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Research Article

Influence of the Height Value of Cylindrical Specimens of Copper Grade M3 on the Kinetics of Their Cooling and Heat Transfer Processes

Z. Nizomov[1], **S. Sodatdinov**[1], **R. Kh. Saidzoda**[2], **D. Nematov**[3*]

[1]Laboratory of Molecular Spectroscopy, Tajik National University, Dushanbe, Tajikistan
[2]Department of Materials Science, M.S. Osimi Tajik Technical University, Dushanbe, Tajikistan
[3]Quantum Electronics Laboratory, S.U. Umarov Physical-Technical Institute, Dushanbe, Tajikistan
Email: dilnem@mail.ru

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Abstract: The paper presents the results of the influence of height values on the kinetics of their cooling and heat transfer processes of cylindrical samples made of copper M3 grade with a diameter of 1.0 cm. Characteristic cooling times for these processes are calculated. It is found that the characteristic cooling time increases in the series of radiation, heat conduction, and convection, linearly depending on the ratio of the sample volume to its surface area. Using experimental data on the cooling rate of the samples and theoretically calculated values of heat capacity by the Neumann-Kopp rule, the heat transfer coefficients for the processes of convection, heat conduction, and radiation as a function of temperature are estimated. It was found that with increasing temperature, the coefficients of radiative and conductive heat transfer increase, while the convective heat transfer coefficient decreases. A comparison of the heat transfer coefficients shows that within the experimental error, they do not depend on the sample length.

Keywords: copper, cooling, convection, radiation, thermal conductivity, heat transfer coefficient, temperature dependence

1. Introduction

Among the materials used by industry, copper and its alloys occupy a special place due to the successful combination of high technological and operational characteristics [1], [2].

Studies of the mechanical properties of metals and alloys in [3]-[12] show that the results of laboratory tests of samples of small sizes and massive ones used in engineering do not coincide in most cases.

Theories explaining the dependence of thermophysical characteristics on the size of samples do not exist so far. Radiation-convective heat transfer, as the most general case of complex heat transfer, plays a major role in thermal power engineering, heat engineering, and chemical technology. Therefore, the accumulation of experimental data on the effect of sample size on cooling kinetics and heat transfer coefficients is an urgent task.

A fundamental contribution to the studies of heat transfer in free thermal convection was made by L. Lorentz, W. Beckman, V. S. Zhukovsky, M. A. Mikheev, L. S. Eigenson, and E. Schmidt. In [13]-[16], the results of the study of the influence of the diameter of cylindrical aluminum samples of different grades on their cooling kinetics and heat transfer

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coefficients are presented. It is revealed that with the growth of the specimen diameter, the characteristic cooling times of convective and radiant heat transfer increase nonlinearly, and the corresponding heat transfer coefficients decrease.

The aim of the present work is to investigate the effect of the height value of cylindrical copper specimens on their cooling kinetics and heat transfer coefficients. Since the surface states of the specimens are the same, it was assumed that the heat transfer coefficient remains constant. In this case, the system under consideration is a good model for studying the effect of sample size on the characteristic cooling times.

The objects of the study were cylindrical specimens of copper M3 grade with a diameter of 1.0 cm and heights of 5.3 cm and 9.0 cm with a channel drilled out from one end for a thermocouple.

2. Experimental technique

To study the thermophysical properties of solids, heating and cooling methods are usually used. The "cooling" mode is the most convenient and simple. The method is based on measuring the time dependence of the temperature of a sample heated to a certain temperature during its natural cooling in room conditions.

The experiments were carried out on the setup described in detail in [17]. The relative error of temperature measurement in the range from 40 °C to 400 °C was ± 1% and in the range from 400 °C to 1,000 °C ± 2.5%. The accuracy of temperature recording was 0.1 °C. The am*Bi*ent temperature $\Delta T = T - T\_s$ is subtracted from the measured value of the sample temperature. Then the graph of dependence of the differences between the temperature of the sample and the environment on the cooling time is plotted: $\Delta T = f(\tau)$. All processing of the measurement results was carried out on a computer using the Microsoft Office Excel program, and the graphs were plotted and processed using the Sigma Plot 10 program. As a rule, it was possible to find such a dependence of the sample temperature on time that the regression coefficient was not lower than 0.9998.

