Influence of process fluids properties on component surface convective heat emission

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Abstract. When grinding with metal-working process fluid, a thin layer of inhibited liquid is formed between the component and the grinding wheel under the action of viscous forces. This can be defined as a hydrodynamic boundary layer or a thermal boundary layer. In this work, the thickness of the layers is studied depending on the viscosity of the fluid, inertia forces, velocity and pressure of the flow; also the causes of their occurrence are identified. It is established that under turbulent flow, the viscosity of the flow and the diffusion rate are much higher than in laminar flow, which also affects heat emission. Calculation of heat transfer in a single-phase chemically homogeneous medium of process liquids has shown that their properties, such as viscosity, thermal conductivity, density and heat capacity are of primary importance. The results of experimental studies of these characteristics are presented. When determining the heat transfer coefficient, functional correlations between the physical variables of the process fluid and the change in time and space have been established. As a result of the studies carried out to determine the heat transfer coefficient of a plate immersed in the process fluid, it is established that the intensification of the cooling process of the treated surface immersed in the coolant is more intense than with other methods of coolant supplying. An increase in the pulsation rate of the process liquid flow and the length of the flow displacement path leads to an increase in the heat transfer coefficient of the treated surface and a decrease in the temperature that arises during grinding.

1. Introduction
The process of heat transfer between the component surface and the flow of the process fluid is carried out jointly by convection and thermal conductivity due to the simultaneous action of molecular conduction with macroparticles that are mixed in a moving medium [1-8].

2. Methods
When liquid particles come into contact with the treated surface, a thin layer of an inhibited liquid, called as the hydrodynamic boundary layer, is formed under the action of viscous forces. The

thickness of this layer δ depends on the fluid viscosity, the inertia forces and is independent of the flow pressure. If Reynolds number $\mathrm{Re} \equiv \dfrac{v_0 l}{\nu}$, characterizing the inertia, and viscosity correlation is Re << 1, then δ/l >> 1, the liquid viscosity has the greatest influence on the boundary layer thickness.

The liquid layer at the treated surface, in which the temperature varies from the surface temperature of the component to the liquid temperature far from the treated surface, is called the thermal boundary layer. Thickness k of this layer depends on the process fluid flow rate. The flow in the boundary layer can be either laminar or turbulent.

The turbulent flow consists of a regular flow described by the averaged values of the velocities and the instantaneous velocity chaotic pulsation flow superimposed on it.When the velocity rises, mechanical energy is transferred. If there is a temperature difference in the flow, the velocity pulsations lead to a heat transfer, resulting in temperature pulsations. The temperature at a certain fixed point of the turbulent flow fluctuates about an average time value t. Thus, the turbulent flow is a nonstationary process, but if averaged over time velocity and temperature $\vec{v}$ and $\vec{t}$ do not change, then such motion and heat transfer associated with it can be regarded as stationary (quasi-stationary) processes.

In turbulent flow, the flow viscosity and the diffusion rate are much higher than in laminar flow, which also affects heat emission. Thus, on the processed plate with a laminar hydrodynamic boundary layer, heat transfer coefficient $\alpha \propto v^{0,5}$, whereas with the turbulent one - $\alpha \propto v^{0,8}$, when transitioning from a laminar flow regime to a turbulent one - $\alpha \propto v^{1,4}$. Therefore, it is desirable to obtain a turbulent or transition flow regime to increase the heat transfer coefficient. At the same time, as the flow rate increases, the energy expenditure on overcoming the hydraulic resistance raises.

Such properties as viscosity, thermal conductivity, density and heat capacity are of primary importanceforcalculation of heat transfer in a single-phase chemically homogeneous medium of process liquids.

Molecules of liquids perform periodic oscillatory movements with a varying period of oscillation. Furthermore, each molecule is within the range of other molecules, so it moves relatively slowly in the fluid. The thermal conductivity of liquids is caused both by the transfer of energy via the collision of molecules with each other, and by diffusing molecules transferring it. A necessary condition for thermal conductivity process *dQ/dT* is the presence of temperature gradient *dt/dy* in the liquid [9-25]:

$$\frac{dQ}{dT} = -\lambda \frac{dt}{dy} . \tag{1}$$

Thermal conductivity coefficient λ in equation (1) characterizes the ability of a liquid to transfer heat and depends on the type of liquid, temperature and pressure (Fig. 1, a).

The resulting temperature fields can have a significant effect on heat transfer and fluid flow. Thus, at low velocities, the phenomenon of a sharp density stratification of a fluid leads to a slowing of its mixing and can cause complete attenuation of turbulence. The intercorrelation between fluid density and temperature is characterized by thevolumetric expansion coefficient:

$$\frac{dQ}{dT} = -\lambda \frac{dt}{dy} . \tag{2}$$

The results of research of the dependence of the density on temperature in various fluids are shown in Fig. 1, b.

