

Improvement of engineering methodology of design of shell-and-tube heat exchangers in MathCad mathematical system

A. R. Lebedev¹, V. V. Romanov¹, N. S. Alekhin¹, S. O. Kireev¹, and G. A. Galka^{1*}

¹Don State Technical University, 1, Gagarin Sq., 344002 Rostov-on-Don, Russia

Abstract. The problems of optimal design of shell-and-tube heat exchangers, widely spread in industry, acquire new aspects of relevance due to the rapid development of digital design technologies and computer mathematics systems. The review of works of domestic and foreign researchers in the field of design of shell-and-tube heat exchangers is carried out. The aim of the work is to increase the efficiency of shell-and-tube heat exchanger design by applying the methods of optimal design. Materials and methods. The traditional method of calculation of shell-and-tube heat exchanger is analyzed, on the basis of which the ways of its modernization are determined. A new calculation scheme consisting of three parts is proposed. In the first part, formulas and reference data are used, the calculation and selection of which do not require the use of search procedures. The second part consists of a set of functions describing the design parameters of the heat exchanger, the arguments of which are control parameters. The third part of the method solves the optimization problem of obtaining the extremum of the target parameter under the action of a number of constraints on the structural parameters of the apparatus. To verify the efficiency of calculations, a parametric solid-state model of the heat exchanger is used, with the use of which the thermal-hydraulic calculations were carried out. The results of the research. On a concrete example it is shown that the proposed methodology of optimal design of shell-and-tube heat exchanger allows to obtain a design with minimum total weight of tubes. A number of calculations of the heat exchanger are carried out to illustrate that it is practically impossible to achieve the optimal parameters of the apparatus by methods of "manual counting". Thermal-hydraulic calculation of the optimal design of the apparatus showed good adequacy of the results obtained by the proposed method and the data of thermal calculation with the help of CAD-system.

1 Introduction

Shell and tube heat exchanger (STHE) is a widely used apparatus used in manufacturing industry, oil refining, heat and power plants, etc. The tasks of optimal design of STHE design are becoming more and more urgent, especially in connection with the emergence of

* Corresponding author: jukova-84@mail.ru

new digital modeling tools that open for design engineers wide horizons of opportunities to obtain the product with minimum costs.

The authors of [1] show that traditional methods of achieving the minimum cost of a heat exchanger include manual calculations and repeating the same calculations by changing several parameters until a minimum solution is obtained. However, this method requires a lot of effort and time, but in the end, it does not guarantee an optimal solution. This paper presents new efficient algorithms for finding the optimal solution to the apparatus calculation problem.

In [2], the authors applied global optimization techniques and automation of the design process using new CAD systems, thus minimizing manual calculation methods and ensuring the creation of more accurate and cost-effective designs.

In [3], the authors show the problems of heat exchanger design arising from the multimodality and nonlinearity of the design functions. Due to this, the algorithms face the problems of slow convergence rate and tendency to local optima, making it difficult to achieve satisfactory solutions. The authors developed an improved Levy Opposition Equilibrium Optimizer (LOEO) optimization algorithm and applied it to heat exchanger calculations.

In [4], the problem of multiobjective optimization of shell-and-tube heat exchanger is also solved using evolutionary algorithms Predator-Prey, Multiobjective Particle Swarm Optimization and Non-Dominated Sorting Genetic Algorithm II.

In [5], the authors also address the optimization of heat exchanger design, with special attention to the problem of selecting the target function. The work critically reviews and compares objective functions on a sequential basis to show their impact on equipment configuration and to evaluate their respective advantages and disadvantages. The results show that the choice of the objective function strongly influences the resulting “optimal” design that some commonly used functions are counterproductive and can lead to impractical configurations from an engineering point of view.

The study [6] presents a novel layout optimization scheme for shell-and-tube heat exchangers using a reliability-based design optimization approach. The system combines a surrogate model based on control variables and a hybrid metaheuristic algorithm. The integration of this approach with a mathematical model that considers factors such as inlet flow temperature, mass flow rate, and fouling resistance demonstrated the system's ability to balance the trade-off between cost and reliability under uncertainty.

