THE USE OF DILATOMETRY TO DETERMINE THE COEFFICIENT OF HEAT TRANSFER BETWEEN A SURFACE AND A MEDIUM

V. S. Batalov

UDC 536.244:536.2.083

We propose a dilatometry method of determining the coefficient of heat transfer between a surface and a medium. It is demonstrated that the advantages of this method lies in its high accuracy and simplicity. The use of dilatometry in a nontraditional research area makes it possible to substantially expand its sphere of application.

The accuracy of all currently existing methods of determining the coefficient of heat transfer between a surface and a medium, despite the fact that they are numerous [1] and diverse, are limited by the accuracy with which the heat flows and the temperature differences between the surface and the medium are determined, since the formula for the calculation of the heat-transfer coefficient includes directly the temperature of the medium and that of the surface and the heat flows between them. In the method utilized in this project and based on an analysis of kinetic curves of thermal expansion for metal wires (or tubes) streamlined by a liquid or gas medium there is absolutely no need in measuring the heat flows, and the role of the temperature measurement is determined for all intents and purposes by the need to refer the heat-transfer coefficient to a given temperature interval. The high sensitivity of the dilatometer makes it possible to assume that the accuracy of the proposed method does not fall below 1%. It should be stressed that the transfer of heat between the medium and a cylindrical surface (wire, tube) was measured for a number of reasons; nevertheless, the potentials of the method are in no way limited to such a case.

As a specific physical model let us examine the process of thermal change in the size of a cylindrical wire of length l and radius R ($R \ll l$) from a high-melting metal with a known heat capacity c_V per unit volume, initially heated to high temperatures and then cooled with a medium exhibiting a temperature T_1. The magnitude of the absolute deformation Δl_b of a prismatic body exhibiting a coefficient β of thermal expansion under the condition that the temperature change ΔT is identical or all of its internal points is given [2] by the equation

$$\Delta l_b = l\beta\Delta T. \tag{1}$$

When the temperature change (taking place with the passage of time) of a cylinder whose $x = 0$ end is fixed and whose $x = l$ end can move freely is different for the various segments of the specimen, it is necessary to turn to the examination of the thermal expansion of an infinitely small segment dx whose elongation dl_b during the time dt is given by

$$dl_b = dx\beta \frac{\partial T}{\partial t} dt. \tag{2}$$

Having calculated the elongation dl of the entire cylinder during the time dt and then turning to the rate W of thermal expansion at which the free end $x = l$ moves, we find

$$W = \frac{dl}{dt} = \beta \int_0^l \frac{\partial T}{\partial t} dx. \tag{3}$$

The quantity $\partial T/\partial t$ in a wire exhibiting a thermal conductivity k is determined in this case by the familiar heat-conduction equation [3]

$$\frac{\partial T}{\partial t} = \frac{k}{c_V}\frac{\partial^2 T}{\partial x^2} - \frac{\alpha}{c_V}\frac{2}{R}(T - T_1), \tag{4}$$

where α is the coefficient of heat transfer between the surface and the medium.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 17, No. 1, pp. 164-167, July, 1969. Original article submitted June 5, 1968.

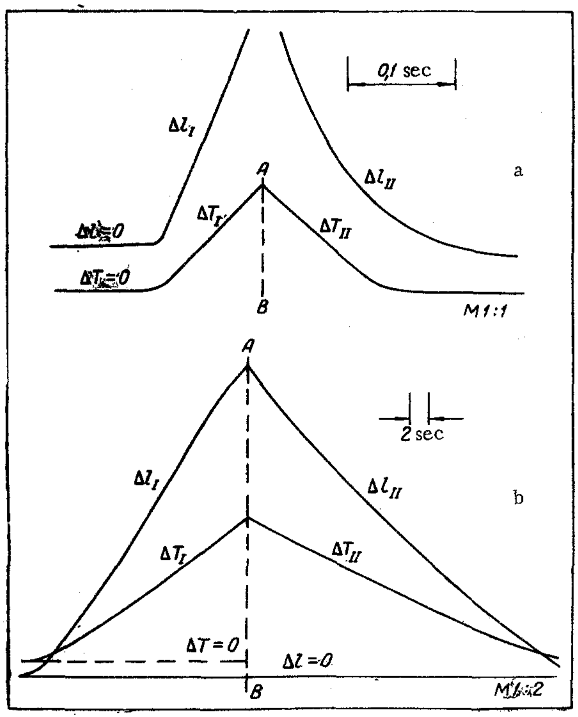

Fig. 1. Dilatometer record and temperature heating curves (Δl_I and ΔT_I) and cooling temperature curves (Δl_{II} and ΔT_{II}) for st. 45 steel (a) and cobalt (b): AB) the line at which the heating is stopped.

