OPTIMIZATION OF HEAT EXCHANGER OPERATING MODES BY MEANS OF COMPUTATIONAL FLUID DYNAMICS METHODS

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Summary

The article presents a method of optimizing hydrodynamic and thermal parameters of heat exchange equipment. The proposed method is based on the use of the SolidWorks Flow Simulation CFD application in combination with the methods of similarity theory and dimensions. The criterion equation obtained as a result of research allows you to quickly find model parameters that satisfy the optimization conditions.

Keywords: heat exchanger, optimization, theory of similarity and dimensions, computational hydrodynamics.

Introduction

At the moment, a significant number of studies have been conducted, which are devoted to the optimal design of heat exchange equipment (Hauzen, 1981, Arsenyeva et al., 2011; Liu et al., 2017; Raja et al., 2017). It is known that a large number of parameters, in particular geometrical and regime, thermophysical properties of raw materials, influence the flow of processes that take place in heat exchange equipment. Therefore, the set optimization task is multifactorial, and in order to simplify the mathematical model, it was decided to use the methods of the theory of similarity and dimensions (Novikov, Borishanskij, 1979). The results of works devoted to the basics of the theory of similarity and dimensions make it possible to reduce the number of determining factors that affect the hydrodynamic and thermal processes occurring in heat exchange equipment. This significantly reduces the number of computational iterations in the optimization search and allows you to quickly find a number of defining parameters that satisfy the optimization condition. The paper presents the methods of parametric optimization of the geometric and operating parameters of the shell-and-tube heat exchanger, although the proposed method can be extended to other types of heat exchange equipment.

Research aim: to establish a criterion relationship between the parameters that affect the heat exchange process in the shell and tube heat exchanger.

The following **objectives** have been set to achieve the aim:

1. Create a model of the heat exchange process using the SolidWorks Flow Simulation system;
2. Create a database of parameter values that affect the heat exchange process;
3. Establish the type of dimensionless criteria of the heat exchange process;
4. Calculate the value of constant coefficients included in the criterion equation;
5. Optimize the parameters of the heat exchanger, taking the heat transfer efficiency as the objective function.

Research object and methods

The combination of the latest computer-integrated technologies with classical research methods is an extremely effective tool in the hands of a scientist, which investigates certain processes, and also makes it possible to quickly and efficiently design new equipment designs and optimize existing ones. In the presented research, the methods of computational hydrodynamics, implemented using the SolidWorks FlowSimulation CFD application, were combined with the methods of the similarity theory of mass and heat transfer processes, which made it possible to present the optimization model in the form of a criterion equation, convenient for analysis. SolidWorks as three-dimensional modeling system and the integrated FlowSimulation application can be used in the study of hydrodynamics and heat transfer of a wide range of technological equipment in order to determine the efficiency of countercurrent heat exchange equipment and analyze its hydrodynamic resistance, as well as the temperature fields of the flow inside it (Alyamovskij et al, 2005). With the help of FlowSimulation, you can easily determine the efficiency of the heat exchanger, and by studying the flow and temperature distribution, you can get an idea about the physical processes that take place in the heat exchanger, which will give ideas for improving its design.

Research results and discussion

Fig. 1 presents a parameterized solid-state model of a shell-and-tube heat exchanger, which was created in the SolidWorks system. The scheme of movement of the coolant is shown. Using the tools of the FlowSimulation application, a number of geometric and mode parameters were set, for which the output parameters that can be used in the optimization process were calculated, namely: the heat transfer coefficient between heat carriers, the efficiency of the heat exchanger, its hydraulic resistance, etc.

The efficiency of the heat exchanger was chosen as an optimization criterion - a parameter that is an integral characteristic of the efficiency of the heat exchanger. To determine it, we will use the following considerations.

