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A. A. Andrizhievski, D. Sc. (Engineering), professor (BSTU);
V.V. Dudarev, PhD (Engineering), assistant professor (BSTU);
A.B. Sukhotski, PhD (Engineering), assistant professor (BSTU).

TESTING BIMETALLIC FINNED TUBES BY MAGNITUDE OF THERMAL RESISTANCE OF MECHANICAL CONTACT OF SUPPORTING TUBE AND INTEGRALLY STIFFENED SHELL

The results of an experimental study of thermal characteristics of bimetallic finned tubes and dependence of thermal resistances in places of interface of heat exchange surfaces from heat stress and thermal are presented.

Introduction. At the power equipment market of the Republic of Belarus there is a wide range of heat exchangers for different purposes, and of different configuration of heat exchange surfaces and different component sets.

One of the ways to reduce the production costs and simplify promotion to the market heat exchangers is to develop methods of computational analysis of their thermal and hydrodynamic characteristics of heat exchange surfaces of industrial design. Such methods will significantly reduce the entire production cycle - from design to implementation.

Definition of the research problem. The method of analysis of thermal-hydraulic characteristics of multilayer heat exchange surfaces comprises the analysis of real configuration of these surfaces and its use as a reference in the analysis of the proposed designs to the implementation. One of the key moments of this analysis is to determine the thermal resistance of the contact surfaces. This problem can be solved by inverse or direct heat exchange problems based on multi-dimensional computational analogues using tests of industrial models of heat transfer surfaces or direct measurements of thermal resistances in specialized experiments.

This paper presents the results of an experimental study of thermal characteristics of bimetallic finned tubes and, in particular, dependence of the thermal resistances at the heat transfer surfaces interface on heat capacity and cooling conditions. These results are not only self-sufficient, but also can be used for solving direct and inverse problems of heat exchange to verify the appropriate computational analogues [1].

Description of the research subject. Bimetallic finned tubes (BFT) consisting of a smooth steel tube and aluminum shell of integral finned tubes (Fig. 1), are used in heat-exchange sections of air-cooled apparatus (ACA) of fuel and energy complex, in compressor stations of gas trunk pipelines, in oil-refining plants, as air-heating radiators, in ventilation or refrigeration condensers.

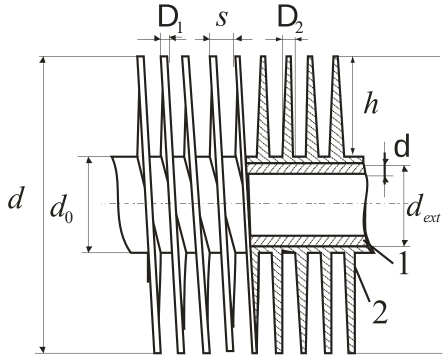


Fig. 1. Bimetallic finned tube:
1 - smooth steel tube; 2 – aluminium finned shell;
d - outer diameter of the fin; *h*, *s*, D = 0.5(D$_1$ + D$_2$) 2) - height, fin spacing, and the average thickness of the ribs, respectively, $d_0 = d - 2h$ – diameter of the rib by its base; d_{ext}- external diameter of a pipe; d - thickness of the plain tube.

The combination of two structural elements in BFT, made from different materials having significantly different linear expansion coefficients (for aluminum its value is 2 times higher than that of steel), leads to a weakening mechanical contact when BFT is heated with the hot water inside the tube. The difference of thermal deformations of the support tube and aluminum finned shell during operation leads to an increase of micro-cavities in BFT when aluminum fins being rolled, which creates an additional thermal contact resistance (TCR), calculated by the ratio/

$$R_k = \frac{DT_k}{q_k}, \qquad (1)$$

where ΔT_k - the temperature difference between the surfaces of the contact, K; q_k- the density of heat flow through the contact zone, W/m^2.

In ref. [2] there is a method for calculating the interference between the contacting surfaces of the steel tube and aluminum fins. According to this method, to calculate deformation interference and contact pressure it is necessary to know TCR; its value depends on the constructive parameters of BFT and technological peculiarities of rolling fins.

Thermal Test BFT Series conducted in this work have shown that the temperature dependence of the TCR in contact is linear in nature. Thus, to test BFT after manufacture, and then during operation, a reliable and convenient express method of TCR is necessary. To develop such method was the aim of this work.

Testing express method for TCR definition was carried out on the basis of four- beam chess bank of equilateral arrangement with transverse and diagonal space $s_1 = s'_2 = 33$ mm (Fig. 2).

