A STUDY OF HEAT TRANSFER DURING CONVECTION OF A FLUID IN A HIGH-FREQUENCY ELECTROMAGNETIC FIELD

M. S. Bakirov, V. G. D'yakonov,
and A. G. Usmanov

UDC 536.242:536.252

This is the first study concerning the effect of an electromagnetic field at a 650 kHz frequency on the heat transfer during natural convection of water, acetone, benzene, and transformer oil.

Tests were performed in a vessel typically used for studying the heat transfer during natural convection. The heaters were copper, chrome-plated copper, and brass tubes 6 mm in diameter and 260 mm long. A tube was energized with high-frequency electric current so that an electromagnetic field appeared around it.

It has been established, as a result, that the heat-transfer rate increases appreciably in a high-frequency field. For water at 17°C, for example, the heat-transfer coefficient is 2.2 times higher in an electric field (α_E) than without a field (α_0). As the heat load q is increased, both α_E and α_0 increase, but their ratio α_E/α_0 is almost independent of q. As the temperature of the fluid rises, the ratio α_E/α_0 decreases for water, acetone, and benzene (Fig. 1).

A smaller increase in the heat-transfer rate was noted in tests with the brass tube. This could be explained by the lower intensities of the electric field E and the magnetic field H at the surface of the brass tube than at the surface of the copper tube under equal heat loads.

It is to be noted that a high-frequency electromagnetic field even of a moderate intensity (in this case E of the order of $5 \cdot 10^3$ V/m and H of the order of $5 \cdot 10^3$ A/m) has a strong boosting effect on the heat transfer during natural convection of a fluid. According to the data obtained by other authors, approximately the same increase in low-frequency electric fields requires an intensity E of the order of $5 \cdot 10^5$ V/m.

The increased rate of heat transfer in a high-frequency field may be due to electromagnetic forces acting on the thermal boundary layer and due to changed thermophysical properties of the fluid when in a field.

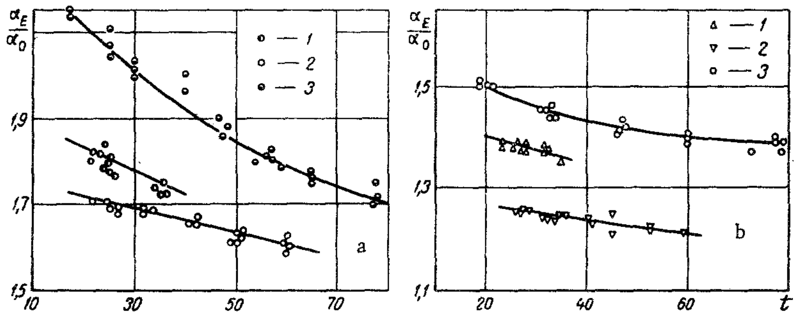

Fig. 1. Ratio α_E/α_0 as a function of the temperature for (a) a copper tube and (b) a brass tube: 1) acetone; 2) benzene; 3) water.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 24, No. 1, pp. 160-165, January, 1973. Original article submitted July 7, 1970; abstract submitted June 23, 1972.

An estimate of these forces has shown that they are smaller than the forces due to natural gravity convection. Unlike the gravitational forces, however, these forces alternate at double the field frequency.

The possibility that the thermophysical properties of a fluid may change in a field has been hinted at in [1], where the authors speculated about a structural transformation of water in a high-frequency field.

The effect of a field on the heat transfer can be accounted for by introducing into the conventional criterial equation the effective thermophysical coefficients for water in a field.

An evaluation of test data in these terms has yielded a relation for the complex of effective thermophysical properties of a fluid in a field, as functions of the heat load and of the potential difference between tube and vessel wall.

LITERATURE CITED

1. S. A. Bruns, V. A. Chanturiya, and R. Sh. Shafeev, Dokl. Akad. Nauk SSSR, 168, 152 (1966).

MASS TRANSFER IN A SOLID – LIQUID SYSTEM UNDER HIGH-VOLTAGE SPARK DISCHARGES THROUGH A TUBE

G. A. Aksel'rud, A. D. Molchanov,
I. N. Fiklistov, and V. P. Kosyk

UDC 621.9.044

The feasibility of accelerating the process of external mass transfer by means of spark discharges has been demonstrated in [1]. Inasmuch as dissolution processes on an industrial scale are realized most economically in tubular apparatus [2], the kinetics of dissolution in a tubular apparatus under spark discharges were studied here both theoretically and experimentally.

