# INTENSIFICATION OF HEAT EXCHANGE BY APPLICATION OF NANO-MODIFIED GALVANIC COATINGS TO HEAT-EMITTING SURFACES

**Yu. V. Litovka, E. N. Tugolukov,**
**A. G. Tkachev, I. A. Diakov,**
**A. A. Gravin, and R. Yu. Mukhin**

*Basic criteria for improvement in the level of heat emission are examined. The expediency of use of nano-disperse materials to achieve the stated goal and reveal positive results of their use is substantiated in detail. Two hypotheses for the development of the effect in question are experimentally confirmed.*

A significant amount of thermo-physical, kinetic, geometric, and external factors affect the intensity of heat emission; theoretical analysis and quantitative assessment of the values of the coefficients of heat emission and heat transfer in specific situations therefore present considerable difficulties, and are the basic source of errors in performing heat calculations and in mathematical modeling of thermal processes.

Studies in the area of heat-emission intensification have been conducted for an extended period of time [1, 4], and nevertheless, they are becoming all the more urgent owing to more stringent requirements continuously introduced for improvement in the efficiency of production equipment.

Methods of increasing heat emission from components of thermally loaded equipment can be classified in the following manner: structural solutions; methods associated with regime parameters; methods of influencing the properties of the heat-transfer medium (cooling agent); methods associated with a combination of thermal and other processes; and solutions associated with properties of heat-emitting and heat-transferring surfaces. The latter include: selection of the material of the heat-transferring layer with the required set of thermo-physical characteristics; methods of varying surface roughness; use of porous materials as a cover layer of heat-exchange surfaces; creation of microrelief on the heat-emitting surface; and improvement in the emissivity of the surface.

As a rule, combinations of the above-cited methods are employed in actual design and production solutions.

One promising trend in intensification of heat-exchange processes is the use of nano-disperse materials. Here, the following two directions are possible for their use: addition of nano-disperse particles to the heat-transfer media to improve their thermal properties and correct the properties of the heat-emitting surfaces.

This study deals with the second direction.

The objectives of the investigation are:

1) improving the energy efficiency of a power-generating plant by varying the roughness of the heat-emitting surfaces by application of nano-modified galvanic coatings; and

2) experimental and computational determination of the coefficients of heat emission from surfaces with nano-modified galvanic coatings.

Fuller-like Taunit carbon nanotubes (CNT) – long hollow fibers consisting of graphene layers of a Fuller-like construction – are added to galvanic electrolytes to produce the modified coating. The number of graphene layers is no more than 30, and the diameter ranges from 10 to 60 nm. Moreover, the amount of structured carbon is no less than 95% [5].
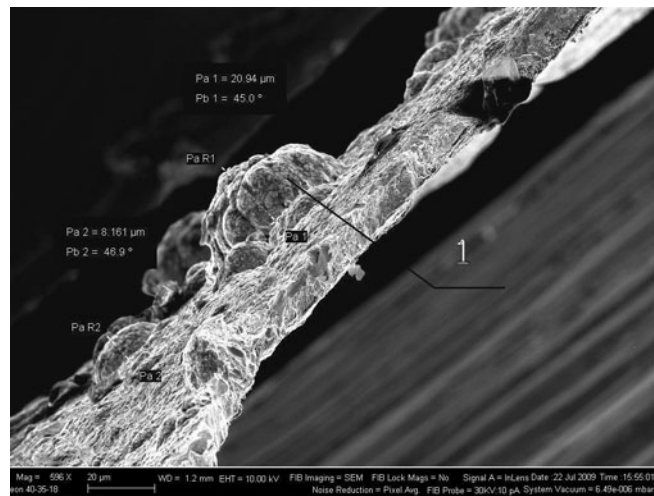
Fig. 1. Appearance of profile of galvanic nickel nano-modified coating: *1*) projection
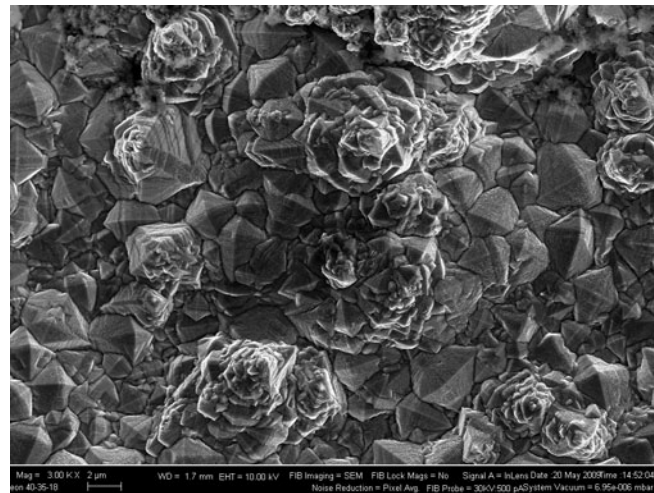of fine-crystalline formation.



