moisture content, %; W_{R_1}, moisture content in inner layers of model at $\tau_I = 0$, %; R_1, R_2, inner and outer radii of model, cm; r, radius, cm; $h = (R_2 - R_1)$, insulation thickness of model, cm; a_m, moisture-diffusion coefficient, cm^2/min; τ, time, min; τ_{tot}, length of drying, min; τ_I, length of isothermal drying, min; t, temperature, °C; P, pressure, mm Hg.

LITERATURE CITED

1. I. F. Pikus and L. A. Koshepavo, Inzh.-Fiz. Zh., 30, No. 1 (1976).
2. G. Beer et al., "Transformers," in: The International Conference on Large Electric Systems (CIGRÉ), Vol. 2, Paris (1966).
3. A. Csernatoni-Hoffer, IEEE Trans. Electr. Insul., EI-3, No. 4 (1968).
4. T. Terada and F. Enokubo, J. Inst. Electr. Eng. Jpn., 92A, No. 5 (1972).
5. M. Beyer, Grundlangen der Vakuumtrocknung von Flüssigen Isolierstoffen und Papierisolation, GFR (1966).
6. M. Beyer and H. D. Grossekatthofer, "Berechnung und Optimisierung des Trocknungprozess von Hochspannungs Papierisolation," Elektrotech. Z., A95, No. 8 (1974).
7. S. D. Lizunov, Drying and Degassing Insulation of High-Voltage Transformers [in Russian], Énergiya, Moscow (1971).
8. I. F. Pikus, L. A. Koshepavo, T. B. Zhilyaev, and L. I. Filatova, in: The Electrical Engineering Industry (High-Voltage-Apparatus Series) [in Russian], No. 10 (1976).
9. P. S. Kuts, I. F. Pikus, and L. S. Kalinina, in: Heat and Mass Transfer [in Russian], No. 6, ITMO Akad. Nauk BelorusSSR, Minsk (1972).
10. W. Lampe, Arch. Elektrotech., 53, No. 2 (1969).
11. W. Lampe, Arch. Elektrotech., 53, No. 3 (1969).
12. V. M. Tret'yakov, "Investigation of the technological process of drying of high-voltage cables," Author's Abstract of Candidate's Dissertation, Moscow Power Institute (1968).
13. I. F. Pikus, L. A. Koshepavo, and N. A. Gudko, in: Thermophysics and the Technology of Thermal Drying Processes [in Russian], ITMO Akad. Nauk BelorusSSR, Minsk (1975).

KINETICS OF VARIATION AND UNSTEADY FIELDS OF TRANSPORT POTENTIALS IN HIGH-TEMPERATURE VACUUM DRYING OF HIGH-VOLTAGE CELLULOSE INSULATION

P. S. Kuts, I. F. Pikus, and V. D. Kononenko

UDC 66.047.2

The results of an analytical investigation are used to analyze the development of temperature fields and internal-pressure fields in high-temperature vacuum drying of cylindrical high-voltage electrical insulation elements.

The cellulose insulation of high-voltage equipment and high-voltage electrotechnical components (the active part of power and measuring transformers, high-voltage lead-ins, cables, etc.) is usually dried to low residual moisture content in a relatively high vacuum (0.1-0.001 mm Hg) at elevated temperature (100-130°C). The characteristic model objects usually chosen for analysis of the drying of high-voltage insulation are the difficult-to-dry multilayer cylindrical elements wound, for example, from cable paper [1-3]. The moisture in electrically insulating cellulose materials is mainly in the adsorption-bound state; in a vacuum at high temperature the mechanism of moisture transfer within the considered insulation elements is determined mainly by filtration–diffusion vapor transport in a radial direction due to the arising pressure gradient [1, 4].

