GENERALIZED THERMAL CONDUCTIVITY OF DISSIMILAR HEAT-SENSITIVE BODIES CONNECTED BY A THIN INTERMEDIATE LAYER

Yu. M. Kolyano, E. P. Khomyakevich, and I. O. Goi UDC 539.3

Generalized conditions are formulated for the nonideal contact of dissimilar heat-sensitive crystalline solids in order to determine their Kirchhoff variables.

The studies [1, 2] formulated generalized conditions of nonideal thermal contact of dissimilar solids and generalized heat-transfer boundary conditions for bodies with thin coatings for the case when the thermophysical characteristics of elements of the piecewise-uniform bodies in question are independent of temperature. Generalized boundary conditions for heat-sensitive bodies with thin coatings were formulated in [3]. Here, we present generalized conditions of nonideal thermal contact of dissimilar heat-sensitive bodies connected through a thin, heat-sensitive intermediate layer.

Let two nonmetallic crystalline bodies be connected by a thin, nonmetallic intermediate layer. The thermal conductivities and volumetric heat capacities of the bodies are different and at low temperatures are proportional to the cube of the absolute temperature [4, 5]:

$$\lambda_i(t_i) = \tilde{\varkappa}_i t_i^3,\ c_i(t_i) = \tilde{\beta}_i t_i^3\ (i = 0,\ 1,\ 2). \tag{1}$$

The system is heated by internal heat sources and then by radiation. Generalized conditions of ideal thermal contact exist between the bodies and the intervening layer.

In this case, we have the following equation of generalized heat conduction [6-8] to determine the temperature field in the piecewise-uniform body, referred to a system of curvilinear orthogonal coordinates (α, β, γ)

$$\frac{1}{H_1H_2H_3}\left\{\frac{\partial}{\partial\alpha}\left[\frac{H_2H_3}{H_1}\lambda_i(t_i)\frac{\partial t_i}{\partial\alpha}\right]+\frac{\partial}{\partial\beta}\left[\frac{H_1H_3}{H_2}\lambda_i(t_i)\frac{\partial t_i}{\partial\beta}\right]+\frac{\partial}{\partial\gamma}\left[\frac{H_1H_2}{H_3}\lambda_i(t_i)\frac{\partial t_i}{\partial\gamma}\right]\right\}=l_i[c_i(t_i)\dot{t}_i-w_i], \tag{2}$$

along with the generalized conditions of ideal contact

$$t_0 = t_1,\ \tilde{\Phi}_1^{(0)} = \tilde{\Phi}_1^{(1)}\ \text{on}\ S_1,\ t_0 = t_2,\ \tilde{\Phi}_2^{(0)} = \tilde{\Phi}_2^{(2)}\ \text{on}\ S_2, \tag{3}$$

generalized Stefan–Boltzmann boundary conditions

$$\lambda_i(t_i)\frac{\partial t_i}{\partial n_i'} + l_i(\tilde{\sigma}_i t_i^4 - q_i) = 0\ \text{on}\ \ S_i' \tag{4}$$

and initial conditions

$$t_i = t_0^{(0)},\ \dot{t}_i = 0\ \ \text{at}\ \ \tau = 0, \tag{5}$$

where

$$l_i = 1 + \tau_r^{(i)}\frac{\partial}{\partial\tau},\ \tilde{\Phi}_j^{(i)} = \frac{1}{\tau_r^{(i)}}\int_0^\tau \lambda_i(t_i)\exp\left(\frac{\xi-\tau}{\tau_r^{(i)}}\right)\frac{\partial t_i}{\partial n_j}d\xi\ (i = 0,\ 1,\ 2,\ j = 1,\ 2).$$

With allowance for Eqs. (1), boundary-value problem (2)-(5) for crystalline solids is completely linearized by means of Kirchhoff variables