Combining the capabilities of computer mathematics systems and modern CAD-systems generates new prospects for achieving efficiency in the design of new technical products. In particular, in [7] a methodology of three-dimensional finite-element calculation of the unsteady heating mode of a composite structure of complex shape was developed. New finite element models describing thermal fields in the structure during its fabrication are proposed. In [8-10] it is shown how the use of computer mathematics systems together with CAD system allows to obtain optimal variants of designs of various products in mechanical engineering.

In [11] it is noted that optimal design of heat exchangers is a difficult task because there is a complex nonlinear relationship between various design parameters. The authors developed a full-size shell and tube heat exchanger model using two common methods (Kern and Bell-Delaware) based on the logarithmic mean temperature difference method. As a result, it was possible to reduce the design cost by 54 %.

In the article [12] it is noted that shell-and-tube heat exchangers are important equipment used in all industries. Mathematical models describing the thermal-hydraulic behavior of this equipment generate a complex search space. Because of this complexity, traditional gradient algorithms do not converge in the neighborhood of the global optimum. In this paper, four optimization examples for shell and tube heat exchangers are considered.

For each example, the use of Kern and Bell-Delaware methods with discrete and continuous pipe diameters is considered, which leads to the solution of 16 optimization problems (four problems for each example), where the objective function is the total annual cost of the equipment.

In [13], the Taguchi method is applied to the results of numerical simulation of a shell-and-tube heat exchanger with staggered baffles in order to optimize its design parameters corresponding to the maximum heat transfer rate and minimum pressure drop. The authors applied CFD simulation to find the optimal combination of control parameters.

The relevance of the problem lies in the fact that, on the one hand, design methods for shell-and-tube heat exchangers are based on the preliminary acceptance of some recommended values of the design parameters within some limits (e.g., the velocity of fluid flow in tubes 1-2 m/s [14, 15]), which subsequently have to be refined or adjusted to obtain the desired result. On the other hand, design optimization techniques [1-6, 12-13] are usually complicated and incomprehensible for design engineers involved in the actual design of heat exchangers.

In this paper, a design methodology for shell-and-tube heat exchangers is developed, in which optimization procedures are carried out in MathCad program, which has a simple and understandable interface, suitable for wide use by design engineers in the design office.

The aim of the work is to improve the efficiency of shell-and-tube heat exchangers design. The objectives of the study are: to analyze the traditional engineering methodology for calculating the design parameters of heat exchangers, to identify the relationships between the parameters, to form a system of target and variable design parameters; to implement the design methodology in MathCad system; to build a solid parametric model of the heat exchanger for thermal-hydraulic calculations; to conduct a series of comparative tests for the proposed and traditional methods of design of shell-and-tube heat exchangers; to analyze the results of the study.

2 Materials and methods

Calculation methods of design of shell-and-tube heat exchangers are oriented on different types of heat transfer fluids and structural designs of apparatuses. Consideration of all variants of heat exchanger design is beyond the scope of our research. We intentionally limit ourselves to the variant of shell-and-tube single-phase single-pass water-water heat exchangers. Initial data and an example for heat exchanger calculation are given in Table 1.

Table 1. Initial data of the calculation methodology.

№	Name	Designation	Dimension	Number
1	Volumetric flow rate of the hot water pump	V_g	m ³ /hour	10
2	Heat load	Q	kW	100
3	Hot water inlet temperature	t_{1n}	°C	75
4	Inlet temperature of heated water	t_{2n}	°C	15
5	Temperature of heated water at the outlet	t_{2k}	°C	32
6	Heat transfer coefficient of tubes (steel 12X18H10T)	λ_{tp}	W/(M·K)	16

The calculation methodology is divided into the following main parts. The first part (thermal calculation) contains formulas, working based on initial and reference data, which do not require search procedures for setting the values of design parameters of the heat exchanger. The composition of such formulas and an example of calculation are given in Table 2.

Table 2. Formulas of the first part of the heat exchanger calculation methodology.