With the adoption of some assumptions an approximate mathematical model of transport processes in high-temperature vacuum drying of cylindrical cellulose insulation elements in generalized variables can be formulated in the following way [5]:

$$\frac{\partial T(X, \mathrm{Fo})}{\partial \mathrm{Fo}} = \frac{1}{1-K}\left[\frac{\partial^2 T(X, \mathrm{Fo})}{\partial X^2} + \frac{1}{X}\frac{\partial T(X, \mathrm{Fo})}{\partial X}\right] + \frac{\mathrm{Bu}}{1-K}\frac{\partial P(X, \mathrm{Fo})}{\partial \mathrm{Fo}}, \quad (1)$$

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$$\frac{\partial P(X,\ \mathrm{Fo})}{\partial \mathrm{Fo}} = (1-K)\,\mathrm{Ly}_p\left[\frac{\partial^2 P(X,\ \mathrm{Fo})}{\partial X^2}+\frac{1}{X}\,\frac{\partial P(X,\ \mathrm{Fo})}{\partial X}\right]-$$

$$-\frac{K}{\mathrm{Bu}}\left[\frac{\partial^2 T(X,\ \mathrm{Fo})}{\partial X^2}+\frac{1}{X}\,\frac{\partial T(X,\ \mathrm{Fo})}{\partial X}\right]. \tag{2}$$

We regard the problem as symmetric, i.e.,

$$\frac{\partial T(0,\ \mathrm{Fo})}{\partial X}=\frac{\partial P(0,\ \mathrm{Fo})}{\partial X}=0;\quad T(0,\ \mathrm{Fo})\neq\infty,\quad P(0,\ \mathrm{Fo})\neq\infty. \tag{3}$$

In application to the investigated process the dimensionless boundary conditions are written in the following way:

$$\frac{\partial T(1,\ \mathrm{Fo})}{\partial X}-\mathrm{Bi}\,[1-T(1,\ \mathrm{Fo})]=0 \text{ when } X=1, \tag{4}$$

$$P(1,\ \mathrm{Fo})=-1 \text{ when } \mathrm{Fo}>0 \text{ and } X=1, \tag{5}$$

$$T(X,\ 0)=P(X,\ 0)=0 \text{ when } \mathrm{Fo}=0. \tag{6}$$

The solution of the system of Eqs. (1) and (2) with the indicated boundary conditions is given in [5] and has the following form:

$$T(X,\ \mathrm{Fo})=1+\sum_{n=1}^{\infty}\sum_{j=1}^{2}C_{nj}J_0(\nu_j\mu_n X)\exp(-\mu_n^2\mathrm{Fo}), \tag{7}$$

$$P(X,\ \mathrm{Fo})=-\left[1+\frac{1}{\mathrm{Bu}}\sum_{n=1}^{\infty}\sum_{j=1}^{2}C_{nj}(\nu_j^2+K-1)\,J_0(\nu_j\mu_n X)\exp(-\mu_n^2\mathrm{Fo})\right]. \tag{8}$$

The averaged values of the transport potentials are determined from the relations

$$\overline{T}(\mathrm{Fo})=1+\sum_{n=1}^{\infty}\sum_{j=1}^{2}D_{nj}\exp(-\mu_n^2\mathrm{Fo}), \tag{9}$$

$$\overline{P}(\mathrm{Fo})=-\left[1+\frac{1}{\mathrm{Bu}}\sum_{n=1}^{\infty}\sum_{j=1}^{2}D_{nj}(\nu_j^2+K-1)\exp(-\mu_n^2\mathrm{Fo})\right]. \tag{10}$$

Expressions for calculation of the coefficients C_{nj} and D_{nj} and the characteristic equation, from which the roots μ_n are determined, are given in [5].

The obtained solutions can be used as a first approximation for qualitative analysis of the general nature of the kinetics of the unsteady transport potential fields and the development of these fields in relation to the conditions of high-temperature vacuum drying of insulation elements. On this basis, in consideration of the dependence of some laws of internal heat and mass transfer on individual similarity criteria the transport coefficients, the thermodynamic characteristics of the material being dried, and the regime parameters can be provisionally regarded as constant.

In addition, in carrying out numerical calculations from relations (7)-(10) for the obtainment of plots of the kinetics of the dimensionless temperature and pressure we used ranges of variation of the absolute values of the factors affecting the considered process (drying temperature, residual partial pressure of water vapor in the atmosphere, geometric dimensions of model specimens of insulation elements, duration of heat and vacuum treatment), state variables, and transport characteristics of the material being dried which correspond most closely to the most probable ranges of variation of these factors and the characteristics in the actual process of vacuum drying of electrical insulation elements. We made extensive use of published data and the results of the comprehensive experimental research, conducted

