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ENERGY TRANSPORT BY RADIATION IN A COMPOSITE CHANNEL

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An approximate solution is proposed for the heat flux and temperature distribution in a channel comprised of cylindrical and conical sections.

The simplest composite channels (Fig. 1) are windows in chambers with high temperature or pores of a continuous body. They can be made complicated by the quantity of sections and by their shape. There is no transverse energy transport. We also neglect longitudinal transport in the walls. But the walls reflect and reradiate the energy absorbed, and the medium dissipates it. Sources and sinks are arranged only on the endfaces. Consequently, the power of the resultant flux is constant, Q = const, W, while the channel is called conservative or adiabatic. The geometric and optical characteristics of the bodies and the endface temperature are given. The magnitude of Q and the temperature distribution over the channel length are determined.

The solution of the general problem is given in [1] on the basis of differential equations but it turns out to be quite complex even for gray bodies. An approximate, very simplified solution is proposed in this paper.

Represented in Fig. 2 are systems of coaxial cylinders or concentric spheres and channel section specimens. The analytic solutions for the system 2a are in handbooks [2, 3] but with the flaw that they do not take account of the jump in potential in a layer of the medium because of expansion of the flux of the radiant energy transport vector. Given below is a correct solution.

The systems of bodies in Fig. 2 are simulated by an electrical loop. We consider $\Theta \equiv n^2\sigma T^4$ the transport potential. The quantity $\Theta_1 - \Theta_2$ is the analog of the electromotive force and is distributed over the external and internal sections of the closed loop. Three outer sections are shown in the diagram. The jumps in the potential are written by analogy to the Ohm's law for the loop sections:

$$\Delta\Theta_1' = \frac{Q}{F_1}\frac{R_1}{A_1},\ \Delta\Theta_2' = \frac{Q}{F_2}\frac{R_2}{A_2},\ \Delta\Theta' = \frac{Q}{F_1}r_{12}.$$

The first two are lumped in points on the surfaces while the third is distributed in the medium. The internal reduction in the potential is also comprised of three parts with jumps due to $\Delta\Theta_1''$ — the action of sources in body 1, $\Delta\Theta_2''$ and $\Delta\Theta''$ — the action of sinks in body 2, where $\Delta\Theta''$ appears during "leakage" of the sinks over the surface F_2 when the density of the resultant flux is reduced. Similarly to electrodes of the current source, surfaces 1 and 2 comprise a unit. The channel section is a heat machine in which the heater cannot act without a refrigerator according to the second law of thermodynamics. But the surfaces are separated more greatly as contrasted to the electrodes, the jumps $\Delta\Theta_1''$ and $\Delta\Theta_2''$ are at their external sides while $\Delta\Theta''$ is between them. In fact, $\Delta\Theta_2''$ and $\Delta\Theta''$ are not related to the resistance to the flux. Nevertheless, we simulate all the jumps by sections of the loop. The complete jumps in the potential on and between the surfaces equal

$$\Delta\Theta_1 = \Delta\Theta_1' + \Delta\Theta_1'',\ \Delta\Theta_2 = \Delta\Theta_2' + \Delta\Theta_2'',\ \Delta\Theta = \Delta\Theta' + \Delta\Theta''.$$

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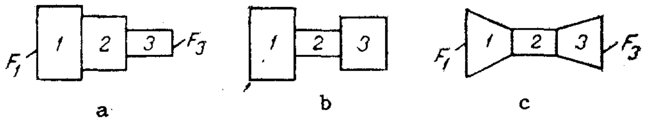

Fig. 1. Simplest examples of composite channels.

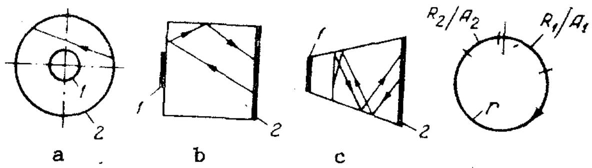

Fig. 2. Approximate similarity of three systems of bodies and the electrical diagram to simulate energy transport.