№	Name	Designation, Dimension	Formula or selection condition	Number
1	Density of heated water	ρ_2 , kg/m ³	According to the table of properties of water at temperature t_{2n}	998.9
2	Specific heat capacity of heated water	c_2 , kJ/(kg·K)	According to the table of properties of water at temperature t_{2n}	4.19
3	Density of hot water	ρ_1 , kg/m ³	According to the table of properties of water at temperature t_{1n}	974
4	Specific heat capacity of hot water	c_1 , kJ/(kg·K)	According to the table of properties of water at temperature t_{1n}	4.19
5	Mass flow rate of heated water	G_2 , kg/sec	$G_2 = \frac{Q}{(t_{2k} - t_{2n}) \cdot c_2}$	1.4
6	Volume flow rate of heated water	V_h , m ³ /hour	$V_h = \frac{G_2 \cdot 3600}{\rho_2}$	5.06
7	Mass flow rate of hot water	G_1 , kg/sec	$G_1 = \frac{V_g \cdot \rho_1}{3600}$	2.71
8	Hot water outlet temperature	t_{1k} , °C	$t_{1k} = t_{1n} - \frac{Q}{G_1 \cdot c_1}$	66.18
9	Average hot water temperature	t_{1cp} , °C	$t_{1cp} = \frac{t_{1n} + t_{1k}}{2}$	70.59
10	Average logarithmic head	Δt_{cp} , °C	$\Delta t_{cp} = \frac{(t_{1k} - t_{2n}) - (t_{1n} - t_{2k})}{\ln\left(\frac{t_{1k} - t_{2n}}{t_{1n} - t_{2k}}\right)}$	46.97
11	Average heated water temperature	t_{2cp} , °C	$t_{2cp} = t_{1cp} - \Delta t_{cp}$	23,62
12	Kinematic viscosity of hot water	ν_1 , m ² /sec	According to the table of properties of water at temperature t_{1cp}	4,12·10 ⁻⁷
13	Heat transfer coefficient of hot water	λ_1 , W/(m·K)	According to the table of properties of water at temperature t_{1cp}	0.67
14	Prandtl number for hot water	Pr_1	According to the table of properties of water at temperature t_{1cp}	2.53
15	Kinematic viscosity of heated water	ν_2 , m ² /sec	According to the table of properties of water at temperature t_{2cp}	9.3·10 ⁻⁷
16	Heat transfer coefficient of heated water	λ_2 , W/(m·K)	According to the table of properties of water at temperature t_{2cp}	0.61
17	Prandtl number for heated water	Pr_2	According to the table of properties of water at temperature t_{2cp}	6.44
18	Prandtl number for average wall temperature	Pr_{cr}	According to the table of properties of water at temperature $(t_{1cp} + t_{2cp})/2$	3.76

The second part of the design methodology consists of a set of functions of several variables, the arguments of which are the parameters of the apparatus design and the flow of liquids in its volumes that can be varied within specified limits. Such parameters include n - number of tubes, d - outer diameter of tubes (mm), ω_1 - flow velocity of heating water in

tubes (m/s); ω_2 - flow velocity of heated water in the casing of the apparatus (m/s). The composition of functions is given in Table 3.

Table 3. Functions of the second part of the heat exchanger calculation methodology.

