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MOVING DYNAMIC THERMOCOUPLE

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UDC 536.532:533.08

It is shown theoretically that the temperature measured by a dynamic thermocouple corresponds to the mean mass temperature of the junction. A method of a moving dynamic thermocouple is proposed.

Among contact methods of the diagnostics of thermal plasma, the dynamic thermocouple occupies a special place, since it allows local values of the plasma temperature, heat flux, and heat-transfer coefficient in the thermocouple to be obtained from the result of a single measurement. In the measurements, the change in heating temperature of the thermocouple junction in a regular cycle is measured as a function of the time. However, it remains unclear what temperature of the thermocouple is meant here, since a temperature difference is established over the radius of the thermocouple in regular conditions.

To simplify the solution of the given problem, consider that a cylindrical thermocouple is used, i.e., a butt-welded thermocouple. For the calculations it is assumed that the temperature is zero on the thermocouple axis and changes linearly over the radius

$$T_p(r) = k_1 r_p. \tag{1}$$

Then the emf (E) on a rectilinear section of the curve E = f(T) will be of analogous form

$$E_p(r) = k k_1 r_p. \tag{2}$$

Since calculation shows that in a plasma jet with $T \approx 4000°K$ and $v \approx 100$ m/sec, for a junction with $r_{pc} \approx 0.5 \cdot 10^{-3}$ m, the temperature drop over the radius is no more than 200°K, while the temperature coefficient of resistivity $\alpha_0 = 2.6 \cdot 10^{-4}$ deg^{-1} is small, the change in resistivity over the thermocouple radius may be neglected. Then, dividing the cross section of the thermocouple junction into concentric rings of equal area, they may be regarded as independent sources of emf, with equal internal resistance, connected in parallel. In this case the effective emf may be expressed as

$$E_e = \frac{1}{n} \sum_{i=0}^{n-1} E_i. \tag{3}$$

In view of Eq. (2), Eq. (3) may be rewritten in the form

$$E_e = \frac{k_1 k_2}{n} \sum_{i=0}^{n-1} r_{pi}. \tag{4}$$

The value of r_{pi} may be obtained from the condition that the concentric rings into which the thermocouple cross section is divided are of equal area

$$r_{pi} = r_{pc} \sqrt{\frac{n-1}{n}}. \tag{5}$$

Finally,

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TABLE 1. Numerical Values of the Coefficient $\frac{1}{n}\sum_{i=0}^{n-1}\sqrt{\frac{n-1}{n}}$

n	2	5	10	15	20	50
$\frac{1}{n}\sum_{i=0}^{n-1}\sqrt{\frac{n-1}{n}}$	0,85	0,75	0,71	0,70	0,68	0,67

TABLE 2. Limits of Applicability of Dynamic Thermocouple

N	Bi	4000 K		5000 K		6000 K		8000 K	
		$T_{p\min}$	$T_{p\max}$	$T_{p\min}$	$T_{p\max}$	$T_{p\min}$	$T_{p\max}$	$T_{p\min}$	$T_{p\max}$
1	0,001	4	1721	5,7	1721	6	1720	8	1719
2	0,01	40	1706	49	1702	60	1698	80	1689
3	0,05	190	1641	247	1615	285	1600	380	1560
4	0,1	364	1567	455	1528	545	1488	770	1410
5	0,5	1333	1150	1666	1007				

$$E_e = \frac{k_1 k_2 r_{pc}}{n}\sum_{i=0}^{n-1}\sqrt{\frac{n-1}{n}}. \tag{6}$$

Calculation from Eq. (6) gave the results in Table 1, from which it is evident that, accurate to 1%, $E_e = 0.67k_1k_2r_{pc}$.

Whether the value of E_e obtained corresponds to the mean mass temperature of the thermocouple T_{pM} will now be checked. For this purpose, segments enclosing the thermocouple junction of length h are imagined. In the junction cross section, the radial temperature distribution is described by Eq. (1). The heat content of the layer

$$\Delta H = \pi r_{pc}^2 h \rho_p C_{pp} T_{pM}. \tag{7}$$

On the other hand, ΔH may be defined as

$$\Delta H = 2\pi h k_1 \rho_p C_{pp}\int_0^{r_{pc}} r_p^2 dr_p. \tag{8}$$

Hence, from Eqs. (7) and (8)

$$T_{pM} = \frac{2}{3}T_{pc}. \tag{9}$$

From a comparison of Eq. (9) with the numerical values in Table 1, it is evident that the mean temperature value of the thermocouple junction corresponds to the effective emf. Hence, in plasma diagnostics using a dynamic thermocouple, the mean mass temperature of the junction is measured; in a regular heating cycle, this corresponds to the temperature value inside the junction at a distance of $0.67r_{pc}$.

