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Research Article

Effect of Size on Cooling Kinetics of Spherical Samples from Different Grades of Aluminum

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Abstract: The influence of the size of spherical specimens of different aluminum grades (A0, A5, A6, AB98, and A5N) on their characteristic cooling times and heat transfer coefficients in a wide temperature range has been investigated. It is shown that the cooling process of spherical samples in all cases is carried out by convective and radiative mechanisms of heat exchange with the environment, possessing characteristic times. The values of characteristic times of cooling due to convection and radiation are estimated. Using experimental data on the cooling rate of samples and theoretically calculated values of their heat capacity according to the Neumann-Kopp rule, the coefficients of radiant and convective heat transfer as a function of temperature are determined. It was compared with the regularities of the effect of sample size on the thermophysical properties of cylindrical samples. It is found that spherical specimens cool faster than cylindrical specimens of the same mass, and the heat transfer coefficients are larger. During the experiment, it turned out that the convective heat transfer coefficient lies in the range of 10-20 $W/m^2 \cdot K$.

***Keywords*:** aluminum of different grades, cooling, convection, thermal radiation, size influence, temperature dependence

1. Introduction

Aluminum is one of the most used metals in the world. It is widely used in industry, construction, transportation, agriculture, and households. Low density, high thermal and electrical conductivity, plasticity, lightness, and corrosion resistance are unique properties of aluminum [1]-[4]. Aluminum has an important place in the modern world. The heat capacity of aluminum strongly depends on temperature and is much higher than that of other metals. The ability to store heat well is widely used in industry and heat engineering, making aluminum indispensable.

The problem of the influence of the size and shape of metal products on heat transfer processes is of great importance in terms of predicting the behavior of metals and alloys in real large-size structures based on laboratory studies of small samples. This problem today is paid much attention in many countries of the world.

The relevance of the problem is explained, first of all, by the vast field of its applications in modern conditions. 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.

Analysis of literature data shows that the influence of the shape and size of samples on their mechanical properties

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is well enough studied [5]-[7].

In our laboratory we have studied the thermophysical properties of pure metals [8], various grades of aluminum, technical aluminum of different degrees of purity [9], alloyed with alkaline-earth and rare-earth metals alloys Zn5Al and Zn55Al [10]-[11], where cylindrical samples had a constant size (diameter of 16 mm and height of 30 mm). In [12]-[15], we investigated the influence of the diameter of cylindrical samples made of different grades of aluminum on their cooling kinetics. It was shown that as the diameter of cylindrical samples increases, the characteristic cooling times due to convective heat transfer and radiation increase, and the heat transfer coefficients decrease.

In addition to these works, we did not find information on the influence of the size and shape of samples on the kinetics and mechanisms of cooling in the available databases of scientific literature.

The main purpose of this study was to experimentally investigate the cooling kinetics and heat transfer coefficients of spherical aluminum of different grades in a wide temperature range and to establish the regularities of their variation depending on the size.

Aluminum grades A0 (99.0%), A5 (99.5%), A6 (99.6%), A5N (99.999%), and AB98 (98%) were selected as the object of study. Spherical samples with diameters of 1.765 cm, 2.82 cm, and 3.35 cm were prepared from cylindrical samples. The mass of the sample was kept constant. The chemical composition of the samples was determined using a Spectrolab spectrometer in the physical laboratory of TALCO.

2. Experimental technique

Heating and cooling methods are used to investigate the thermophysical properties of solids. For purely physical reasons, it is extremely difficult to maintain a sufficiently monotonous change in the temperature of the object in the "heating" mode due to the presence of a whole chain of external factors. The most convenient and simple from this point of view is the "cooling" mode. This method is based on the measurement of the sample temperature from time and the Newton-Richman cooling law. In this method, the main measured parameter is the dependence of the sample temperature on time with natural air heat dissipation. The measurement of the sample temperature from the cooling time of the metals was carried out on a setup described in detail in [8], [16]-[17]. The relative temperature measurement error in the range from 40 °C to 400 °C was ±1% and in the range from 400 °C to 1,000 °C ± 2.5%. Subtract the ambient temperature $\Delta T = T - T_0$ from the measured sample temperature. Next, we plot the dependence of the temperature difference between the sample and the environment on time: $\Delta T = f(\tau)$. The measurement results were processed on a computer using the Microsoft Office Excel program, and the graphs were built using the Sigma Plot 10 program. As a rule, choosing such a dependence of the sample temperature on time made it possible that the regression coefficient was maximum, indicating high data reliability.

