optimizing; transport systems; mathematical models

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OPTIMIZATION OF PARAMETERS OF HEAT EXCHANGERS VEHICLES

Summary. The relevance of the topic due to the decision of problems of the economy of resources in heating systems of vehicles. To solve this problem we have developed an integrated method of research, which allows to solve tasks on optimization of parameters of heat exchangers vehicles. 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 authors 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.

ОПТИМИЗАЦИЯ ПАРАМЕТРОВ ТЕПЛООБМЕННЫХ АППАРАТОВ ТРАНСПОРТНЫХ СРЕДСТВ

Аннотация. Актуальность темы обусловлена решением задач ресурсоэнергосбережения в системах обогрева транспортных средств. Для решения данной проблемы разработан комплексный метод исследований который позволяет решать задачи оптимизации параметров теплообменных аппаратов транспортных средств. Данный метод решает многокритериальную задачу оптимизации с помощью программы нелинейной оптимизации на базе программного комплекса с введением массива температур полученных с помощью тепловизионной съемки. Авторами разработана математическая модель процесса теплообмена на теплообменных поверхностях аппаратов с решением многокритериальной задачи оптимизации и проверкой ее адекватности на экспериментальном стенде при помощи визуализации тепловых полей, сформирован оптимальный диапазон управляемых параметров, влияющие на процесс теплообмена при минимуме металлоемкости и максимуме теплопроизводительности ребра теплообменного аппарата, определены закономерности процесса теплообмена с получением обобщающих зависимостей распределения температуры на теплоотдающей поверхности теплообменного аппарата транспортных средств, определена сходимость результатов исследований при расчете на основании теоретических зависимостей и решения математической модели.

1. INTRODUCTION

Conducting applied scientific research for the optimization of the basic parameters of heat exchangers is urged by the requirements for energy saving in heating systems of vehicles.

The appearance of new techniques, namely a complex method of research, allows combining mathematic modeling with the visualization of thermal fields and obtaining the optimal parameters of heat transfer elements of devices for given systems [1].

The aim of this research was to establish the optimal parameters of heat-exchange device and find the correlation of design and technological elements in it. For this purpose, we conducted the present study with the help of the complex method, which includes optimization of heat transfer parameters based on multi- criteria and parameter mathematical models, and we carried out experimental research using visualization techniques of thermal fields.

The main characteristics of heat exchangers, such as heat transfer, the heat exchange area, metal intensity and the price depend on the size of the ribs, so the optimal height of the ribs determines largely the perfection of the design [3].

2. PROBLEM STATEMENT

To find the minimum mass of the ribs of the heat-exchange apparatus at the maximum heat productivity we have developed mathematical model of multi-criteria parameter optimization of heat-giving elements of the heat-exchange apparatus, which is solved by the method of nonlinear optimization [2, 5, 7] (Fig. 1).

