the flows are ideal gases, and their total heat capacities in the sections of the apparatus are the same, is it theoretically possible to implement the process of reversible heat transfer with an infinitely large surface of the heat exchanger.

It is necessary to note one more significant difference between technical and own losses, which arises in the thermodynamic analysis of the heat exchanger, which leads to the justification of the choice of the excluded types of losses. Technical losses can be a priori set in the form of specific values of hydraulic resistances and heat flow between the apparatus and the environment. At the same time, own losses, as a rule, can only be calculated after calculating the processes that they characterize.

Thus, in a heat exchanger, hydraulic losses and heat flow from the surroundings are excluded from consideration, and the first step is to apply the constraints consistently

$$D_{hs} = 0. \tag{7}$$

$$D_{pi} = 0, i = 1, 2. \tag{8}$$

To fulfill equality (7), it is sufficient to set $Q_3 = 0$, and to achieve the fulfillment of conditions (8), it is necessary to equate the flow pressures at the outlet of the apparatus to the corresponding inlet pressures.

The next step of this method involves solving the energy balance equation (4) with respect to the selected unknown quantity. The selection procedure itself is generally informal and consists in specifying the nodal point, the parameter of which can be considered as an unknown quantity. Such a choice may be based on a hypothesis based on logical premises about the assumed influence of idealization (using equalities (7) or (8)) on the thermodynamic functions of the nodal points of the heat exchanger.

Taking into account the influence of hydraulic resistance on the procedure for idealizing a heat exchanger seems to be the clearest. If there were no hydraulic losses in the flow of the working fluid, then the pressures in inlet and in outlet for this flow of heat exchanger are equal. This gives grounds to assume that the use of expressions (7) causes only a change in the flow pressure at its outlet from the apparatus. Consequently, the application of equality (8) to any of the flows implies the solution of the energy balance equation (4) with respect to the enthalpy at the point of flow exit. In this case, the thermodynamic functions at all other nodal points are assumed unchanged.

There is no such clarity for the case of excluding heat Q_3. In principle, the use of constraint (7) can be accompanied by a change in thermodynamic functions at various nodal points, which depends on the design of the heat exchanger. However, if we ignore the design and keep in mind that only one unknown can be determined from equation (4), then it is necessary to choose a specific (calculated) point. Since equality (7) is an idealization, which should be accompanied by an increase in the efficiency of the heat exchanger, it is advisable to make this choice based on the purpose of the apparatus. The purpose of heat exchangers for low-temperature technology is to lower the temperatures of direct streams. Therefore, it makes sense for them to restrict such a choice to any of the outlets of direct streams. If the direct stream is the only one, then the choice will be unambiguous. If there are several direct streams, it is necessary to opt for the highest priority stream. Consequently, for this type of loss, equation (4) is solved with respect to the enthalpy at $Q_3 = 0$.

In principle, the value of D_{hf} could be determined by setting all other components of the total losses D_S to be equal to zero. However, this approach presupposes a more complex and insufficiently logically reasoned choice of thermodynamic parameters at individual nodal points.

Further calculation of the contributions of various components of losses is reduced to determining the thermodynamic functions at selected points from the known values of pressures and enthalpy, as well as calculating new values of total losses from equation (2).

It should be emphasized that due to the peculiarities of the considered method for determining the components of D_S, the procedure for excluding various types of losses is of no fundamental importance.

The last step of the considered method for determining the components of exergy losses does not need additional comments.

4. Results

The tasks of calculating the components of exergy losses are reduced to:

1. Revealing the contribution of certain types of losses in order to increase the thermodynamic efficiency of the heat exchanger.
2. Determination of their signs in order to establish the fact that the heat exchanger is operable at known parameters (pressures and temperatures) not only at its ends, but at arbitrary section of the heat exchanger, that is determined as the end of apparatus.

Due to options for choosing independent variables in the thermodynamic analysis of heat exchangers, it is difficult to expect generalizing results of calculations and corresponding conclusions without performing numerous calculations for specific devices. In addition, solving the first problem separately for a heat exchanger can lead to a situation where a decrease in losses in it will cause a let-down in the thermodynamic efficiency of the entire installation. Additional difficulties at the design stage of the installation are caused by the need to set the values of hydraulic resistance and heat inflows as initial data. For heat exchangers of some cryogenic plants, recommendations for the selection of these values are given in [31-35].

Below are the initial data and results of exergy analysis of two-flow heat exchangers used in cryogenic technology. The main initial data for the calculations of two-flow heat exchangers are reflected in Table 1. Heat exchangers of high and medium pressure air separation and fluidizing plants operating at different temperature levels were selected for modelling.

***Table 1** – Data for calculations of two-flow heat exchangers*

Heat exchangers	Working substances		Rate, kg/hr		Heat leakage, *W*
	M_{m1}	M_{n1}	M_{m1}	M_{n1}	
HE1	air	air	121,6	115,4	268,7
HE2	air	nitrogen	4853,1	3685,7	523,8
HE3	air	nitrogen	517,2	374,5	222,2
HE4	air	oxygen	258,6	214,2	138,9

Table 2 shows the thermodynamic parameters of the calculated heat exchangers at the nodal points. The pressures and temperatures at points 1, 2, 4 correspond to the data of the used literature sources. As a rule, pressure losses for forward flow are not presented in the literature. Therefore, the pressures at point 3 were selected according to the recommendations of [36-38].

