released. Moreover, a band appears in the IR spectrum that corresponds to the carbonyl group C=O, which indicates the destruction of the irradiated PVTMS and its oxidation. With an increase in the radiation dosage the carbonization of the polymer becomes significant, and this brings about a noticeable change in the color of the film from light yellow in the case of a radiation dose of $2 \cdot 10^{15}$ cm^{-2} to dark brown for the case in which $D = 10^{16}$ cm^{-2}. Thus, modification of the polymer ion-implantation materials, given optimum radiation regimes, for appropriate ion-polymer systems, will yield a significant improvement in the gas-separation properties and it exhibits a number of advantages over other methods.

LITERATURE CITED

1. V. P. Belyakov, S. G. Durgar'yan, and V. A. Miroyan, Khim. Neft. Mashinostroenie, No. 11, 15-16 (1981).
2. "A method for the fabrication of selective membranes," USSR Inventor's Certificate No. 924,063; MKI³ S 08-5/22.
3. L. Ya. Alimova, I. E. Dzhamaletdinova, V. S. Ovchinnikov, et al., Inzh.-Fiz. Zh., 48, No. 1, 96-100 (1985).
4. M. S. Wintersgill, Instr. and Meth. B, 1, 595-598 (1984).
5. T. Venkatesan, Nucl. Instr. and Meth. B, 7/8, 461-467 (1985).
6. W. Brown, Rad. Eff., 98, 115-137 (1986).
7. K. Rossler, Rad. Eff., 99, 21-70 (1986).
8. I. E. Dzhamaletdinova, L. Ya. Alimova, A. I. Kamardin, et al., in: Abstracts of the All-Union Conference "The Interaction of Atomic Particls and Solids," Part II, Minsk (1984), pp. 33-34.
9. "A method for the modification of an asymmetric gas-separation membrane," USSR Inventor's Certificate No. 1,457,950; MKI⁴ VOID 13/04.
10. G. Betz and G. Vener, Atomization of Solids by Ion Bombardment [Russian translation], Moscow (1986), pp. 25-133.
11. G. I. Epifanov, O. Knab, P. E. Kondrashov, and L. S. Mironenko, in: Abstracts of the 7th International Conference on Ion Implantation in Semiconductors and Similar Materials, Vil'nius (1983), pp. 168-169.

STUDYING THE COEFFICIENT OF THERMAL CONDUCTIVITY FOR LIQUID METALS

A. I. Veinik, G. V. Markov, and É. B. Matulis

UDC 536.221

We discuss a method for an experimental study of the coefficient of thermal conductivity, specific heat capacity, and the specific electrical resistance of metals in the solid and liquid states, as well as the data that we have obtained with respect to the indicated properties of Bi, In, Cd, and Pb.

At the present time the coefficients of thermal conductivity for liquid metals have not been adequately studied [1]. This applies particularly to alloys. Such a situation can be ascribed to the limited development of reliable experimental methods, to the difficulties of carrying out such studies, particularly at high temperatures [2], and to the absence of sufficiently well-founded methods of calculating these properties [3].

In the present paper we examine a method intended for the experimental study of the coefficient of thermal conductivity λ, as well as of the specific electrical resistance ρ, and the specific heat capacity c_p for metals and alloys in the liquid and solid states. The method is based on one covered in [4-6] for the study of the thermophysical properties of metals in the solid state, and it essentially involves the following. Let a liquid metal of mass m be contained within a metal tube of length ℓ, and these two metals not reacting with each other chemically. We will assume that the cross-sectional area of the orifice

Physicotechnical Institute, Academy of Sciences of the Belorussian SSR, Minsk.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 6, pp. 892-896, December, 1989. Original article submitted June 22, 1988.

is equal to F_c, the cross-sectional area of the tube walls is given by F_c^t and that its mass is m_t. We will mount heaters at the ends of the tube and we will place the entire "tube—metal—heater" system into a vacuum chamber with a wall temperature T_0 and a wall area considerably greater than the side surface F_s of the tube.