No	Name	Designation, Dimension	Functions or selection condition
1	Reynolds number for heating water flow	Re_1	$Re_1(d, \omega_1) = \frac{\omega_1 \cdot d}{\nu_1 \cdot 10^3}$
2	Nusselt criterion for turbulent water flow in the tube	Nu_1	$Nu_1(d, \omega_1) = 0.021 \cdot Re_1(d, \omega_1)^{0.8} \cdot Pr_1^{0.43} \cdot \left(\frac{Pr_1}{Pr_{1st}} \right)^{0.25}$
3	Tube wall thickness	δ , mm	$\delta(d)$, choose from the tables of tube sizes depending on the diameter d
4	Heat transfer coefficient from the heating water to the tube wall	α_1 , (W/(m ² ·K))	$\alpha_1(d, \omega_1) = \frac{Nu_1(d, \omega_1) \cdot \lambda_1 \cdot 10^3}{d - 2 \cdot \delta(d)}$
5	Outer diameter of the shell	D , mm	$D(n, d) = 1.5 \cdot d \cdot \sqrt{n}$, then select the nearest value from the reference tables
6	Casing wall thickness	δ_k , mm	$\delta_k(D(n, d))$, choose from pipe size tables depending on diameter D
7	Inner diameter of the casing	D_v , mm	$D_v(n, d) = D(n, d) - 2 \cdot \delta_k(D(n, d))$
8	Equivalent diameter for heated water flow	D_e , mm	$D_e(n, d) = D_v(n, d) - (d - 2 \cdot \delta(d)) \sqrt{n}$
9	Reynolds number for heated water flow in the shell	Re_2	$Re_2(n, d, \omega_2) = \frac{\omega_2 \cdot D_e(n, d)}{\nu_2 \cdot 10^3}$
10	Nusselt criterion for turbulent water flow in the shell	Nu_2	$Nu_{12}(n, d, \omega_2) = 0.021 \cdot Re_2(n, d, \omega_2)^{0.8} \cdot Pr_1^{0.43} \cdot \left(\frac{Pr_2}{Pr_{1st}} \right)^{0.25}$
11	Heat transfer coefficient from the tube wall to heated water	α_2 , (W/(m ² ·K))	$\alpha_2(n, d, \omega_2) = \frac{Nu_2(n, d, \omega_2) \cdot \lambda_2 \cdot 10^3}{D_e(n, d)}$
12	Heat transfer coefficient	K_r , (W/(m ² ·K))	$K_r(n, d, \omega_1, \omega_2) = \frac{1}{\frac{1}{\alpha_1(d, \omega_1)} + \frac{\delta(d) \cdot 10^{-3}}{\lambda} + \frac{1}{\alpha_2(n, d, \omega_2)}}$
13	Heat flux density	q , W/m ²	$q = K_r(n, d, \omega_1, \omega_2) \cdot \Delta t_{cp}$
14	Heating surface area	F , m ²	$F(n, d, \omega_1, \omega_2) = \frac{Q \cdot 10^3}{q(n, d, \omega_1, \omega_2)}$
15	Length of the heat exchanger tubes	L , mm	$L(n, d, \omega_1, \omega_2) = \frac{F(n, d, \omega_1, \omega_2) \cdot 10^6}{\pi \cdot d \cdot n}$

The third part of the design methodology includes solving the problem of determining the optimal levels of varying parameters n, d, ω_1, ω_2 , at which the selected target parameter of the heat exchanger design is maximized (or minimized). Other design parameters of the apparatus are enclosed within the limits of permissible values. There can be quite a lot of variants of statement of optimization design problem. It is possible, for example, to require to obtain a heat exchanger of minimum length, maximum diameter, maximum heat exchange area or minimum number of tubes.

The practical experience of applying this methodology has shown that the customer is interested in the variant in which the mass F_{tr} of the heat exchanger heating tubes will be minimized. Function for calculating the parameter F_{tr} (kg)

$$F_{tr}(n, d, \omega_1, \omega_2) = L(n, d, \omega_1, \omega_2) \cdot n \cdot \frac{\pi(d^2 - (d - \delta(d))^2)}{4} \cdot \rho, \quad (1)$$

where ρ - density of tube material, (for steel $7,81 \cdot 10^{-6}$ kg/mm³)

Then the problem of heat exchanger design optimization can be formulated as follows: to determine the minimum value of the function F_{tr} , under the following system of constraints on the design parameters and water flow in the heat exchanger:

Limit on the number of tubes:

$$n > 0, \quad (2)$$

which does not allow search procedures towards negative values of n ;

Limitations on tube diameters

$$d_{min} < d < d_{max}, \quad (3)$$

where d_{min} , d_{max} – minimum and maximum outer diameter of the heat exchanger tubes, set by the design task.

Restrictions on fluid velocities

$$\omega_{1min} < \omega_1 < \omega_{1max} \quad \omega_{2min} < \omega_2 < \omega_{2max}, \quad (4)$$

where ω_{1min} , ω_{1max} , ω_{2min} , ω_{2max} , – minimum and maximum water velocities in the tubes and in the heat exchanger shell, respectively;

Limitations on the heat exchanger shell diameter

$$D_{min} < D(n, d) < D_{max}, \quad (5)$$

where D_{min} , D_{max} – minimum and maximum outer diameter of the heat exchanger shell, set by the design task.