Solving the hydrodynamic problem of fluid flow oscillations excited by spark discharges through a tube leads to the following expression for the critical Reynolds number:

$$\mathrm{Re}_{\mathrm{M}} = \frac{E\omega d_0}{P_0 F \nu}. \tag{1}$$

The kinetics of dissolution of KNO_3 salt specimens held in place was studied in a tubular apparatus 32 mm in diameter, and the dissolution of gypsum powder was studied in a rectangular apparatus 40 × 40 mm in cross section. The schematic diagram of the apparatus and the test procedure had been shown earlier [3]. An evaluation of the test data has yielded the following critical equations of dissolution kinetics under spark discharges:

1. With spark discharges in a stationary fluid ($W_F = 0$):

$$\mathrm{Nu}_D = 3.4\sqrt{\mathrm{Re}_{\mathrm{M}}} + 21. \tag{2}$$

   This relation fits test data within the ranges $3600 < \mathrm{Re}_M < 67{,}600$ and $E/F = 6\text{–}23\ \mathrm{J/cm^2}$, with $F = 9.1\ \mathrm{cm^2}$, $P_0 = (0.5\text{–}3.65) \cdot 10^5\ \mathrm{N/m^2}$, and $\mathrm{Pr}_D = 720$.

2. With spark discharges in a steady stream of fluid ($W_F \neq 0$):

$$\mathrm{Nu}_D = \mathrm{Nu}_0 \sqrt{1.02 + 27.2\,\frac{E\omega}{P_0 F W_F}}. \tag{3}$$

   This relation fits test data within the ranges $0.015 < E\omega/P_0FW_F < 0.26$, $730 < \mathrm{Re}_0 = W_F d_0/\nu < 12{,}500$, and $W_F = 6.4\text{–}109$ cm/sec, with $E = 55$ J, $\mathrm{Pr}_D = 720$, and $P_0 = 10^5\ \mathrm{N/m^2}$.

Original article submitted March 9, 1972; abstract submitted May 25, 1972.

In the case of gypsum powder dissolving in distilled water in a suspension bed inside a tubular apparatus, the kinetics of the process is described by the relation

$$\mathrm{Nu}_D=\mathrm{Nu}_0\sqrt{0.9+40\frac{E\omega}{P_0FW_S}}, \tag{4}$$

valid within the ranges $0.02 < E\omega/P_0FW_S < 0.017$ and $E = 20\text{–}50$ J, with $P_0 = 10^5\ \mathrm{N/m^2}$, $W_S = 7.5$ cm/sec, and $d_0 = 1.0\text{–}1.5$ mm.

NOTATION

Nu_D, Nu_0	are the Nusselt diffusion numbers, under spark discharges and without spark discharges, respectively;
Pr_D	is the Prandtl diffusion number;
Re_M	is the modified Reynolds number;
E	is the energy of charged capacitor;
ω	is the frequency of discharges;
d_0	is the diameter of solid particles;
P_0	is the external pressure above the liquid;
F	is the cross-section area of the tube;
ν	is the kinematic viscosity;
T	is the period of plasma cavity pulsations;
W_F	is the velocity of steady fluid stream;
W_S	is the velocity of suspension.

LITERATURE CITED

1. A. D. Molchanov, G. A. Aksel'rud, A. I. Chernyavskii, I. N. Fiklistov, Inzh.-Fiz. Zh., 18, No. 2, 293-298 (1970).
2. N. S. Spirin, in: Technological Problems in Processing Halurgical Raw Materials [in Russian], Trudy VNIIG, Khimiya, Moscow–Leningrad (1967).
3. A. D. Molchanov, G. A. Aksel'rud, and I. N. Fiklistov, Vestnik Leningradsk. Politekh. Inst., No. 36, 65-67 (1969).