Identical boundary conditions at the ends allow us to assume that

$$\frac{\partial T}{\partial x}(0) = -\frac{\partial T}{\partial x}(l). \tag{5}$$

Substituting the value of $\partial T/\partial t$ from (4) into (3) and bearing in mind Eq. (5), after integration of (3) over the entire length we obtain

$$W = -\beta \frac{2}{c_V}\left[k \frac{\partial T}{\partial x}(l) + \frac{\alpha}{R}\int_0^l (T - T_1)\,dx\right]. \tag{6}$$

The quantity k $\partial T/\partial x$ (l) in (6) determines the removal of heat from the ends of the wire, and it can be neglected with appropriate selection of dilatometer design and the cooling conditions at the end (this is also made possible by the condition $R \ll l$). Thus, neglecting the term k $\partial T/\partial x$ (l) and dropping the "minus" sign in (6), this sign denoting that the wire does not increase in size, but rather diminishes in size, we rewrite (6) to be the form

$$W = \alpha \frac{2}{c_V R}\beta \int_0^l (T - T_1)\,dx. \tag{7}$$

Relationship (7) admits of further simplification if we take into consideration that

$$\beta \int_0^l (T - T_1)\,dx = \Delta l, \tag{8}$$

where Δl is that limit change in the wire size which corresponds to a change in its temperature from the instantaneous value T (x) to the temperature T_1 of the medium. The final formula for the calculation of α has the form

$$\alpha = c_V \frac{R}{2}\frac{W}{\Delta l}. \tag{9}$$

Experimental confirmation of (9) was given by an analysis of the dilatometer records for metallic wires heated by electric current on an integrated installation designed for the study of phase conversions under conditions of rapid heating [4], and under conditions of cooling of water and air, after shutting off the current, with the free convection of the water and the air. The measurement of the wire temperatures was accomplished by means of two Chromel–Copel thermocouples connected to the specimens; the temperature curve in this case was recorded on the same photographic paper as the dilatometer records for the heating and the cooling. The minimum distance between the time markers on the photographic paper correspond to an interval of 0.02 sec.

A typical form of a dilatometer record of the water cooling of st. 45 steel (in the temperature range 30-500°C) and the dilatometer records for the cooling of cobalt wire in air in free convection (in the range

TABLE 1. Values of the Coefficient α (kcal/m$^2\cdot$h$\cdot$deg) at Various Temperatures

Medium	Wire temperature °C							
	100		200		300		400	
	a	b	a	b	a	b	a	b
Air	37,6	35	41,3	40	43,5	42	44,7	43
Water	6510	6500	6530	—	6540	—	6550	—

30-450°C) are shown in Fig. 1. Table 1 shows the values of α for various temperatures in each of the cases, as derived in this paper (a) in comparison with the data (b) known from the literature [5] (α is expressed in kcal/$m^2 \cdot h \cdot deg$).

In conclusion, the author regards it his pleasant duty to express his gratitude to N. F. Chernenio and S. P. Oshkaderov, senior scientific workers at the Metalophysics Institute of the Ukrainian SSR Academy of Sciences, for making available to the authors the dilatometer records in connection with the cooling of metal wires in air and water media.

LITERATURE CITED

1. A. V. Luikov and B. M. Smol'skii (editors), Heat and Mass Transfer [in Russian], Vol. 1, Izd-vo Akad Nauk BSSR (1967).
2. K. P. Yakovlev (editor), A Concise Physicotechnical Handbook [in Russian], Vol. 2, Fizmatgiz (1960).
3. P. Schneider, Engineering Problems in Heat Conduction [Russian translation], IL (1960).
4. Yu. Ya. Meshkov, S. P. Oshkaderov, and N. F. Chernenko, "Problems of metal physics and metallurgy," No. 20, in: Science Transactions of the Institute of Metalophysics [in Russian], Izd-vo Akad. Nauk UkrSSR (1964).
5. B. Balaika and K. Sikora, Processes of Heat Transfer in Chemical Engineering Equipment [Russian translation], Gos. Nauchnotekhn. Izd-vo Mashinostroit. Litratury (1962).