The solution of private problems for optimization heat exchangers parameters

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Abstract. The relevance of the topic due to the decision of problems of the economy of resources in heating systems of buildings. To solve this problem we have developed an integrated method of research which allows solving tasks on optimization of parameters of heat exchangers. This method decides multicriteria optimization problem with the program nonlinear optimization on the basis of software with the introduction of an array of temperatures obtained using thermography. The author have developed a mathematical model of process of heat exchange in heat exchange surfaces of apparatuses with the solution of multicriteria optimization problem and check its adequacy to the experimental stand in the visualization of thermal fields, an optimal range of managed parameters influencing the process of heat exchange with minimal metal consumption and the maximum heat output fin heat exchanger, the regularities of heat exchange process with getting generalizing dependencies distribution of temperature on the heat-release surface of the heat exchanger vehicles, defined convergence of the results of research in the calculation on the basis of theoretical dependencies and solving mathematical model.

1. Introduction
The conduct of practical studies to optimize basic parametres in engineering systems of buildings is urged by power-saving requirements [11,12,22]. The given practical problem of improving engineering systems is to optimize the design of the heat exchanger in air heating systems of buildings. Air heating systems of buildings are resource-consuming systems, for this reason, improving their resource efficiency appears to be of great significance. Heating of air is provided by heat exchangers, which have been studied quite thoroughly. The studies involved different authors to deal with particular aspects of improving heat exchange elements [19,20,21]. The main properties of heat exchangers, such as amount of heat exchange, area of heat exchange, metal capacity and cost of an apparatus depend largely on the size of ribbing, so the efficiency of the design is determined by the optimal height of the rib [16,17,18]. One of the authors of this paper V.M. Khrustalev looked into the criterion to assess the efficiency of heat exchanger design. The paper also suggests theoretical dependencies to calculate technical characteristics of heat exchangers. However, these dependencies do not allow optimization on several parametres [6]. A.A. Melekhin in his previous papers studied the multi-criterion optimization of the rib in heat exchangers based on two criteria, however, other parametres were not considered [1]. In the given paper the author makes a thermodynamic analysis and optimizes heat exchangers of air-cooling, at the same time these improvements are not based on the complex approach [13]. The occurrence of new methods, namely a complex method, allows combining mathematical modeling with visualization of heat fields, and as a result, obtaining optimal parametres of heat exchangers for the given systems [1]. The purpose of the given study is improving the efficiency of heat exchangers by optimizing their parametres and design.

To achieve this goal we set and solved the following tasks:
– we have developed a mathematical model of multi-criterion problem to optimize heat exchange on the ribbed heat exchanging surfaces.
using the mathematical model we developed, we have determined the mechanism of heat exchanging process and have derived dependencies of temperature distribution on heat exchange surfaces in heating systems of buildings during the heating season;
- we have made a comparison of the obtained results with the results based on the established theoretical dependencies;
- we have reduced the metal capacity of the heat exchanger by improving its heat engineering characteristics.

The novelty of the given paper lies in the following:
- we have elaborated a new complex research technique, based on multi-criterion problems with generic dependencies, obtained from empirical data.
- we have obtained functional dependence of process parameters on heat exchanging surfaces on optimal geometrical parameters of the heat exchanger.

The practical value of the paper is in the following:
- we have derived semi-empirical equations for computing and designing air heating systems in buildings;
- we have reduced metal capacity of heat exchangers which are used in air heating systems of buildings.

2. Materials/methods
In order to set optimal parameters for the heat exchanger and balance its design with technological elements the author conducted actual studies with the help of the complex method. It comprises optimization of parameters for heat exchanging process based on multi-criterion multi-parameter mathematical models and experiments with thermal fields visualization.

The optimization problems are solved using the method of non-linear optimization in computing complex IOZO NM 3.0b [9,10].