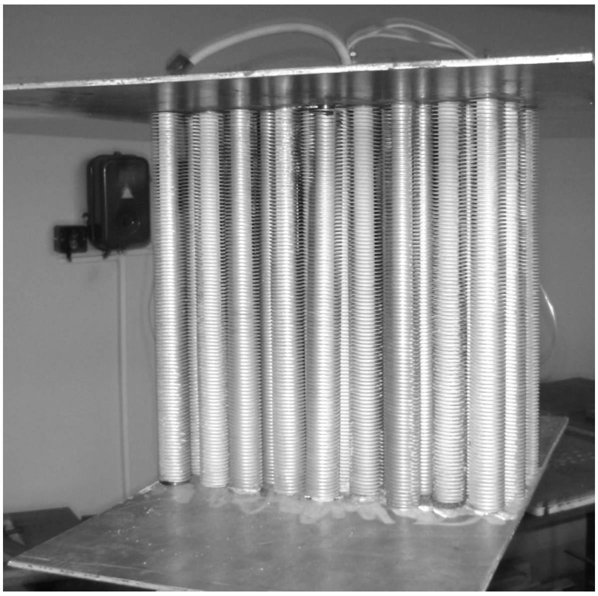


Fig. 2. Experimental BFT tube bank

BFT comprises the following parameters (Fig. 1): $d = 26$ mm; h = 5.75 mm; s = 2.7 mm; Δ = = 0.33 mm; $d_0 = d - 2h$ = 14.5 mm. The outer diameter of the steel supporting tube d_{cet} = 12 mm, and wall thickness δ_1 = 1.25 mm. Aluminum fins are rolling single-cut.

The length of the working area of each beam tube is 300 mm. This type of tube is industrially manufactured and is widely used in practice. When assembling the beam in the first or third row, it is possible to install BFT-heater, which is a steam-electric mini-boiler. Source of generated electric heat is electric energy. Electric power supplied to the BFT-heaters, is regulated by a rheostat and measured by electro-complex K-505.

To test the above described BFT tube bank, the experimental stand was used to determine the aerodynamic and heat characteristics of bimetallic finned tube banks.

To measure the temperature in the BFT-heater contact zone, thermoelectric converters were used; they were connected with the registering Glare millivoltmeter B7-35 of type through a low-resistance switch.

Methods of measuring the contact resistance. Graphical explanation of the determination TCR method by ratio (1) is given in Fig. 3.

The constituent value of this ratio, that is the temperature difference between the contact surfaces $\Delta T_k = t_{k1} - t_{k2}$ was determined as the difference of temperatures of the outer surface of the supporting steel tube t_{k1} and the inner surface of the finned aluminum shell t_{k2}, were calculated according to the formula:

$$\begin{cases} t_{k1} = \dfrac{t_t^{out} + t_t^{in}}{2} - q_k \left(\dfrac{\delta_t - \delta_s}{\lambda_t} \right), \\ t_{k2} = \dfrac{t_{al}^{out} + t_{al}^{in}}{2} + q_k \left(\dfrac{\delta_{al} - \delta_s}{\lambda_{al}} \right), \end{cases}$$

where t_t^n, t_t^{in} and t_{al}^{out}, t_{al}^{in} are the appropriate temperatures measured by four copper-constantan thermoelectric converters, their hot junctions are at the outside edges of the tube, and at the contact interface of the parent tube and aluminum shell, δ_t, δ_{al}, δ_s - thickness of the supporting steel tube and ribbed aluminum shell, the setting depth of thermal converter; λ_t, λ_{al} - thermal conductivity of steel and aluminum.

The heat flux density in the contact zone was defined as

$$q_k = \frac{Q}{F_k}$$

where the heat flux in the contact zone is calculated by the heat balance equation:

$$Q = W - Q_{loss}$$

W - electric power, transformed by BFT air-heater to heat:

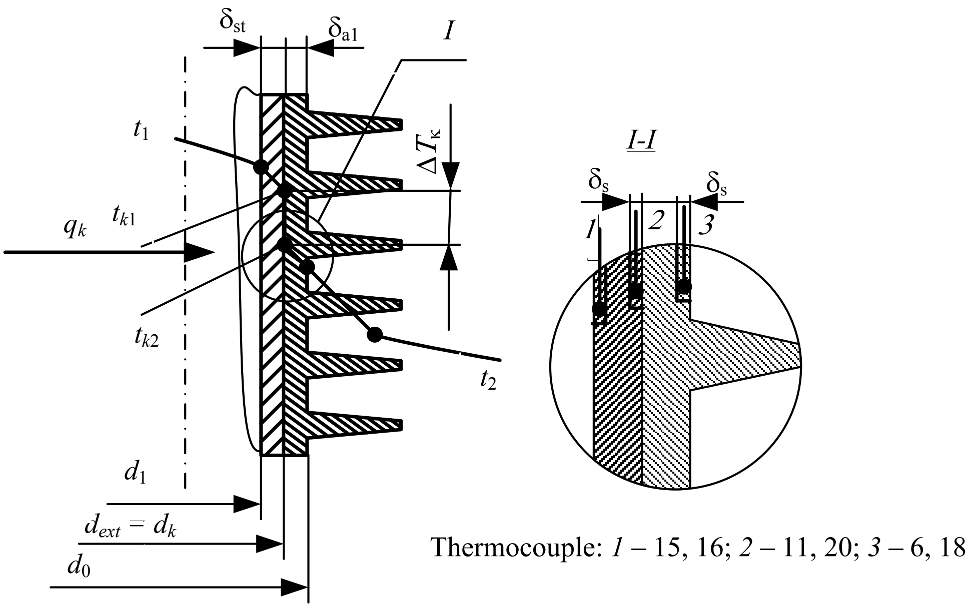
$$Q_{loss} = Q_{el} + Q_{ends} + Q_{rad},$$

where Q_{loss} - the total heat loss; Q_{el} - power for electrolysis; Q_{ends} - heat losses at the ends of BFT-heater and hydraulic lock; Q_{rad} - heat flow radiated from BFT-heater. The total heat loss defined in the equipment testing, amounted to Q_{loss} =20%.

The contact area of the parent tube and finned shell for investigated tube bank was determined by the formula $F_k = \pi d_{out} l_t$ and equals 1.13×10^{-2}m$^{2.}$

Results of the study. Testing the quality of the contact supporting tube and aluminum finned shell (Fig. 1, 3) was carried out in the following thermal and aerodynamic mode: generated heat amount in the calorimeter varied in the range Q = 210-670 Wt, Reynolds numbers interval for the air flux was Re $\cong$2,000–9,000.

The generalized results of the experimental studies are shown in Fig. 4. Each point symbol corresponds to its experiment series.



Thermocouple: *1* – 15, 16; *2* – 11, 20; *3* – 6, 18

Fig. 3. Scheme of the temperature distribution along the cross section of bimetallic finned tube: t_1 - temperature of the operating heat conductor; t_2- temperature of gas streaming flow (air).

As follows from Fig. 4, the dependence $R_k = f(\Delta T_k)$ is linear, i.e., it can be described at first approximation by straight line equation.

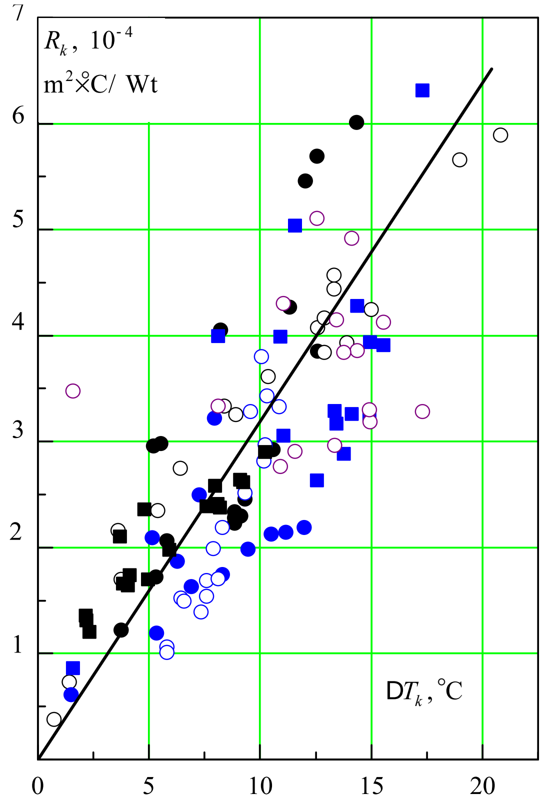


Fig. 4. Experimental dependence of thermal contact resistance on the magnitude of temperature difference in contact (point symbols correspond to each separate series of experiments)

For the tested standard size BFT (Fig. 1), this equation has the form

$$R_k = 3.2\cdot10^{-5}\cdot\Delta T_k,$$

where ΔT_k - temperature difference in the contact zone.