3. Results and discussion

The experimentally obtained dependences of the temperature of the samples on the cooling time are described with reasonably good accuracy by the following equation [12]-[15]:

$$\Delta T = \left(\Delta T_1\right)_{\tau=0} e^{-\tau/\tau_1} + \left(\Delta T_2\right)_{\tau=0} e^{-\tau/\tau_2} \tag{1}$$

where $(\Delta T_1)_{\tau=0}$ and $(\Delta T_2)_{\tau=0}$ are the temperature difference between the heated body and the environment at the start of measurements; that is, at $t = 0$, t_1 and t_2 are the characteristic cooling times for the first and second heat transfer processes when the temperature amplitude decreases by 2.71 times.

Differentiating (1), we obtain the formula for the cooling rate:

$$\frac{dT}{d\tau} = -\frac{\left(\Delta T_1\right)_{\tau=0}}{\tau_1} e^{-\tau/\tau_1} - \frac{\left(\Delta T_2\right)_{\tau=0}}{\tau_2} e^{-\tau/\tau_2}, \tag{2}$$

where $\frac{(\Delta T_1)_{\tau=0}}{\tau_1}$ and $\frac{(\Delta T_2)_{\tau=0}}{\tau_2}$ are values of the cooling rate at the start of measurements.

For example, Figure 1 shows the temperature dependence on the cooling time of a spherical sample of A0 aluminium marked with a diameter of 1.765 cm.

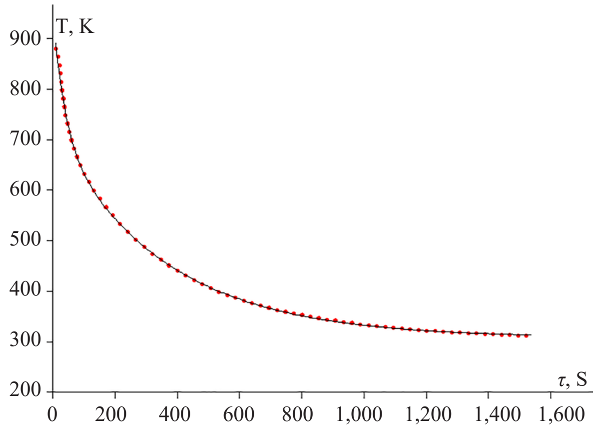

Figure 1. The temperature dependence of the cooling time of an A0 grade aluminium spherical sample with a diameter of 1.765 cm

The literature dedicated to heat transfer by radiation [18]-[25] is believed to follow the Stefan-Boltzmann law. However, the obtained dependence of temperature on cooling time (formula (1)) shows that heat is transferred to the environment simultaneously in two ways. The amount of heat transferred is proportional to the sample's surface area, the temperature difference between the body and the environment, and the corresponding heat transfer coefficient for any heat transfer mechanism (convection or radiation). Figures 2 and 3 show the temperature dependences of the difference between the samples and the environment on the cooling time for spherical samples made of A0 aluminium with a diameter of 1.765 cm and A5N with a diameter of 2.82 cm for the processes of convective heat transfer and radiation, as well as the general cooling curve.

As can be seen from the figures, the cooling rate due to radiation proceeds faster than the cooling rate due to convection. The contribution of thermal radiation is noticeable at high temperatures.

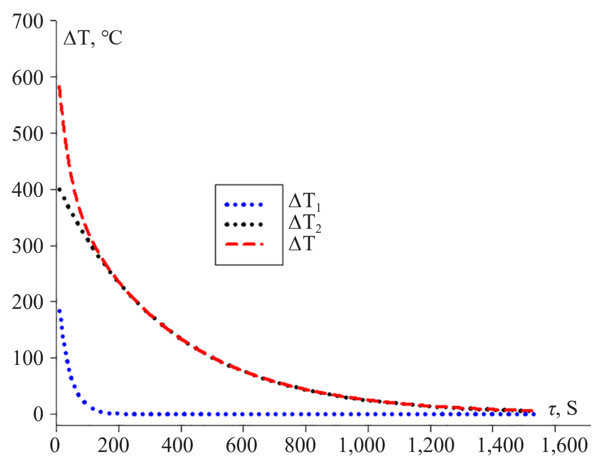

Figure 2. Dependence of the temperature difference on the cooling time for aluminium grade A0 with a diameter of 1.765 cm