Restriction of tubing placement in the hood

$$D(n, d)^2 > K_T \cdot d^2 \cdot n, \quad (6)$$

where K_T – tube placement coefficient, equal, for example, for the ring circuit 2.75.

Limitations on heat transfer coefficients

$$\alpha_1(d, \omega_1) < \alpha_{max} \quad \alpha_2(n, d, \omega_2) < \alpha_{max}, \quad (7)$$

where α_{max} – limit value of the heat transfer coefficient for the current media (e.g. for water $\alpha_{max} = 15000$ W/(m²·K).

Restriction on turbulent water flow in the tubes and in the casing

$$Re_1(d, \omega_1) > Re_{max} \quad Re_2(n, d, \omega_2) > Re_{max}, \quad (8)$$

where Re_{max} – Reynolds number, which guarantees turbulent water flow in the tubes and in the heat exchanger shell (e.g. for Re_{max} water = 10000).

Tubing length limitation

$$L_{\min} < L(n, d, \omega_1, \omega_2) < L_{\max} \tag{9}$$

where L_{\min}, L_{\max} – minimum and maximum length of the heat exchanger tubes, set in the design task.

Restriction on hood stiffness

$$\frac{L(n, d, \omega_1, \omega_2)}{D(n, d)} < K_j \max, \tag{10}$$

where $K_{j\max}$ – the limiting ratio of the shell length to its diameter, which ensures the rigidity of the heat exchanger.

The methodology described above provides for the selection of the optimal heat exchanger design variant and can be realized only with the use of automated design tools. The authors applied the computer mathematics program MathCad, which has all the necessary set of tools, the main of which include: setting and calculation of mathematical expressions and functions; data exchange with external files, databases; solving blocks for systems of equations, inequalities, optimization procedures.

The design parameters defined in MathCad and supplemented with a number of parameters that were not included in the above methodology (number of baffles, socket diameters, coordinates of the centers of the tube grid openings) are transferred using a text file to the CAD system Compass 3D and transformed into external variables of the parametric model of the heat exchanger (Figure 1).

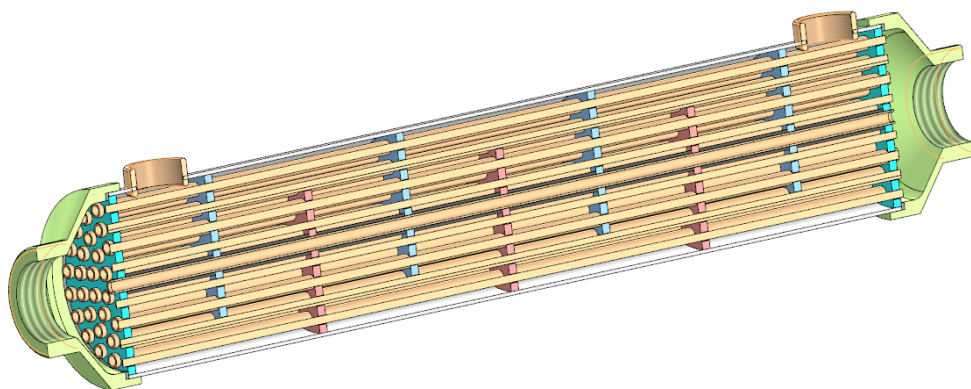


Fig. 1. Parametric model of shell-and-tube water-to-water heat exchanger (authors' figure).

The obtained solid-state model of the heat-exchange apparatus can be traditionally applied for manufacturing of design documentation. The authors of the article applied the model of the apparatus to carry out thermal-hydraulic calculations in order to verify the adequacy of the developed design methodology.