By means of the heaters between the ends of the tubes we set up a small temperature difference $\Delta T = T_{in} - T_{out}$. A constant electric current of strength $I_\psi^{(I)}$ is passed through the tube, initially in one (I) and then in the reverse $I_\psi^{(II)}$ (II) directions. In principle, $I_\psi^{(I)} \neq I_\psi^{(II)}$. The magnitude of the current then changes slightly and it is again made to flow in the forward and reverse directions. Having analyzed the scheme of these experiments, we can state that the following flows of heat are present in the "tube—metal" system in the steady-state regime, and namely: the flow of heat entering the system from the hotter heater; the Joule heat flow; the Thomson heat flow generated or absorbed by the system in dependence on current direction; the flow of heat radiated by the tube to the ambient medium; the flow of heat being discharged from the system to the less-heated heater. When the current strength is altered, the magnitudes of all of the heat flows are changed, as well as the mean temperature of the system.

Let the "tube—metal" system be heated to some average temperature T and let the temperature difference across the ends of the tube be equal to ΔT. We will assume that the coefficient of tube thermal conductivity λ_t and its specific heat capacity c_t are known and change little in the temperature interval $(T - \Delta T, T + \Delta T)$, and also that there exists an ideal thermal contact between the tube and the metal being studied. Let us examine the heat-balance equation of the "tube—metal" system in the steady-state regime, when T(t)—const. For a current strength of $I_\psi^{(I)}$, when the current passes through the system in direction (I), where we will assume that we are dealing with a Thomson flow of heat, the equation assumes the form

$$-(\lambda F_c)_{eff}\frac{dT^+}{dx}\bigg|_{T_{in}} + U^{(I)}I_\psi^{(I)} + \sigma_{eff}\Delta T I_\psi^{(I)} = \varepsilon_t F_s\sigma\,[(T^+)_a^4 - T_0^4] - (\lambda F_c)_{eff}\frac{dT^-}{dx}\bigg|_{T_{out}}. \quad (1)$$

Here

$$(\lambda F_c)_{eff} = \lambda F_c + \lambda_t F_c^t; \quad (T^+)_a^4 = \frac{1}{l}\int_0^l [T^+(x)]^4 dx. \quad (2)$$

If we reverse the direction of current passage, the heat-balance equation for the system in the steady state will be as follows:

$$-(\lambda F_c)_{eff}\frac{dT^-}{dx}\bigg|_{T_{in}} + U^{(II)}I_\psi^{(II)} - \sigma_{eff}\Delta T I_\psi^{(II)} = \varepsilon_t F_s\sigma\,[(T^-)_a^4 - T_0^4] - (\lambda F_c)_{eff}\frac{dT^-}{dx}\bigg|_{T_{out}}, \quad (3)$$

where

$$(T^-)_a^4 = \frac{1}{l}\int_0^l [T^-(x)]^4\, dx.$$

From Eqs. (1) and (3) we will then obtain

$$(\lambda F_c)_{eff}\,\delta\left(\frac{dT}{dx}\right) + UI_\psi = \varepsilon_t\, F_s\sigma\,(T^4 - T_0^4). \quad (4)$$

Here

$$\frac{dT^+}{dx}\bigg|_{T_{in}} + \frac{dT^-}{dx}\bigg|_{T_{in}} = 2\,\frac{dT}{dx}\bigg|_{T_{in}}; \quad \frac{dT^+}{dx}\bigg|_{T_{out}} + \frac{dT^-}{dx}\bigg|_{T_{out}} = 2\,\frac{dT}{dx}\bigg|_{T_{out}}$$

$$\frac{dT}{dx}\bigg|_{T_{out}} - \frac{dT}{dx}\bigg|_{T_{in}} = \delta\left(\frac{dT}{dx}\right); \quad (T^+)_a^4 + (T^-)_a^4 = 2T^4;$$

$$U^{(I)}I_\psi^{(I)} + U^{(II)}I_\psi^{(II)} = 2UI_\psi.$$

We have neglected the term $\sigma_{eff}\Delta T(I_\psi^{(I)} - I_\psi^{(II)})$ in Eq. (4) because of its smallness relative to the other terms.

