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HAZARDS OF STANDARD HEAT-EXCHANGE EQUIPMENT IMPLEMENTATION IN CHEMICAL TECHNOLOGY WITHOUT CONSIDERING THE PROCESS SPECIFIC CHARACTER*

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Standard equipment is a considerable part of modern equipment of chemical plants. In particular, standard heat exchangers are widespread. Possible deviations in the operation of heat exchangers at plants from the preset parameters of their operation can lead to deterioration of the operation of the whole technological system. For this reason an attempt is made in the article to suggest a hypothesis explaining what can lead to disfunction in the operation of heat exchangers. The authors use a method of calculating technological reliability to study the operability of a vertical shell-and-tube heat exchanger. First, the size of the heat transfer surface of the vertical heat exchanger is calculated for specific conditions of work, and a standard device is chosen. Then a method of calculating the technological reliability of the calculated and standard heat exchangers is applied. An operating problem is solved on the assumption that external impacts on the heat transfer process are not fixed, but varied and are within their acceptable intervals. After comparing the probability of the workability of the calculated heat exchanger and of the chosen standard apparatus, a conclusion is made about the expediency of using the standard heat exchanger.

Keywords: *heat exchange, reliability, standard equipment, similarity theory, condensation.*

In recent years, not enough attention is paid to heat exchange, in particular, to such a widespread chemical industry process as heat exchange in shell-and-tube heat exchangers. Essentially, articles are devoted only to design [1, 2]. However, the technological operating modes of a heat exchanger can also cause problems and even result in its mechanical destruction. Analysis of the technological reliability of a vertical heat exchanger with condensation of the heating steam occurring in it shows the ambiguity of modern approaches to the choice of equipment in some cases.

The reliability analysis in this article is carried out according to the theory of technological reliability [3]. This theory is most relevant for evaluating the operation of a heat exchanger if a mathematical model is available. This method of calculating the technological reliability indicator is chosen, because it is correct and allows revealing the most harmful external effects and eliminating them, thereby increasing the operation reliability of the apparatus (or, as a result, of the whole technological scheme).

Let us give two main definitions [4].

Reliability is operability in time.

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Operability is the state of an object (system), at which the values of all parameters characterizing the ability of the object (system) to perform its target functions conform to the requirements of normative-technical and/or design documentation.

This work is based on a mental experiment. The main calculations were made within this experiment using the conventional calculation procedure improved by the authors for solving the operational task. In this case the results are of both practical and scientific interest.

The main task is formulated to check the hypothesis [3] of the disadvantage of excessive heat exchange surface. In this case the author of [3] believed that the problem is the considerable surface excess in heat exchangers that are considered to be standard in many cases, in particular, in modern computer programs for calculating heat transfer. This is logical. However, we will use the mental experiment to answer the question: what is the influence of the excess heat exchange surface?

Problem Definition

Let us imagine a process of heat exchange with an infinite surface (see Figure 1). Then two extreme cases are possible. First, the outlet temperatures differ slightly (in case of counter-flow shown in the figure, the inlet and outlet temperatures of two flows), i.e., according to the technology the temperature of the heat transfer agent is close of that of the working fluid. A second case is when the difference in temperatures provides a strong driving force of the process, but it is assumed that the temperatures of the flows at the end of the heat exchanger are different (for counter-flow see Figure 1). On the basis of the heat transfer formula (1) [5, 6] let us assume that the heat exchanger with the infinite surface is capable of transferring an infinite heat quantity.

$$Q = KF\Delta_t \qquad (1)$$

However, if the area is fixed and K is assumed to be constant (it slightly changes as compared to infinity), we still have a variable driving force – the logarithmic difference of temperatures. When the temperatures at the ends of the heat exchanger become equal, infinity is multiplied by 0, and an indeterminate form appears. In this case it can be said that when the heat exchange surface is infinite, the difference of temperatures at the ends of the heat exchanger cannot be more than an infinitely small quantity. Otherwise, an infinite quantity of heat that just does not exist in the flow is transferred in the stationary process. In fact, heat transfer up to $\Delta_t \rightarrow 0$ will occur in this case. Thus, the second option presented in the experiment is unrealizable.