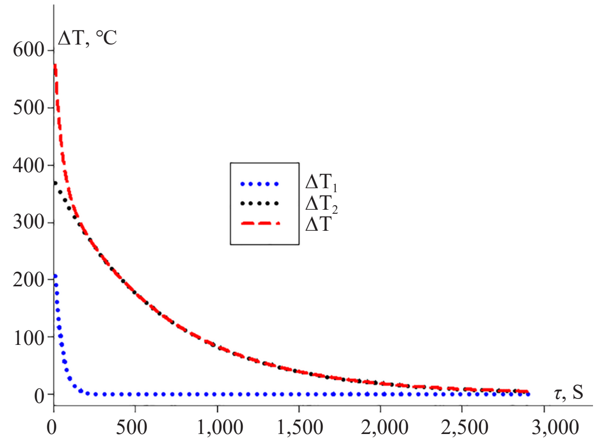

Figure 3. Dependence of the temperature difference on the cooling time for A5N aluminium with a diameter of 2.82 cm

Figures 4 and 5 show the dependences of the cooling rate on time for spherical samples of aluminium grades A0 and A5N with a diameter of 1.765 cm.

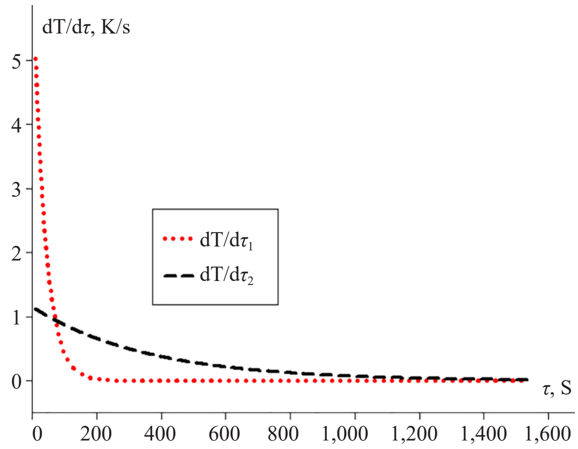

Figure 4. Dependence of the cooling rate on time for an A0 grade aluminium spherical sample with a diameter of 1.765 cm

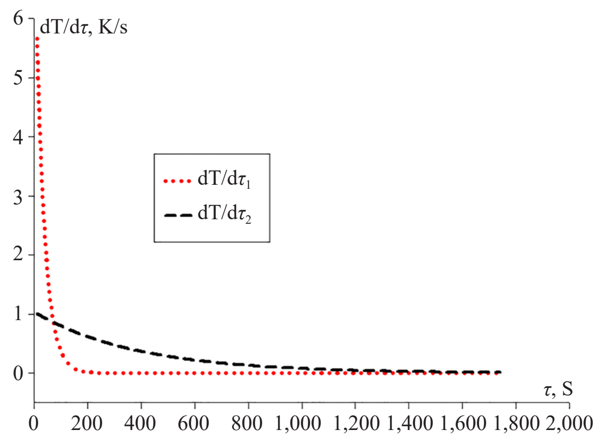

Figure 5. Dependence of the cooling rate on time for a spherical sample made of A5N aluminium with a diameter of 1.765 cm

As can be seen from Figures 5 and 6, the samples are mainly cooled due to convective heat transfer. The rate of cooling due to radiation rapidly decreases.

Tables 1-3 show the found values of the constants in the equation for the dependence of temperature (equation 1) and the sample cooling rate on time (equation 2) for the samples under study.

Table 1. The value of the constants in the equation for the dependence of the sample temperature (1) and the cooling rate on the cooling time (2)