We will slightly alter the magnitude of the current strength so that it would not lead to any significant change in the thermophysical properties of the system and we will set it equal to $I_{\psi 1}$. From the heat-balance equation for the two current directions we will obtain an equation such as (4):

$$(\lambda F_c)_{eff}\,\delta\left(\frac{dT_1}{dx}\right) + U_1 I_{\psi 1} = \varepsilon_t F_s \sigma (T_1^4 - T_0^4). \tag{5}$$

Here

$$\left.\frac{dT_1^+}{dx}\right|_{T_{in}} + \left.\frac{dT_1^-}{dx}\right|_{T_{in}} = 2\left.\frac{dT_1}{dx}\right|_{T_{in}}; \quad \left.\frac{dT_1^+}{dx}\right|_{T_{out}} + \left.\frac{dT_1^-}{dx}\right|_{T_{out}} = 2\left.\frac{dT_1}{dx}\right|_{T_{out}};$$

$$\left.\frac{dT_1}{dx}\right|_{T_{out}} - \left.\frac{dT_1}{dx}\right|_{T_{in}} = \delta\left(\frac{dT_1}{dx}\right); \quad (T_1^+)_a^4 + (T_1^-)_a^4 = 2T_1^4;$$

$$(T_1^+)_a^4 = \frac{1}{l}\int_0^l [T_1^+(x)]^4\,dx; \quad (T_1^-)_a^4 = \frac{1}{l}\int_0^l [T^-(x)]^4\,dx;$$

$$U_1^{(I)} I_{\psi 1}^{(I)} + U_1^{(II)} I_{\psi 1}^{(II)} = 2U_1 I_{\psi 1}.$$

It follows from Eqs. (2), (4), and (5) that

$$\lambda = \frac{U_1 I_{\psi 1} - \eta U I_\psi}{F_c\left[\eta\delta\left(\frac{dT}{dx}\right) - \delta\left(\frac{dT_1}{dx}\right)\right]} - \lambda_t\,\frac{F_c^t}{F_c}; \tag{6}$$

$$\varepsilon_t = \frac{(\lambda F_c)_{eff}\,\delta\left(\frac{dT}{dx}\right) + U I_\psi}{F_s \sigma (T^4 - T_0^4)}; \tag{7}$$

$$\eta = \frac{T_1^4 - T_0^4}{T^4 - T_0^4}. \tag{8}$$

When the current strength is changed the temperature of the "tube—metal" system is changed. For the initial instants of time after this change, the heat-balance equation has the form

$$(c_p m + c_t m_t)\left.\frac{dT}{dt}\right|_{t=0} = U_1^{(I)} I_{\psi 1}^{(I)} - U^{(I)} I_\psi^{(I)}. \tag{9}$$

Hence we find that the specific heat capacity for the metal being studied can be found from the expression

$$c_p = \frac{U_1^{(I)} I_{\psi 1}^{(I)} - U^{(I)} I_\psi^{(I)} - c_t m_t \left.\frac{dT}{dt}\right|_{t=0}}{m\left.\frac{dT}{dt}\right|_{t=0}}. \tag{10}$$

We can treat the "tube—metal" system as two resistances connected in parallel. The specific heat resistance ρ for the metal being investigated was calculated by means of the following formula:

$$\rho = \frac{F_c}{\dfrac{(I_\psi^{(I)} + I_\psi^{(II)})\,l}{U^{(I)} + U^{(II)}} - \dfrac{F_c^t}{\rho_t}}. \tag{11}$$

Thus, if we know the coefficient of thermal conductivity λ_t for the tube and its specific heat capacity c_t, on the basis of formulas (6), (10), and (11), proceeding from the re-

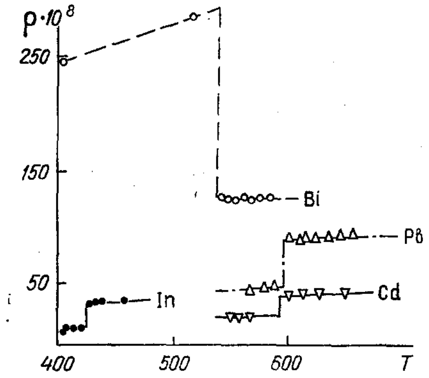

Fig. 1. Change in the specific electrical resistance of bismuth, indium, lead, and cadmium in melting.

sults of the experimental measurements, we can find the coefficient of thermal conductivity λ, the specific heat capacity c_p, and the resistivity ρ for the metal being studied, regardless of whether it is in the solid or liquid state.