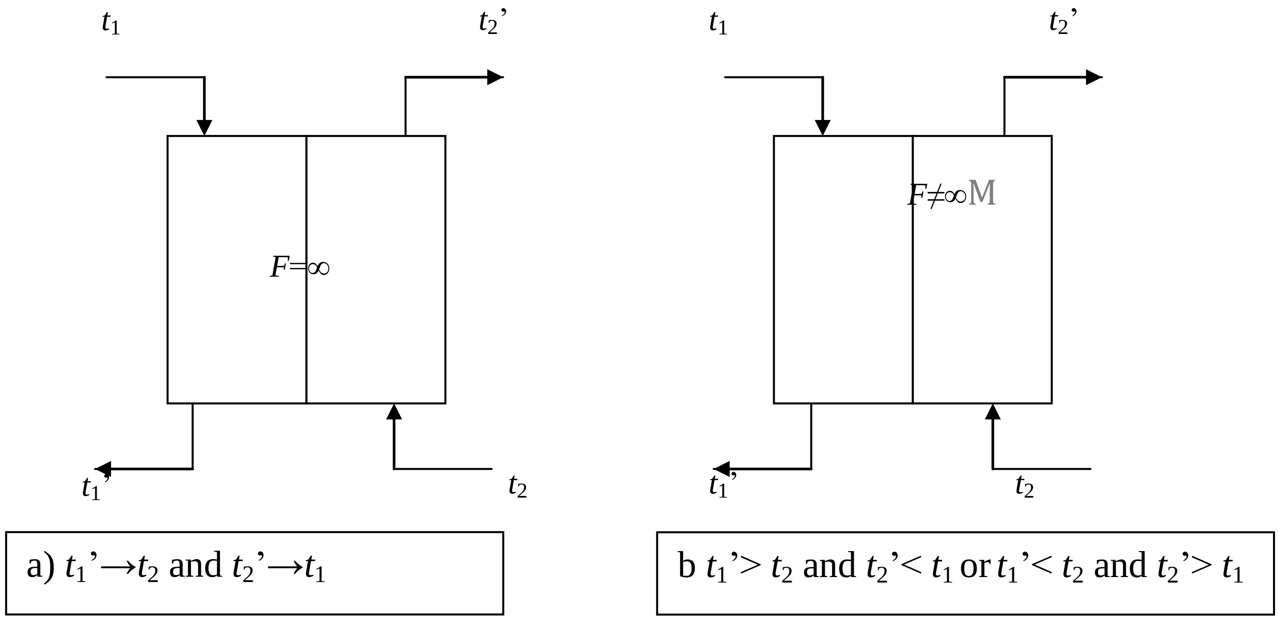

Figure 1. Counterflow heat transfer: a) with an infinite heat-transfer surface; b) with a finite heat-transfer surface.

Thus, it can be assumed that excessive surface is most harmful in case of a strong driving force, i.e., when the flow temperatures considerably differ and one flow should be heated just to a specific temperature, but not to a temperature maximally close to the heating flow temperature. Thus, we need to check how a small excess of area affects the technological reliability of the heat exchanger when, first, there is a physical restriction for the top temperature of the flow and, second, there is an essential difference in temperatures between the flows.

Such heat exchangers are not uncommon in practice in petrochemistry, where it is possible to heat flows with saturated vapor only from already available steam lines with standard fixed pressures. In addition, the condensing temperature of saturated vapor is not always the required temperature.

The following calculation task was formulated:

A vertical shell-and-tube heat exchanger is heated with vapor with pressure p = 6±0.5 at. The quantity of water in the heat exchanger is G_{water} = 5±0.75 kg/s, and the water is heated from temperature t_2 = 20±10°C to temperature t_2’ = 95±5°C. The fluctuation of steam quantity at the heat exchanger inlet is ±15% of the mass flow. The inaccuracy of all scientific information is also 15%.

The solution was divided into three consecutive steps:

1. Choosing a heat exchanger for the preset process parameters (the design task).
2. Finding the outlet temperatures of the chosen heat exchanger with the same inlets (the operational task required for further calculation of reliability).
3. Determining the reliability of four different apparatuses: a standard and a custom-designed heat exchanger with the reference surface calculated taking into account and without taking into account the inaccuracy of scientific information.