Fig. 2. Distribution of fine-crystalline formations on coating formed from Watts'
nickel-plating electrolyte with addition of 80 mg/liter of Taunit CNT (×3000).

It is established as a result of our experiments that the addition of Taunit nano-carbon tubes to an electrolyte solution in the amount of from 100 to 500 mg/liter will ensure a specific microrelief of the galvanic coating – projections with a shape close to conical, and a height of the order of 30 μm (Figs. 1 and 2).

**Experimental Investigations.** We investigated heat emission from the surfaces of rectilinear cylindrical articles with a nano-modified galvanic coating, and compared it with heat emission from surfaces with a traditional galvanic coating.

For these purposes, we prepared an experimental device, the basic element of which is a 500 × 185 × 100-mm hermetically sealed heat exchanger. Water emitting heat to test articles (flow rate of 6.6 liters of water/h) was pumped through the heat exchanger. DTPL-type thermocouples connected to a Termodat 19E recording instrument, were affixed to the outside of each article. Another thermocouple was positioned in the zone where the articles were placed to measure the temperature of the water flow. The Termodat 19E instrument was connected to a personnel computer for processing and storage of the experimen-

tal data. The experiments were performed at a constant velocity of the water flow. Moreover, automated and manual adjustments were employed for heat compensation of the thermocouples. Plots of the dynamics of the temperature variation were constructed from the experimental data. The data were approximated for subsequent calculation of heat-emission coefficients.

It was established from the experiments that the heat-emission coefficients of steel St3 specimens with a nano-modified nickel coating exceed the heat-emission coefficients of specimens with the traditional nickel coating by 14–18% on average.

**Evaluation of Factors Responsible for Increase in Rate of Heat Exchange.** The increase in the rate of heat exchange can be explained by the effect of two factors: by an increase in the area of the heat-exchange surface, and by formation in the near-surface section of a thermal boundary layer corresponding to the height of the projections of the surface relief.

The increase in the area of the heat-exchange surface was calculated, proceeding from the following assumptions: the elements of the relief are cones with a base radius $r$ and height $h$, and occupy a portion $f$, of the surface while the height of the profile of the initial relief $h_0 < h$. Then, the volume fraction of the elements of the relief in the volume of a layer with a thickness exceeding the relief above the height of the initial projections (per unit area of heat-exchange surface) is

$$\nu_{r0} = \frac{V_k}{V_s} = f \frac{\frac{1}{3}(h-h_0)\pi\left(\frac{h-h_0}{h}r\right)^2}{\pi r^2 h} = \frac{f}{3}\left(\frac{h-h_0}{h}\right)^3,$$

where $\nu_{r0}$ is the volume fraction of relief elements within the volume of layer, $V_k$ is the volume of the relief elements, and $V_s$ is the total volume of the layer with the thickness of the relief exceeding the height of the initial projections.

Moreover, the increase in the area of the heat-exchange surface is equal to the ratio of the difference in the areas of the lateral surfaces of the cones exceeding the level of the projection and the areas of their bases at the level of the projections to the area of their bases at the level of the heat-exchange surface per unit area of heat-exchange surface:

$$\Delta_s = f\frac{S_c - S_b}{S_{ar}} = f\frac{\pi\left(\frac{h-h_0}{h}r\right)\sqrt{(h-h_0)^2 + \left(\frac{h-h_0}{h}r\right)^2} - \pi\left(\frac{h-h_0}{h}r\right)^2}{\pi r^2} =$$

$$= f\left(\frac{h-h_0}{hr}\right)\left(\sqrt{(h-h_0)^2 + \left(\frac{h-h_0}{h}r\right)^2} - \left(\frac{h-h_0}{h}r\right)\right),$$

where $\Delta_s$ is the relative increase in the area of the heat-exchange surface, $S_c$ is the total area of the surface of the relief elements (cones), $S_b$ is the total area of the bases of the relief elements, and $S_{ar}$ is the area of the heat-exchange surface in the absence of relief elements.