The actual heat transfer from a hot to a cold coolant can be calculated either as energy lost by the hot fluid or as energy gained by the cold fluid (Hauzen, 1981). The maximum possible heat transfer is achieved if one of the fluids has undergone temperature changes equal to the maximum temperature difference in the heat exchanger, which is the difference between the temperature of the cold and hot fluids at the inlet to the heat exchanger:

$$T_h^{in} - T_c^{in},$$

where T_h^{in} and T_c^{in} are the temperatures of the hot and cold coolants, respectively, at the inlet to the heat exchanger, *K*.

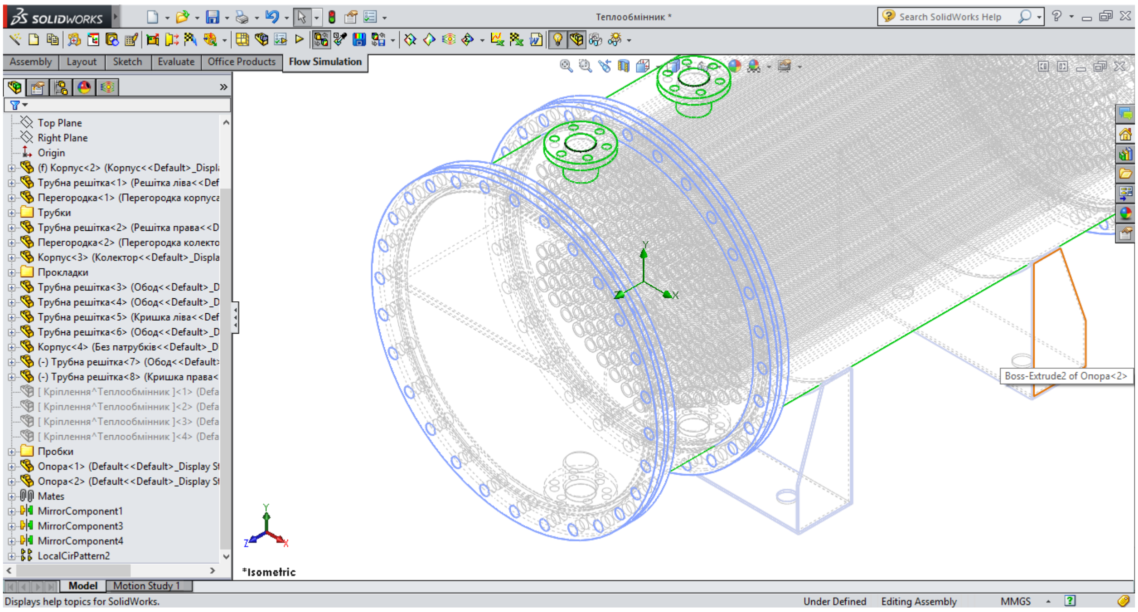

Fig. 1. Shell-and-tube heat exchanger model in the SolidWorks system

Thus, the efficiency of the countercurrent heat exchanger in the event that the power factor of the hot fluid is less than the power factor of the cold medium:

$$\varepsilon = \frac{T_h^{in} - T_h^{out}}{T_h^{in} - T_c^{in}},$$

where T_h^{out} and T_c^{out} are the temperatures of the hot and cold coolants at the exit from the heat exchanger, *K*.

If the power coefficient of the hot fluid is greater than the power coefficient of the cold medium, then the efficiency of the heat exchanger will be equal to:

$$\varepsilon = \frac{T_h^{out} - T_c^{in}}{T_c^{out} - T_c^{in}}$$

As a result of our research, the efficiency of the countercurrent heat exchanger was calculated. In the calculation process, the average temperature of the heat exchanger tubes was also determined. The resulting temperature value can be used further for strength and fatigue calculations.