Besides, the solution of such problems is also possible with the help of non-linear optimization program Generalized Reduced Gradient (GRG2), designed by Leon Lasdon, University of Texas at Austin and Allan Waren, Cleveland State University, and based on the method of conjugate gradients – iterative method for unconstrained optimization in multidimensional space. The main advantage of this software package is that it is able to solve the quadric optimization problem within finite number of moves. So, first the author describes the method of conjugate gradients to optimize the quadric functional, then he derives iterative formulas and estimates convergence rate. Next, the author demonstrates, how the method of conjugate gradients is generalized to optimize arbitrary functional, looks at different variations of the method, assesses convergence. The shortcoming is that controllable and non-controllable parameters and criteria are constrained [14].

It is possible to use as a mathematical model a two-criterion problem of clusterization with fuzzy constraints. The fuzzy constraints can be set by specific preference functions. The solution is made in Boolean variables with the help of stochastic search, improved by heuristics. The algorithm is implemented in the form of a universal software module [15,16].

Solution of multi-criterion multi-parameter non-linear optimization problem of engineering systems in buildings suggested applying software package IOSO NM version 3.0b, where the author entered empirical data from thermal imaging. A special feature of this software is its compatibility with Microsoft Excel and other programs. IOSO package allows setting controllable and non-controllable parameters, optimal criteria, and constraints for the process. Further, IOSO program establishes optimal process parameters by using the data from Excel.

Preliminary IOSO procedure is forming the initial experiment plan, which can be passive (using the previously obtained information about variable parameters, optimization criteria and constraints), as well as active, when the set is generated in the initial search field in accordance with the preset partition law. Each vector of variable parameters for optimization and constraints implies direct use of mathematical model of the object studied. The number of points in the initial experiment plan depends on the problem dimension and the chosen variant of approximation function.
3. Results and discussion
To find the minimum mass of the ribs of the heat-exchange apparatus with the maximum of its heat productivity developed mathematical model of multi-criteria optimization problem heat-giving elements of the heat-exchange apparatus (Fig. 1) systems of air heating of buildings, which is solved using the method of nonlinear optimization [2,3]. Formulation of the mathematical model has been made for the outer surface of the radial ribs (Fig. 1).

![Radial edge](image)

**Figure 1.** Radial edge

The temperature on the surface of the ribs defines heat output, and the height of the rib - metal heat-exchange apparatus, so as the optimality criteria for staging a mathematical model selected [4]:
1) the temperature on the surface of the ribs ($J_1$);
2) the height of the ribs ($J_2$).

As unmanaged parameters taken: the radius of the carrier pipe, of a thickness of edges, the thermal conductivity of the ribs, the location of the beam in a heat exchanger, step ribs, the number of ribs, the number of the Nusselt number for the air, the Reynolds number for the air, the coefficient of heat transfer from the wall to the air, etc. ($x_1 \ldots x_n$).

In work the estimation of influence of these parameters on the process of heat exchanger.

As of controlled parameters are: ambient air temperature, the temperature of the heat-carrier ($U_1 \ldots U_n$) as the most influence on the heat transfer process.

In the process of heat exchange occurs between the warm water and the environment, which depend on parameters of water and air. Parameters that characterize these changes are within the permissible limits, established for the process.

The dependence of optimization criteria [5] and process parameters:

\[
J_1 = J_1(x_1, \ldots x_{21}; U_1, U_2) \rightarrow \max, \\
J_2 = J_2(x_1, \ldots x_{21}; U_1, U_2) \rightarrow \min.
\]  

Restrictions on the parameters of the process, is within the following limits:

\[
x_{1\text{min}} \leq x \leq x_{1\text{max}}, \\
J_{J\text{min}} \leq J_j(x_j) \leq J_{J\text{max}}, \\
r = r_0; \; \vartheta = \vartheta_0; \; r = r_0'; \; \frac{d\vartheta}{dr}, \; \delta_0, \; \lambda, \; c_2 = \text{const}.
\]  

The task of searching for the optimal height of the ribs is to find $x \in D$ in cases, when

\[
J_1(x_1, \ldots x_{21}, U_1, U_2) \rightarrow \max, \\
J_2(x_1, \ldots x_{21}, U_1, U_2) \rightarrow \min.
\]
Thus, the problem can be formulated as follows: it is required to find such controlled parameters of the element heat exchanger (fins), which are optimal from the perspective of the selected criteria under the given constraints.