Besides, a number of essential assumptions for this task should be mentioned. They do not always exist in real life, which often significantly complicates the calculation of reliability of a specific exchanger. These are the following assumptions:

– All the inlets do not depend on the outlets: this is a necessary condition for reliability calculation.
– Only one parameter at the heat exchanger outlet is controlled, while the system can come to a failure mode also because of the second flow (condensate overcooling or partial condensation).
– It is not taken into account whether wet or dry vapor is supplied. We believe that inlet pressure fluctuations are due to the fact that the vapor is brought to the condition of saturation by special devices at the inlet. Another cause of pressure fluctuations is partial condensation of the vapor in the tubes.
– We believe that the stationary state calculated by formulas from [5, 6] is achievable, because the heat transfer coefficient is calculated with the use of semi-empirical dependences. Thus, the achievability of this stationary state is tested through practice. Nevertheless, note that it is necessary to bring the heat exchanger to this specific equilibrium state in the course of start-up for correct estimation of reliability. In this case the plurality of stationary conditions of the heat exchanger is possible even when the heat transfer equation has a unique solution, and this will depend not only on it, but also on the whole system up to the considered heat exchanger.

Let us explain the physical nature of the upward restriction of flow temperature. When temperature rises to 100°C at 1 atm, water boiling in the heat exchanger tubes is possible. This will undoubtedly result in the heat exchanger destruction in a short time because of hydraulic shocks. Analyzing mechanical failures of heat exchangers in a real enterprise [7] showed a substantial proportion of heat exchangers failing before corrosion start because of mechanical damage and inaccuracies of fabrication. This is largely due to incorrect technological modes, including the use of the standard equipment.

Calculation and Methodology

In order to solve the task let us first create a table of external influences and preset parameters (Table 1) according to the mathematical model.

Table 1. Table of external influences and preset parameters

External influences			
External influence	Designation	Unit of measure	Type of external influence
Tubes size	d	mm	Dimensional defect of equipment
Heat exchanger surface area	F	m^2	
Inlet water temperature	t_2	°C	Fluctuations of technological parameters in the flow due to external environment and equipment precision
Vapor pressure	p	Pa	
Steam flow	V_v	kg/s	
Water flow	V_{liq}	kg/s	
Starting solution heat capacity	c_0	kJ/(kg·K)	Inaccuracy of scientific information
Coefficient of dynamic viscosity of water	μ_2	Pa·s	
Coefficient of heat conduction of water	λ_2	W/(m·K)	
Water density	ρ_2	kg/m^3	
Evaporation heat	r	J/kg	
Coefficient of dynamic viscosity of condensate	μ_2’	Pa·s	
Coefficient of heat conduction of condensate	λ_2’	W/(m·K)	
Condensate density	ρ_2’	kg/m^3	
Prandtl number	Pr	–	
Nusselt number	Nu	–	
Coefficient of heat transmission from vapor to tube (absorption factor $A \cdot 1.06 \cdot H^{0.25}$)	A_0	–	
Preset parameters			
Preset parameter	Designation	Unit of measure	–
Outlet water temperature	t_2’	°C	

The design task was solved according to [5, 6]. Let us give the basic formulas for calculating heat transfer (1), heat transfer coefficient (2), logarithmic difference of temperatures (3) and Nusselt number (4). Besides, balance equations were applied, including balance by heating steam (5). It is important that when calculating the heat transfer, vapor condensation is calculated only up to point 2’ (Figure 2). At the same time excessive surface will probably result in condensate cooling, that is, the substance will come to state 3. This is the main problem of conventional calculation: it is assumed for simplicity that condensation is the only heat loss process. The condensate cooling is not taken into account, because the heat quantity per vapor degree is small as compared to the enormous heat of condensation. In this work we will try to take into account this process completely.

$$\frac{1}{K} = \frac{K^{1/3}\Delta_t^{1/3}}{A^{4/3}} + \frac{\delta_{cm}}{\lambda_{cm}} + \frac{1}{\alpha_2} \tag{2}$$

$$\Delta_t = \frac{\Delta_2 - \Delta_1}{\ln\left(\frac{\Delta_2}{\Delta_1}\right)} = \frac{(t_1 - t_2^{'}) - (t_1^{'} - t_2)}{\ln\left(\frac{(t_1 - t_2^{'})}{(t_1^{'} - t_2)}\right)} \tag{3}$$