Brand	Diameter, m	$(\Delta T_1)_{\tau=0}$, K	τ_1, s	$(\Delta T_2)_{\tau=0}$, K	τ_2, s	$\frac{(T_1-T_0)}{\tau_1}$, K/s	$\frac{(T_2-T_0)}{\tau_2}$, K/s
A0	0.0176	241.0	36.5	410.6	357.1	6.6	1.1
	0.0282	152.6	54.0	465.2	714.3	2.8	0.6
	0.0335	227.7	67.1	413.9	1,000	3.4	0.4
A5	0.0176	265.8	36.8	406.8	344.8	7.2	1.2
	0.0282	178.8	49.0	443.7	714.3	3.6	0.6
	0.0335	161.9	56.8	443.5	909.1	2.8	0.5
A6	0.0176	265.1	31.7	402.8	370.4	8.3	1.1
	0.0282	228.2	51.0	401.6	714.3	4.5	0.6
	0.0335	179.9	67.1	413.8	909.1	2.7	0.4
AB98	0.0176	302.3	41.5	427.5	370.4	7.3	1.1
	0.0282	170.7	50.5	423.3	666.7	3.4	0.6
	0.0335	181.9	55.9	413.4	1,000	3.3	0.4
A5N	0.0176	251.2	32.7	397.35	384.6	7.7	1.0
	0.0282	259.3	43.3	374.13	666.7	6.0	0.6

Figures 6 and 7 show the dependences of the characteristic cooling time due to thermal radiation and convective heat transfer on V/S of an A5N and AB98 aluminium sample.

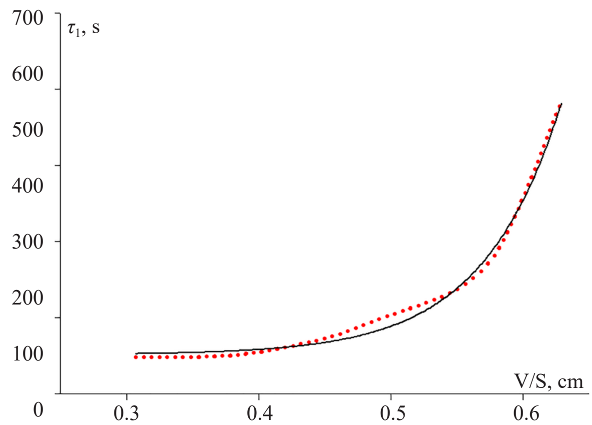

Figure 6. Dependence of the characteristic cooling time due to radiation from the V/S sample of A5N aluminium

Table 2. The value of the constants in the equation for the dependence of the sample temperature (1) and the cooling rate on the cooling time (2)

	Coefficient	Std. Error	t	P	VIF
a	0.0084	0.0085	0.9822	0.3984	1,249.1486 <
b	16.8273	1.6094	10.4559	0.0019	1,196.2336 <

The results of processing the curves of the dependence of the characteristic cooling time due to irradiation on V/S for aluminium samples of different grades obey the equation $\tau_1 = a(e^{bx} - 1)$ (Regression coefficient R = 0.998).

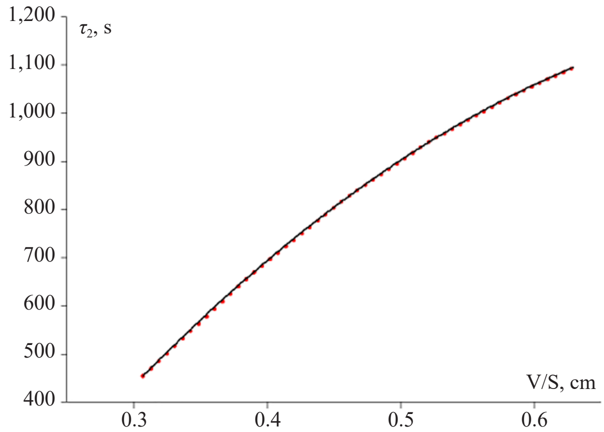

Figure 7. Dependence of the characteristic cooling time due to convective heat transfer on V/S of a spherical sample made of AB98 aluminium

Processing the obtained results of the dependence of the characteristic cooling time due to convective heat transfer on V/S for aluminium samples of different grades showed that it obeys a cubic equation of the $\tau_2 = ax + bx^2$ type, where x = V/S (cm).

Table 3. The value of the constants in the equation for the dependence of the sample temperature (1) and the cooling rate on the cooling time (2)

R	Rsqr	Adj Rsqr	Standard error of estimate		
1.0000	1.0000	1.0000	1.3225		
	Coefficient	Std. error	t	P	VIF
a	4,343.0677	398.8115	10.8900	0.0083	132,159.1441 <
b	-2,433.2456	875.2118	-2.7802	0.1087	182,425.5521 <

Knowing the composition of the samples, according to the Neumann-Kopp rule, the values of their heat capacity were calculated using the temperature dependences of the heat capacity of pure metals given in [26]. Using values of heat capacity and the experimentally obtained dependences of the cooling rate on time for each process, the corresponding heat transfer coefficients were calculated using the formula [21]-[25], [27]-[28]:

$$\alpha(T) = -\frac{\rho d C(T)\left|\left(\frac{dT}{d\tau}\right)\right|}{6(T - T_C)}, \tag{3}$$

where d is the sample diameter.