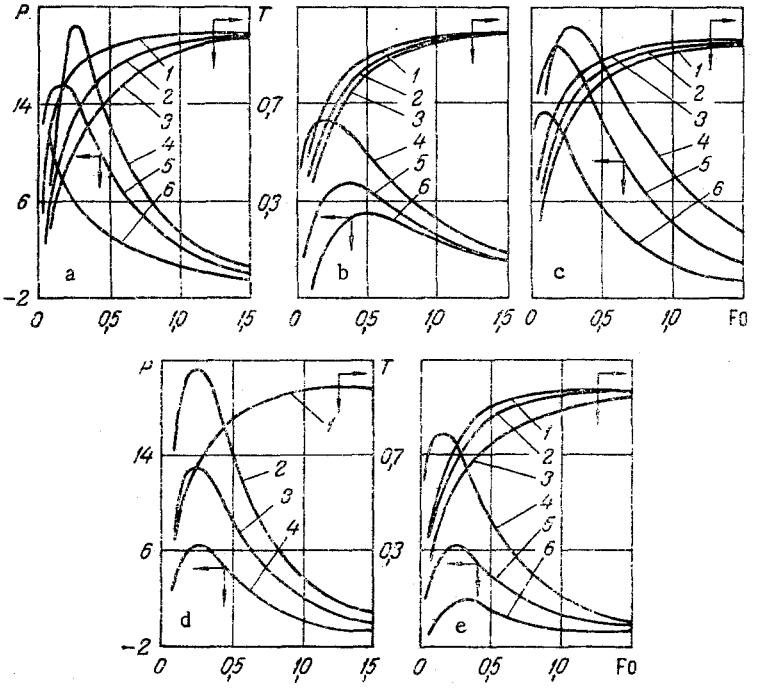

Fig. 1. Kinetics of potentials P and T: a) Bi = 30, Bu = 0.01, K = 0.4, Lyp = 0.7 [1, 6) X = 0.8; 2, 5) 0.5; 3, 4) 0]; b) X = 0.5, Bu = 0.01, K = 0.2, Ly_p = 0.3 [1, 4) Bi = 30; 2, 5) 10; 3, 6) 5]; c) X = 0.5, Bi = 30, Bu = 0.01, K = 0.4 [1, 4) Ly_p = 0.3; 2, 5) 0.5; 3, 6) 1.0]; d) X = 0.5, Bi = 30, K = 0.2, Ly_p = 0.7 [1) Bu = 0.003-0.01; 2) 0.003; 3) 0.005; 4) 0.01]; e) X = 0.5, Bi = 30, Bu = 0.01, Ly_p = 0.7 [1, 6) K = 0.1; 2, 5) 0.2; 3, 4) 0.4].

at the Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, on heat- and mass-transfer processes in high-temperature vacuum drying of cellulose insulation [1, 4, 6-8].

Figure 1a shows that with the very rapid rate of heat supply and continuous evacuation the temperature in all layers of the model specimen at the start of the drying process rises relatively rapidly and produces large temperature gradients in the interior of the material, which gradually decrease; in the region of Fo $\geq$ 1.5 (with the other determining criteria having the absolute values indicated) the dimensionless temperature in all the insulation layers practically evens out and is stabilized at a constant level equal to 1. The unsteady temperature field and the vacuum throughout the material lead to evaporation of the bound moisture at a rate which at the start of heating decreases with increase in distance from the surface of the cylindrical specimen. The calculations indicate that in the material there arises an excess-pressure wave, and the finite rate of relaxation of this pressure through the skeleton of the material in the specimen creates a fairly stable gradient of the potential of filtration-diffusion vapor transport. According to the data shown in Fig. 1a, the extreme parts on the kinetic curves of the dimensionless pressure in the average (over the radial thickness of the insulation) and inner layers of model specimens in the indicated conditions lie in the region Fo = 0.2-0.3.

With further dehydration the pressure in all the insulation layers after passage through the maximum begins to decrease smoothly, asymptotically approaching, along an exponential curve, the level of the residual pressure in the surrounding medium. It is characteristic that equalization and stabilization of the pressure field over the radial thickness of the specimen take place a little later than equalization of the local temperatures of the material (Fo $\geq$ 1.5). It should be noted that the general nature of the calculated layer curves of variation of the insulation temperature and internal pressure in the considered specimens is in good agreement with the results of the experimental investigation [4].

Figure 1b-e shows typical plots of the dimensionless temperature and dimensionless pressure against the characteristic criteria, calculated for average (over the radial thickness) layers of cylindrical model specimens.