A practically important problem of unsteady heat conduction is the problem of heating or cooling of bodies in a medium with constant temperature. The *Bi*o and Fourier criteria are the criteria of thermal similarity. The *Bi* number is the ratio of the rate of conductive heat transfer to the rate of energy storage in the material [18], [19].

$$Bi = \frac{\alpha V}{\lambda S},$$

where α is the heat transfer coefficient from the surface of the body to the environment, and λ is the heat transfer coefficient of the body material. The *Bi*o number is useful for determining whether a small body has a uniform temperature around it or not.

For a temperature of 600 K, the total heat transfer coefficient of copper is $\alpha \approx 60$ W/(mK), thermal conductivity coefficient $\lambda \approx 400$ W/(mK), and $V/S = 0.225$ cm, $Bi \approx 0.035$ [20]-[27]. For our selected study objects, the *Bi* number is small ($Bi \ll 0.1$). Under this condition, the sample is "thermally thin" and the temperature distribution inside the body is assumed to be uniform. At each moment of time, the temperature inside such a body has time to equalize due to intensive heat transfer by heat conduction. Thus, the temperature value depends only on time and does not depend on coordinates. Since the temperature gradient inside the body is practically equal to zero, we will have a heat balance equation instead of the Fourier differential equation of heat conduction.

The reduction of energy accumulated in a solid body must be equal to the heat flux removed from the surface by convection:

$$C\rho V dT = -\alpha S\left(T - T_c\right)d\tau. \tag{1}$$

where C, ρ, V, S, and T are the specific heat capacity, density, volume, area, and temperature of the sample, respectively, α is the heat transfer coefficient, and T_c is the ambient temperature.

This expression can be rewritten as

$$\frac{d\left(T - T_c\right)}{T - T_c} = -\frac{\alpha}{C\rho}\frac{S}{V}d\tau,$$

or

$$\frac{d(\Delta T)}{\Delta T} = -\frac{\alpha}{C\rho}\frac{S}{V}d\tau. \tag{2}$$

Integrating expression (2) in the range from 0 to τ for cooling time, we obtain

$$\ln\frac{\Delta T}{(\Delta T)_{\tau=0}} = -\frac{\alpha}{C\rho}\frac{S}{V}\tau. \tag{3}$$

Exponentiating (3), we obtain

$$\Delta T = (\Delta T)_{\tau=0}\, e^{-\left(\frac{\alpha S}{C\rho V}\right)\tau}. \tag{4}$$

In expression (4), the value

$$\frac{C\rho V}{\alpha S} = \tau_i \tag{5}$$

has the dimension of time. At $\tau = \tau_i$, the temperature difference between the sample and the environment decreases by a factor of 2.71. The value of τ_i depends on the sample material and the type of heat transfer, so we use it as a characteristic cooling time in cooling processes. For a cylinder,

$$\tau_i = \frac{C\rho}{\alpha}\frac{h}{2\left(1+\frac{2h}{d}\right)},$$

where h and d are its height and diameter, respectively.

Taking into account radiative, conductive, and convective heat transfer, equation (4) takes the following form:

$$\Delta T = (\Delta T_i)_{\tau=0}\exp\left(-\tau/\tau_i\right) + (\Delta T_t)_{\tau=0}\exp\left(-\tau/\tau_t\right) + (\Delta T_k)_{\tau=0}\exp\left(-\tau/\tau_k\right). \tag{6}$$

Indices i, t, and k indicate radiative, conductive, and convective heat transfer, $(\Delta T_i)_{\tau=0}$, $(\Delta T_t)_{\tau=0}$, and $(\Delta T_k)_{\tau=0}$, indicate temperature difference between the heated body and the environment at the moment of the beginning of measurements, and τ_i, τ_t, and τ_k indicate characteristic cooling times for the processes of heat transfer by radiation, conduction, and convection.

With the help of formula (6), it is possible to determine the temperature of the sample at any moment, which corresponds to the practical solution of the problem of non-stationary heat conduction about the cooling of bodies in a medium with a constant temperature. Thus, at small values of the *Bi* number, at free cooling the equation of similarity is described by expression (6).