According to the balance of the jumps

$$\Delta\Theta_1 + \Delta\Theta_2 + \Delta\Theta = \Theta_1 - \Theta_2. \tag{1}$$

The problem is to determine the jumps $\Delta\Theta_1''$, $\Delta\Theta_2''$, and $\Delta\Theta''$. For a short-circuited loop $R_1 = R_2 = r_{12} = 0$. The internal jumps remain and

$$\Delta\Theta_1'' + \Delta\Theta_2'' + \Delta\Theta'' = \Theta_1 - \Theta_2. \tag{2}$$

Two equations are still necessary for (2). The angular distribution of the rays does not change for the cold surface 2, consequently

$$q_1/q_2 = \eta_{s1}/\eta_{s2} = \bar{\Theta}_1''/\bar{\Theta}_2'' = F_2/F_1, \tag{3}$$

where all the quantities characterize a medium in contact with the surfaces; $\eta_s = 4n^2\sigma T_r^4$, and the radiant temperature equals the ordinary temperature, $T_r = T$.

For a zero temperature of the surface 2, $\bar{\Theta}_2'' = \Delta\Theta_2''$. Then taking (3) into account

$$\Delta\Theta_1'' + \Delta\Theta_2''(F_2/F_1) = \Theta_1 - \Theta_2 \tag{4}$$

is obtained from (2).

We also assume that the jumps $\Delta\Theta_1''$ and $\Delta\Theta_2''$ are proportional to the flux densities and therefore $\Delta\Theta_1''/\Delta\Theta_2'' = F_2/F_1$. Substituting $\Delta\Theta_2'' = (\Theta_1 - \Theta_2)F_1/(2F_2)$ into (4), we have $\Delta\Theta_1'' = (\Theta_1 - \Theta_2)/2$, $\Delta\Theta'' = (\Theta_1 - \Theta_2)(1 - F_1/F_2)/2$. In the presence of external resistances, the complete potential jumps have the form

$$\Delta\Theta_1 = \frac{Q}{F_1}\left(\frac{R_1}{A_1} + \frac{1}{2}\right), \quad \Delta\Theta = \frac{Q}{F_1}\left[r_{12} + \frac{1}{2}\left(1 - \frac{F_1}{F_2}\right)\right], \quad \Delta\Theta_2 = \frac{Q}{F_2}\left(\frac{R_2}{A_2} + \frac{1}{2}\right). \tag{5}$$

After substitution into (1)

$$q_1 = \frac{Q}{F_1} = \frac{\Theta_1 - \Theta_2}{(1/A_1) + r_{12} + (F_1/F_2)R_2/A_2}. \tag{6}$$

For black surfaces

$$q_{01} = (\Theta_1 - \Theta_2)/(1 + r_{12}). \tag{7}$$

We represent (6) as

$$\frac{q_{01}}{q_1} = 1 + \frac{q_{01}}{\Theta_1 - \Theta_2}\left(\frac{R_1}{A_1} + \frac{F_1}{F_2}\frac{R_2}{A_2}\right), \tag{8}$$

which corresponds to the solution in [2, p. 678, Table 17.5].

A computation of the temperature jumps is presented in [4] for the system of Fig. 2a in a diffuse approximation. According to (5) the quantity $\Delta\Theta''$ was not extracted. The flux density, if it is relatively small, is computed for coaxial cylinders according to the formula

TABLE 1. Thermal Resistance of a Layer of the Medium between Coaxial Long Cylinders r_{12} (upper numbers are a computation according to [5] and formula (6) and the lower are according to the Rosseland approximation (11))

$\tau_0 = k(\rho_2 - \rho_1)$	ρ_2/ρ_1	
	2	10
0	0	0
1	0,48 0,52	0,15 0,19
2	0,98 1,04	0,32 0,38
4	2,00 2,08	0,64 0,77
6	3,06 3,12	1,00 1,15
8	4,00 4,16	1,34 1,54
10	5,25 5,20	1,70 1,92

$$\frac{\Theta_1 - \Theta_2}{q_1} = \frac{1}{A_1} - \frac{1}{2} + \frac{\rho_1}{\rho_2}\left(\frac{1}{A_2} - \frac{1}{2}\right) + \frac{3}{4}k\rho_1 \ln\frac{\rho_2}{\rho_1} + \frac{3}{16}\,\frac{1}{k\rho_1}\left[1 - \left(\frac{\rho_1}{\rho_2}\right)^2\right]. \tag{9}$$

It is written with misprints in the handbook [3] where the last term is omitted. The condition $k\rho_1 \gtrsim 1$ shows that the error is not large if the optical thickness of the medium is sufficiently large, more exactly, if the photon mean free path is less than ρ_1. Formula (6) has no such constraints.