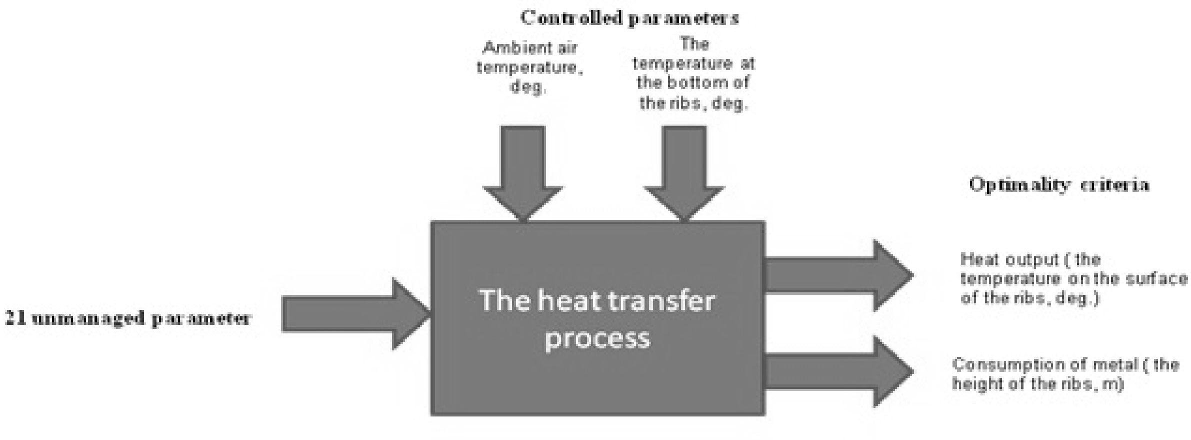

Fig. 1. The scheme of setting the mathematical model of the process of heat transfer on the ribs
Рис. 1. Схема постановки математической модели процесса теплообмена на ребре

Formulation of the mathematical model has been made for the outer surface of the rectangular profile radial ribs (Fig. 2).

Given that the temperature on the ribs surface defines the heat output, and the height of the rib defines the metal consumption of the heat-exchange apparatus, we have selected the optimality criterion for the following mathematical model:

1) x - the temperature on the surface of the ribs (J1);
2) y - is the height of the ribs (J2).

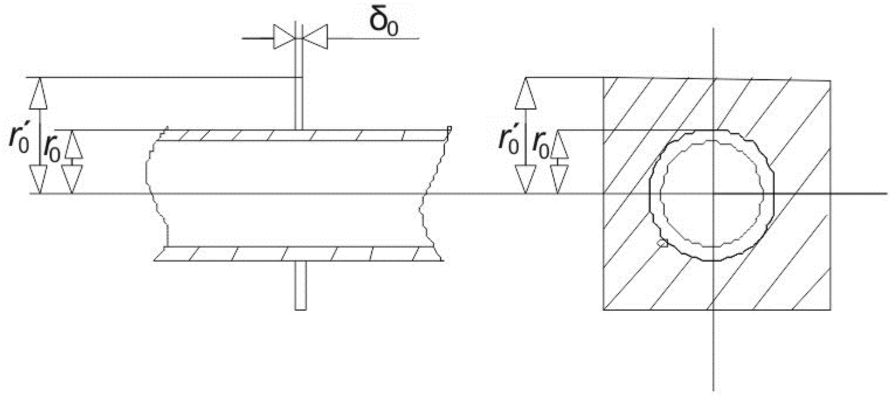

Fig. 2. Radial edge of a rectangular profile (r0 – is the radius of the carrier pipes; r0´– is the radius of the pipe with finning δ0 - thickness of the ribs)

Рис. 2. Радиальное ребро прямоугольного профиля (r_0 – радиус несущей трубы; r'_0 – радиус трубы с оребрением; δ_0 – толщина ребра)

We took the following parameters as unmanageable: the radius of the carrying pipe, the thickness of ribs, 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. (x1 ... x21). We also tried to estimate influence of these parameters on the heat exchange process.

The manageable parameters are ambient air temperature, and the temperature of the heat-carrier (U1 ... U2). They have been selected as the most influential on the heat transfer process. There is a heat exchange between the warm water and the environment, which depends on parameters of the water and the air. The parameters that characterize these changes are within the permissible limits established for the process.

The dependence of optimization criteria and process parameters can be represented in the following form:

$$J_1 = J_1(x_1,...x_{21},U_1,U_2) \to \max,$$
$$J_2 = J_2(x_1...x_{21},U_1,U_2) \to \min. \tag{1}$$

Restrictions on the process parameters are within the following limits:

$$x_i^{\min} \le x \le x_i^{\max},$$
$$J_i^{\min} \le J_i(x_i) \le J_i^{\max} \tag{2}$$

$$r = r_0;\ \vartheta = \vartheta_0;\ r = r_0';\ \frac{d\vartheta}{dr},\ \delta_0,\ \lambda = \text{const}.$$

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

$$J_1(x_1,...x_{21},U_1,U_2) \to \max$$
$$J_2(x_1,...x_{21},U_1,U_2) \to \min. \tag{3}$$

Thus, the problem can be formulated in the following way: it is necessary to find such manageable parameters of the of heat exchanger element (the height of the ribs), which are optimal from the viewpoint of chosen criteria within certain constraints.