$$Nu = 0,008 \cdot \mathrm{Re}^{0,9} \cdot \mathrm{Pr}^{0,43} \tag{4}$$

$$Q = G_{nap} r + G_{nap} c_1 t_1^{'} - G_{nap} c_1 t_1 \tag{5}$$

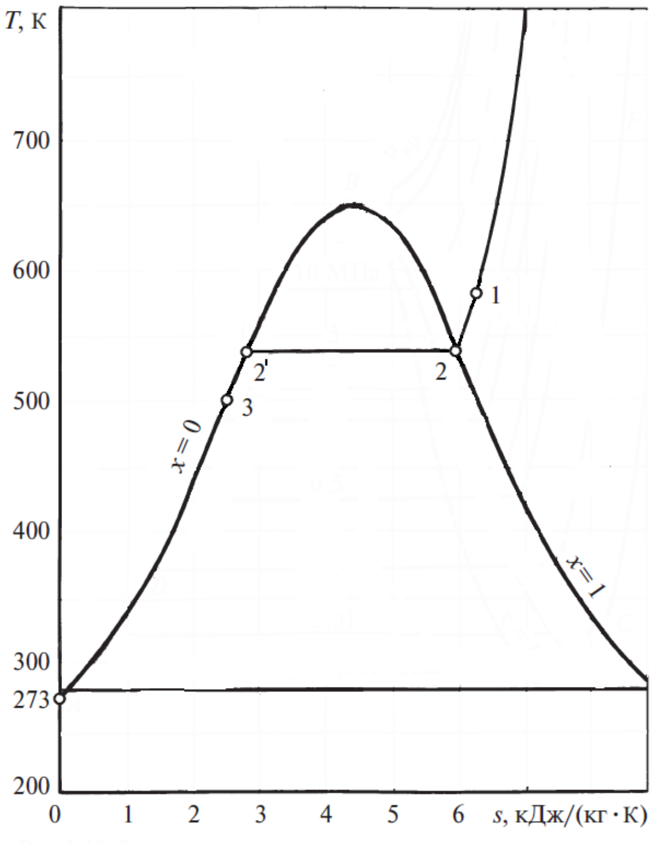

Figure 2. T-S state diagram of water.

[кДж/(кг·К) means kJ/(kg·K)]

Note that a standard shell-and-tube double-pass heat exchanger with a surface of 17 m^2 was chosen to select a heat exchanger with a calculated area of 15.2 m^2. Besides, only vapor condensation was taken into account when calculating, and, therefore, choosing the heat exchanger.

In order to calculate the operational task an original scheme was suggested. The required formulas were taken from the design task [5, 6]. The dependences of all physical properties on temperature were approximated by functions of different complexity for the subsequent numerical experiment. As for the calculation complexity, it is caused by the fact that the sought-for outlet temperatures are included in the calculation formulas in the form of average logarithmic difference of temperatures and should be iterated along with the heat exchange coefficient.

In order to take into account condensate cooling the same heat transfer coefficient was used. This is due to the fact that the abstraction dividing the heat exchanger into parts cannot be applied, because the vapor is condensed on all the surface of the tubes, and the condensate is cooled anyhow on the tubes only where it was condensed. In this case the calculation of the coefficient of heat transfer from the casing, that is α_2, to be exact, *Nu*, from which it is calculated, should be corrected. Because coefficients for the calculation of *Nu* are obtained in laboratory experiments, we had no opportunity to specify its values, and we took the value of this coefficient as it is calculated in case of condensation [6].

The precision of this calculation is rather poor. It is complicated also by the fact that the variation amplitude of the calculated values is initially extremely large and can lead to the emergence of negative logarithm. Thus, it is necessary to introduce a restriction for condensate temperature in the calculation. If it is impossible to transfer the necessary amount of heat in the standard calculation, condensate temperature can exceed vapor temperature. Condensate temperature was just replaced with vapor temperature considering that the vapor was not condensed completely. A considerable increase in the amount of transferred heat due to the above-mentioned high amplitude of variations when searching for a solution caused a situation when condensate temperature could become lower than the temperature of the second flow contacting with it. In this case condensate temperature was replaced with the temperature of the second flow plus 5 degrees.