The basis of mathematical model equations Bessel, describing the temperature distribution on the outer surface of the ribs.

Modified Bessel equation for the radial fin of rectangular profile is:

\[ r^2 \frac{d^2 \theta}{dr^2} + r \frac{d \theta}{dr} - m^2 r^2 \theta = 0, \]

\[ m = \frac{2 \alpha}{\lambda_c \delta}, \]

where, \( m \) – the dimensionless complex; \( \alpha \) – heat transfer coefficient from the outer surface to the air, Watt/(m\(^2\) * degrees); \( \lambda_c \) – thermal conductivity of fin, Watt/(m* degrees); \( \delta \) – thickness of fin, m.

The heat transfer coefficient from the outer surface to the air, Watt/(m\(^2\) *grad.):

\[ \alpha = \frac{\text{Nu}_v \cdot v_v}{h}, \]

where \( \text{Nu}_v \) – is the Nusselt number for air; \( v_v \) – coefficient of kinematic viscosity of air, m\(^2\)/s; \( h \) – fin height, m.

The Nusselt number for turbulent regime of the air movement:

\[ \text{Nu}_v = 0.096 \cdot \text{Re}_v^{0.72} \left( \frac{d}{h_p} \right)^{0.54} \left( \frac{h}{h_p} \right)^{-0.14}, \]

where \( R \) – step rib, m; \( d \) – outside diameter of pipe, m; \( h \) – height of fin, m; \( \text{Re}_v \) – Reynolds number for air.

Given the heat transfer coefficient:

\[ \alpha_{2np} = \alpha_2 \left( \frac{F_p \cdot \theta_0}{F_{pc} \cdot \theta_1} + \frac{F_n}{F_{pc}} \right), \]

where \( \alpha_2 \)– heat transfer coefficient, Watt/(m\(^2\)*degrees); \( \theta_0 \) - is the difference between the temperatures of the surfaces of the ribs and of air, degrees; \( \theta_1 \) – the difference in temperature between the core tube surface and air, degrees; \( F_n \) – surface area between the ribs, m\(^2\); \( F_{pc} \) – area finned surface, m\(^2\); \( F_p \) – area of fins, m\(^2\) .

The General solution is determined by the ratio:
\[ \theta = C_1 J_0(mr) + C_2 K_0(mr). \]  

(9)

The constant \( K_1, K_0, J_0, J_1 \) is calculated in accordance with boundary conditions described above.

\[ \theta_0 = C_1 J_0(mr_0) + C_2 K_0(mr_0'), \]

(10)

\[ 0 = C_1 J_1(mr_0) + C_2 K_1(mr_0). \]

Calculating C1, C2 we find the temperature distribution along fin height for the radial fin of rectangular shape (grad.):

\[ \theta(r) = \frac{\theta_0 \left( (K_1(mr_0') \cdot J_0(mr) + J_1(mr_0') K_0(mr)) \right)}{J_0(mr_0') K_1(mr_0') + J_1(mr_0') K_0(mr_0')}, \]

(11)

where \( \theta_0 \) is the temperature on the surface of the carrier pipe, degrees.

To estimate the heat flux from the surface of the ribs used in the work the dependence proposed by Bessel:

\[ q_0 = 2\pi r_0 \lambda \theta_0 \frac{J_1(mr_0) K_1(mr_0) - K_1(mr_0) J_0(mr_0)}{J_0(mr_0') K_1(mr_0') + J_1(mr_0') K_0(mr_0')}. \]

(12)

Thus, the problem can be formulated in the following way: it is required to find such managed parameters element of heat exchanger (the height of the edges), which are optimal from the point of view you are the chosen criteria under certain constraints. The basis of mathematical model based on Bessel equation describing the distribution of temperature on the outer surface of the ribs [6].