Let us examine further intensification of heat exchange due to formation of microrelief on the heat-exchange surface during application of nano-modified galvanic coatings.

Since the thermal conductivity of the material forming the heat-exchange surface is, as a rule, appreciably higher than that of the liquid or gas forming the thermal boundary layer, the equivalent thermal conductivity will also be significantly higher than the thermal conductivity of the stationary liquid for the portion of the boundary layer with a thickness equal to the height of the surface relief.

The intensification of heat exchange $\Delta$ can be determined from the relative change in the coefficient of heart emission:

$$\Delta = \frac{\alpha_1 - \alpha}{\alpha_1} \cdot 100\%,$$

where $\alpha_1$ is the coefficient of heat emission to the surface with the nano-modified coating, and $\alpha$ is the coefficient of heat emission to the initial surface of the coating.

The coefficient of heart emission $\alpha$ can be determined from a criterial equation corresponding to the conditions of heat emission. As the flow of substance moves along a rectilinear cylindrical channel, for example, the coefficient of heat emission to the wall of the channel in a turbulent regime is determined from the equation [6]:

$$\text{Nu} = 0.021\,\text{Re}^{0.8}\,\text{Pr}^{0.4}, \tag{1}$$

where $\text{Nu} = \alpha d/\lambda$; $\text{Re} = wd\rho/\mu$; $\text{Pr} = \mu/c\lambda$; $w$ is the average velocity of the flow in m/sec; $d$ is the diameter (equivalent) of the channel in m; $c$, $\rho$, $\mu$, and $\lambda$, are, respectively, the heat capacity in J/(kg·K), density in kg/m$^3$, dynamic viscosity in Pa·sec, and thermal conductivity in W/(m·K) of the substance at the temperature of the flow.

Equation (1) is valid for $\text{Re} > 10000$.

The coefficient of heat emission $\alpha_1$ can be defined as the inverse of the sum of the heat components of the thermal boundary layer:

$$\alpha_1 = \frac{1}{\sum\limits_{i=1}^{n} \frac{\delta_i}{\lambda_i}},$$

where $\delta_i$ are the thicknesses of the layers comprising the thermal boundary layer in m, and $\lambda_i$ are the thermal conductivities of the layers that make up the thermal boundary layer in W/(m·K).

Let us evaluate the total thickness of the thermal boundary layer in m:

$$\delta_t = \lambda/\alpha.$$

For comparison, the estimated thickness of the laminar hydrodynamic boundary layer in m:

$$\delta_l = d/\text{Re}^{0.5}.$$

The thermal boundary layer consists of two components: one is formed by the substance of the flow, and the other has a thickness corresponding to the height of the elements of the surface relief, and includes both the relief elements, and also the substance of the flow between them.

Let us assume that the equivalent thermal conductivity of the layer $\lambda_e$ in W/(m·K), which includes the elements of the surface relief, is determined additively:

$$\lambda_e = \lambda_s v_{r0} + \lambda(1 - v_{r0}),$$

where $\lambda_s$ is the thermal conductivity of the material in the surface in W/(m·K).

**Sample Calculation.** Let us examine the heat emission toward a flow of water in a rectilinear section of a cylindrical pipeline; this corresponds to the parameters of the experiment. We will compare the surfaces of the nano-modified nickel galvanic coating and the traditional nickel galvanic coating.

Let the inside diameter of the pipeline $d = 21 \cdot 10^{-3}$ m. The heat-transfer medium is water. The average velocity of the flow $w = 1$ m/sec. The temperature $t = 60°$C. The height of the projections on the initial heat-exchange surface $h_0 = 10^{-5}$ m. The height of the relief on the heat-exchange surface $h = 30 \cdot 10^{-6}$ m. The relief is formed by nickel cones. The angle of the generatrix of a cone to the base $\beta = 45°$ (in that case, the radius of the base $r = h$). The portion of the surface occupied by the cones $f = 20\%$. The thermal conductivity of nickel $\lambda_{\text{Ni}} = 90.9$ W/(m·K). The properties of the water at 60°C are: density $\rho = 983$ kg/m$^3$; thermal conductivity $\lambda = 0.659$ W/(m·K); dynamic viscosity $\mu = 0.47 \cdot 10^{-3}$ Pa·sec; and Prandtl number $\text{Pr} = 2.98$.