To verify the validity of the method, we set up an experimental unit on which we studied the coefficient of thermal conductivity for pure Bi, In, Pb, and Cd in the liquid and solid states. The studies involved the use of tantalum tubes ℓ = 100 mm in length, with an outside diameter of 6 mm and an inside diameter of 4 mm, in a vacuum no less than $1 \cdot 10^{-4}$-$1 \cdot 10^{-5}$ mm Hg. As demonstrated by actual practice and calculations, for these dimensions of the "tube—metal" system the quantity ΔT should not exceed 5-7 K, while the change $|I_\psi^{(I)} - I_\psi^{(II)}| \leq$ 2-3 A. In this case, the error in the measurement of the coefficient of thermal conductivity λ does not exceed 15-20%, the error in the calculation of the specific heat capacity c_p is no greater than 7-15%, and that for the resistivity ρ does not exceed 2-5%.

Let us examine the results from our investigation into the quant[illegible] λ and ρ for pure Bi, In, Pb, and Cd in the liquid and solid states. It follows from t[illegible]hat for Bi, whose melting point is 544.3 K [7], the thermal conductivity λ at 523 K is [illegible] to 8.5 W/(m·K), while at 567 K it is equal to 15.5 W/(m·K). If we neglect the functions λ(T) in the solid and liquid states, then for Bi the change in the thermal conductivity at the melting point is $\lambda_s/\lambda_\ell \approx 0.55$. According to [8], for Bi we have $\lambda_s/\lambda_\ell = 0.49$. For In we find that at T = 402 K, when In is in the solid state, its thermal conductivity λ_s = 40.1 W/(m·K). With T = 435 K for liquid In we have λ_ℓ = 37.5 W/(m·K). Consequently, here $\lambda_s/\lambda_\ell = 1.07$. It follows from [1] that for In, $\lambda_s/\lambda_\ell = 1.09$. Such excellent agreement in the results was also obtained for Pb. Thus, with T = 580 K its coefficient of thermal conductivity λ_s = 30 W/(m·K), while for T = 608 K, λ_ℓ = 16.6 W/(m·K). Then $\lambda_s/\lambda_\ell = 1.81$, which differs only insignificantly from the data derived in [1], where $\lambda_s/\lambda_\ell = 1.85$. Thus, for Bi, In, and Pb we have found good agreement in the experimental data. A somewhat greater divergence in the data is noted for Cd. Thus, according to our data, with T = 580 K, λ_s = 76.6 W/(m·K), while with T = 605 K, σ_ℓ = 34.7 W/(m·K), and consequently, for Cd the ratio $\lambda_s/\lambda_\ell = 2.21$. According to the data presented in [1], this ratio is equal to 2.5.

Figure 1 shows the results from an investigation into the resistivities of Bi, In, Pb, and Cd in the solid and liquid states. The temperature intervals have been chosen near the melting point. Comparison of the derived functions ρ(T) in the solid and liquid states with the data from [1] shows excellent agreement.

Thus, proceeding from the results obtained in our study of the specific electrical resistance and the coefficient of thermal conductivity for Bi, In, Cd, and Pb in the solid and liquid states, we can draw the conclusion that our original assumptions and the calculation formulas of the method are valid.