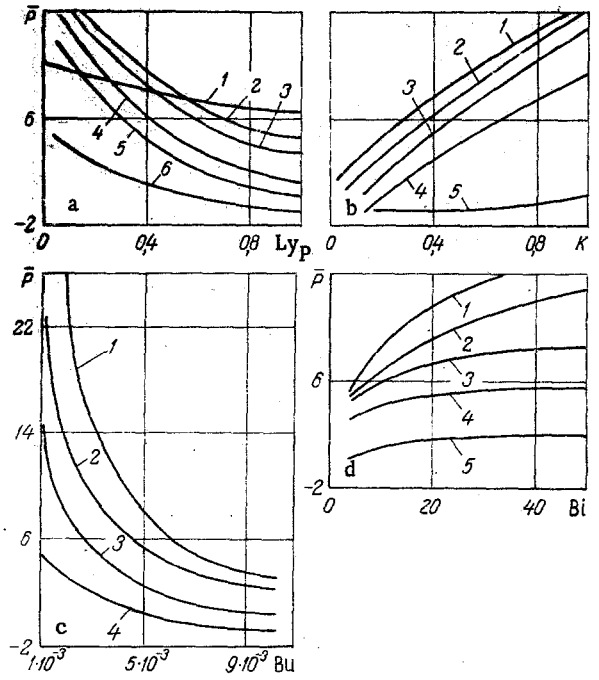

Fig. 2. Plots of $\bar{P}$ versus similarity criteria: a) $\bar{P} = f(Ly_p)$ for Bi = 30, Bu = 0.01, K = 0.4 [1) Fo = 0.1; 2) 0.3; 3) 0.4; 4) 0.6; 5) 0.7; 6) 1.5]; b) $\bar{P} = f(K)$ for Bi = 30, Bu = 0.01, Ly_p = 0.7 [1) Fo = 0.1; 2) 0.3; 3) 0.4; 4) 0.6; 5) 1.5]; c) $\bar{P} = f(Bu)$ for Bi = 30, K = 0.2, Ly_p = 0.7 [1) Fo = 0.2; 2) 0.1; 3) 0.7; 4) 1.0]; d) $\bar{P} = f(Bi)$ for K = 0.2, Bu = 0.01, Ly_p = 0.3 [1) Fo = 0.1; 2) 0.3; 3) 0.5; 4) 0.7; 5) 1.0].

An analysis of the unsteady fields of heat- and mass-transfer potentials showed that in the investigated range of variation of the influencing factors the surface heat-transfer criterion (Bi) has relatively little effect on the temperature distributions and has a significant effect on the development of the pressure fields (especially in the region of moderate values of Fo, see Fig. 1b). An increase in Bi probably leads to a slight increase in the average temperature of the moist material at the start of vacuum drying, which leads to a sharp increase in internal pressure in the specimen and to a shift of the extrema on the kinetic curves in the direction of smaller Fo.

Unfortunately, in application to vacuum-drying conditions the possibility of regulating heat and mass transfer by a change in Bi is restricted to the insignificant convective component of external heat transfer; the radiative component (which affects the value of the effective heat-transfer coefficient) is limited by the permissible temperature level of the process, which is determined by the limit of thermal stability of the cellulose insulation.

Figure 1c indicates that reduction of Ly_p (which characterizes the lag of the fields of filtration–diffusion potential of heat and mass transfer relative to the temperature fields) is accompanied by more rapid heating of the insulation and appreciable intensification of the development of pressure fields in the specimen. An interesting feature here is the increase in absolute values of the extrema, which, other conditions being equal, become sharper and move toward higher Fo as Ly_p decreases in the range 1.0–0.3. The lack of correspondence between the rates of propagation of the field P in comparison with the temperature-field development for low Ly_p at the relaxation stage of the internal pressure in the insulation specimen is particularly clearly manifested (see Fig. 1c). For instance, when Ly_p = 1 the temperature of the material and the dimensionless pressure in the middle layers of the specimen (X = 0.5) become stable when Fo = 1.5–2.0, whereas reduction of Ly_p to 0.3 has practically no effect on the leveling-out of the kinetic curve T = f(Fo), while the leveling-out of the value of P is shifted into the region Fo > 1.5–2.0. The similar nature of the kinetic curve of the internal pressure in the drying insulation against Ly_p is due primarily to the special nature of the mechanism of filtration–diffusion vapor transfer in such systems and to the resistance offered to this transfer by the capillary-porous structure of cellulose material.