3. Results and their discussion

The temperature dependences of cylindrical M3 copper specimens with a diameter of 1.0 cm and different heights on time in a wide temperature range have been investigated by the cooling method. Experimentally obtained time dependences of the temperature of the samples are described with good enough accuracy by equation (6) [28].

As can be seen from formula (5), the characteristic cooling times depend on the ratio of the sample volume to its heat exchange surface area with the environment and the heat transfer coefficient of the corresponding cooling process:

$$N = \frac{\tau}{\tau_i} = \frac{\alpha S\tau}{C\rho V} = \frac{\alpha S\tau}{C\rho V}\frac{\lambda}{\lambda}\frac{V}{V}\frac{S}{S} = Bi\frac{S^2}{V^2}\frac{\lambda\tau}{C\rho} = Bi\frac{\alpha\tau S^2}{V^2} = BiFo. \tag{7}$$

In the case of radiative heat transfer, a radiative Biot number is introduced, defined by the formula $Bi = \sigma T^3 V/\lambda S$, where σ is the degree of blackness.

For the aluminum specimens, the upper-temperature limit was 620 °C. They exhibit conductive-convective (together) and radiant heat transfer. As can be seen from formula (6), the expansion of the temperature study area allowed us to observe all components of heat transfer separately for the first time. In the heat transfer process between the sample and air, heat is transferred through the solid-gas boundary. First, heat is transferred through thermodiffusion, which is the transfer of heat particles to an area with an average temperature. Then heat is transferred through convection, which occurs in the surrounding medium, the air.

Then, differentiating (6), we obtain the following formula for calculating the cooling rate:

$$\frac{dT}{d\tau} = -\frac{(\Delta T_1)_{\tau=0}}{\tau_1}e^{-\tau/\tau_1} - \frac{(\Delta T_2)_{\tau=0}}{\tau_2}e^{-\tau/\tau_2} - \frac{(\Delta T_3)_{\tau=0}}{\tau_3}e^{-\tau/\tau_3}. \tag{8}$$

Where $\frac{(\Delta T_1)_{\tau=0}}{\tau_1}$ and $\frac{(\Delta T_2)_{\tau=0}}{\tau_2}$ are the values of the cooling rate at the moment of measurement start. For simplicity, we replaced indices i, t, and k by 1, 2, and 3.

Figures 1 and 2 show the dependences of temperature difference between the samples and the environment ΔT, cooling by radiation ΔT_1, thermal conductivity ΔT_2, and convective heat transfer ΔT_3 for cylindrical copper samples with a diameter of 1.0 cm and heights of 5.3 cm and 9.0 cm.

As can be seen from Figures 1 and 2, the radiation cooling process is faster than conduction and convective heat transfer. Figures 3-4 show the dependences of the cooling rate on time for copper samples with a diameter of 1.0 cm and heights of 5.3 and 9.0 cm.

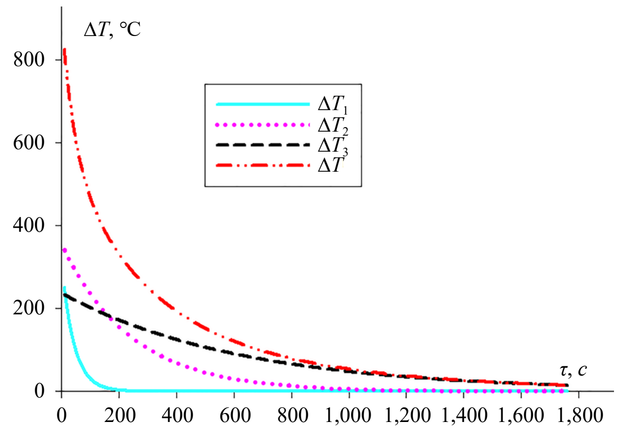

Figure 1. Time dependence of total cooling, cooling by thermal radiation, thermal conduction, and convective heat transfer with the environment for a specimen with a height of 9.0 cm