For the staging of the mathematical model are determined boundary conditions of the process of heat transfer in the work of the air heating systems, described in the dependencies (2).

To create the most resource-efficient heat exchangers in the article the low temperature and middle temperature of the heating system of the buildings with the following parameters the heat-carrier from +45 to +95 degrees. With these parameters the heat exchanger of the most metal-consuming.

To identify the most critical conditions of heat exchange on the surface of the ribs considered by the turbulent mode of movement of the heat-carrier temperature of ambient air from -35 up to 10 degrees.

The analysis of use of brands fans in systems of air heating of buildings. Set the maximum speed of the air entering the heat exchanger - 7 kg/(m²• degrees), which would consider in selecting the data of heat exchangers. Solution of the task is carried out with the help of the method of conjugate gradients - iterative method for unconstrained optimization of the multidimensional space, of the solution of a quadratic optimization problem for a finite number of steps.

To check the adequacy of the mathematical model and definition of the experimental dependences of the temperature distribution we have developed and installed an experimental stand (Fig. 2).

This stand is certified by the Federal state institution «the Perm centre of standardization and Metrology (certificate № 001 from 15.04.2009). Experimental stand consists of aerodynamic installations and oil circuit diagram of which is shown in Fig. 2. The design of the stand provides change of speed of movement heat transfer environments, the ability to measure the initial and final parameters (temperature, pressure, flow rate) and the stabilization of the above-mentioned parameters. Stabilization of parameters is provided by the office of the capacity of the sources of thermal energy of the stand (caldrons), as well as the heat insulation of the water and the aerodynamic contour. The equipment of the stand makes it possible to obtain data to determine the performance of the heat. The alignment of fields of velocities and temperatures is provided by the size of the aerodynamic parts of the stand.
Figure 2. The basic scheme and the General view of the wind tunnel parts of the stand for investigation of heat-releasing surface of the unit: 1 - the experimental model of the element of heat-exchange apparatus; 2 - air line; 3 - Registrar «Terem-4»; 4 - controller-controller «Miniterm 400-21»; 5 - heat-counter «Logic SPT 943.1»; 6 - enclosure; 7 - fan eti 14-46-5; 8 - fixing duct; 9 - insulation; 10 - grid with temperature sensors; 11 - receivers pressure; 12 - motor.

To measure the costs and temperatures were used flatware, General data and characteristics of which are given below. All measuring devices registered in the State register of means of measurements. The design of the test bench provides the movement of the working environment (air, water), the possibility of measuring the start and end parameters temperature pressure and flow working environments and stabilization of these parameters when tested under the following limits:
- the temperature of air from -35 up to +35 degrees (accuracy of maintenance of the received parameter 0,5 degrees);
- the temperature of the water in the circuit - from 10 up to 100 degrees (With the accuracy of maintenance 0,5 degrees);
- the speed of the air - from 0 to 10 m/s accuracy of maintaining adopted by the parameter of a 0.1 m/s);
- the speed of water - 0.5 m/s (the accuracy of the maintenance of the received parameter ± 0.01 m/s).

Figure 3. The basic scheme and the General appearance of the stand for the visualization of the temperature field on the surface of the ribs: 1 - the Registrar of temperatures; 2 - thermal imager; 3 - ventilator; 4 - the experimental model of the element of heat-exchange apparatus; 5 - plate; 6 - air line; 7 - pump; 8 - electric boiler; 9 - expansion tank; 10 - meter; 11 - the heat counter; 12 - thermocouple, 13 - pipeline; 14 - converter heat.