We assumed what all external influences are random values distributed normally, and the limits of their variations are determined by the range within which there are all possible values of parameters. Thus, we take the nominal value as the mathematical expectation, and we will obtain the value dispersion on the basis of the fact that this range is equal to 3σ. Thus, if a is the nominal value, Δa is the possible value dispersion, then $M = a$, $\sigma = \Delta a/3$. The random values were obtained from [8], where, in turn, normal distributions were obtained from the uniform distributed random variations of pressure with the use of the Box-Muller transform. For the deviation of physical and chemical constants (for which fluctuations were taken according to measurement and approximation accuracy [9]) the random quantity with $M = 0$, $\sigma = \Delta a/3$ was added to the calculated value. Besides, the inaccuracy of the approximating formulas for calculating heat transfer coefficients was considered.

Temperature exceeded the preset range in the operational calculation with the standard heat exchanger. It was decided to carry out the numerical experiment with two different heat exchange surfaces taking into account and without taking into account the scientific information accuracy (see [3]). The first calculations are given for the standard heat exchanger, the subsequent calculations – for a heat exchanger designed *ad hoc* with the calculated surface area.

Results and Discussion

The probability of operability of the heat exchanger designed *ad hoc* was found to be rather low because of the considerable flows fluctuations, both without taking into account the inaccuracy of scientific information and taking it into account. It slightly decreased in the latter case (see Table 2)

Table 2. Results of reliability calculation

	Standard heat exchanger	Heat exchanger designed *ad hoc*
Without taking into account the inaccuracy of scientific information	$P = 0.247$	$P = 0.456$
Taking into account the inaccuracy of scientific information	$P = 0.334$	$P = 0.443$

In case of the standard heat exchanger the results were much lower than in case of the designed one. As supposed, the main shift was towards outlet temperature overestimation, (Figure 3). This overestimation is a direct consequence of the excess surface through which a larger quantity of heat contained in the heating steam was transmitted (see Figure 2). The fact that similar shift does not occur in the rated heat exchanger is rather logical too.

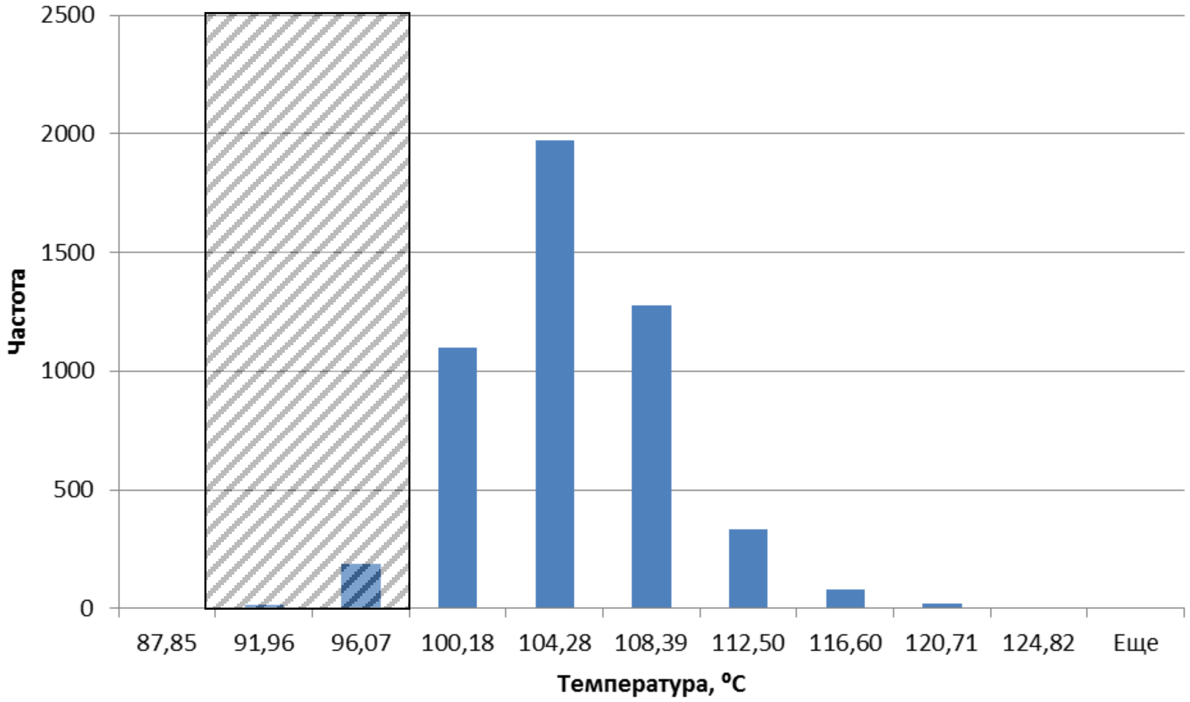

Figure 3. Temperature distribution at the standard heat exchanger outlet without taking into account the inaccuracy of scientific information.