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$$\vartheta_i = \frac{1}{\varkappa_i} \int_0^{t_i} \lambda_i(\xi)\, d\xi$$

and it takes the following form for the thin intermediate layer, referred to curvilinear coordinates of the mixed type, after the appropriate simplifications [2]

$$\frac{\partial^2 \vartheta_0}{\partial \gamma^2} + p^2 \vartheta_0 = -l_0 \frac{w_0}{\varkappa_0}, \tag{6}$$

$$\vartheta_0 = \vartheta_1,\ \Phi_1^{(0)} = \Phi_1^{(1)} \text{ on } S_1,\ \vartheta_0 = \vartheta_2,\ \Phi_2^{(0)} = \Phi_2^{(2)} \text{ on } S_2, \tag{7}$$

$$\varkappa_0 \frac{\partial \vartheta_0}{\partial n_0'} + l_0(\sigma_0 \vartheta_0 - q_0) = 0 \quad \text{on } S_0', \tag{8}$$

$$\vartheta_0 = \vartheta_0^{(0)},\ \dot{\vartheta}_0 = 0 \quad \text{at} \quad \tau = 0, \tag{9}$$

where

$$\dot{\vartheta}_0 = \frac{\partial \vartheta_0}{\partial \tau},\ p^2 = \Delta - \frac{\beta_0}{\varkappa_0} l_0 \frac{\partial}{\partial \tau},\ \sigma_0 = 4\tilde{\sigma}_0 \frac{\varkappa_0}{\tilde{\varkappa}_0},$$

$$\Delta = \frac{1}{AB}\left[\frac{\partial}{\partial \alpha}\left(\frac{B}{A}\frac{\partial}{\partial \alpha}\right) + \frac{\partial}{\partial \beta}\left(\frac{A}{B}\frac{\partial}{\partial \beta}\right)\right],$$

$$\Phi_j^{(i)} = \frac{\varkappa_i}{\tau_r^{(i)}} \int_0^{\tau} \exp\left(\frac{\xi - \tau}{\tau_r^{(i)}}\right) \frac{\partial \vartheta_i}{\partial n_j} d\xi.$$

If we average Eqs. (6), (8), and (9) in accordance with the integral characteristics of the Kirchhoff variable [9]

$$\theta = \frac{1}{2\delta} \int_{-\delta}^{\delta} \vartheta_0 d\gamma,\ \theta^* = \frac{3}{2\delta^2} \int_{-\delta}^{\delta} \gamma \vartheta_0 d\gamma, \tag{10}$$

we obtain:

$$\Lambda_0 p^2 \theta + \varkappa_0 \left[\left(\frac{\partial \vartheta_0}{\partial \gamma}\right)^+ - \left(\frac{\partial \vartheta_0}{\partial \gamma}\right)^-\right] = -l_0 W_0,$$

$$\Lambda_0 p^2 \theta^* + 3\varkappa_0 \left[\left(\frac{\partial \vartheta_0}{\partial \gamma}\right)^+ + \left(\frac{\partial \vartheta_0}{\partial \gamma}\right)^-\right] - \frac{6}{r_0}(\vartheta_0^+ - \vartheta_0^-) = -l_0 W_0^*, \tag{11}$$

$$\varkappa_0 \frac{\partial \theta}{\partial \gamma} + l_0(\sigma_0 \theta - \tilde{q}_0) = 0,\ \varkappa_0 \frac{\partial \theta^*}{\partial \gamma} + l_0(\sigma_0 \theta^* - \tilde{q}_0^*) = 0 \text{ on } S_0', \tag{12}$$

$$\theta = \vartheta_0^{(0)},\ \dot{\theta} = 0,\ \theta^* = 0,\ \dot{\theta}^* = 0 \quad \text{at} \quad \tau = 0, \tag{13}$$

where

$$\Lambda_0 = 2\varkappa_0 \delta,\ r_0 = \frac{2\delta}{\varkappa_0},\ \left(\frac{\partial \vartheta_0}{\partial \gamma}\right)^{\pm} = \left(\frac{\partial \vartheta_0}{\partial \gamma}\right)_{\gamma = \pm\delta},\ \tilde{q}_0 = \frac{1}{2\delta} \int_{-\delta}^{\delta} q_0 d\gamma,$$

$$\tilde{q}_0^* = \frac{3}{2\delta^2} \int_{-\delta}^{\delta} \gamma q_0 d\gamma,\ \vartheta_0^{\pm} = \vartheta_0|_{\gamma = \pm\delta},\ W_0 = \int_{-\delta}^{\delta} w_0 d\gamma,\ W_0^* = \frac{3}{\delta} \int_{-\delta}^{\delta} \gamma w_0 d\gamma.$$