The calculations were performed in the CFD system Flow Simulation, into which the solid model of the heat exchanger was transferred using the “stp” format. The main parameters of CFD calculation: type of problem - internal, stationary; the first sub-area of flow - water through the tubes of the heat exchanger; the second sub-area of flow - water in the casing of the heat exchanger. Boundary conditions of the first sub-area - at the inlet hot water temperature t_{1n} and mass flow rate G_1 , at the outlet - ambient pressure. Boundary conditions of the second sub-area - at the inlet temperature t_{2n} of heated water and mass

flow rate G_2 , at the outlet - ambient pressure. The target parameter of calculation is the average flow rate temperature of fluid media. Determination of temperatures at any point of the heat exchanger was carried out using the tool “Measurements at a point”

Investigation of the effectiveness of the presented methodology of heat exchanger design was carried out by means of comparative analysis of a number of design variants, for each of which the technical and economic parameters were evaluated.

3 Results of the study

For the initial data from Table 1, the calculation was carried out using the method described above. The results of the calculation are shown in Figure 2.

The optimization target parameter - the total mass of tubes was 2.15 kg. The length of tubes $L=505$ mm, the diameter of the casing $D=101.6$ mm. This result is obtained for the following set of constraints: $d_{\min}=10$ mm; $d_{\max}=16$ mm; $D_{\min}=80$ mm; $D_{\max}=200$ mm; $\omega_{1\min}=0.8$ m/s ; $\omega_{1\max}=3$ m/s ; $\omega_{2\min}=0.8$ m/s $\omega_{2\max}=2$ m/s; $\alpha_{\max}=15000$ W/(m²K); $Re_{\max}=10000$; $L_{\max}=1000$ mm; $Kj_{\max}=10$. Composition of optimal parameters $n=37$; $d=10$ mm; $\omega_1=2.33$ m/s; $\omega_2=2$ m/s.

Let us analyze a number of variants of heat exchanger calculations, obtained by the above formulas, but without the optimization procedure of searching for the minimum mass of tubes. Such calculations are performed by designers during “manual calculation”, when the changed design parameters are taken “within the recommended values”. The results of the analysis are presented in Table 4.

Table 4. Options for “manual calculation” of the heat exchanger.

№	Tubes diameter d , mm	Number of tubes n	Water velocity in the casing ω_2 , m/sec	Water velocity in the tubes ω_1 , m/sec	Casing diameter D , mm	Tubes length, L , mm	Tubes weight F , kg
1	10	30	1	1	101.6	1024	3.58
2	16	35	1.5	1.8	154	464	4.56
3	12	40	2	1.2	114.3	498	4.13
4	14	45	2	2	154	356	3.91
5	12	35	2	2	108	507	3.68
6	10	40	1	1.5	101.6	695	3.24
7	10	30	2	2	101.6	648	2.27
8	14	20	2.3	2	101.6	752	3.67
9	14	40	1.5	1.5	133	465	4.53
10	16	25	2	2	129	558	3.92

$ntr = 37$	$dtr = 10$	$\omega_1 = 2.33$	$\omega_2 = 2$
Total weight of heating tubes, kg	$Ftr(ntr, dtr, \omega_2, \omega_1) = 2.15$		
Heat load (kW)	$Q = 100$		
Length of heat exchanger pipes, m	$L(ntr, dtr, \omega_2, \omega_1) = 498.21$		
Heat exchanger shell diameter, mm	$Dnar(ntr, dtr) = 101.6$		
Volume flow rate of the heat pump (m ³ /hour)	$Vg = 10$		
Volume flow rate of heated water pump (m ³ /hour)	$Vh = 5.06$		
Hot circuit fluid flow rate (kg/sec)	$G1 = 2.71$		
Liquid flow rate in the cold water circuit (kg/sec)	$G2 = 1.4$		
Number of heat exchanger tubes	$ntr = 37$		
Diameter of heat exchanger tubes, mm	$dtr = 10 \quad \delta_{st}(dtr) = 1$		
Pipe grid diameter, mm	$Dvn(ntr, dtr) = 99.6$		
Heating surface area, m ²	$F(ntr, dtr, \omega_2, \omega_1) = 0.579$		
Equivalent diameter of intertube space, mm	$dekv(ntr, dtr) = 44.86$		
Heat transfer coefficient W/(m ² deg)	$Kof(ntr, dtr, \omega_2, \omega_1) = 3676.05$		
Hot water inlet temperature, deg C	$t1n = 75$		
Hot water outlet temperature, deg C	$t1k = 66.18$		
Inlet temperature of heated water, deg C	$t2n = 15$		
Outlet temperature of heated water, deg C	$T2k = 32$		
Average log head, deg	$\Delta t_{sr} = 46.97$		
$Re1(dtr, \omega_1) = 56509.611$	$Re2(ntr, dtr, \omega_2) = 96126.627$		
$Nu1(dtr, \omega_1) = 179.55$	$Nu2(ntr, dtr, \omega_2) = 518.21$		
$\alpha_1(dtr, \omega_1) = 15000$	$\alpha_2(ntr, dtr, \omega_2) = 6999.64$		