In solving the given problem it has been assumed that the temperature varies linearly over the radius of the junction. The real temperature distribution over the radius may be obtained, however, from the solution of the heat-conduction equation with boundary conditions of the third kind. At the moment that the thermocouple reaches a regular heating cycle, the radial temperature distribution may be approximated as

$$T_p(r) = T_{pc}\frac{r_p^{3/2}}{r_{pc}^{3/2}} \tag{10}$$

for a cylindrical thermocouple and

$$T_p(r) = T_{pc}\left(\frac{r_p}{r_{pc}}\right)^2 \tag{11}$$

for a spherical thermocouple.

For rough estimates of the lower limit of applicability of the dynamic thermocouple, a formula for determining the minimum temperature drop over the radius of the junction may be obtained from boundary conditions of the third kind for the heating of the body, and then measurements of the heat fluxes may be made

$$\Delta T_p = \frac{T_q + \mathrm{Bi}}{1 + \mathrm{Bi}}\,. \tag{12}$$

From the heat-balance equation, taking account of Eqs. (10) and (11), a formula for determining the time of irregular heating may be obtained for a cylindrical

$$t_{\mathrm{I}} \approx 0.28\,\frac{r_{pc}^2}{a_p} \tag{13}$$

and spherical thermocouple

$$t_{\mathrm{I}} = 0.2\,\frac{r_{pc}^2}{a_p}. \tag{14}$$

The maximum permissible mean mass temperature at which the heat fluxes of the dynamic thermocouple may be measured may be estimated from the formula

$$T_{p\max} < T_{\mathrm{pm}} - \frac{0.43 T_q \mathrm{Bi}}{1 + \mathrm{Bi}} \tag{15}$$

for a cylindrical thermocouple and

$$T_{p\max} < T_{\mathrm{pm}} - \frac{0.4 T_q \mathrm{Bi}}{1 + \mathrm{Bi}} \tag{16}$$

for a spherical thermocouple.

Using Eqs. (12) and (15), the limits of applicability of a dynamic thermocouple of cylindrical form for the diagnostics of thermal plasma may be determined (Table 2). Analogous values of T_{pmin} and T_{pmax} are also obtained for a spherical thermocouple, since Eqs. (15) and (16) differ only slightly.

It is evident from an analysis of Table 2 that the use of a dynamic thermocouple for thermal-plasma diagnostics is possible right up to temperatures of 8000°K. However, in each case it is necessary to determine the range of operating temperatures of the thermocouple in which the plasma parameters may be determined. Note that the value of the Biot number has a significant influence on the region of applicability of a dynamic thermocouple. When $\mathrm{Bi} \geqslant 0.5$, the dynamic thermocouple becomes unsuitable for thermal-plasma diagnostics with $T_q \approx 4000$°K.

For a given plasma temperature, with known Bi, the limits of thermocouple temperature values at which the measurement results are reliable may be selected from Table 1.

Consider the possibility of applying a moving dynamic thermocouple for plasma diagnostics when only those temperature values given in Table 1 are used for interpretation.

Earlier [6], an attempt was made to use a spherical body of diameter 10^{-3} m moving through the plasma at a velocity of 1 m/sec to measure the heat fluxes. From the results of measuring the thermocouple temperature, the local value of the heat flux was determined in conditions of axisymmetric distribution in solving the Abelian integral equation. The whole procedure may be simplified if instead of a ball, a dynamic thermocouple moves through the plasma at constant velocity v_p. In this case the heat-balance equation for the thermocouple at each point of the jet takes the form

$$q_x = A r_p C_{pp} \rho_p \left(\frac{dT_p}{dt}\right)_x. \tag{17}$$

The measurement results will be influenced by the velocity of motion through the plasma. The minimum value of the velocity of thermocouple motion in a plasma jet of diameter D_g at which no melting of its surface is observed may readily be derived from the heat-balance equation for a spherical body [7]