Using the operator method, we write the general solution of Eq. (6) in the form

$$\vartheta_0 = \frac{\cos p\gamma}{2\cos p\delta}\left[\vartheta_0^+ + \vartheta_0^- - \frac{l_0(Q_0^+ + Q_0^-)}{\varkappa_0 p^2}\right] + \frac{\sin p\gamma}{2\sin p\delta}\left[\vartheta_0^+ - \vartheta_0^- - \frac{l_0(Q_0^+ - Q_0^-)}{\varkappa_0 p^2}\right] + \frac{l_0 Q_0}{\varkappa_0 p^2}, \tag{14}$$

where

$$Q_0^{\pm} = Q_0|_{\gamma=\pm\delta}, \quad Q_0 = p \int_0^{\gamma} w_0 \sin p(\xi - \gamma)\, d\xi.$$

Taking Eqs. (10) and (14) into account, we find that

$$\theta = \frac{\operatorname{tg} p\delta}{2p\delta}\left[\vartheta_0^+ + \vartheta_0^- - \frac{l_0(Q_0^+ + Q_0^-)}{\varkappa_0 p^2}\right] + \frac{l_0\tilde{Q}_0}{\varkappa_0 p^2},$$
$$\theta^* = \frac{3}{2}\,\frac{1 - p\delta \operatorname{ctg} p\delta}{p^2\delta^2}\left[\vartheta_0^+ - \vartheta_0^- - \frac{l_0(Q_0^+ - Q_0^-)}{\varkappa_0 p^2}\right] + \frac{l_0\tilde{Q}_0^*}{\varkappa_0 p^2}, \tag{15}$$

where

$$\tilde{Q}_0 = \frac{1}{2\delta}\int_{-\delta}^{\delta} Q_0\, d\gamma, \quad \tilde{Q}_0^* = \frac{3}{2\delta^2}\int_{-\delta}^{\delta} \gamma Q_0\, d\gamma.$$

Inserting Eqs. (15) into (11-13), considering conditions (7), passing to the limit at $\delta \to 0$ in the resulting relations, and keeping the constants Λ_0, C_0, r_0, W_0, W_0^*, we obtain the following generalized conditions for the contact of crystalline bodies connected by a thin intermediate crystalline layer:

$$\Lambda_0\Delta(\vartheta_1 + \vartheta_2) + 2\sum_{i=1}^{2}\left[\varkappa_i \frac{\tau_r^{(0)}}{\tau_r^{(i)}}\frac{\partial\vartheta_i}{\partial n_i} + \left(1 - \frac{\tau_r^{(0)}}{\tau_r^{(i)}}\right)\Phi_i^{(i)}\right] = C_0 l_0(\dot{\vartheta}_1 + \dot{\vartheta}_2) - 2l_0 W_0,$$

$$\Lambda_0\Delta(\vartheta_1 - \vartheta_2) + 6\sum_{i=1}^{2}(-1)^{i-1}\left[\varkappa_i \frac{\tau_r^{(0)}}{\tau_r^{(i)}}\frac{\partial\vartheta_i}{\partial n_i} + \left(1 - \frac{\tau_r^{(0)}}{\tau_r^{(i)}}\right)\Phi_i^{(i)}\right] =$$
$$= C_0 l_0(\dot{\vartheta}_1 - \dot{\vartheta}_2) + \frac{12}{r_0}(\vartheta_1 - \vartheta_2) - 2l_0 W_0^* \text{ on } S_0, \tag{16}$$

$$\varkappa_0 \frac{\partial(\vartheta_1 + \vartheta_2)}{\partial n_0'} + \sigma_0 l_0(\vartheta_1 + \vartheta_2) - 2l_0\bar{q}_0 = 0 \text{ and}$$
$$\varkappa_0 \frac{\partial(\vartheta_1 - \vartheta_2)}{\partial n_0'} + \sigma_0 l_0(\vartheta_1 - \vartheta_2) - 2l_0\bar{q}_0^* = 0 \text{ on } L_0, \tag{17}$$

$$\vartheta_1 = \vartheta_2 = \vartheta_0^{(0)}, \quad \dot{\vartheta}_1 = \dot{\vartheta}_2 = 0 \text{ at } \tau = 0 \text{ on } S_0 \cup L_0. \tag{18}$$

Let us examine special cases of conditions (16).