The mathematical model is based on Bessel equation describing the distribution of temperature on the outer surface of the ribs [6].

To make the mathematical model we have determined boundary conditions of the heat transfer process in the work of heat exchangers vehicles, described in the dependencies (3).

The range of average monthly ambient air temperatures was set according to SNIP 2.04.05-91 for the Ural region.

To create the most resource-efficient heat exchangers the article looks at the low temperature and middle temperature heating systems of the buildings where the heat-carrier parameters were set from +45 to +95 degrees. Under these parameters, the heat exchangers are the most metal consuming.

To identify the most critical conditions of heat exchanger on the surface of the ribs, we have studied the turbulent mode of movement of the heat-carrier, with ambient air temperature from -35 up to 10 degrees. We have analyzed the work of different fan brands in air heating systems of buildings. We set the maximum speed of the air entering the heat exchanger - 7 kg/(m2 · degrees), which is typical in selecting the data for heat exchangers. The problem solution is carried out with the help of the conjugate gradients method - iterative method for unconstrained optimization of the multidimensional space, which is represented in the solution of a quadratic optimization problem for a finite number of steps [4].

This method was implemented in the software complex Generalized Reduced Gradient (GRG2), developed by the Leon Lasdon, University of Austin Texas and Allan Waren, Cleveland State University Prisma.

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 air temperature from -35 up to 10 degrees;
- radius of the pipe without fins adopted 0.03 m - const;
- radius of the pipe with ribs from 0.035 to 0.12 m;
- the thermal conductivity of the ribs from 25 to 40 W/(m · degrees) ;
- the thickness of the ribs adopted 0.002 m - const;
- coefficients for the calculation made on the basis of modified Bessel functions.

3. ANALYSIS OF THE OBTAINED RESULTS

When solving mathematical model we found a lot of optimal temperatures on the surface of the ribs within limits of the process parameters. This allowed us to determine the optimal size of the rib depending on the temperature of the ambient air.

We found the optimal range of the rib heights from 27 to 30 mm when the heat exchangers work at below zero temperatures from -35 up to 10 degrees and the temperature of the heat-carrier is from 45 to 95 degrees, in such conditions optimum temperature on the surface of the ribs varies from 3.5 to 65 degrees. We established dependence of Nusselt number on Reynolds number when the rib height is from 5 up to 90 mm and the optimum rib is from 27 to 30 mm (Fig. 3).

The drawn curves are described with the help of semi-empirical dependencies. So, we obtained the following dependencies for a range of ribs from 5 up to 90 mm (formula 5), and a range of ribs from 27 to 30 mm (formula 4):

$$Nu = 41{,}396 \cdot \mathrm{Re}^{0{,}011}, \tag{4}$$

$$Nu = 44{,}349 \cdot \mathrm{Re}^{0{,}001} \tag{5}$$

To check the validity of the mathematical model and identify the experimental dependences of the temperature distribution we have developed and installed an experimental stand (Fig. 4).

This stand [1] is certified by the Federal state institution «the Perm centre of standardization and Metrology (certificate № 001 from 15.04.2009). It consists of aerodynamic installations and oil circuit, its scheme is shown in Fig. 4. The design of the stand provides speed change of heat-transferring environments movement, it also makes possible to measure the initial and final parameters (temperature, pressure, flow rate) and to set the above-mentioned parameters. Stabilization of parameters is ensured by managing the heat-generating capacity of the stand (caldrons), as well as by heat insulation of the water and the aerodynamic contour. The stand equipment makes it possible to obtain data to determine the heat performance. The alignment of velocity fields and temperatures is provided by the size of the aerodynamic parts of the stand.