Parameterization of the model, which is characteristic of the SolidWorks automated design system, allows you to quickly change its geometric dimensions, which will lead to immediate reconstruction and recalculation of all dependent parameters. SolidWorks FlowSimulation tools also allow you to conduct multivariate studies by gradually changing one or more optimization parameters without operator involvement. In our case, this made it possible to obtain a large database of the values of the objective function (hydrodynamic resistance, efficiency and heat transfer coefficient of the heat exchanger) depending on the set of input parameters of the optimization (the dimensions of the heat exchanger, the diameter of the pipes used in it, the consumption of coolants and their thermophysical properties, etc.). The presence of such a database makes it possible to find the global minimum of the objective function faster, avoiding a large number of calculation operations that occur with direct optimization search methods. The resulting database of parameters opens up possibilities for creating a mathematical model, which, as is known, is better amenable to optimization by search methods.

Adequacy of a computer model created using SolidWorks Flow Simulation can be pre-estimated from parameter pictures in various cross-sections of the solid-state model. Fig. 2 shows a picture of the temperature field in the cross section of the heat exchanger.

Since the development of nature is based on the laws of geometric progression, power-law dependencies and random processes, the exponential equations most often determine the essence of the course of the process from the point of view of physical and more general characteristics. As a result, the dependence between process parameters can be represented by the equation:

$$K_1 = CK_2^m K_3^n ... K_\pi^p,$$

where C, m, n, p are constants that must be found by mathematical analysis of experimental data.