Air flow is measured with the help of the anemometer «Testo 450»; water - electromagnetic counter heat «the Logic of STF-943». Air temperature thermocouples using as a secondary device of measurement of «Terem-4», the water temperature is measured by a resistance thermometer with the conclusion of the heat-counter «the Logic of STF-943». The temperature field on the surface of the fin is measured by the thermal imager «Irtis-2000» (fig 3.). This metrological equipment at the time of the research believe and passes periodic calibration.
A distinctive feature of this stand is the presence of a thermal imaging camera, which allows the FIC to fix the temperature field on the heat transfer surfaces of heat exchangers [1].

For research is designed and manufactured an experimental model of transferring element with a steel fins. The air temperature at the inlet of the heat exchanger changes due to natural-climatic factors of the region. Air speed is adjusted by means of a frequency Converter installed on the motor fan.

The speed of water is regulated with the help of frequency converters of electric motors of pumps the temperature of the water - using the set point temperature with the conclusion of the electric heater boiler.

For the experiment, we developed a research ribs. Studied the temperature field of the ribs on 230×230 axis with an interval of 1 mm. The studies were carried out at temperatures of ambient air from -35 from 10 degrees. In the course of the experiment was received more than 500 photos with temperatures of ambient air within a year.

In Fig. 4,5 shows one of the thermal imaging photos of the investigated surface fins.

![Figure 4. Thermal imaging photo. The ambient air temperature -5 degrees. The temperature of the coolant 45 degrees. Temperature on surface from 73.72 ÷ 7.59 degrees.](image1)

![Figure 5. Thermal imaging photo. The ambient air temperature -35 degrees. The temperature of the coolant +95 degrees. Temperature on surface from 38.56 ÷ -3.63 degrees.](image2)

Data of temperature fields thermal imaging photos processed. On the basis of thermal imaging photos constructed the dependence of temperature distribution on the surface of the ribs at various ambient air temperatures during the heating season. The arrow shows the direction of movement of the air when carrying out the experiment.

As a result of solving the mathematical model using the IOSO NM version 3.0b in Microsoft Excel [19] found the optimum fin height at ambient temperatures from -35 to +10 °C.

The mathematical model is designed for the following parameters of the process:
- the temperature at the bottom of the ribs from 45 to 95 degrees;
- the temperature of air from -35 up to 10 degrees;
- radius of the pipe without fins adopted 0.03 m - const;
- radius of the pipe with finning from 0.035 to 0.12 m;
- the thermal conductivity of the ribs from 25 to 40 W/(m• degrees) ;
- the thickness of the edges adopted 0.002 m - const;
- coefficients for the calculation made on the basis of modified Bessel functions.

In Fig. 6 shows the temperature distribution on the surface of the rib when the coolant temperature of +45; +70; +95 °C, was found on the basis of theoretical relations and the solution of mathematical models [6, 13].
Figure 6. Egression curves of temperature distribution on the surface of the fin at different ambient temperatures, was found in the theoretical dependencies and based on the decision of a mathematical model
□ - chart is based on the theoretical dependencies Bessel at a coolant temperature of 45 degrees; Δ - chart is based on the theoretical dependencies Bessel at a coolant temperature of 70 degrees; х - chart is based on the theoretical dependencies Bessel at a coolant temperature of 95 degrees; ■ - the diagram is in the solution of mathematical models in the software package at a coolant temperature of from 45 to 95 degrees.

Figure 7. Schedules of dependence of the Reynolds Number on the height of the ribs

In Fig.6 shows Paratoo-optimal array [2,3] of values of $x \in D$ for solving multi-parameter optimization of a fin heat exchanger with the help of analytical software complex. Obtained optimal values. For easy understanding of the obtained values of the graphs obtained for each controlled parameter. In Fig.7 shows the graphs constructed in the solution of theoretical dependencies and Paratoo-optimal set of values of $x \in D$ for solving multi-parameter optimization of a fin heat exchanger with the help of analytical software complex. At the height of the ribs from 5 to 90 mm and the given constraints of the parameters of the optimal range of heat exchanger fins ranges from 27 to 30 mm.