Formula (9) also corresponds to (8) but the resistance of a layer of the medium is computed differently upon comparison with (7)

$$r_{12} = \frac{3}{4}k\rho_1 \ln\frac{\rho_2}{\rho_1} + \left\{\frac{3}{16}\,\frac{1}{k\rho_1}\left[1 - \left(\frac{\rho_1}{\rho_2}\right)^2\right] - \frac{1}{2}\left(1 - \frac{\rho_1}{\rho_2}\right)\right\}. \tag{10}$$

The analytic solution (6) is exact in the measure of the quantity r_{12}. In the Rosseland approximation

$$\mathbf{q} = -\frac{4}{3}\,\frac{1}{k}\operatorname{grad}\Theta \text{ and } r_{12} = 0.75k\rho_1 \ln(\rho_2/\rho_1)$$

or

$$r_{12} = f_1(\tau_0)\, f_2(\rho_2/\rho_1), \tag{11}$$

where

$$f_1 = 0.75\tau_0, \quad \tau_0 = k(\rho_2 - \rho_1), \quad f_2 = \frac{\ln(\rho_2/\rho_1)}{(\rho_2/\rho_1) - 1}.$$

The differences between (10) and (11) are substantial but they are still greater according to the complete formula in [4].

The correct solution for coaxial cylinders is obtained in [5] by the Monte Carlo method. It confirms the jump in the potential in the derivation of (6) and the formula itself (see also the nomograms in [2, p. 695] and [3, p. 354] (jointly)).

Compared in the table are computations of r_{12} from the nomogram in [5] and by means of (11). It is seen that the solution (11) has no constraints in $k\rho_1$, is sufficiently exact, but exaggerates the flux even for $\rho_2/\rho_1 = 2$, with the exception of the lower value. As $\rho_2/\rho_1 \to 1$, in the passage to a plane layer, $f_2 \to 1$, $f_1 = 0.75\,\tau_0$. According to the most exact relationship in the literature [1]

$$f_1 = 0.75\tau_0 + 0{,}06\,[1 - \exp(-3\tau_0)].$$

In this case (11) understates the result.

Analysis of the diffusion approximation in [6] showed the dependence of the transport coefficient on a number of conditions and the possibility of its correction only in limited cases.

The systems in Figs. 2a and b are similar with a reservation. The direct flux for $\Theta_1 > \Theta_2$ is determined by the same formula (6) but with an additional error associated with the inhomogeneity of the quantity q_2. In the limit of the coming together of the surfaces, the inhomogeneity of q_2 and the unsuitability of (6) are evident. In such a case, the surfaces should be divided into zones with sufficiently homogeneous flux densities. But this method is not examined here. Consequently, we continue the analysis under the condition that the surfaces are sufficiently remote from each other.

For the reverse flux ($\Theta_2 > \Theta_1$) a part of the endface 1 forms a diaphragm with the potential jump $(Q/F_1)(1 - F_1/F_2)$. There are no diaphragms in the system 2a but the effect is the same: part of the rays directed past the surface 1 is returned to the surface 2. The jump because of the growth of the line density of the resultant flux vector is written for $r_{12} = 0$ in (5) but with opposite sign. The total jump is realized and it is obtained exactly as for the direct flux

$$\Delta\Theta = (Q/F_1)(1 - F_1/F_2)/2,$$

with the conservation of the reciprocity relation upon changing the flux direction. The quantity r includes the wall resistance and r = 0 only in the absence of a medium and specularity of the ray reflections from the walls. The conicity of the side surface in Fig. 2c changes the form of the diaphragm. For any angle at the cone apex a part of the rays is returned to surface 2 and the jump remains the same.