Figures 8 and 9 show the temperature dependences of the heat transfer coefficient of a spherical sample made of aluminium grade AB98 of different diameters due to radiation α_1 and convection α_2 [29]-[33]. As can be seen from the figures, natural air cooling has a low heat transfer coefficient range (10-20 $W/m^2 \cdot K$).

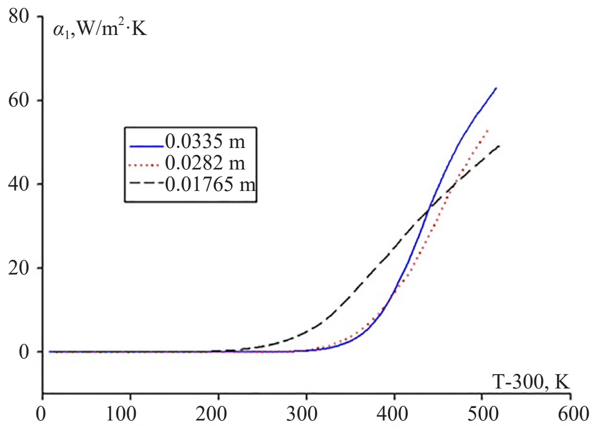

Figure 8. Temperature dependence of the heat transfer coefficient of a spherical sample made of AB98 aluminium of different diameters due to thermal radiation

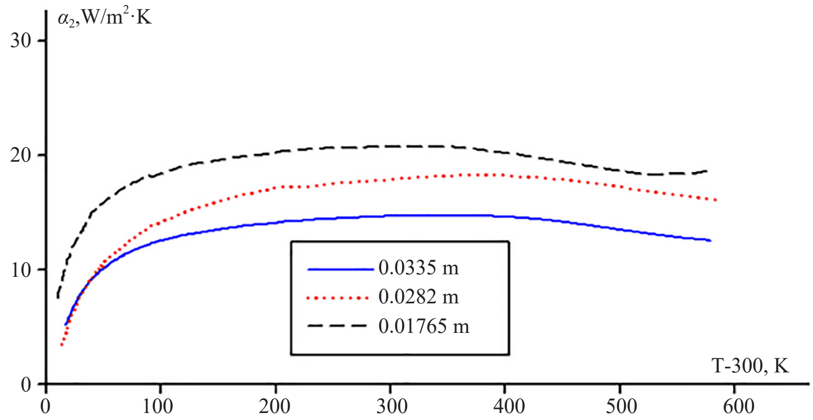

Figure 9. Temperature dependence of the heat transfer coefficient of a spherical sample made of AB98 aluminium of different diameters due to convective heat transfer

4. Conclusion

The effect of the size of spherical specimens of different grades of aluminum (A0, A5, A6, A5N, and AB98) on their characteristic cooling times and heat transfer coefficients has been investigated. It is revealed that spherical specimens of different grades of aluminum are cooled by radiant and convective heat transfer in all cases. The value of their characteristic cooling times has been estimated. It is shown that the characteristic cooling time due to radiation is less than the characteristic cooling time due to convection. It is found that with increasing diameter of cylindrical and spherical samples, the heat transfer coefficients decrease. The comparison shows that spherical specimens cool faster than cylindrical specimens of the same mass. The results of the present work agree satisfactorily with the similarity theory and data of other authors, which indicates the reliability of the results presented in this paper.

The results presented in this work are of fundamental importance for the study of the processes occurring during the cooling of metal products. The discovered dependences of cooling kinetics and heat transfer coefficients on size are of interest for the physics of thermal processes. The scale dependence of the thermophysical properties of aluminum established in this work can become an indisputable basis for the modernization of the macroscopic theory of heat transfer of metals, and the results on the temperature dependence of the convective and radiative heat transfer coefficients are a significant addition to the bank of reference data on the thermophysical properties of metals.

Conflict of interest

The authors declare no competing financial interest.

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