1. If the thermophysical characteristics of the two bodies are identical ($\lambda_1 = \lambda_2 = \lambda$, $\kappa_1 = \kappa_2 = \kappa$, $\tau_r^{(1)} = \tau_r^{(2)} = \tau_r$), $W_0^* = 0$, $q_0^* = 0$, $\bar{n}_1 = -\bar{n}_2 = \bar{n}$, then instead of (16-18) we have:

$$\Lambda_0\Delta\vartheta + 2\varkappa\frac{\tau_r^{(0)}}{\tau_r}\frac{\partial\vartheta}{\partial n} + 2\frac{\varkappa}{\tau_r}\left(1 - \frac{\tau_r^{(0)}}{\tau_r}\right)\int_0^{\tau}\exp\left(\frac{\xi - \tau}{\tau_r}\right)\frac{\partial\vartheta}{\partial n}\, d\xi = C_0 l_0\dot{\vartheta} - l_0 W_0 \text{ on } S_0,$$

$$\varkappa_0\frac{\partial\vartheta}{\partial n_0'} + \sigma_0 l_0\vartheta - l_0\bar{q}_0 = 0 \text{ on } L_0,$$

$$\vartheta = \vartheta_0^{(0)}, \quad \dot{\vartheta} = 0 \text{ at } \tau = 0 \text{ on } S_0 \cup L_0.$$

2. If $\tau_r^{(0)} \to 0$, $\tau_r^{(1)} \neq 0$, $\tau_r^{(2)} \neq 0$, then instead of (16-18) we have:

$$\Lambda_0\Delta(\vartheta_1 + \vartheta_2) + 2\sum_{i=1}^{2}\frac{\varkappa_i}{\tau_r^{(i)}}\Phi_i^{(i)} = C_0(\dot{\vartheta}_1 + \dot{\vartheta}_2) - 2W_0,$$

$$\Lambda_0\Delta(\vartheta_1-\vartheta_2)+6\sum_{i=1}^{2}(-1)^{i-1}\Phi_i^{(i)}-\frac{12}{r_0}(\vartheta_1-\vartheta_2)=C_0(\dot\vartheta_1-\dot\vartheta_2)-2W_0^*\ \text{on}\ S_0,$$

$$\varkappa_0\frac{\partial(\vartheta_1+\vartheta_2)}{\partial n_0'}+\sigma_0(\vartheta_1+\vartheta_2)=2\tilde{q}_0\ \text{and}$$

$$\varkappa_0\frac{\partial(\vartheta_1-\vartheta_2)}{\partial n_0'}+\sigma_0(\vartheta_1-\vartheta_2)=2\tilde{q}_0^*\ \text{on}\ L_0,$$

$$\vartheta_1=\vartheta_2=\vartheta_0^{(0)},\ \dot\vartheta_1=\dot\vartheta_2=0\ \text{at}\ \tau=0\ \text{on}\ S_0\cup L_0.$$

3. Let $\tau_r^{(0)}\to 0$, $\tau_r^{(1)}\to 0$, $\tau_r^{(2)}\neq 0$. Then

$$\Lambda_0\Delta(\vartheta_1+\vartheta_2)+2\left(\varkappa_1\frac{\partial\vartheta_1}{\partial n_1}+\Phi_2^{(2)}\right)=C_0(\dot\vartheta_1+\dot\vartheta)-2W_0,$$

$$\Lambda_0\Delta(\vartheta_1-\vartheta_2)-6\left(\varkappa_1\frac{\partial\vartheta_1}{\partial n_1}+\Phi_2^{(2)}\right)-\frac{12}{r_0}(\vartheta_1-\vartheta_2)=C_0(\dot\vartheta_1-\dot\vartheta_2)-2W_0^*\ \text{on}\ S_0,$$