The heat capacity is determined by the amount of thermal energy necessary to heat the liquid mass 1 kg per 1 K at constant pressure:

$$c_p = \frac{\Delta Q}{\Delta T} . \tag{3}$$

The results of the change in the heat capacity of various liquids at constant flow pressure depending on temperature are shown in Fig. 1, c.
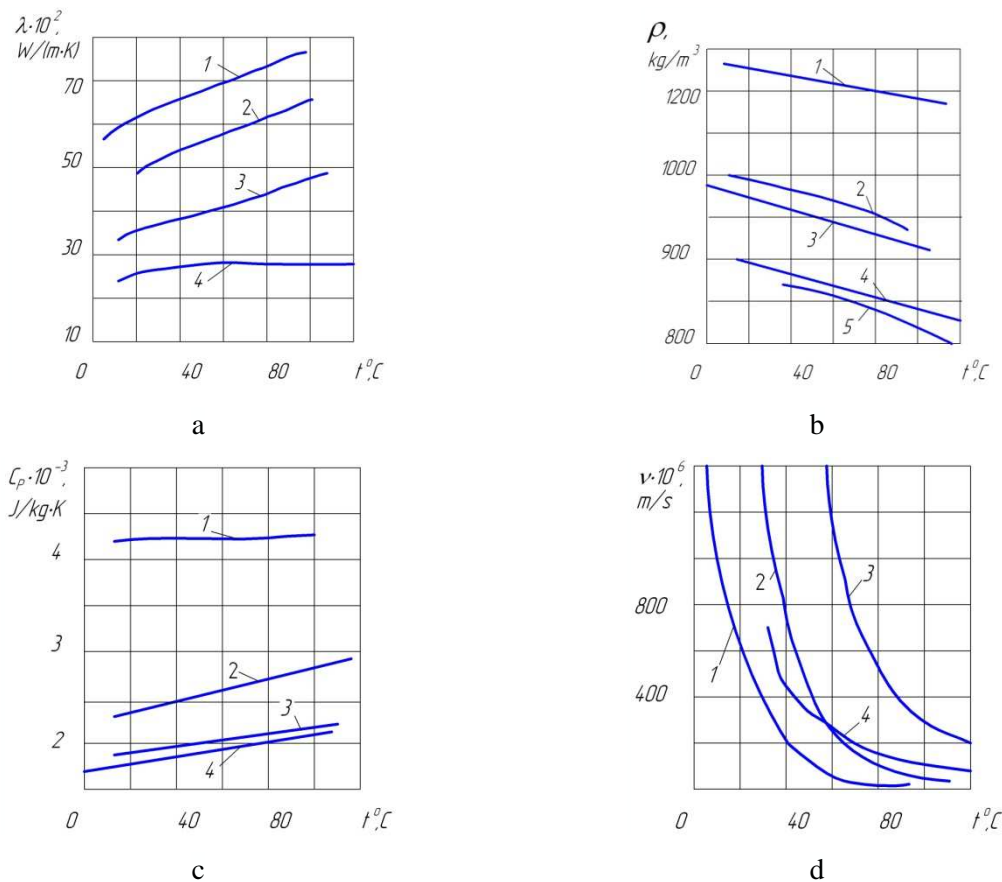
Figure 1. Dependence of a) thermal conductivity coefficient, b) density, c) heat capacity, d) viscosity of various liquids on the temperature: 1 – water, 2 – aqueous emulsions, 3 – hydrocarbon process fluids, 4 – oil-water emulsions

The heat transfer process in the boundary layer from the treated surface to the liquid heat-transferring agents has a stabilizing effect due to the viscosity of the process fluid, which is characterized by the degree of particle mobility and depends on the temperature (Fig. 1, d). Viscosity determines the hydrodynamic and thermal characteristics of liquids. A high viscosity under other similar conditions gives a lower Reynolds number, i. e. can lead to the transition of the flow regime from turbulent to laminar one. The greater the liquid viscosity, the greater the velocity at which the flow regime changes, and in viscous liquids the flow remains laminar at significant velocity.

Thus, with convective heat transfer there is a close correlation between the temperature and velocity fields. On the one hand, in the flow of a liquid, the temperature field depends on the velocity field and its changes. On the other hand, with a temperature change, the viscosity and other physical properties of the liquid vary substantially, which causes a change in the velocity field.