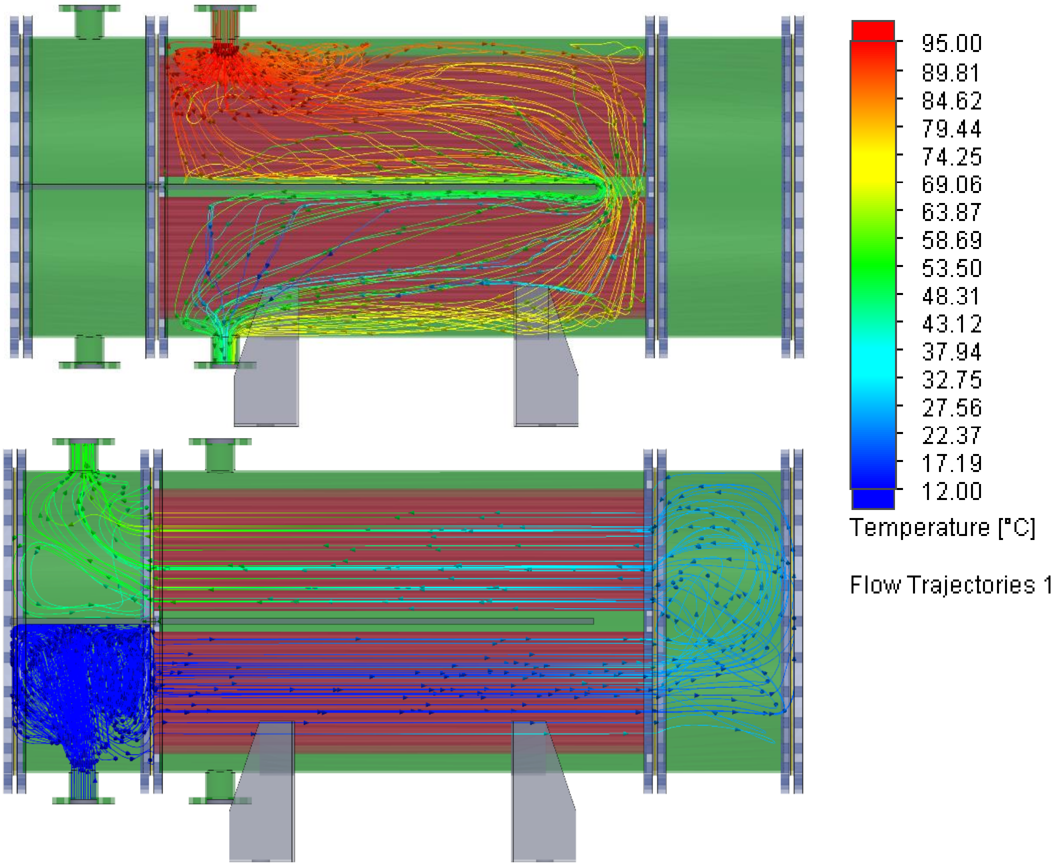

Fig. 2. Temperature distribution in the cross section of the heat exchanger

The criterion equation establishes a relationship between dimensionless complexes - criteria. The task of establishing the form of the complexes included in the equation is solved by many methods: directly from the differential equation of the process; by the method of similar transformations with the representation of similarity constants; by the method of dividing the original equation by one of its members; by the method of conversion to new independent units of measurement of physical quantities, etc. However, the use of all these methods requires the availability of the original equation. In the absence of such an equation that describes the process, the dimensional analysis method is usually used. The use of this method is based on the logic of the selection of physical quantities that determine the course of the process, but this can give a positive effect only in the case of the selection of initial factors, which is not always possible when studying processes that have not been studied before.

Buckingham's theorem (π-theorem) establishes a connection between N physical quantities, the dimension of which is expressed through n basic units of measurement and the number π of similarity parameters (Novikov, Borishanskij, 1979):

$$\pi = N - n. \tag{1}$$

The transition from dimensional characteristics of the process to dimensionless ones not only narrows the area of use of this equation, but also leads to a decrease in the number of variables. The second similarity theorem (Federman-Beckingham theorem) says that the numerical results of experiments should be presented in the form of an equation that expresses the relationship between similar parameters of the process being studied. That is,

$$K_1 = f\left(K_2, K_3, ..., K_\pi\right), \tag{2}$$

where π is the number of similarity criteria found using equation (1).

According to work (Hauzen, 1981), the most important factors that characterize heat transfer between two environments include: geometric parameter of model *D*; heat transfer coefficient α of the coolant to the partition wall; heat transfer coefficient λ of the coolant; heat carrier density ρ; heat transfer speed *v*; dynamic viscosity of the coolant μ; specific heat capacity of the coolant *c*.

Let's create a matrix of dimensions, each column of which is determined by the basic units of the SI system (tabe. 1).

Table 1. The dimensional matrix of the criterion equation

	D	α	λ	ρ	μ	c	v
L (lenght)	1	0	1	-3	-1	2	1
M (mass)	0	1	1	1	1	0	0
T (час)	0	-3	-3	0	-1	-2	-1
T (temperature)	0	-1	-1	0	0	-1	0

From the entire set of parameters that determine the process, it is necessary to select *N* - *n* such that the determinant of the matrix *M*, obtained from the dimensions of the selected values, is not equal to zero. Let us denote these values by A_D , and the rest by A_U .

Let's choose *D*, λ, μ, *v* as defining values. Then

$$|M| = \begin{vmatrix} 1 & 1 & -1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & -3 & -1 & -1 \\ 0 & -1 & 0 & 0 \end{vmatrix} = 1 \neq 0.$$

Let's determine the matrix of indicators of degrees of similarity criteria using the equation:

$$K_i = M^{-1} A_{Ui} ,$$

where M^{-1} is the matrix inverted to the matrix *M*, *i* = 1...*N* – *n*.

Therefore, the matrix of indicators of degrees of physical quantities belonging to the criteria of similarity will have the form (Table. .):

Table 2. Matrix of indicators of degrees of the criterion equation

	D	α	λ	ρ	μ	c	v
K_1	1	1	-1				
K_2	1			1	-1		1
K_3			-1		1	1	

Thus,

$$K_1 \equiv \frac{D\alpha}{\lambda}; \; K_2 \equiv \frac{D\rho v}{\mu}; \; K_3 \equiv \frac{\mu c}{\lambda}.$$

It is also easy to notice that the similarity criteria found are well-known criteria of heat exchange convective processes, namely:

$$\frac{D\alpha}{\lambda} = Nu \, ; \; \frac{D\rho v}{\mu} = Re \, ; \; \frac{\mu c}{\lambda} = Pr \, .$$

Therefore, the dependence (2) takes the form

$$K_1 = C K_2^m K_3^n \text{ or } \frac{D\alpha}{\lambda} = C\left(\frac{D\rho v}{\mu}\right)^m \left(\frac{\mu c}{\lambda}\right)^n ,$$

where *C*, *m* and *n* are constants that must be found by analyzing experimental data.