The development of the fields of transport potentials in high-temperature vacuum drying of capillary-porous materials is significantly affected by K, which characterizes the local relation between the heat expended on evaporation of moisture and the heat expended on heating of the material in isobaric conditions in an infinitely small time. It should be noted that K, which is in essence the thermodynamic characteristic of the material, reflects features of the drying kinetics of an elementary volume of the material and establishes a relation between local heat transfer and mass transfer. This criterion is the reciprocal of

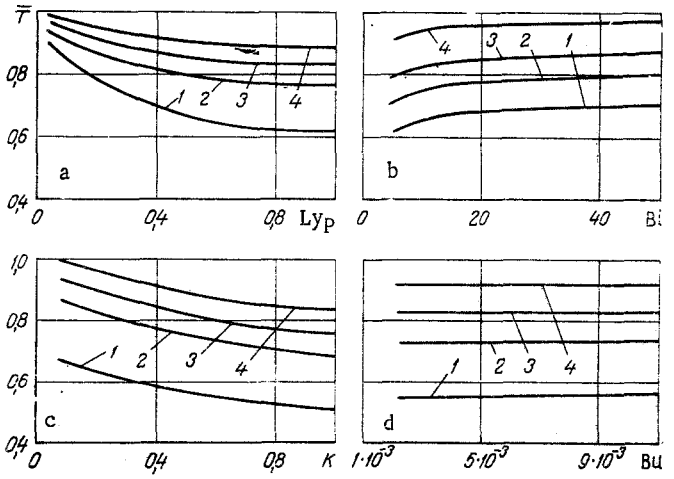

Fig. 3. Plots of $\bar{T}$ versus similarity criteria: a) $\bar{T} = f(Ly_p)$ for Bi = 30, Bu = 0.01, K = 0.4 [1) Fo = 0.1; 2) 0.3; 3) 0.4; 4) 0.6]; b) $\bar{T} = f(Bi)$ for K = 0.2, Bu = 0.01, Ly_p = 0.3 [1) Fo = 0.1; 2) 0.2; 3) 0.3; 4) 1.0]; c) $\bar{T} = f(K)$ for Bi = 30, Bu = 0.01, Ly_p = 0.7 [1) Fo = 0.1; 2) 0.3; 3) 0.4; 4) 0.6]; d) $\bar{T} = f(Bu)$ for Bi = 30, K = 0.2, Ly_p = 0.7 [1) Fo = 0.1; 2) 0.2; 3) 0.3; 4) 0.5].

the local Rebinder number [9] for isobaric conditions. In application to the considered process of drying of high-voltage cellulose insulation the absolute value of K can vary between 0.1 and 5. Figure 1e shows that the increase in K is due to reduction of the heating rate of the material and to an increase in the dimensionless potential of filtration–diffusion mass transfer. Since this criterion is largely determined by the instantaneous local state variables of the cellulose insulation (temperature and moisture content), in analysis of the effect of K on the variation of P and T in the considered process we must take into account not only the qualitative, but also the quantitative interrelation between internal heat and mass transfer and, accordingly, between the unsteady temperature and pressure fields. Although we discovered a definite effect of the absolute value of K on the rate of heating of the material and the excess pressure in the specimen, it was difficult to determine the relationship between this criterion and the main laws of formation of the maximum on the kinetic curves of P = f(Fo) and the position of the characteristic regions of these curves relative to the Fo axis.

In agreement with published data [10-12], the results of our calculations showed that in high-temperature vacuum drying the value of Bu has practically no effect on the kinetics and distribution of the temperature field in insulation elements (see Fig. 1d). The potential of filtration–diffusion vapor transfer is inversely proportional to this criterion, and the characteristic regions on the curves of P = f(Fo) (for instance, the regions corresponding to the extremum of the external pressure or to its complete relaxation) are practically stationary relative to the Fo axis when Bu changes.

By analogy with [10] Figs. 2 and 3 show plots of the dimensionless transport potentials ($\bar{P}$, $\bar{T}$), averaged over the radial thickness, versus the individual characteristic criteria, constructed from relations (9)-(10) for different values of Fo.