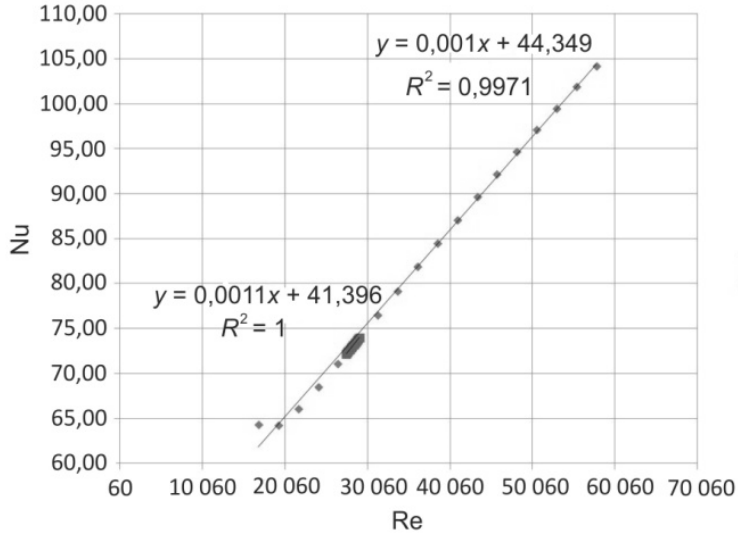

Fig. 3. The dependence of Nusselt number on Reynolds number
Рис. 3. Зависимость числа Нуссельта от числа Рейнольдса

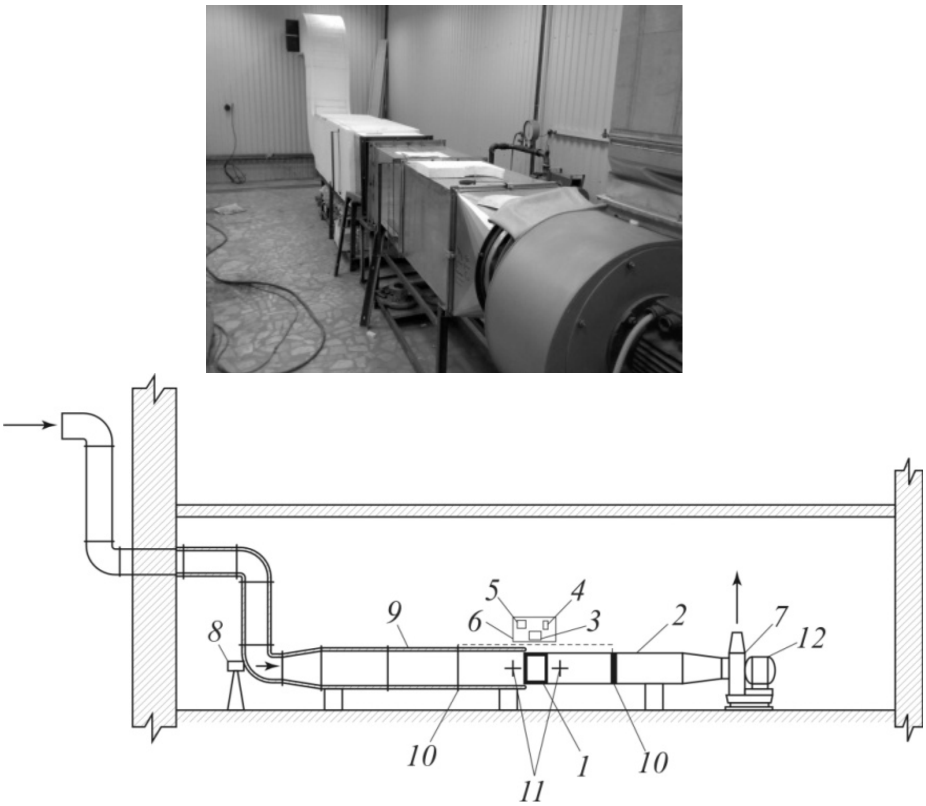

Fig. 4. The basic scheme and the General view of the wind tunnel parts of the stand for investigation of heat-releasing surface of the unit: 1 – the experimental model of the element of heat-exchange apparatus; 2 – air line; 3 – detector «Terem-4»; 4 – controlling regulator «Miniterm 400.-21»; 5 – heat-meter «Logica SPT 943.1»; 6 – enclosure; 7 – fan VC 14-46-5; 8 – fixing duct; 9 – insulation; 10 – grid with tempera ture sensors; 11 – pressure receiver; 12– motor