Figure 8. Plot the heat transfer coefficient from the Nusselt number

Figure 9. Plots of coefficient of heat transfer from the height of the ribs
In Fig. 8 shows the graphs constructed in the solution of theoretical dependencies and Paratoo-optimal set of values of $x \in D$ for solving multi-parameter optimization of a fin heat exchanger with the help of analytical software complex. The coefficient of heat transfer from the finned surface to air ranges from 115 to 25 (Watt/m²*degrees) for ribs from 5 to 90 mm. At the height of the ribs of the heat exchanger 27 to 30 mm and the given constraints of the parameters of the optimal range of the coefficient of heat transfer from the finned surface to air ranges from 68 to 65 (Watt/m²*degrees) when the Nusselt number from 63 to 66.

In Fig. 9 shows the graphs constructed in the solution of theoretical dependencies and Paratoo-optimal set of values of $x \in D$ for solving multi-parameter optimization of a fin heat exchanger with the help of analytical software complex. The coefficient of heat transfer from the finned surface to air ranges from 115 to 25 (Watt/m²*degrees) for ribs from 5 to 90 mm. At the height of the ribs of the heat exchanger 27 to 30 mm and the given constraints of the parameters of the optimal range of the coefficient of heat transfer from the finned surface to air ranges from 68 to 65 (Watt/m²*degrees) at the height of the ribs from 0,025 to 0,030 mm.

In Fig. 10 shows the graphs constructed in the solution of theoretical dependencies and Paratoo-optimal set of values of $x \in D$ for solving multi-parameter optimization of a fin heat exchanger with the help of analytical software complex. The Nusselt number varies from 65 to 104, the Reynolds number of 20 000 to 60 000 for ribs from 5 to 90 mm. The mode of movement of turbulent air. At the height of the ribs of the heat exchanger 27 to 30 mm and the given constraints of the parameters of the optimal range Nusselt number ranges from 72 to 74 and when the Reynolds number from 27 000 to 29 000. Built curves described with the help of semi-empirical dependencies. As a result the following dependencies for a range of ribs from 5 up to 90 mm (formula 14), and a range of ribs from 27 to 30 mm (formula 13):

$$Nu = 41,396 \cdot Re^{0.0011},$$

$$Nu = 44,349 \cdot Re^{0.001}.$$

As a result of solving multivariable multiobjective optimization problem obtained optimal parameters of the fin heat exchanger for air heating systems of the building.
4. Conclusion
Improving the energy efficiency of engineering systems of buildings and structures, reduction of energy consumption through the optimization of their operation, introduction of energy saving technologies and optimization of structural elements of engineering systems is important.
As applied problems of improvement of engineering systems of buildings considered an example of optimization of heat exchanger element air heating system of the building.
Finding the best managed of the parameters of the heat exchanger element air heating system of a building is possible with the developed by the author of a comprehensive method of research based on multi-criteria parameter optimization with the introduction of empirically obtained data.
When developing a mathematical model of the heat exchanger element air heating system of a building used for the basic equations of heat and mass transfer. The decision of tasks of optimization carried out using the method of nonlinear optimization in design-software complexes IOZO.
The aim of the study is to increase the efficiency of engineering systems of buildings by optimising the parameters of the elements of heat exchangers used in air heating systems of buildings.
To achieve this goal the author posed and solved the following tasks:
– developed a mathematical model of multicriteria optimization problems of the process of heat transfer on finned heat transfer surfaces of the apparatus;
– the regularities of process of heat exchange with the receipt of the generalized dependency of the temperature distribution on the heat-transfer surface of heat exchanger air heating systems of the buildings at work during the heating period using the developed mathematical model;
- a comparison of the obtained results with the known theoretical dependencies;
– reduced metal heat exchanger optimized thermal performance.

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