The thermodynamic consistency of the results cannot be achieved without the model of equation state. For instance, the energy balance equation (4) is determined based on different forms of equation state.

The most common in practice are cubic equations of state of the van der Waals type [39, 40]. In this work cubic Redlich – Kwong – Wilson equation of state [41] is applied to determine thermodynamic properties of substances

Table 2 *– Temperatures and pressures at the nodal points of the two-flow heat exchangers*

Heat ex-changers	Temperature, K				Pressure, MPa			
	1	2	3	4	1	2	3	4
HE1	295,0	300,0	175,7	81,5	0,10	20,0	19,0	0,12
HE2	298,0	303,0	276,4	253,0	0,10	20,0	19,6	0,13
HE3	295,0	300,0	175,0	85,0	0,11	7,0	6,5	0,15
HE4	195,0	200,0	99,5	95,0	0,10	5,0	4,7	0,125

It should be noted that the use of the Redlich – Kwong – Wilson equation of state gives a satisfactory description of the thermodynamic properties of the working substances of the simulated heat exchangers with the parameters given in Table 2. For all variants are good agreement between calculated values of temperatures at point 3 with corresponding literature data.

The results of the components of exergy losses for the variants of heat exchangers considered above are shown in Table 3. Used names of the components of exergy losses in this table are D_{p1} – due to hydraulic resistance of a cold flow; D_{p2} – due to hydraulic resistance of a warm flow; D_{hs} – due to heat leakage from the surroundings; D_{hf} – due to non-equilibrium heat transfer between the flows of working substances; D_{Σ} – total losses from irreversibility in the heat exchangers.

Table 3 *– The results of the components of exergetic losses for two-flow heat exchangers*

Heat exchangers	Exergy losses, kW				
	D_{p1}	D_{p2}	D_{hs}	D_{hf}	D_{Σ}
HE1	0.506	0.126	0.195	3.407	4.234
HE2	23.940	2.664	0.044	2.642	29.290
HE3	2.076	0.744	0.159	11.124	14.903
HE4	1.433	0.132	0.282	13.196	15.043

5. Discussion

Analysis of the data in Table 3 gives the basis for the following conclusions:

1. The contribution of heat leakage from the surroundings to the total exergy losses of the heat exchangers under consideration is insignificant. This testifies to the sufficient efficiency of the thermal insulation used for these heat exchangers.

2. Despite the fact that for double-flow heat exchangers the hydraulic resistances in the cold flow are much less than in the warm flow, their share in D_S is significantly higher than the share of hydraulic resistances in the forward flow.

3. Table 3 shows that the main components of exergy losses of the investigated heat exchangers are losses from non-equilibrium heat transfer and hydraulic resistances of low pressure flows. Hydraulic losses in cold flows are limited and amount to (0,02…0,04) MPa for cryogenic systems. The values of specific losses from non-equilibrium heat transfer significantly depend on the temperature range in which the apparatus operates. The influence of these two factors determines the relationship between considered types of losses. For example, for the HE2 heat exchanger, which is in air separation plant and operates near the ambient temperature, the main contribution is the hydraulic losses in the cold flow.

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Термодинамічний аналіз теплообмінників у кріогенних системах

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У статті розглядаються проблеми термодинамічного аналізу, пов'язані з теплообмінниками, які використовуються в кріогенній техніці. Для моделювання були обрані теплообмінники повітророздільних та псевдозріджених установок високого та середнього тиску, що працюють на різних рівнях температуи. Існує багато ознак, за якими проводиться класифікація теплообмінників. До цих ознак належать такі факти, як кількість потоків робочої рідини, взаємний напрямок потоків робочих речовин, призначення апарату та ін. Ці особливості також пов'язані з конструкцією теплообмінників і програмним забезпеченням для проектування, яке містить термодинамічні розрахунки. Загальний термодинамічний підхід базується на рівнянні для значень термодинамічних характеристик ефективності та накладених на них обмежень. При ексергетичному методі аналізу відповідний баланс базується на рівнянні балансу енергії. На основі цього балансу можна безпосередньо визначити втрати від необоротності обраного об'єкта та його ексергетичну (термодинамічну) ефективність. В теплообміннику існують обидва типи втрат, але неможливо виявити внесок кожного типу в загальні втрати з використанням тільки ексенергетичного балансу. Це пов'язано з тим, що даний баланс складається для замкнутої контрольної поверхні, яка відображає фізичний об'єкт, а не логічних причин, пов'язаних з цим об'єктом. Водночас визначення технічних втрат є актуальною задачею, оскільки зміна термодинамічних параметрів, що регулюють ці втрати, є основою підвищення коефіцієнта термодинамічної ефективності аналізованої системи. Запропоновано метод і алгоритм розрахунку складових втрат від необоротності в цих теплообмінниках. Для розрахунку складових втрат для деяких двопотокових теплообмінників використано ексергетичний метод термодинамічного аналізу. Представлено дослідження отриманих результатів розрахунку.

Ключові слова: *Кріогенна технологія; Теплообмінник; Рівняння стану; Ексергетичний метод; Втрати від незворотності процесів*

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