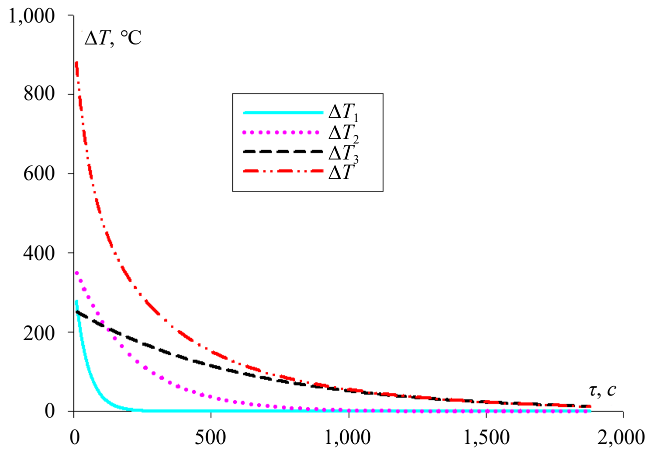

Figure 2. Time dependence of total cooling, cooling by radiation, heat conduction, and convective heat exchange with the environment for a specimen with a height of 5.3 cm

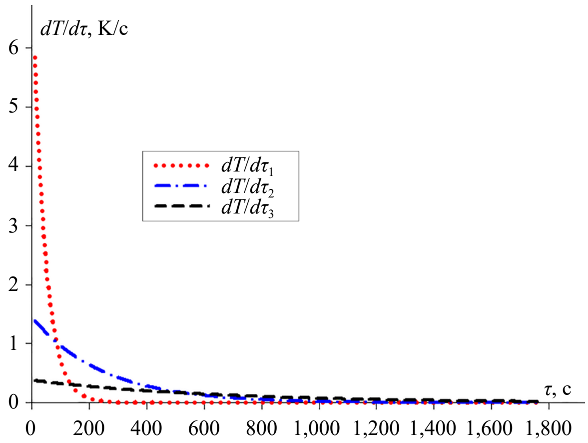

Figure 3. Time dependence of cooling rate due to radiation, conduction, and convective heat transfer for a specimen with a height of 5.3 cm

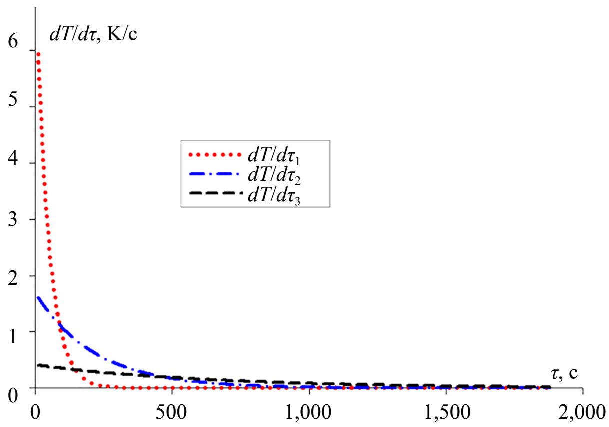

Figure 4. Dependence of cooling rates on time for a cylindrical copper specimen with a diameter of 1.0 cm and a height of 9.0 cm

The Table 1 below summarizes the values of constants in equation (6).

Table 1. Parameters of expression (6)

h, cm	$(\Delta T_1)_{\tau=0}$, K	τ_1, s	$(\Delta T_2)_{\tau=0}$, K	τ_2, s	$(\Delta T_3)_{\tau=0}$, K	τ_3, s	V/S, cm
5.3	317	43	355	244	237	625	0.21
9.0	345	47	367	217	256	625	0.225

Processing of the wing dependence of characteristic cooling times on the ratio of the cylinder volume to its surface area V/S for copper samples of different heights using the Sigma Plot 10 program showed that within the limits of the determination error, it is expressed by the equation

$$\tau_i = a\frac{V}{S}, \tag{9}$$

where a = 133 s/cm for τ_1, 900 s/cm for τ_2, and 1,750 s/cm for τ_3.

According to [29], the dependence of specific heat capacity of copper on temperature is expressed by the formula

$$C(T-300) = 388.47 + 17.94 \times 10^{-2}x - 2 \times 10^{-2}x^2 + 0.22 \times 10^{-3}x^3 \tag{10}$$

where $x = (T - 300)/100$.