$$\varkappa_0\frac{\partial(\vartheta_1+\vartheta_2)}{\partial n_0'}+\sigma_0(\vartheta_1+\vartheta_2)=2\tilde{q}_0\ \text{and}$$

$$\varkappa_0\frac{\partial(\vartheta_1-\vartheta_2)}{\partial n_0'}+\sigma_0(\vartheta_1-\vartheta_2)=2\tilde{q}_0^*\ \text{on}\ L_0,$$

$$\vartheta_1=\vartheta_2=\vartheta_0^{(0)},\ \dot\vartheta_2=0\ \text{at}\ \tau=0\ \text{on}\ S_0\cup L_0.$$

4. For metals ($\tau_r^{(0)}=\tau_r^{(1)}=\tau_r^{(2)}=\tau_r$) we obtain:

$$\Lambda_0\Delta(\vartheta_1+\vartheta_2)+2\sum_{i=1}^{2}\varkappa_i\frac{\partial\vartheta_i}{\partial n_i}=C_0l_0(\dot\vartheta_1+\dot\vartheta_2)-2l_0W_0,$$

$$\Lambda_0\Delta(\vartheta_1-\vartheta_2)+6\sum_{i=1}^{2}(-1)^{i-1}\varkappa_i\frac{\partial\vartheta_i}{\partial n_i}-\frac{12}{r_0}(\vartheta_1-\vartheta_2)=C_0l_0(\dot\vartheta_1-\dot\vartheta_2)-2l_0W_0^*\ \text{on}\ S_0,$$

$$\varkappa_0\frac{\partial(\vartheta_1+\vartheta_2)}{\partial n_0'}+\sigma_0l(\vartheta_1+\vartheta_2)=2l\tilde{q}_0\ \text{and}$$

$$\varkappa_0\frac{\partial(\vartheta_1-\vartheta_2)}{\partial n_0'}+\sigma_0l(\vartheta_1-\vartheta_2)=2l\tilde{q}_0^*\ \text{on}\ L_0,$$

$$\vartheta_1=\vartheta_2=\vartheta_0^{(0)},\ \dot\vartheta_1=\dot\vartheta_2=0\ \text{at}\ \tau=0\ \text{on}\ S\cup L_0,$$

where $\ell = 1+\tau_r(\partial/\partial\tau)$.

Finally, multiplying each term of conditions (16) by r_0 and ignoring the terms containing the products $\Lambda_0 r_0$, $C_0 r_0$, we arrive at the following boundary conditions:

$$\sum_{i=1}^{2}\left[\varkappa_i\frac{\tau_r^{(0)}}{\tau_r^{(i)}}\frac{\partial\vartheta_i}{\partial n_i}+\left(1-\frac{\tau_r^{(0)}}{\tau_r^{(i)}}\right)\Phi_i^{(i)}\right]=-l_0W_0,$$

$$\sum_{i=1}^{2}(-1)^{i-1}\left[\varkappa_i\frac{\tau_r^{(0)}}{\tau_r^{(i)}}\frac{\partial\vartheta_i}{\partial n_i}+\left(1-\frac{\tau_r^{(0)}}{\tau_r^{(i)}}\right)\Phi_i^{(i)}\right]-\frac{2}{r_0}(\vartheta_1-\vartheta_2)=-\frac{1}{3}l_0W_0^*\ \text{on}\ S_0,\tag{19}$$

$$\varkappa_0\frac{\partial(\vartheta_1+\vartheta_2)}{\partial n_0'}+\sigma_0l_0(\vartheta_1+\vartheta_2)=2l_0\tilde{q}_0\ \text{and}$$

$$\varkappa_0\frac{\partial(\vartheta_1-\vartheta_2)}{\partial n_0'}+\sigma_0l_0(\vartheta_1-\vartheta_2)=2l_0\tilde{q}_0^*\ \text{on}\ L_0,\tag{20}$$

$$\vartheta_1=\vartheta_2=\vartheta_0^{(0)},\ \dot\vartheta_1=\dot\vartheta_2=0\ \text{at}\ \tau=0\ \text{on}\ S_0\cup L_0.\tag{21}$$