Рис. 4. Принципиальная схема и общий вид аэродинамической части стенда для исследования теплоотдающей поверхности аппарата: 1 – исследуемый экспериментальный образец элемента теплообменного аппарата; 2 – воздуховод; 3 – регистратор «Терем-4»; 4 – контролер-регулятор «Минитерм 400.21»; 5 – счетчик тепловой энергии «Логика СТП943.1»; 6 – щит управления; 7 – вентилятор ВЦ 14-46-5; 8 – крепеж воздуховода; 9 – теплоизоляция; 10 – сетка с температурными датчиками; 11 – приемники давления; 12 – электродвигатель

To measure the costs and temperatures we use instruments, general data and characteristics of which are given below. All measuring devices are certified by the State register of measurements means. The design of the test stand ensures the movement of the working environments (air, water), the possibility of measuring the initial and final parameters (temperature, pressure and flow) of working environments and stabilization of these parameters when tested within the following limits:
- the air temperature from -35 up to +35 degrees (accuracy of retaining the received parameter is 0,5 degrees);
- the temperature of the water in the circuit - from 10 up to 100 C (With the accuracy of retaining 0,5 degrees);
- the air speed - from 0 to 10 m/s (accuracy of retaining the adopted parameter is 0.1 m/s);
- the water speed of - 0.5 m/s (the accuracy of retaining the received parameter ± 0.01 m/s).

Airflow is measured by the anemometer «Testo 450»; water - electromagnetic heat meter « Logica STF-943». Air temperature is measured by thermocouples; «Terem-4» was used as a secondary device. A resistance thermometer connected to the heat-counter «Logica STF-943» measures the water temperature. The temperature field on the surface of the rib is measured by the thermal imager «Irtis-2000». This metrological equipment was checked at the time of the research and is regularly calibrated.

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 [2,4] (Fig. 5).

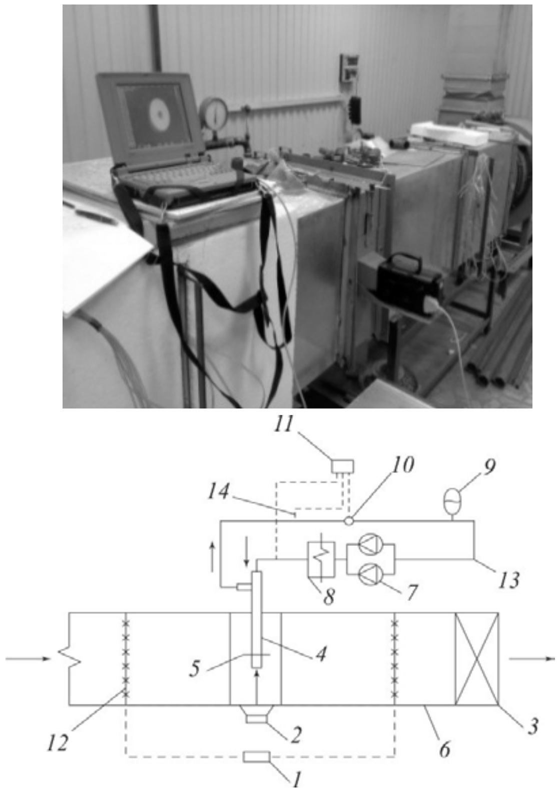

Fig. 5. The basic scheme and the General appearance of the stand for the visualization of the temperature field on the surface of the ribs: 1 – temperature detector; 2 – thermal imager; 3 – ventilator; 4 – the experimental model of the element of heat-exchange apparatus; 5 – plate; 6 – air line; 7 –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