Using the calculated values of temperature dependence of copper heat capacity according to formula (10) and experimentally obtained dependence of cooling rate on time, for each process we calculated the corresponding heat transfer coefficients according to the formula [28]-[31].

$$\alpha(T) = \frac{\rho r h C(T)\left|\left(\frac{dT}{d\tau}\right)\right|}{2(r+h)(T-T_0)}, \tag{11}$$

where r and h are the radius and height of the sample. Figures 5 and 6 show temperature dependences of the total heat transfer coefficients α, heat transfer by radiation α_1, conduction α_2, and convection α_3.

Figures 7-10 show comparisons of heat transfer coefficients for two values of cylinder height.

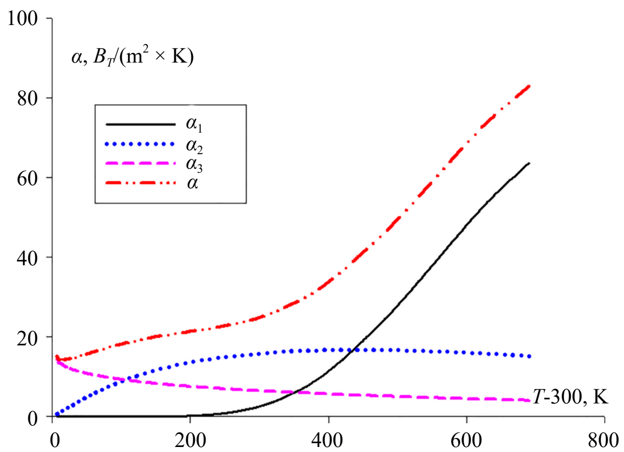

Figure 5. Temperature dependence of the total heat transfer coefficients α, heat transfer by radiation α_1, heat transfer by conduction α_2, and heat transfer by convection α_3 for M3 copper with a diameter of 1.0 cm and a height of 5.3 cm

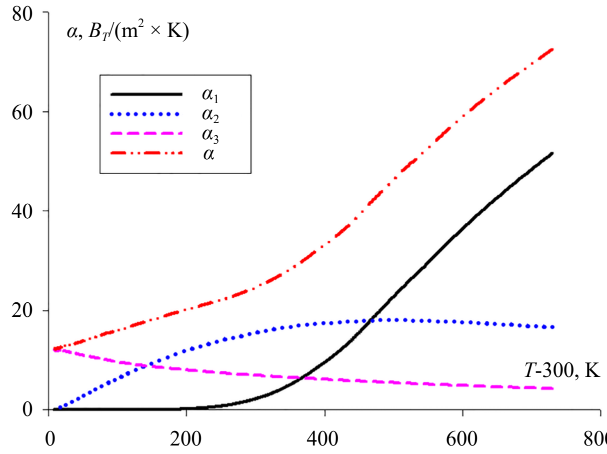

Figure 6. Temperature dependence of the total heat transfer coefficients α, radiation heat transfer α_1, conduction heat transfer α_2, and convection heat transfer α_3 for 9.0 cm high copper M3 specimens

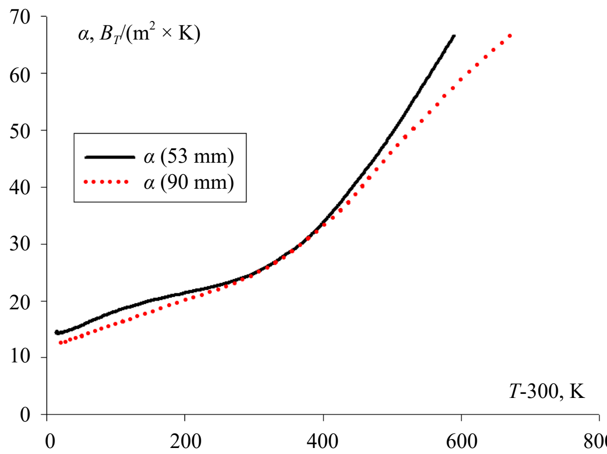

Figure 7. Temperature dependence of total heat transfer coefficients for M3 copper specimens with a diameter of 1.0 cm and heights of 5.3 cm and 9.0 cm