Fig. 2. Results of the heat exchanger calculation in MathCad (authors' figure).

In Table 4, we intentionally took absolutely random values of the varied parameters within the accepted constraints to show the efficiency of the optimization procedure. The number of different combinations of the four parameters is quite a large number. Therefore, it is practically unrealistic to assume that the designer will “play” all possible combinations and reach an acceptable result without solving the optimization problem. The result of the thermal calculation for the optimal heat exchanger design is shown in Figure 3.

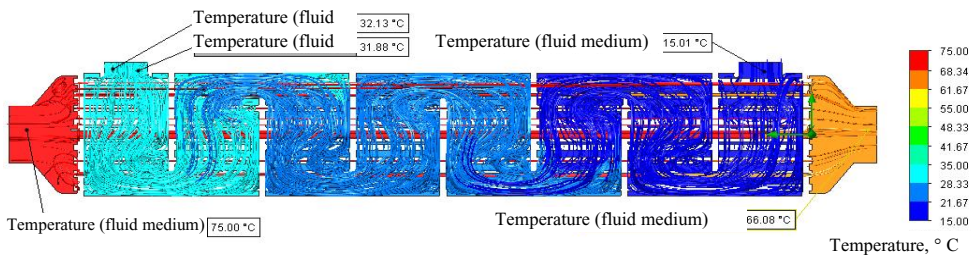


Fig. 3. Result of the thermal calculation (authors' figure).

The analysis of thermal calculation of the heat exchanger showed good compliance with the calculation formulas of the proposed methodology. So the temperature at the outlet of the heated water circuit was from 31,88°C to 32,13°C, which fully corresponds to the temperature $T_{2k} = 32^{\circ}\text{C}$ set in the initial data (Table 1). The temperature at the outlet of the heating water circuit was 66.8 °C, and in the calculation methodology the value $T_{1k}=66.18^{\circ}\text{C}$ was obtained.

4 Discussion and conclusion

The conducted research is aimed at solving the problem of modernization of the engineering method of calculation of shell-and-tube water-water heat exchanger. The analysis of the traditional method of calculation is carried out, during which it is found out that practically all design parameters of the heat exchanger (diameters of tubes and shell, length of tubes, area of heat exchange, etc.) are calculated by formulas including four control parameters - diameter d and number n of tubes, velocities of flowing media ω_1 and ω_2 . The traditional method provides assignment of a number of parameters within the recommended values and requires checks of compliance of these or those values with any conditions. For example, the recommended value of liquid velocity in the heat exchanger tubes can vary from 1 to 3 m/s, the heat transfer coefficient of water cannot be higher than the maximum limit. Calculations according to the traditional methodology do not provide for multivariate search procedures to achieve some optimal value of the target design parameter. A number of works [1-6, 11-13] point out a similar problem and, as a solution, propose various algorithms for optimizing the design of heat exchangers.

There are three main parts of the proposed calculation method. The first one uses formulas and reference data, the calculation and selection of which does not require the application of control parameters d , n , ω_1 ω_2 . The second part consists of a set of functions describing the design parameters of the heat exchanger, the arguments of which are the control parameters. The third part of the method solves the optimization problem of obtaining the extremum of the target parameter under the action of a number of constraints on the structural parameters of the apparatus.