The increase in the area of the heat-exchange surface

$$\Delta_s = f\left(\frac{h - h_0}{h}\right)^2 \left(\sqrt{2} - 1\right) = 0.2\left(\frac{(30 - 10) \cdot 10^{-5}}{30 \cdot 10^{-5}}\right)^2 \left(\sqrt{2} - 1\right) = 0.036 = 3.6\%.$$

The increase in the area of the heat-exchange surface due to formation of microrelief in the case under consideration is negligible (falls within the range of errors of estimated calculations).

Let us evaluate further intensification of heat exchange due to formation of a thermal boundary layer at the surface.

The Reynolds number:

$$\text{Re} = \frac{wd\rho}{\mu} = \frac{1 \cdot 21 \cdot 10^{-3} \cdot 983}{0.47 \cdot 10^{-3}} = 43900.$$

The estimated thickness of the laminar boundary of the hydrodynamic layer:

$$\delta_l = \frac{d}{\text{Re}^{0.5}} = \frac{21 \cdot 10^{-3}}{43900^{0.5}} = 10^{-4} \text{ m.}$$

The coefficient of heat emission:

$$\alpha = \frac{\lambda}{d} 0.021 \cdot \text{Re}^{0.8} \text{Pr}^{0.43} = \frac{0.659}{21 \cdot 10^{-3}} 0.021 \cdot 43900^{0.8} 2.98^{0.43} = 5460 \text{ W/(m}^2 \cdot \text{K).}$$

The estimated thickness of the thermal boundary layer:

$$\delta_\text{t} = \frac{\lambda}{\alpha} = \frac{0.659}{5460} = 1.2 \cdot 10^{-4} \text{ m.}$$

Thus, the values of $\delta_l$ and $\delta_\text{t}$ are comparable, and, consequently, any of them can be used in the calculations.

The volume fraction of relief elements in the volume of a layer with a thickness exceeding the relief above the initial projections is:

$$v_{r0} = \frac{f\left(\dfrac{h - h_0}{h}\right)^3}{3} = \frac{0.2\left(\dfrac{(30 - 10) \cdot 10^{-5}}{30 \cdot 10^{-5}}\right)^3}{3} = 2 \cdot 10^{-2} = 2\%.$$

The equivalent thermal conductivity of the layer with a thickness of the relief is estimated by the additive law:

$$\lambda_e = \lambda_s v_{r0} + \lambda(1 - v_{r0}) = 90.9 \cdot 0.02 + 0.659 \cdot (1 - 0.02) = 2.46 \text{ W/(m} \cdot \text{K).}$$

The estimate of the coefficient of heat emission is the inverse of the sum of the thermal resistances of the thermal boundary layer:

$$\alpha_1 = \frac{1}{\dfrac{h - h_0}{\lambda_e} + \dfrac{\delta_\text{t} - (h - h_0)}{\lambda}} = \frac{1}{\dfrac{20 \cdot 10^{-6}}{2.46} + \dfrac{100 \cdot 10^{-6}}{0.659}} = 6260 \text{ W/(m}^2 \cdot \text{K).}$$

The computed increase in the coefficient of heat emission is:

$$\Delta = \frac{\alpha_1 - \alpha}{\alpha_1} \cdot 100\% = \frac{6260 - 5460}{6260} \cdot 100\% = 14.6\%.$$

The result obtained correlates well with the experimental data.

**Conclusions**

1. A 14–18% increase in the coefficients of heat emission from surfaces with a nano-modified nickel galvanic coating toward water as compared with the traditional galvanic coatings is obtained experimentally.

2. Two hypotheses for the development of this effect are confirmed: the increase in the area of the heat-exchange surface and the formation of a thermal boundary layer in the near-surface section. It is revealed that the first factor exerts a negligible influence on heat emission; the second factor is the basic one.

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