EVAPORATION OF A LIQUID IN A HIGH-TEMPERATURE GAS STREAM

A. L. Suris

UDC 536.423.1

The equation of evaporation for a single droplet in a high-temperature gas stream can be written as follows:

$$\frac{dG_d}{d\tau}=-4\pi\rho\frac{\lambda}{C_V}\ln\left|1+\frac{C_V(T-t_S)}{R_*}\right|. \tag{1}$$

Retaining only the first term of the series expansion

$$\ln X=2\left[\frac{X-1}{X+1}+\frac{1}{3}\left(\frac{X-1}{X+1}\right)^3+\frac{1}{5}\left(\frac{X-1}{X+1}\right)^5+\dots\right], \tag{2}$$

Original article submitted March 24, 1972; abstract submitted July 10, 1972.

using the relation for a monodisperse system where the density of the solution varies with time

$$G_{\mathrm{d}} = \frac{G}{G_0} G_{\mathrm{d}}^0 = G_{\mathrm{d}}^0 g = \frac{4}{3} \pi \gamma_{\mathrm{s}} \rho_0^3 g = \frac{4}{3} \pi \rho^3 \left[\gamma_{\mathrm{L}} + \left(\frac{\rho_0}{\rho}\right)^3 (\gamma_{\mathrm{s}} - \gamma_{\mathrm{L}})\right],$$

$$T = \frac{\dfrac{G_{\mathrm{G}}}{G_0} T_0 - \dfrac{R^*}{C_{\mathrm{Gm}}^{T_0}} + \dfrac{R^*}{C_{\mathrm{Gm}}^{T_0}} g}{\dfrac{G_{\mathrm{G}}}{G_0} \dfrac{C_{\mathrm{Gm}}^{T}}{C_{\mathrm{Gm}}^{T_0}} + \dfrac{C_{\mathrm{Vm}}^{T}}{C_{\mathrm{Gm}}^{T_0}} - \dfrac{C_{\mathrm{Vm}}^{T}}{C_{\mathrm{Gm}}^{T_0}} g}, \tag{2}$$

we transform (1) into

$$\frac{dg}{d\tau} = -\frac{(P+Fg)}{(u+hg)\beta} \left(g + \frac{\gamma_{\mathrm{L}}}{\gamma_{\mathrm{L}}} - 1\right)^{1/3}, \tag{3}$$

where

$$u = \left(2R_* - C_{\mathrm{Vm}}^{t} t_{\mathrm{s}}\right) \left(\frac{G_{\mathrm{G}}}{G_0} \frac{C_{\mathrm{Gm}}^{T}}{C_{\mathrm{Gm}}^{T_0}} + \frac{C_{\mathrm{Vm}}^{T}}{C_{\mathrm{Gm}}^{T_0}}\right) + C_{\mathrm{Vm}}^{T} \left(\frac{G_{\mathrm{G}}}{G_0} T_0 - \frac{R^*}{C_{\mathrm{Gm}}^{T_0}}\right);$$

$$\beta = \left(\frac{\gamma_{\mathrm{L}}}{\gamma_{\mathrm{p}}}\right)^{1/3} \frac{\gamma_{\mathrm{p}} \rho_0^2}{6\lambda}; \quad P = \frac{G_{\mathrm{G}}}{G_0} T_0 - \frac{R^*}{C_{\mathrm{Gm}}^{T_0}} - t_{\mathrm{s}} \left(\frac{C_{\mathrm{Gm}}^{T}}{C_{\mathrm{Gm}}^{T_0}} + \frac{G_{\mathrm{G}}}{G_0} \frac{C_{\mathrm{Gm}}^{T}}{C_{\mathrm{Gm}}^{T_0}}\right);$$

$$F = \frac{R^*}{C_{\mathrm{Gm}}^{T_0}} + t_{\mathrm{s}} \frac{C_{\mathrm{Vm}}^{T}}{C_{\mathrm{Gm}}^{T_0}}, \quad h = -R_* \frac{C_{\mathrm{Vm}}^{T}}{C_{\mathrm{Gm}}^{T_0}}; \quad R_* = R^* + C_{\mathrm{Vm}}^{t} t_{\mathrm{s}} = R + C_{\mathrm{L}} (t_{\mathrm{s}} - t_{\mathrm{m}}).$$

Here G, G_0 are the weight rates of liquid flow at any apparatus section and at the inlet, respectively; G_{d}, G_{d}^0 are the instantaneous mass and the initial mass of a droplet, respectively; τ is time; ρ, ρ_0 are the radii of a liquid droplet surface at any instant and at the first instant of time; T, T_0 are the instantaneous and the initial temperature of the vapor–gas mixture; t_{s}, t_{m} are the surface temperature and the mean temperature of a droplet; λ is the thermal conductivity of the vapor–gas mixture; C_{Gm}^{T}, $C_{\mathrm{Gm}}^{T_0}$, C_{Vm}^{T}, C_{Vm}^{t} are the mean specific heat of the gas and of the vapor, respectively, within temperature intervals from standard to T, T_0, and t_{s}, respectively; C_{L} is the mean specific heat of the liquid within the temperature interval from t_{m} to t_{s}; C_{V} is the mean specific heat of the vapor within the temperature interval from t_{s} to T; R is the heat of evaporation; γ_{s}, γ are the initial and the instantaneous density of the solution; and γ_{L} is the density of the solvent.