[Частота means Frequency; Температура means Temperature; Ещё means More]

The paradox of the standard heat exchanger is due to the violation of the hypothesis given in [3] which says that taking into account additional external influences can only worsen the reliability indicator. However, comparing Figure 3, Figure 4 and Table 3, it is fair to say that there are situations when taking into account additional external influences can slightly improve the reliability indicator. This occurs due to dispersion growth and change of the type of the preset parameter distribution function, if mathematical expectation exceeds the limits of the allowed range of parameter variations. It follows from the conditions of the emergence of such situation that even at unidirectional restriction of the allowed range growth of the reliability indicator is possible only if its value $P < 0.5$ and is strongly limited due to the mathematical expectation.

Table 3. Statistics of outlet temperature distribution

Standard heat exchanger				Calculated heat exchanger	
Taking into account the inaccuracy of scientific information		Without taking into account the inaccuracy of scientific information		Taking into account the inaccuracy of scientific information	
Average	95.1	Average	102.8	Average	89.1
Standard error	0.1323	Standard error	0.0597	Standard error	0.142
Median	97.8	Median	102.6	Median	91.1
Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard deviation	9.35	Standard deviation	4.21	Standard deviation	10.05
Sample variance	87.3	Sample variance	17.77	Sample variance	101.0
Kurtosis	–0.507	Kurtosis	0.971	Kurtosis	0.1032
Asymmetry	–0.649	Asymmetry	0.435	Asymmetry	–0.713
Interval	53.4	Interval	37.0	Interval	65.8
Minimum	61.1	Minimum	87.9	Minimum	49.5
Maximum	114.5	Maximum	124.8	Maximum	115.3

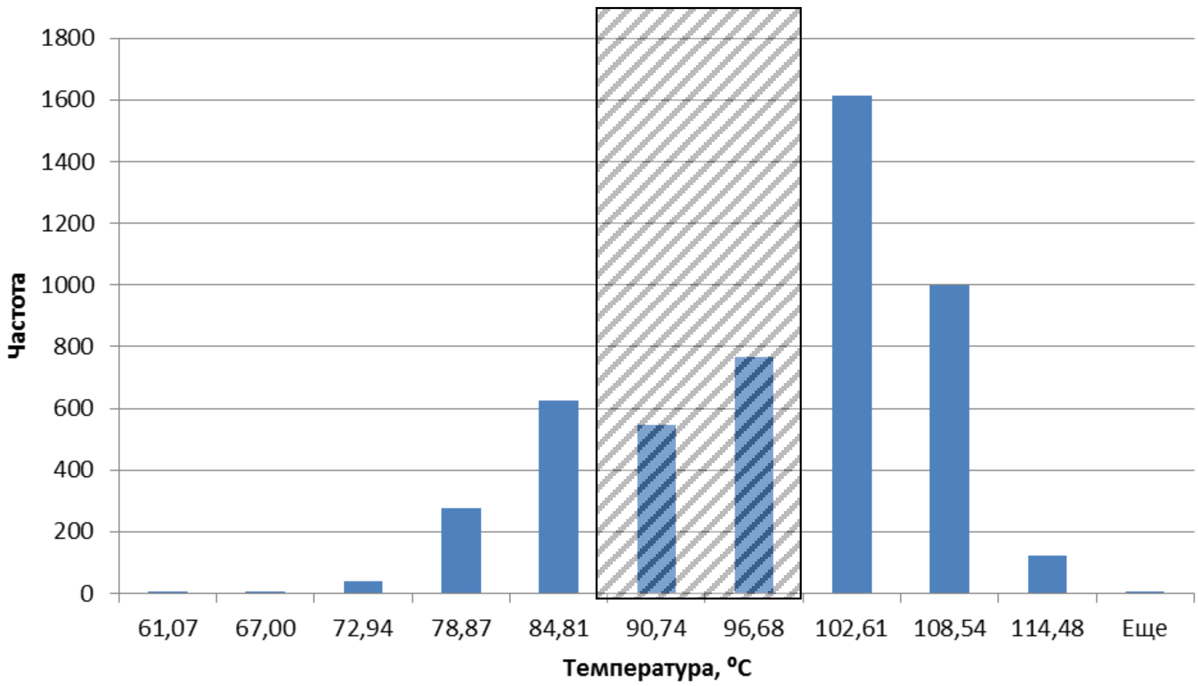

Figure 4. Distribution of temperatures at the standard heat exchanger outlet taking into account the inaccuracy of scientific information.