NOTATION

λ, coefficient of thermal conductivity, W/(m·K); ρ, specific electrical resistance (resistivity), Ω·m; c_p, specific heat capacity, J/(kg·K); m, mass of the metal being studied, kg; ℓ, tube length, m; F_c^t, cross-sectional area of the tube walls, m²; m_t, tube mass, kg; T_0, wall temperature of vacuum chamber, K; F_s, area of the side surface of the tube, m²; T_{in}, T_{out}, temperatures of the more and less-heated ends of the tube, K; ΔT, temperature drop across the tube ends, K; $I_\psi^{(I)}$, $I_\psi^{(II)}$, strength of current passing through the "tube—metal" system in the forward (I) and reverse (II) directions, A; t, time, sec; $T^+(x)$, $T^-(x)$, temperature distribution along the system when the Thomson heat is either released or absorbed, K; $U^{(I)}$, $U^{(II)}$, voltage drops for two current directions, V; σ, Stefan–Boltzmann constant, $W/(m^2 \cdot K^4)$; σ_{eff}, effective Thomson coefficient for the "tube–metal" system, V/K; ε_t, emissivity of the tube. Superscripts: t, tube; subscripts: eff, effective; ψ, ψl, current magnitudes; c, cross-sectional area; s, side surface.

LITERATURE CITED

1. A. R. Regel' and V. M. Glazov, Physical Properties of Electron Melts [in Russian], Moscow (1980).
2. L. P. Filippov, Investigating the Thermal Conductivities of Liquids [in Russian], Moscow (1980).
3. D. K. Belashchenko, Transport Phenomena in Liquid Metals and Semiconductors [in Russian], Moscow (1970).
4. G. V. Markov, Izv. Akad. Nauk BSSR. Ser. Fiz.-Tekh. Nauk, No. 3, 24-28 (1978).
5. A. I. Veinik, Thermodynamic Vapor [in Russian], Minsk (1973).
6. A. I. Veinik, Metallurgy [in Russian], Minsk (1979), No. 13, pp. 9-11.
7. I. K. Kikoin (ed.), Tables of Physical Quantities [in Russian], Moscow (1976).
8. Ya. I. Dutchak and P. V. Panasyuk, Fiz. Tverd. Tela, No. 8, 2805-2810 (1966).

FORMATION OF A LAYER OF A LIQUID AS IT IMPINGES ON A HORIZONTAL PLANE

G. R. Shrager and I. V. Shcherbakova

UDC 532.62

We have conducted a numerical study of the spreading out of a liquid over a horizontal plane, with the liquid, in this case, running off over the surface of a semiinfinite vertical cylinder.

When a liquid impinges on a horizontal surface it spreads out and as a result a liquid layer of a specific thickness is formed on the surface. A characteristic unique feature of the flow achieved in this case is the presence of a free surface. The flow of a viscous liquid over a horizontal surface with a relatively small layer thickness has been studied in a number of papers [1-6]. Attempts have been made numerically to solve the problem of the spreading out of a column of liquid under the force of gravity [7-9]. In this particular study we examine the axisymmetric motion of a viscous liquid over a horizontal plane, with the liquid, in this case, running off over the surface of a semiinfinite vertical cylindrical rod, impinging on a horizontal plane. The motion is assumed to be creeping, so that the inertial forces may be regarded as negligibly small in comparison to the viscosity forces. The capillary forces are assumed to be small in comparison to the viscosity and gravitational forces, and thus are also not taken into consideration.

1. Formulation of the Problem. In a cylindrical coordinate system the system of equations describing the flow, in conjunction with the above assumptions, has the form

$$\mu\Delta u - \frac{\partial p}{\partial z} - \rho g = 0, \quad \mu\left(\Delta v - \frac{v}{r^2}\right) - \frac{\partial p}{\partial r} = 0, \quad \Delta p = 0. \tag{1}$$

The third of the equations in (1) is a consequence of the first two and of the condition of incompressibility.

The conditions specifying an absence of tangential stress, equality of the normal stress to the external pressure, and the kinematic condition, are all satisfied at the free surface:

Scientific Research Institute of Applied Mathematics and Mechanics, Tomsk State University.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 6, pp. 896-600, December, 1989. Original article submitted May 31, 1988.