All the relationships for the channel section are obtained with the assumption of uniformity and isotropy of the effective flux at the endface-source. Analysis of the channel is simplified if this is extended to the input sections of all portions of arbitrary number. The thermal resistances of the channel elements are combined. The thermal flux is obtained underestimated since the flux densities are actually elevated on the channel axis as compared with the circumference. For the composite channel in Fig. 1a, the jumps in the potential on the elements are written successively

$$\frac{Q}{F_1}\left(\frac{R_1}{A_1} + \frac{1}{2}\right); \quad \frac{Q}{F_1} r_1; \quad \frac{Q}{F_2}\left(1 - \frac{F_2}{F_1}\right)\Big/2 \text{ on the first diaphragm;}$$

$$\frac{Q}{F_2} r_2; \quad \frac{Q}{F_3}\left(1 - \frac{F_3}{F_2}\right)\Big/2 \text{ on the second diaphragm.}$$

Summation of the jumps yields

$$q_3 = \frac{\Theta_3 - \Theta_1}{\dfrac{1}{A_3} + F_3 \sum\limits_{i=1}^{3} \dfrac{r_i}{F_i} + \dfrac{F_3}{F_i}\dfrac{R_1}{A_1}},$$

$$q_1 = \frac{\Theta_1 - \Theta_3}{\dfrac{F_1}{F_3}\dfrac{1}{A_3} + F_1 \sum\limits_{i=1}^{3} \dfrac{r_i}{F_i} + \dfrac{R_1}{A_1}}.$$

with conservation of the equality $F_1 q_1 = -F_3 q_3$.

For the channel in Fig. 1b

$$q_1 = (\Theta_1 - \Theta_2)\Big/\left[\frac{R_1}{A_1} + \frac{F_1}{F_2} + F_1 \sum_{i=1}^{3} \frac{r_i}{F_i} + \frac{F_1}{F_3}\frac{R_3}{A_3}\right].$$

Channel 1c is a model of channel 1b for which only the computation of the quantity

$$\sum_{i=1}^{3} r_i/F_i = r_{12}/F_1 + r_2/F_2 + r_{23}/F_2$$

changes, where

$$r_{12}/F_1 = r_{21}/F_2, \quad r_{23}/F_2 = r_{32}/F_3.$$

This method agrees with the results in [7] obtained for molecular fluxes by virtue of their analogy to radiant fluxes. In contrast to [7], the channel is made complicated while the jumps in the potential are determined on its elements. The heat flux is obtained by summing the jumps.

NOTATION

k, attenuation coefficient, m^{-1}; r, thermal resistance to radiant flux, dimensionless; q, resultant flux density, W/m^2; $\Theta \equiv n^2\sigma T^4$; A, endface absorptivity; $R = 1 - A$; F, channel section area, m^2; Q, resultant flux power in the channel, W; T, temperature, K; ρ, radius, m; τ_0, optical thickness of a layer of the medium.

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OPTIMIZATION OF THE THERMAL MODE OF POLYMER SUBSTRATES DURING THEIR VACUUM METALLIZATION

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An analytic expression is obtained for the specific heat of the vacuum metallization process. Optimal values of the evaporation temperature are determined for a number of metals and maximal deposition rates are estimated at which thermal rupture of the polymer materials does not occur.

Utilization of the highly productive technology of vacuum metallization of polymer materials by the method of evaporation and condensation of metal atoms is constrained to a significant extent by their relatively low thermal stability and the substantial change in their physicochemical properties during heating. The multivariety of the thermal action to which a substrate is subjected during vacuum metallization and the complex nature of the change in the system thermophysical properties during metal film growth produce a number of difficulties in the strict formulation and resolution of the appropriate transport equations [1-3]. To a considerable extent this circumstance governs the lack of a simple method, but sufficiently completely reflecting the features of metallization, for computing the substrate temperature and determining the influence of fundamental technological parameters of coating superposition on its values. An approach is developed in this paper for the selection of the technological metallization modes that are optimal in the energetic action on the substrate that is based on utilization of the specific heat of the process.

In the general case, the energy obtained by the substrate for any method of producing the vapor phase of a metal consists of the energy of radiation of the surface of the metal being evaporated, and the energy of the phase transitions of the coating material. Since the metallization process proceeds at low pressure, heat transmission from the evaporator to the substrate because of convection and heat conduction is negligible. Then if there is no chemical interaction in the formation of the coating then the heat flux density perceived by the substrate can be determined from the relationship

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