[Частота means Frequency; Температура means Temperature; Ещё means More]

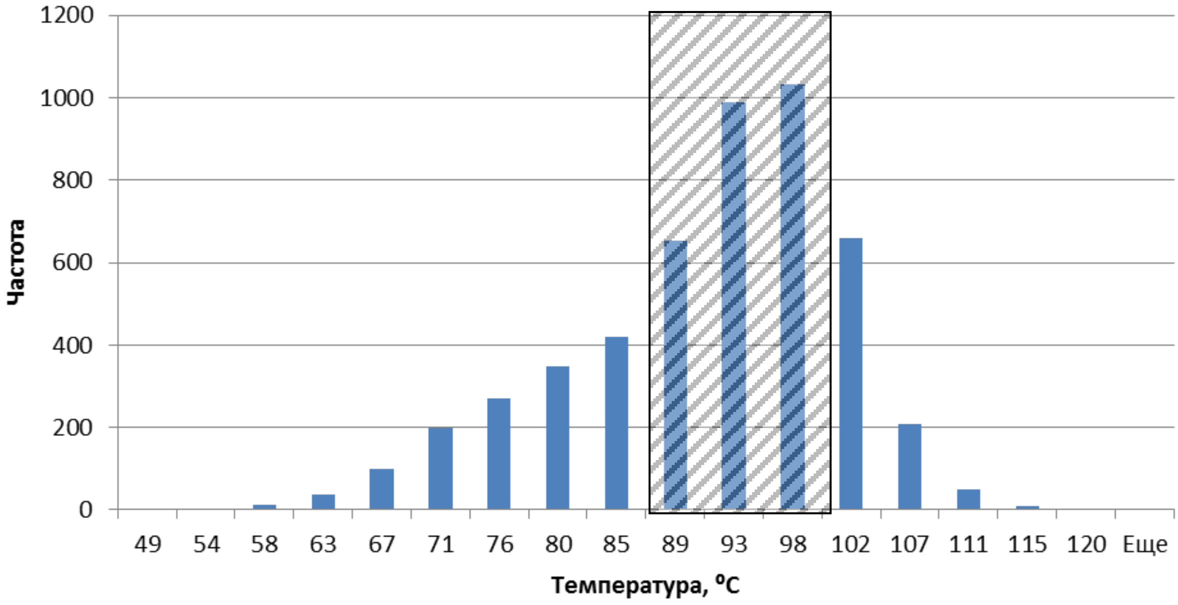

Figure 5. Distribution of temperatures at the calculated heat exchanger outlet taking into account the inaccuracy of scientific information.

[Частота means Frequency; Температура means Temperature; Ещё means More]

Besides, comparing figure 4 and figure 5 it is possible to see that the shift of the mathematical expectation is the reason of lower reliability of the system.

Conclusions

1. Condensate cooling can be of considerable importance in case of heat exchange upon condensation, especially in case of strong driving forces. Thus, its cooling should be considered when calculating condensation.
2. Condensation in the heat exchanger remains ideal without condensate overcooling. Thus, no change of the standard calculation method is required. However, in case of choosing a standard heat exchanger it is necessary either to use the correct technological calculation (see 1) and to calculate the system reliability with the standard heat exchanger and with the calculated one or to choose at once the calculated heat exchanger if studying reliability is impossible or expensive.
3. It is shown that even a small excessive surface is extremely dangerous in the conditions of a large temperature difference. Conventions of technological calculation can "hide" such problem from technologists, which results both in considerable shifts of the material balance and in breakdown of heat exchangers because of flow boiling in the tubes. It is important to

remember that *the probability of operability of the whole system cannot be higher than the probability of operability of its parts.*

4. Technological reasons can lead to mechanical failures of the system, which explains the large number of heat exchangers failing at the early stage of operation. In this case it is possible either to increase the heat exchanger cost increasing its strength characteristics or to exclude technological factors resulting in mechanic failure, that is, to improve technological reliability.

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