When calculating the heat transfer coefficient, a dimensional method or similitude method is used to determine the correlation between dimensionless groups, called similarity numbers (criteria) which characterize the entire process of convective heat transfer. If the similarity criteria made up of the quantities entering single-valuedness conditions are similar, then the phenomena are similar. Single-valuedness conditions distinguish the entire process from other qualitatively identical processes and consist of geometric conditions, physical conditions, initial and boundary conditions which characterize the course of the process at the boundaries of the liquid medium and the surface being treated. This proposition is of great importance in the modeling of convective transfer during mechanical operation of components [26-27].

In most cases, some physical parameters are variables and dependent on other variables. When

determining the heat transfercoefficient, it is necessary to establish a functional correlation between the physical variables of the process fluid, which vary in time and space.

The most important heat transfer characteristic is the Prandtl number, which characterizes the process fluid thermophysical properties:

$$\mathrm{Pr} = \frac{v}{a} = \frac{\mu \cdot c_p}{\lambda}. \tag{4}$$

where v is the kinematic viscosity coefficient, m^2/s; a - the thermal diffusivity coefficient, m^2/s; λ - thermal conductivity coefficient, W/(m · K); c_p is the specific isobaric heat capacity, J/(kg · K); μ is the dynamic viscosity coefficient, Pa·s.

In the physical sense, Pr is a measure of temperature and velocity fields' similarity. When Pr = 1, i.e. if v = a, the fields of temperature and velocity are similar. Consequently, for a forced convective flow, the Prandtl number reflects the correlation of the temperature and hydrodynamic boundary layers thickness:

$$\frac{\delta_T}{\delta} \, equal \, Pr^{-0.5}. \tag{5}$$

where δ_T is the thickness of the thermal boundary layer, m; δ is the thickness of the hydrodynamic boundary layer, m.

In liquids, the Prandtl numbers are greater than one; so the hydrodynamic boundary layer is thicker than the temperature layer, and in various oil liquids the Prandtl numbers reach tens of thousands, so the temperature boundary layer is located in a viscous sublayer.

The Prandtl number of liquids varies in a very wide range and is distinguished by an explicit temperature dependence (Figure 2). Viscosity is the only physical parameter included in the Prandtl number that depends on the temperature, therefore the nature of the change in Pr with the temperature is similar to the change in viscosity (Fig. 3).
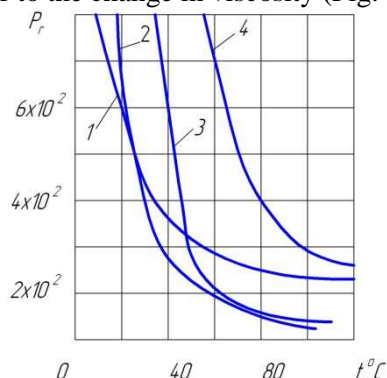
Figure 2. The Prnumber of different liquids: 1 – water, 2 – aqueous emulsions, 3 – hydrocarbon process fluids, 4 – oil-water emulsions
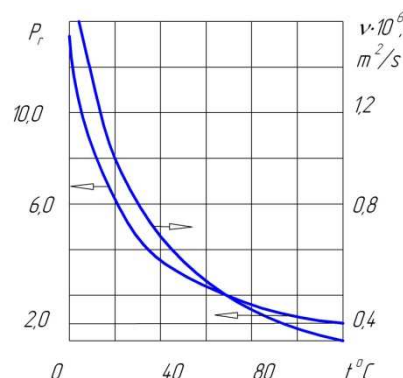
Figure 3. Dependence of kinematic viscosity and Prandtl number for water on temperature

When calculating the heat transfer coefficient, the Nusselt number is used:

$$N_u = \frac{\alpha \cdot l}{\lambda}, \tag{6}$$

where l is the geometric parameter of the material being processed.

With free convection, the Nusselt number is a function of the Prandtl and Reynolds numbers

$$N_u = f(P_r, P_e); \tag{7}$$

or in the expanded form for the heat transfer coefficient, this dependence for a flat surface face grinding has the form:

$$\frac{\alpha \cdot l}{\lambda} = \left(\frac{\upsilon_{ucm} \cdot l}{\nu}\right)^{0.8} \cdot \left(\frac{\nu}{a}\right)^{0.35} \cdot 0.024 \ . \tag{8}$$

When wedge-shaped bodies transferring heat, the Nusselt criterion in dimensionless form is:

$$Nu = 0.56 \frac{(\beta + 0.2)^{0.1}}{\sqrt{2-\beta}} \mathrm{Re}^{0.5} \mathrm{Pr}^{0.333+0.067\beta-0.026\beta^2} \ ; \tag{9}$$

heat transfer coefficient is:

$$\alpha = \frac{\lambda}{\sqrt{2-\beta}} \sqrt{\frac{\upsilon_x}{\nu \cdot x}} c_2 = \frac{\lambda \cdot 0.56(\beta+0.2)^{0.1} \mathrm{Pr}^{0.333+0.067\beta-0.026\beta^2}}{\sqrt{2-\beta}} \sqrt{\frac{\upsilon_x}{\nu \cdot x}} \ , \tag{10}$$

where x is the linear dimension of the treated surface.