Рис. 5. Принципиальная схема и общий вид части стенда для визуализации температурных полей на поверхности ребра: 1 – регистратор температур; 2 – тепловизор; 3 – вентилятор; 4 – исследуемый экспериментальный образец элемента теплообменного аппарата; 5 – пластина; 6 – воздуховод; 7 – насос; 8 – электрический котел; 9 – расширительный бак; 10 – расходомер;11 – счетчик тепловой энергии; 12 – термопара; 13 – трубопровод; 14 – термический преобразователь

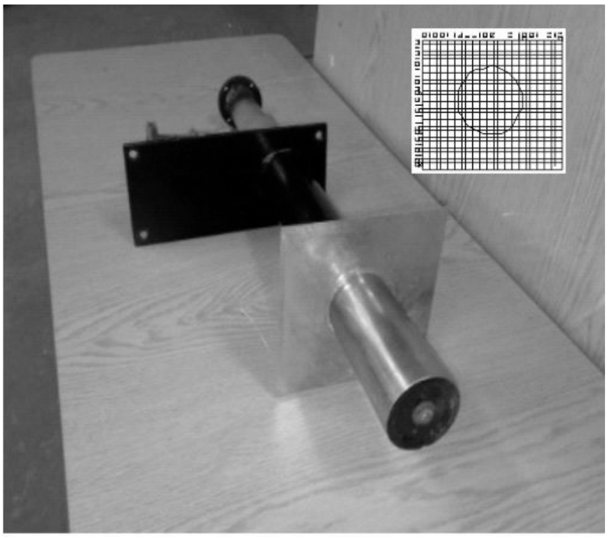

Fig. 6. The experimental sample is an element of heat exchanger
Рис. 6. Экспериментальный образец – элемент теплообменного аппарата

For research, we have designed and manufactured an experimental model of transferring element with steel ribs (Fig. 6). The air temperature at the inlet of the heat exchanger changes due to natural climatic factors of the region. Air speed is adjusted by the frequency converter installed on the fan motor.

The speed of water is regulated by frequency converters of electric pump motors; the temperature of the water is regulated by the temperature setter connected to the electric boiler. We developed a certain scheme for examining the rib during the experiment.

We looked at 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, we received more than 500 photos at ambient air temperatures during the year. Fig. 7 shows one of the thermal imaging photos of the investigated surface fins.

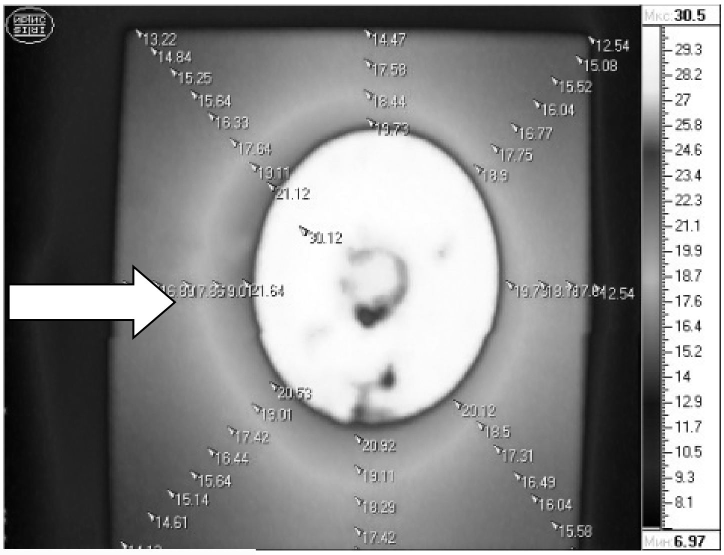

Fig. 7. Thermal imaging photo of the heat exchanger rib
Рис. 7. Тепловизионное фото ребра теплообменного аппарата

We entered the temperature data in the specially developed mathematical mode of calculation. Finally, we constructed the graph showing dependence of temperature distribution on the rib surface while operating the heating systems of vehicles.

The data of the dependence allowed building a generalized function of temperature distribution on the surface of the ribs at work throughout the year (Fig. 8):

$$y = 3E + 06x^2 - 203759x + 3200{,}7,$$
$$R^2 = 0{,}9987 \qquad (6)$$

where y is the height of the ribs, m; x - the temperature on the surface of the ribs, degrees.