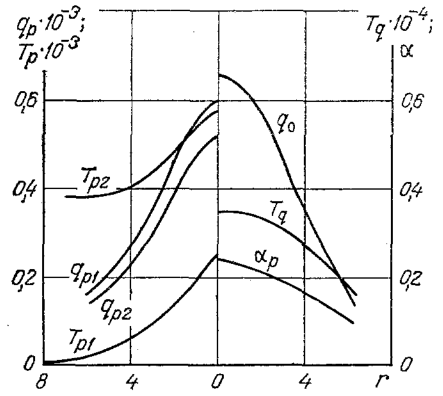

Fig. 1. Distribution of the temperature, heat flux, and heat-transfer coefficient over the plasma-jet radius, obtained using a moving dynamic thermocouple (Pt—Pt + 10% Rh) of diameter $1.5\cdot10^{-3}$ m. Plasmotron operating parameters: J = 120 A; U = 270 V; $\Phi_{noz} = 14\cdot10^{-3}$ m; $G_g = 2.9\cdot10^{-3}$ kg/sec, for air; $l = 4\cdot10^{-2}$ m. r, mm; $q_p\cdot10^{-3}$, W/cm²; $T_p\cdot10^{-3}$, °K; α, W/cm²·°K; $T_q\cdot10^{-4}$, °K.

$$v_p \geqslant \frac{3\mathrm{Bi}D_q}{\ln\Theta}\,\frac{\bar{a}_p}{r_{pc}^2},\quad \Theta=\frac{T_q-T_{p0}}{T_q-T_p}. \tag{18}$$

The value of $\overline{\mathrm{Bi}}$ may be estimated from the expression

$$\overline{\mathrm{Bi}}=\frac{\int\limits_0^{v_q}\mathrm{Bi}\,(D_q)\,dx}{D_q}. \tag{19}$$

The velocity of thermocouple motion must be chosen so that Eq. (18) is satisfied and all the transient processes in the measurement period vanish with thermocouple motion over a distance equal to one-twentieth of the jet radius, i.e.,

$$v_{p2}=\frac{D_c\bar{a}_p}{8r_p^2}. \tag{20}$$

The value of v_{p2} must be greater than or equal to v_{p1}; otherwise, the measurements will be distorted after the surface of the body reaches the melting point.

For a cylindrical thermocouple, an expression analogous to Eq. (18) may be obtained:

$$v_p=\frac{\mathrm{Bi}\,D_q}{2\ln\dfrac{T_q-T_{p0}}{T_q-T_p}}\,\frac{\bar{a}_p}{r_{pc}^2}. \tag{21}$$

Plotting the curve of $T_p(D_q)$ using a moving thermocouple and differentiating this signal, local values of the heat flux at various T_p may be obtained. The values of α_p and T_q cannot be calculated. To find T_{qx}, g_{tr}, and α_{px}, a cold thermocouple is passed through the plasma jet, and then, in the same direction, a thermocouple heated to 700-800°K. For the first and second curves corresponding to the same point of the jet, the following equations may be written

$$q_x'=\alpha_p(T_{qx}-T_p'),\ q_x''=\alpha_p(T_{qx}-T_p''). \tag{22}$$

From this system of equations, it is found that

$$T_{gx} = \frac{q_x'' T_{px}' - q_x' T_{px}''}{q_x'' - q_x'}, \tag{23}$$

$$\alpha_x = \frac{q_x'' - q_x'}{T_{px}' - T_{px}''}. \tag{24}$$

An expression for the heat flux in the thermocouple at any point of the jet may readily be obtained from Eqs. (23), (24):

$$q_x^{T_{px}} = \frac{q_x''(T_{px}' - T_{px}) - q_x'(T_{px} - T_{px}'')}{T_{px}' - T_{px}''}. \tag{25}$$

Thus, the proposed method allows the radial distribution of the local values of T_q, α_p, and q to be obtained from two measurements. The results of determining the plasma parameters using a moving dynamic thermocouple are shown in Fig. 1.

Note that in calculating heat fluxes from the results of measuring the dynamic-thermocouple temperature, the "mean" value of C_{pp} is used. Depending on the thermocouple temperature, however, C_{pp} may vary by a factor of 2-3 [8]. At the same time, the rate of thermocouple heating will depend not on the mean value of C_{pp}, but on the value of C_{pp} corresponding to the given temperature at which the derivative is taken. This becomes especially important when using a moving dynamic thermocouple to find the distributions q(x), $T_q(x)$, and $\alpha_p(x)$.