Equation (10) gives the dynamics of the heat transfer coefficient change on the surface of wedge-shaped objects depending on their wedge angle β.

The thermophysical properties of the metal-working process fluid affect the heat transfer coefficient in different ways. With an increase in thermal conductivity λ, heat transfer coefficient α increases in proportion. The heat transfer coefficient sharply decreases with increasing of fluid kinematic viscosity ν and the thermal diffusivity coefficient a.

The Staton number - St - can also be expressed through the Nusselt number Nu:

$$St = \frac{Nu}{\mathrm{Re} \, \mathrm{Pr}} = \frac{\alpha}{\rho c_p \upsilon_0} \ , \tag{11}$$

or in an explicit form:

$$St = \frac{0.5 c_f}{0.93 + 12.5\sqrt{0.5 c_f}\left(\mathrm{Pr}^{2/3}-1\right)} \ . \tag{12}$$

In practical use of the similarity criteria, it is recommended for Pr_l to take the temperature of the liquid far from body t_0, for Pr_s, to take the temperature of the treated surfacets. Also it is recommended to select the coordinate, which is accounted for from the beginning of the heat transfer section, determining linear dimension. Recommendations for the effect of the liquids physical properties variability on heat emission are shown graphically in Fig. 4.
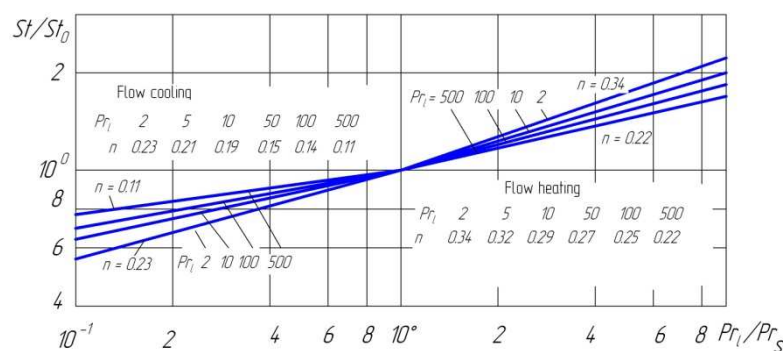
Figure 4. Influence of the dropping liquid physical properties variability on heat transfer at a turbulent boundary layer.

Using Prandtl formula $c_f = \dfrac{0.0592}{\mathrm{Re}_{lx}^{0.2}}$ and introducing correction $\left(Pr_l / Pr_s\right)^{0.25}$, let us obtain the following formula:

$$Nu_{lx} = 0.0296\,\mathrm{Re}_{lx}^{0.8}\,\mathrm{Pr}_{l}^{0.43}\left(\frac{\mathrm{Pr}_{l}}{\mathrm{Pr}_{s}}\right)^{0.25} \tag{13}$$

Having written down the Stanton and Reynolds numbers and substituting the value of the Prandtl number from Eq. (13), one can write the heat transfer coefficient dependence of the surface washed by the liquid turbulent flow on the velocity of this flow:

$$\alpha = 0.0296 v_{l}^{0.85}. \tag{14}$$

Theresults ofheat transfer coefficient calculating are presented graphically (Fig. 5 curve 1). The change in the heat transfer coefficient in dependence of the flow typehas the form shown in Fig. 5. With an increase of the metal-working process, fluid incident flow turbulence degree in the turbulent boundary layer, transverse velocity pulsations and the length of the displacement path increase. This first of all manifests itself in the outer region of the layer and, as a consequence, the heat transfer coefficient increases.
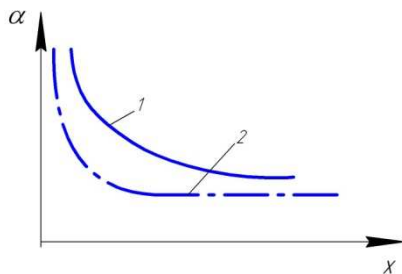
Figure 5. The heat transfer coefficient change along the plate: 1 – turbulent flow (when the plate is immersed), 2 – laminar flow (freely falling metal-working process fluidjet).

3. Conclusion
As a result of the studies carried out to determine the heat transfer coefficient of the plate immersed in the metal-working process fluid, it is established that:

1. Intensification of the treated surface immersed in the cooling process of the metal-working process fluid is more intense than with other methods of supplying process fluid.

2. An increase in the process fluid flow pulsating rate and the length of the flow displacement path leads to an increase of the treated surface heat transfer coefficient, α, and to a decrease of the temperature arising during grinding.

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