The solution to Eq. (3) with the initial condition g(0) = 1 can be written as

$$\frac{h}{2} y^2 + \left(m - \frac{hn}{F}\right) \left\{\frac{1}{6} \left(\frac{F}{n}\right)^{\frac{1}{3}} \ln \frac{\left(\frac{n}{F}\right)^{\frac{2}{3}} - \left(\frac{n}{F}\right)^{\frac{1}{3}} y + y^2}{\left[\left(\frac{n}{F}\right)^{1/3} + y\right]^2} + \left(\frac{F}{n}\right)^{1/3} \frac{1}{\sqrt{3}} \operatorname{arctg} \frac{2y - \left(\frac{n}{F}\right)^{1/3}}{\left(\frac{n}{F}\right)^{1/3} \sqrt{3}}\right\} - \xi = -\frac{F}{3\beta} \tau, \tag{4}$$

where

$$\xi = \frac{h}{2} y_0^2 + \left(m - \frac{hn}{F}\right) \left\{\frac{1}{6} \left(\frac{F}{n}\right)^{\frac{1}{3}} \ln \frac{\left(\frac{n}{F}\right)^{\frac{2}{3}} - \left(\frac{n}{F}\right)^{\frac{1}{3}} y_0 + y_0^2}{\left[\left(\frac{n}{F}\right)^{1/3} + y_0\right]^2} + \left(\frac{F}{n}\right)^{\frac{1}{3}} \frac{1}{\sqrt{3}} \operatorname{arctg} \frac{2y_0 - \left(\frac{n}{F}\right)^{1/3}}{\left(\frac{n}{F}\right)^{1/3} \sqrt{3}}\right\};$$

$$y = \left(g + \frac{\gamma_{\mathrm{L}}}{\gamma_{\mathrm{S}}} - 1\right)^{1/3}; \quad y_0 = \left(\frac{\gamma_{\mathrm{L}}}{\gamma_{\mathrm{S}}}\right)^{1/3};$$

$$m = u + h\left(1 - \frac{\gamma_{\mathrm{L}}}{\gamma_{\mathrm{S}}}\right); \quad n = P + F\left(1 - \frac{\gamma_{\mathrm{L}}}{\gamma_{\mathrm{S}}}\right).$$

Differentiating (2) with respect to τ, with (4) taken into account, we obtain the rate at which the gas stream is cooled (chilled) by the evaporating liquid. For the evaporation of pure liquids, $\gamma_{\mathrm{S}} = \gamma_{\mathrm{L}}$ in Eq. (4).

DISCHARGE OF A BOILING LIQUID

A. F. Babitskii

UDC 532.529.5

Existing methods of solving the discharge problem in the case of boiling liquids can be classified according to how the system of equations is closed: the isentropic-process scheme [1], the coupled-processes scheme [2], and the hydraulic-process scheme [3]. With the integrated equation of motion for a two-phase fluid [1], one obtains a new solution to this problem under the following conditions: the flow is one-dimensional, steady, and thermodynamically at equilibrium; the temperatures, the pressures, and the velocities of both components are, respectively, equal; there are no mass forces present and no external heat is supplied. The equations of continuity, motion [1], and energy become then, after integration,

$$\rho v f = \rho_0 v_0 f_0 = \mathrm{const}, \tag{1}$$

$$p + \frac{v}{2}(v\rho + v_0\rho_0) = p_0 + \frac{v_0}{2}(v\rho + v_0\rho_0), \tag{2}$$

$$\beta_1 i_1 + \beta_2 i_2 + \frac{v^2}{2} = \beta_{01} i_{01} + \beta_{02} i_{02} + \frac{v_0^2}{2} = \mathrm{const} \tag{3}$$

$$\Big(\rho = c_1\rho_{01} + c_2\rho_{02};\ \ \rho_0 = c_{01}\rho_{01} + c_{02}\rho_{02};\ \ c_1 + c_2 = c_{01} + c_{02} = 1;$$
$$\beta_1 = \frac{c_1\rho_1}{\rho_0};\ \ \beta_{01} = \frac{c_{01}\rho_{01}}{\rho_0};\ \ \beta_1 + \beta_2 = \beta_{01} + \beta_{02} = 1\Big).$$