Note also that a moving dynamic thermocouple allows reliable information to be obtained on the distribution of the plasma parameters only in the central zone, since on entering the jet, when irregular heating occurs, and on leaving it, where the inequality

$$\alpha_p \geqslant \frac{\varepsilon\sigma T_{px}^4}{(T_{qx} - T_{pxc})} \tag{26}$$

is not satisfied, the measurement results will be unreliable. When the thermocouple leaves the plasma jet it is required that $T_{pxc} \leqslant T_{pm}$ and $T_x \geqslant T_{pxc}$. The error in determining the heat fluxes by the method of a moving dynamic thermocouple is associated with the errors in measuring the thermocouple temperature, differentiating, and determining its geometric dimensions. It may be supposed that the total error in measuring the local values of the heat-flux density may be 10%. The error due to recalculation by Eqs. (23)-(25) may be estimated from the formula

$$\eta = \frac{2\Delta T_p \cdot 100\,\%}{T_{p2} - T_{p1}}. \tag{27}$$

It is evident from Eq. (27) that the error decreases with increase in the temperature difference $T_{p2}-T_{p1}$ and is no more than 6% when $T_{p2}-T_{p1} \approx 500$°K. The total measurement and recalculation error in determining the plasma parameters by the method proposed is no more than 16%. The main deficiency of the moving dynamic thermocouple is that it cannot perform measurements at the periphery of the plasma jet.

NOTATION

T, temperature; E, thermoemf; r, radius; ρ, C_p, density and specific heat; k_1, k_2, proportionality coefficients; n, number of concentric rings into which the thermocouple cross section is divided; ΔH, enthalpy of thermocouple layer; Bi, Biot number; v, velocity; a, thermal diffusivity; t, time; A, proportionality coefficient, depending on the form of the thermocouple junction (for a sphere, A = 1/3); q, specific heat flux; D, diameter; α, heat-transfer coefficient; σ, Stefan–Boltzmann constant; ε, reduced emissivity of thermocouple with respect to the surrounding medium. Subscripts: q, plasma; p, thermocouple; c, surface; M, mean; max, maximum; m, melting; x, radial coordinate; 0, value at T ≈ 300°K.

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NATURE OF MASS TRANSFER IN SOLIDS UNDER CONDITIONS OF IMPACT LOADING

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The article presents an explanation of the anomalously high mobility of atoms under the conditions of impact loading when shock waves act on a crystal.

The authors of [1-3] described a newly discovered phenomenon: when metals and alloys are exposed to short-term high-energy loads, the mobility of the atoms in the solid phase increases by many orders of magnitude.

To explain the exceedingly high migration speed of the atoms, the assumption of an interstitial mechanism of mass transfer under the given loading conditions was expressed [2]. The interstitial mechanism is perfectly compatible with the physical regularities accompanying this phenomenon, and in combination with the hypothesis of a motive force [3] it can explain the large depths of penetration of atoms upon impact loading. However, the physical meaning of the motive force remains indeterminate.

In analyzing the possible causes of the high mobility of atoms under the effect of impacts, we may eliminate the vacancy mechanism of migration of atoms from the examination, because it does not correspond to the experimental results [2]. An analogous conclusion also applies to the applicability of the model of mass transfer along dislocation canals [4] and mechanical "agitation" through the penetration of glide lamellas [5]. This, in fact, is testified to by the absence of decoration of the dislocations by traces of the disintegration of radioactive atoms on the microautoradiograms and the presence of a solid solution in the diffusion zone [3]. As regards the interstitial mechanism, the hypothesis of its applicability is compatible with the observed temperature dependence of mass transfer, and it explains the effect of the type of crystal lattice [6], the frequency of loading, and the type of solid solution [3] on the mobility of the atoms in the solid phase of metals and alloys in impact loading. However, a moving screw dislocation with jogs as a source of interstitial atoms does not ensure a sufficient number of such atoms. For instance, with a density of dislocations of 10^{10} $1/cm^2$, the number of interstitial atoms produced by screw dislocations with jogs amounts to 0.001% of the total number of atoms in the investigated zone. Such a number of interstitial atoms is too small for obtaining the observed effects. More likely seems to be the mechanism of the formation of defects, including interstitial atoms, when a shock-wave passes through the crystal lattice of metal in explosive shock loading [7].

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