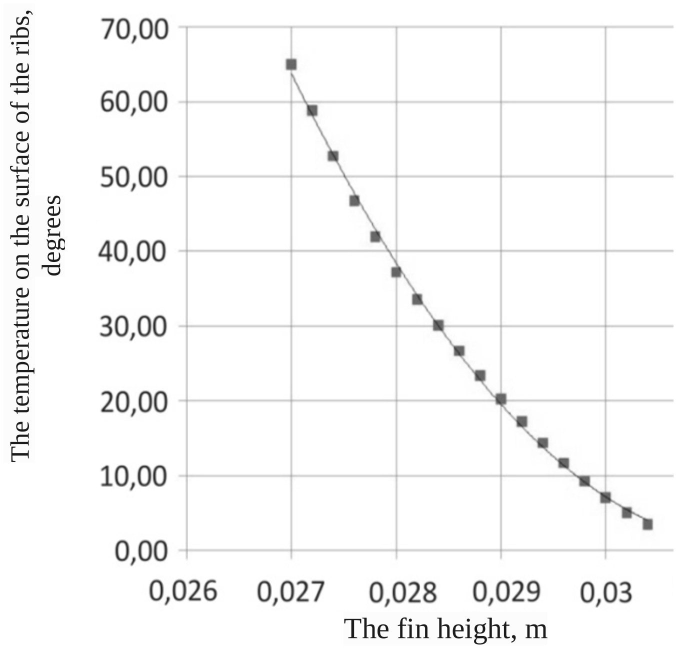

Fig. 8. The graph of the dependence of the temperature distribution on the ribs surface at work during the heating season

Рис. 8. График зависимости распределения температур на поверхности ребра при работе в течении отопительного года

We got the results of temperature field visualization on the ribs surface and compared the actual temperatures with the theoretically calculated temperatures based on the dependencies (2-4).

We have compared the results of the solution of a mathematical model with Bessel dependencies, as a result we managed to confirm theoretical dependences describing the temperature distribution on the ribs surface.

When constructing the regression curves using the method of least squares (OLS) we obtained the following dependencies (7, 8):

- based on the theoretical dependencies:

$$y = 60{,}704 \cdot e^{-53{,}72x}, R^2 = 0{,}9985 \qquad (7)$$

- based on the mathematical model:

$$y = 7436x^2 - 1208{,}1x + 50{,}029, R^2 = 0{,}9987 \qquad (8)$$

where: R^2 is the coefficient of determination for the regression curves; y - the temperature on the surface of the ribs, degrees; the x - height of the ribs, m

The calculations we conducted according to the mathematical model allowed us to develop optimal size of the fins with regard to the influence of natural-climatic conditions of the region and the technical parameters of the heating systems vehicles. Given ribbed surface is of a round form and certain size. To ensure full carrying capacity a beam of finned tubes can be installed. The optimum rib has an idealized round shape.

The dependences of temperature distribution that we received from the thermal imaging survey prove the convergence of theoretical and experimental results of the distribution of temperature and allow constructing optimal profiles of the ribs.

Using complex method for optimization of the elements of heat-exchange devices of heating systems of vehicles allowed us to find the optimal range of rib heights, which reduced metal consumption in the optimization of heat engineering characteristics.

4. CONCLUSION

Studies of the heat exchange process on the finned surfaces of heat exchangers in heating systems of vehicles enable us to draw the following conclusions:

1. We have designed the mathematical model of heat exchange process with the solution of the multi-criterion optimization problem and verification of its adequacy to the experimental stand using visualization of thermal fields.
2. We have been able to find the optimal range of manageable parameters influencing the process of heat exchange using the ribs of the minimum metal capacity and maximum productivity.
3. We have defined regularities of the heat transfer process and obtained generalized dependences of the temperature distribution on the heat-releasing surface of heat-exchange apparatus in heating systems of vehicles during the heating season.
4. We have discovered convergence of research findings in the calculation based on theoretical dependences and the solution of mathematical model.

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