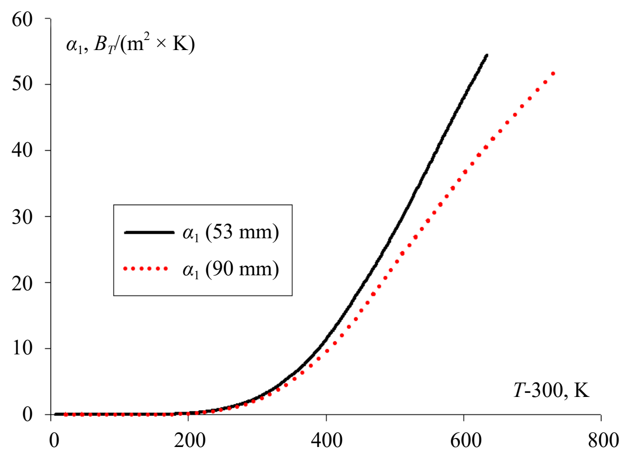

Figure 8. Temperature dependence of the heat transfer coefficient due to radiation α_1

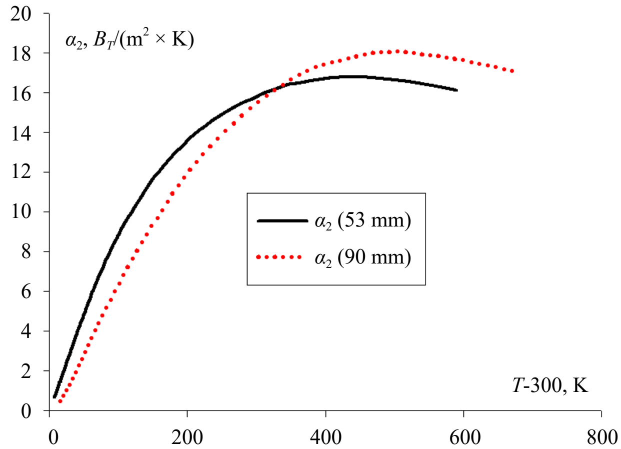

Figure 9. Temperature dependence of the heat transfer coefficient due to thermal conductivity α_2

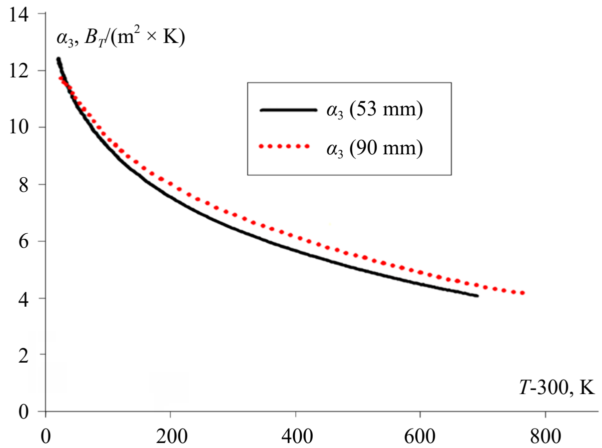

Figure 10. Temperature dependence of the heat transfer coefficient due to convection α_3

As can be seen from Figures 7-10, the heat transfer coefficients within the error of the experiment do not depend on the length of the cylinder but depend on the material and surface condition of the sample.

4. Conclusion

The effect of the height of cylindrical copper specimens on the cooling kinetics under free convection conditions has been investigated. The characteristic cooling time increases in the series of radiation, conduction, and convection. It is found that the characteristic cooling times increase linearly with increasing volume-to-area ratio of the sample within the error of the experiment. It is explained by the fact that at the same state of the surface and material of the samples, the heat transfer coefficient within the error of the experiment does not depend on the height of the cylinder. It is revealed that with increasing temperature under conditions of free convection, the coefficients of radiant and conductive heat transfer increase, and the coefficient of convective heat transfer decreases.

The results stated in the work are of fundamental importance for the study of processes occurring during the cooling of metal products. The dependences of cooling kinetics and heat transfer coefficients on size are of interest for the physics of thermal processes.

Conflict of interest

The authors declare no competing financial interest.

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