By implementing the previously explained mathematical apparatus, the given algorithm and the corresponding developed software make it possible to form criteria of similarity from an arbitrary set of physical quantities, which in turn provides wide opportunities for researchers in many fields of science and technology. The created program is multipurpose and helps to establish dimensionless complexes for many processes and phenomena that can be investigated using the similarity theory.

The database, which contains information about all the parameters of the studied models, allows you to perform multivariate analysis in the MathCAD 15 package in order to establish the unknown constants of the criterion equation (Makarov, 2011).

If we present the criterion equation in the form of a spatial graph, then this dependence will look graphically as shown in fig. 3.

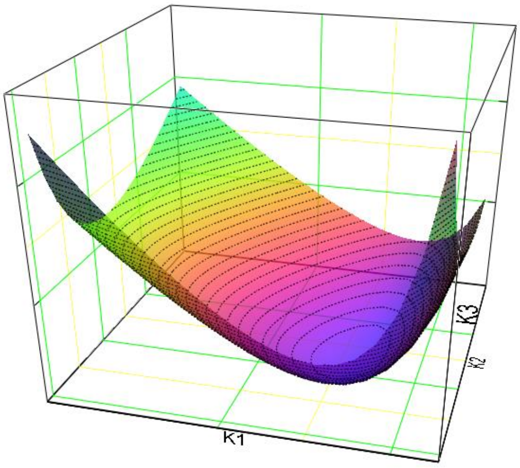

Fig. 3. Dependence between criteria in the form of a spatial surface

Conclusions

As a result of the research, the following conclusions can be drawn:

1. A method of thermal and hydrodynamic process analysis was developed, which was implemented using the CFD program and similarity theory methods.

2. A database of the obtained results was created, which is the basis for obtaining a mathematical model of the heat exchanger operation, which is subject to optimization.

3. A qualitative and quantitative relationship between the parameters in the criterion equation of the heat exchange process was established.

4. Numerical analysis of the obtained equation was carried out, as well as optimization of heat exchange parameters in order to obtain the maximum efficiency of heat transfer from hot to cold coolant.

References

1. Alyamovskij A.A.2008. Komp'yuternoe modelirovanie v inzhenernoj praktike. Edited by A.A. Alyamovskij, A.A. Sobachkin, E.V. Odincov. SPb. BHV-Peterburg. 800 s.
2. Arsenyeva O.P., Tovazhnyansky L.L., Kapustenko P.O. 2011. Optimal design of plate and frame heat exchangers for efficient heat recovery in process industries. *Energy*, Vol. 36, p. 4588–4598.
3. Liu C., Bu W., Xu D. 2017. Multi-objective shape optimization of a plate-fin heat exchanger using CFD and multi-objective genetic algorithm. *International Journal of Heat and Mass Transfer*, Vol. 111, p. 65–82.
4. Raja B.D., Patel V.K., Jhala R.L. 2017. Thermal design and optimization of fin-and-tube heat exchanger using heat transfer search algorithm. *Thermal Science and Engineering Progress*, Vol. 4, p. 45–57.
5. Hauzen H. 1981. Teploperedacha pri protivotoke, pryamotoke i perekrestnom toke. Per. s nemeck. H.Hauzen. M.: Energoizdat, p. 384.
6. Novikov I.I. 1979. Teoriya podobiya v termodinamike i teploperedache. Ed. I.I. Novikov, V.M. Borishanskij. M. : Atomizdat, p. 184.
7. Makarov E. 2011. Inzhenernye raschety v Mathcad 15: uchebnyj kurs. Ed. E. Makarov, SPb.: Piter, p. 400.