An example of application of the methodology of optimal design of shell-and-tube water-water heat exchanger, in which the parameter of total mass of tubes is applied as a target parameter, is considered. The results of the conducted calculations are checked on the specially developed for this purpose three-dimensional parametric model of the heat exchanger in CAD system Compass, with the help of which the thermal calculation was carried out in Flow Simulation system, which showed good adequacy of the proposed methodology to the results of finite element calculation of temperature fields of the heat exchanger model. The heat exchanger was manufactured and bench tested, which confirmed the results of the calculation using the proposed methodology and modeling in CAD-system.

The results of the research can be used in mechanical engineering in the design of heat exchangers to improve their technical and operational characteristics.

References

1. R. M. Rizk-Allah, A. E. Hassanien, A. Marafie, Journal of Engineering Research (2023) DOI: <https://doi.org/10.1016/j.jer.2023.08.019>.

2. Z. Yang, Ch. Zhu, Y. Ji, et al., *Energy* **296**, 131075 (2024) DOI: <https://doi.org/10.1016/j.energy.2024.131075>.
3. R. V. Rao, M. Majethia, *Thermal Science and Engineering Progress* **36**, 101520 (2022) DOI: <https://doi.org/10.1016/j.tsep.2022.101520>.
4. W. H. Saldanha, G. L. Soares, T. M. Machado-Coelho, et al., *Applied Thermal Engineering* **127**, 1049-1061 (2017) DOI: <https://doi.org/10.1016/j.applthermaleng.2017.08.052>.
5. A. C. Caputo, A. Federici, P. M. Pelagagge, P. Salini, *Thermal Science and Engineering Progress* **34**, 101384 (2022) DOI: <https://doi.org/10.1016/j.tsep.2022.101384>
6. J. Jafari-Asl, O. D. L. Montañó, S. Mirjalili, M. G.R. Faes, *Applied Thermal Engineering* **248(Part A)**, 123161 (2024) DOI: <https://doi.org/10.1016/j.applthermaleng.2024.123161>
7. A. V. Maistrenko, *Advanced Engineering Research* **21(3)**, 260-267 (2021) DOI: <https://doi.org/10.23947/2687-1653-2021-21-3-260-267>
8. A. Lebedev, S. Kireev, *Improvement of design of device for production of cycloidal pinion gear*, in Proceedings of XIV International Scientific Conference “INTERAGROMASH 2021”. Smart Innovation, Systems and Technologies, pp. 223-236 (2022) https://link.springer.com/chapter/10.1007/978-981-16-3844-2_24
9. V. Stepanov, S. Kireev *Lecture Notes in Networks and Systems* **510**, 1843-1851 (2023) DOI: https://doi.org/10.1007/978-3-031-11051-1_189
10. S. O. Kireev, A. R. Lebedev, M. V. Korchagina, *Advanced Engineering Research* **23(3)**, 269-282 (2023) DOI: <https://doi.org/10.23947/2687-1653-2023-23-3-269-282>
11. Sh. Han, X. Li, Z. Liu, et al., *Thermal Science and Engineering Progress* **45**, 102085 (2023) DOI: <https://doi.org/10.1016/j.tsep.2023.102085> .
12. O. D. Lara-Montañó, F. I. Gómez-Castro, C. Gutiérrez-Antonio, *Computers & Chemical Engineering* **152**, 107403 (2021) DOI: <https://doi.org/10.1016/j.compchemeng.2021.107403>.
13. D. Thondiyil, S. K. Kodakkattu, *Materials Today: Proceedings* **46(19)**, 9983-9988 (2021) DOI: <https://doi.org/10.1016/j.matpr.2021.04.092> .
14. A. A. Lipin, Y. E. Romanenko, A. V. Shibashov, et al., *Calculation of heat-exchange apparatuses. Shell-and-tube heat exchangers (IGKHTU, Ivanovo, 2017)*
15. V. V. Ryndin, G. G. Abdullina, G. K. Akhmedyanova, et al., *PROGRAM for the Calculation of the Tubular Shell and Tube Heat Exchanger in MATHCAD package. Science and Technology of Kazakhstan* **2** (2024)