The discovered features of the variation and distribution of transfer potentials in higher-temperature vacuum drying of high-voltage cellulose insulation elements can be used for a deeper study of the mechanism of internal heat and mass transfer and a soundly based choice of optimum regime parameters for carrying out this process.

NOTATION

$X = x/R$, dimensionless coordinate; $T = [t(x, \tau - t_0)]/(t_m - t_0)$, dimensionless temperature; $P = (P(x, \tau) - P_0)/(P_0 - P_m)$, dimensionless pressure; Fo, Fourier number; Ly_p, Lykov number; Bu, Bulygin number; Bi, Biot number; $K = (r/C)(\partial u/\partial t)_p$; r, specific heat of evapora-

tion; C, specific heat of material; u, moisture content of material; t, temperature; R, outer radius of cylindrical specimen; x, variable radius of cylinder. Indices: m refers to parameters of surrounding medium; 0 refers to initial state of material.

LITERATURE CITED

1. T. Terada and F. Enokubo, J. Inst. Electr. Eng. Jap., 92A, 207-213 (1972).
2. G. Beer et al., "Transformers," in: The International Conference on Large Electric Systems (CIGRÉ), Vol. 2, Paris (1966), Paper 135.
3. M. Beyer, Grundlangen der Vakuumtrocknung von Flüssigen Isolierstoffen und Papierisolation, GFR (1966).
4. I. F. Pikus and L. A. Koshepavo, Inzh.-Fiz. Zh., 30, No. 1 (1976).
5. P. S. Kuts, I. F. Pikus, and V. D. Kononenko, in: Heat and Mass Transfer [in Russian], Vol. 5, ITMO Akad. Nauk BelorusSSR, Minsk (1976).
6. P. S. Kuts, I. F. Pikus, and L. S. Kalinina, in: Heat and Mass Transfer [in Russian], Vol. 6, ITMO Akad. Nauk BelorusSSR, Minsk (1972).
7. I. F. Pikus and V. D. Kononenko, in: The Electrical Engineering Industry [in Russian], No. 12, Ser. Élektrotekhnicheskie Materialy (1973).
8. I. F. Pikus and I. A. Gubskii, in: Heat- and Mass-Transfer Processes in Drying of Various Materials [in Russian], Minsk (1974).
9. P. P. Lutsik and V. M. Kazanskii, Inzh.-Fiz. Zh., 31, No. 1 (1976).
10. A. V. Lykov and Yu. A. Mikhailov, Theory of Heat and Mass Transfer [in Russian], Gosénergoizdat, Moscow–Leningrad (1963).
11. Yu. A. Mikhailov, Drying with Superheated Vapor [in Russian], Énergiya, Moscow (1967).
12. Yu. A. Mikhailov and I. E. Romanina, Inzh.-Fiz. Zh., 7, No. 1 (1964).

THERMOELECTRIC AND GALVANOMAGNETIC PROPERTIES OF SYSTEMS WITH MUTUALLY PENETRATING COMPONENTS

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UDC 537.32

The effective coefficients of thermal conductivity, electrical conductivity, thermal emf, the effective Hall mobility, and the effective Hall coefficient are determined. The analytical dependences obtained are compared with experimental results for a Bi–Cd alloy.

Thermoelectrical Properties

The equations for the current density $\vec{j}_e$ and the heat flux density (energy) $\vec{j}_q$ in a homogeneous substance under the superposition of electrical and thermal conductivities have the form [1]

$$\vec{j}_e = \sigma\vec{E} - \alpha\sigma\vec{\nabla}T, \tag{1}$$

$$\vec{j}_q = \alpha T\vec{j}_e - \lambda\vec{\nabla}T. \tag{2}$$

The thermal emf coefficient α is determined from (1) for $\vec{j}_e = 0$ and $\vec{\nabla T} \neq 0$, i.e.,

$$\sigma\vec{E} - \alpha\sigma\vec{\nabla}T = 0. \tag{3}$$

The coefficient of electrical conductivity σ is determined from (1) for $\vec{\nabla T} = 0$, and the coefficient of thermal conductivity λ is determined from (2) for $\vec{j}_e = 0$.

Let us determine the coefficients α, σ, λ for a two-component layered system (Fig. 1a) when $\vec{j}_e$ and $\vec{j}_q$ are directed parallel to the layers along the X axis. The equivalent circuit for this structure is shown in Fig. 1b.

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