In conditions (19-21), let $\tau_r^{(0)} \to 0$. We then obtain:

$$\Phi_1^{(1)} - \frac{\vartheta_1 - \vartheta_2}{r_0} = -W_0 - \frac{W_0^*}{3} \text{ and } \Phi_1^{(1)} + \Phi_2^{(2)} = -W_0 \text{ on } S_0, \tag{22}$$

$$\varkappa_0 \frac{\partial(\vartheta_1 + \vartheta_2)}{\partial n_0'} + \sigma_0(\vartheta_1 + \vartheta_2) = 2\tilde{q}_0 \text{ and}$$

$$\varkappa_0 \frac{\partial(\vartheta_1 - \vartheta_2)}{\partial n_0'} + \sigma_0(\vartheta_1 - \vartheta_2) = 2\tilde{q}_0^* \text{ on } L_0, \tag{23}$$

$$\vartheta_1 = \vartheta_2 = \vartheta_0^{(0)},\ \dot{\vartheta}_1 = \dot{\vartheta}_2 = 0 \text{ at } \tau = 0 \text{ on } S_0 \cup L_0. \tag{24}$$

Passing to the limit at $\tau_r^{(1)} \to 0$, $\tau_r^{(2)} \to 0$ in conditions (22-24), with allowance for the limit

$$\lim_{\tau_r^{(j)} \to 0} \frac{\exp \dfrac{(\zeta - \tau)}{\tau_r^{(j)}}}{\tau_r^{(j)}} = \delta_+(\tau - \zeta)$$

we find:

$$2\varkappa_1 \frac{\partial\vartheta_1}{\partial n_1} - 2\frac{\vartheta_1 - \vartheta_2}{r_0} = -W_0 - \frac{W_0^*}{3} \text{ and}$$

$$\varkappa_1 \frac{\partial\vartheta_1}{\partial n_1} + \varkappa_2 \frac{\partial\vartheta_2}{\partial n_2} = -W_0 \text{ on } S_0, \tag{25}$$

$$\varkappa_0 \frac{\partial(\vartheta_1 + \vartheta_2)}{\partial n_0'} + \sigma_0(\vartheta_1 + \vartheta_2) = 2\tilde{q}_0 \text{ and}$$

$$\varkappa_0 \frac{\partial(\vartheta_1 - \vartheta_2)}{\partial n_0'} + \sigma_0(\vartheta_1 - \vartheta_2) = 2\tilde{q}_0 \text{ on } L_0,$$

$$\vartheta_1 = \vartheta_2 = \vartheta_0^{(0)} \text{ at } \tau = 0 \text{ on } S_0 \cup L_0.$$

The above-formulated boundary conditions (16-18) and the special cases that follow from them with constant values of the thermophysical characteristics were presented in [1], while conditions (25), with $W_0 = 0$, were presented in [10].

NOTATION

t_i, w_i, $\tau_r^{(i)}$ ($i = 0, 1, 2$), temperature, density of the heat sources, and relaxation time of heat flux in the intermediate layer and the first and second mated bodies; $\lambda_i(t_i)$, κ_i, $c_i(t_i)$, their thermal conductivities, reference thermal conductivities, and volumetric heat capacities; $\tilde{\sigma}_i$, apparent radiative heat-transfer coefficients from the surfaces S_i'; S_i', outer parts of the surfaces bounding the intermediate layer and the first and second bodies; q_i, heat fluxes of the radiators; n_i, n_i', normals to the surfaces S_i, S_i'; S_0, middle surface of the intermediate layer; S_1, S_2, surfaces of contact of the first and second bodies with the layer; A, B, coefficients of the first quadratic form of the surfaces S_i; H_1, H_2, H_3, Lamé constants; W_0, W_0^*, density of the heat sources and density of the "moments" of the heat sources, referred to a unit area of the middle surface of the layer and characterizing the nonuniformity of the source distribution through the thickness of the intermediate layer.

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