Taking into account the dependence obtained by the methods suggested in [2] evaluative calculations of a number of characteristics were conducted:

– thickness of the equivalent headspace in the contact conjugated heat exchange surfaces:

$$\delta_a = R_k \cdot\lambda_a = 3.2\cdot10^{-4}\cdot3.05\cdot10^{-2} = 9.8\ \mu m,$$

where TCR corresponds to $\Delta T_k = 10°C$, and thermal conductivity in the air space was chosen according to at the average temperature contact $T_k = 80°C$;

– temperature deformation of the steel tube in the contact zone:

$$\Delta_{st} = \alpha_{st} r_{out}\left(T_k - T_{en}\right) =$$
$$= 12\cdot10^{-6}\cdot6\cdot10^{-3}\cdot(80 - 19) = 4.4\ \mu m,$$

where $\alpha_{st} = 12\cdot10^{-6} K^{-1}$ - the temperature expansion coefficient for steel; $r_{out} = 6\cdot10^{-3} m$ - outer radius of the steel tube; $T_{en} = 19°C$-the environment temperature measured in the experiment;

– Temperature deformation of the aluminum shell in the contact zone:

$$\Delta_{st} = \alpha_{st} r_{out}\left(T_k - T_{en}\right) =$$
$$= 12\cdot10^{-6}\cdot6\cdot10^{-3}\cdot(80 - 19) = 4.4\ \mu m,$$

temperature gap because of the difference in temperature deformations of steel and aluminum in the contact area:

$$\Delta_T = \Delta_{al} - \Delta_{st} = 8.4 - 4.4 = 4 \ \mu\text{m}.$$

The obtained experimental results in order of magnitude are consistent with other studies [2].

To validate the calculations of the TCR in the study BFT, and the possibility of making up their computational analogues, profilograms of steel and aluminum contact surfaces were taken (Fig. 5).

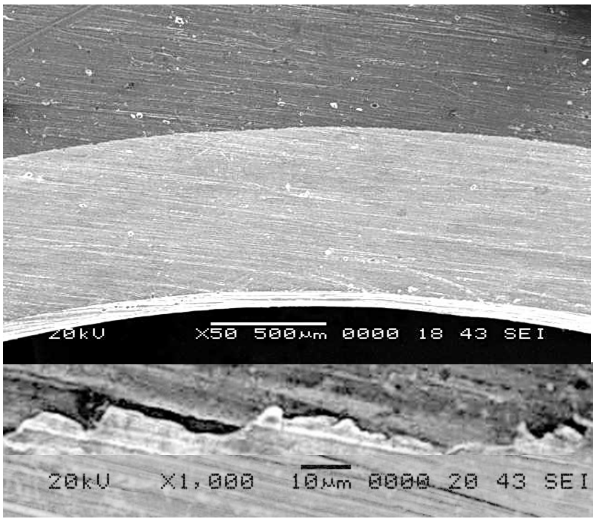


Fig. 5. Electronic photography of contact surface (50-, and 1000-fold) at different multiplications

As it can be seen from Fig. 5, the contact surface has a complex structure with mutual penetration of the separate layer sand heads pace with a nominal thickness $\delta_a = 5\text{–}10\ \mu\text{m}$.

Assuming

$$\lambda_a = 2.59 \cdot 10^{-2} \ \text{Wt/(m}^2 \cdot {}^\circ\text{C) at } 20^\circ\text{C},$$

we obtain the corresponding valueTCR at a given temperature:

$$R_k = \frac{\delta_a}{\lambda_a} = \frac{10 \cdot 10^{-6}}{2.59 \cdot 10^{-2}} = 3.9 \cdot 10^{-4} \ \text{m}^2 \cdot {}^\circ\text{C/ Wt},$$

which is consistent with profilograms of the contacted surfaces of the investigated BFT samples.

Conclusion. The experimental study of thermal characteristics of BFT and, in particular, dependences of thermal resistance of heat transfer interfacing surfaces on thermal capacity and cooling conditions was conducted.

The obtained values of the contact resistances, including temperature gaps due to the difference in steel and aluminum deformation in the contact zone, are consistent with the data of other researchers and profilograms of the contacting surfaces of the BFT studied samples.

The results of this study are self-sufficient, but they can also be used as source data for solving direct and inverse heat transfer problems within the verification of appropriate computational analogues.

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