In the special case $v_0 = 0$, it follows from Eqs. (2) and (3) that the quantity of generated vapor is

$$\beta_2 = 1 - \beta_1 = \frac{\beta_{01} i_{01} + \beta_{02} i_{02} - i_1 - \frac{1}{\rho_{01}}(p_0 - p)}{i_2 - i_1 + \frac{1}{\rho_{01}\rho_{02}}(\rho_{01} - \rho_{02})(p_0 - p)}. \tag{4}$$

If tabulated data are used for determining the thermodynamic properties of the mixture components (water and vapor), then the system of equations (1)-(3) will be a closed one and the problem of discharge will have a unique solution. Moreover, the flow of an ideal mixture is accompanied by an increase in entropy. The velocity and the entropy of the mixture are defined by the following limits:

$$v\,(S = \mathrm{const}) \geqslant v\,(S) \geqslant v\,(S_{\max}) = 0;\ \ S_0 \leqslant S < S\,(v = 0).$$

NOTATION

p is the pressure of the mixture;
v is the velocity of the mixture;
ρ is the density of the mixture;
S is the entropy of the mixture;
c_j is the volume concentration of the j-th component (j = 1, 2);
ρ_j is the density of the j-th component (j = 1, 2);
h_j is the enthalpy of the j-th component (j = 1, 2);
f is the cross-section area of the stream.

Subscripts

1 denotes the liquid;
2 denotes the vapor;
0 denotes the initial state.

LITERATURE CITED

1. A. F. Babitskii, Dokl. Akad. Nauk UkrSSR, Ser. A, No. 7 (1971).
2. N. N. Soldatov, Teploénergetika, No. 1 (1958).
3. M. Stuart and R. Jornell, Engineering, No. 1 (1936).
4. G. Zeuner, Technische Thermodynamik, 1, No. 2 (1890).

Institute of Hydromechanics, Academy of Sciences of the Ukrainian SSR, Kiev. Original article submitted November 4, 1971; abstract submitted July 20, 1972.

HIGH-TEMPERATURE THERMOPHYSICAL MEASUREMENT OF NICKEL PROPERTIES

A. F. Zverev, A. I. Kovalev,
and A. V. Logunov

UDC 536.212:537.311.331

Nickel is a material widely used now as the base in a large group of heat resistant alloys capable of withstanding high temperature. Nevertheless, its properties (for instance, its thermophysical properties) have not been explored thoroughly enough – especially at temperatures above 1000°C.

In this study the authors measured the thermophysical properties of nickel, 99.81% pure specimens, over the temperature range from room to 1400°C. The Rozhdestvenskii apparatus with its temperature range extended to 1000°C was used for measuring λ and ρ from room temperature to 950°C, λ by the relative method [1] and ρ by the compensation method [2]. Measurements in the 1000-1400°C range were made on the apparatus for a composite determination of thermophysical properties [3], where a specimen was heated with electric current in vacuum so that the temperature profile in the center portion would become parabolic. The agreement between thermal conductivity values obtained by two different methods on different apparatus within comparable temperature ranges provides an additional indicator as to the reliability of the results. The specimens for the measurements on each apparatus had been prepared from the same stock of pure nickel.

Rounded off values from these tests are shown in Table 1. The maximum (corresponding to the 95% confidence interval) measurement error (random plus systematic) is: 5.5% for λ, 1.5% for ρ, and 10% for ε in the 200-900°C temperature range, 9% for λ, 2% for ρ, and 11% for ε in the 1000-1400°C temperature range.

TABLE 1. Thermophysical Properties of Pure Nickel (99.81%)

T, °C	20	100	200	300	400	500	600	700
λ, W/cm·°C	—	—	0,77	0,68	0,64	0,63	0,64	0,66
ρ, μΩ·cm	7,68	11,3	17,4	25,2	33,5	37,4	40,2	43,2
$L \cdot 10^8$, W·Ω/(°C)^2	—	—	2,83	3,0	3,18	3,05	2,95	2,93
T, °C	800	900	1000	1100	1200	1300	1400	—
λ, W/cm·°C	0,69	0,72	0,75	0,78	0,81	0,84	0,86	—
ρ, μΩ·cm	45,8	48,4	50,8	53,2	55,8	58,4	61,4	—
$L \cdot 10^8$, W·Ω/(°C)^2	2,94	2,97	2,99	3,02	3,07	3,12	3,16	—
ε	—	—	0,18	0,195	0,21	0,23	0,245	—
ε_λ, $\lambda = 0,65\mu$	—	—	0,385	0,395	0,405	0,415	0,425	—

LITERATURE CITED

1. A. I. Kovalev and A. V. Logunov, in: Methods of Testing, Inspecting, and Studying Materials for Machine Construction [in Russian], Vol. 1, Mashinostroenie (1971).
2. A. V. Logunov and A. F. Zverev, Inzh.-Fiz. Zh., 15, No. 6, 1114 (1968).
3. A. I. Kovalev and A. V. Logunov, in: Thermophysical Properties of Solids [in Russian], Nauka (1971).

Original article submitted November 29, 1971; abstract submitted June 16, 1972.

IRRADIATION OF BODIES WITH SELECTIVE ABSORPTION CHARACTERISTICS OF THE MEDIUM

S. P. Detkov

UDC 536.3

Calculations of the radiative heat transfer between bodies involve an interspersion of problems concerning their geometry and spectra. The first step is to integrate a flux element over the depth of the volume. The next steps depend largely on the sequence of integrations: over the spectrum and with respect to the space angle. The advisability of integrating over the spectrum last is shown here on the example of two-dimensional systems of bodies for which the irradiation coefficients are calculated. According to the method proposed in [1], however, as well as in this method one can use the directional radiation characteristics for the final calculations.

A combination sequence of integration is recommended for systems with a complex geometry: the spectrum is subdivided into ranges. When the spectrum is continuous, then integration with respect to the space angle is within each range performed last. This sequence is particularly convenient in the case of variable temperature, pressure, and concentration fields.

Consideration is given here to a range of the spectrum sufficiently narrow so that the optical properties of the disperse phase and of the surface may be assumed constant. At the same time, such a range covers a multitude of spectral lines of the gas – lines of different intensities but the same contour. The lines or the bands either do not overlap at all or overlap completely. The expressions for the irradiation coefficients are of four different kinds, depending on the combination of volume and surface zones. The angular distribution of radiant flux impinging on a body is described by the Law of Cosines.

The transition from a system with an arbitrary geometry to a system of two-dimensional bodies yields a class of special functions. The following are examples of these new functions appearing in the expressions for the irradiation coefficients:

$$M_{0n}(c,\ \tau) = \gamma \int [K_n(0) - K_n((f + c)\tau)]\, dy,$$

$$M_{m,n}(c,\ \tau) = \gamma \int_{-\infty}^{\infty} f^m K_n((f + c)\tau)\, dy.$$

Here

$$K_n \equiv \frac{4}{\pi} Ki_n(t) = \frac{4}{\pi} \int_0^{\pi/2} \exp\left(-\frac{t}{\cos\alpha}\right) \cos^{n-1}\alpha\, d\alpha,$$

$$c = k/\alpha_0,\quad \alpha_\omega = \alpha_0 f(y),\quad \tau = \alpha_0 l,\quad y = |\omega - \omega_0|/\Delta\omega,$$

ω is the wave number, cm^{-1}; $\Delta\omega$ is the width of a spectrum range; ω_0 is the center of a spectrum range, cm^{-1}; f is the contour of the spectral absorption coefficient α; γ is the normalizing factor; l is the thickness of a body, m; k is the attenuation coefficient of the disperse phase; m, n = 1, 2, ...

Other functions are already well known and found in the technical literature. The values of some of them have been tabulated for the simplest contours f.

A general scheme is proposed for calculating the matrix of irradiation coefficients, its properties and simplifications are analyzed, and a specific example is shown of a radiation band with a dispersive contour.

LITERATURE CITED

1. S. P. Detkov, Inzh.-Fiz.-Zh., 21, No. 2 (1971).

Original article submitted October 25, 1971; abstract submitted June 19, 1972.