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Theoretical foundations of the construction of the operation of heat flow devices

Numerous studies show that non-destructive testing methods satisfy most of the requirements of technical diagnostics of heating networks and technological facilities. Methods of non-destructive testing are based on the observation and automated registration of the temperature state of processes. The developed device is designed to analyze the state of thermal insulation of underground pipelines. The development and research of devices for measuring heat flow requires mandatory consideration of the temperature field of the sensing element, i.e. solutions of the differential equation of thermal conductivity for a body of a certain shape under given boundary conditions. In general, the sensing elements are multi-layered: black coating, calorimetric load, heat-sensitive elements, alternating lacquer and adhesive layers, i.e., the sensing elements are heterogeneous, both in the direction perpendicular to the irradiated surface and in parallel. The heterogeneity in the first case is due to the multi-layering of the sensing element. The article describes solutions to the thermal conductivity equation describing the temperature field of a sensitive element in the form of a hemisphere and a spherical zone, due to the nonequivalence of heat losses during irradiation and calibration by electric current. Taking into account this systematic error makes it possible to increase the accuracy of measuring the energy parameters of radiation. These solutions of the equations formed the basis of the design of the device for measuring heat flow.

Keywords: heat flow, heat flow measuring device, sensing element, temperature field of the sensing element.

Introduction

Heat flow monitoring and measurement devices allow solving energy efficiency and energy saving issues by obtaining reliable data on the source of heat losses and quantitative values. In this regard, the development and creation of heat flow devices for heat supply systems are of particular interest. As the results of numerous studies of thermal insulation of underground heating networks show, the most effective is the method of non-destructive testing based on a comparison of calculated and experimental values of the temperature distribution on the ground surface over heating networks [1, 2].

Non-destructive testing methods use thermal energy coming from the object of control. A temperature anomaly of a fairly regular shape appears on the surface, which differs by several degrees from the average temperature of the detected surface and internal defects deviated from the norm, the presence of local overheating, etc [3].

The initial link of any measuring device or measuring system is the means of obtaining information about the measured value — thermoelectric battery converters. The thermoelectric converter is the primary temperature and heat flow measuring converter. As a thermoelectric battery converter, a sensitive element is used as part of the control and monitoring systems for technological processes. Thermoelectric battery converters, in which the sensing elements are made of metal wires, have received the greatest practical application [4-7].

Problem and research method

In the laboratory "Measurement of Thermal physical quantities" of the Department of engineering thermal physics named after professor Zh.S. Akylbayev of the faculty of physics and technology of academician E.A. Buketov Karaganda University has developed several modifications of heat flow devices based on a thermoelectric battery cell of a special design [8]. A distinctive design of heat flow devices is that it contains a thermoelectric battery converter and a receiving plate, additionally equipped with a thermoelectric refrigerator and a heating element [9]. The devices differ from each other in the shape and size of the sensing element, the number of thermocouples, etc.

To increase the speed and increase the accuracy of measuring the temperature gradient on the surface, we have developed a device for measuring heat flow [10]. A schematic representation of the device for measuring heat flow is shown in Figure 1.

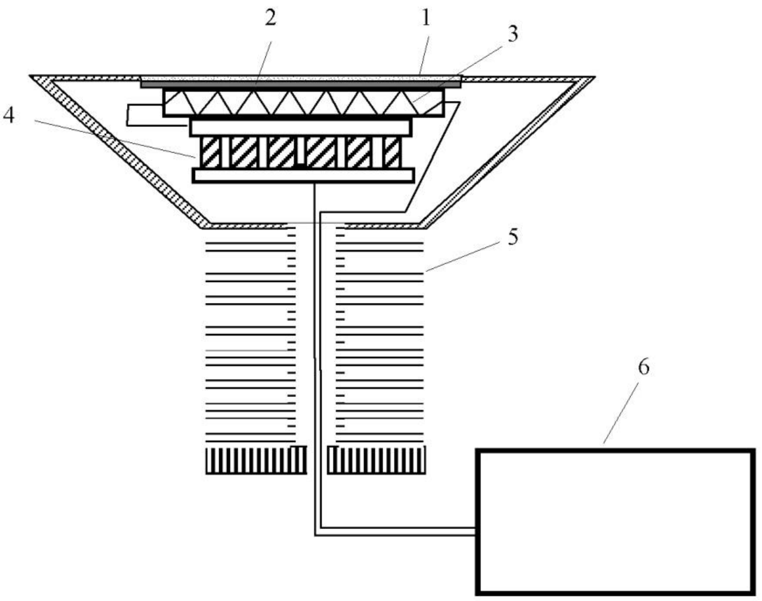

Fig. 1. Schematic representation of a device for measuring heat flow. 1 — insulation layer; 2 — heating element; 3 — thermoelectric battery converter of heat flow; 4 — thermoelectric refrigerator; 5 — radiator; 6 — measuring unit

The radiation flux from a real source incident on the sensitive element of the device has a spice-time heterogeneity, which should be reflected in the boundary conditions of the problem. It is also necessary to take into account the heat exchange of the sensor element with the environment, the device body, etc.

The operation of the device is based on the method of replacing the effect of radiation on the sensing element by the action of an electric current then the presence of a calibration winding should be taken into account in the differential equation of thermal conductivity. In general, the sensing element is multilayer, which means that its thermal physical parameters depend on the coordinates.

The tasks of radiant heating of the body can be replaced by tasks describing the effect of temperature fluctuations of the medium, i.e. the case of irradiation of the body can be considered as a special case of the effect on the body of temperature fluctuations of the adjacent medium. Therefore, it becomes necessary to consider the temperature field of a body of a certain shape placed in a medium with a variable temperature.

Consideration of the temperature field of the sensing element of the heat flow device allows us to obtain new methods for measuring the energy parameters of radiation, including calibration or calibration of the receiver and working formulas for calculating the desired values [11, 12].

Calculations and discussion

The temperature field of a sensing element in the form of a homogeneous spherical zone, a convex or concave surface that is irradiated, is considered. To absorb radiation, this surface is blackened, the non-irradiated surface of the spherical zone exchanges heat with the medium according to Newton's law. Internal heat sources are located between the convex and concave surfaces of the ball zone, creating a heat flow when calibrating the radiation receiver with an electric current.

The thermal conductivity equation for a homogeneous spherical zone has the following form:

$$\frac{1}{a}\frac{\partial T(\mathrm{r},\varphi,\mu,t)}{\partial t}=\frac{1}{r^2}\{\frac{\partial}{\partial r}\left[r^2\frac{\partial T(\mathrm{r},\varphi,\mu,t)}{\partial t}\right]+\frac{\partial}{\partial\mu}\left[\mu^2\frac{\partial T(\mathrm{r},\varphi,\mu,t)}{\partial t}\right]+ \\ +\frac{1}{1-\mu}\frac{\partial T^2(\mathrm{r},\varphi,\mu,t)}{\partial\varphi^2}\}+Q(\mathrm{r},\varphi,\mu,\mathrm{t}) \tag{1}$$

with variable range: $t>0$; $R_1<r<R_2$; $0\le\varphi\le 2\pi$; $\mu_1<\mu<\mu_2$; $\mu=\cos\theta$; $\theta_1<\theta<\theta_2$; $\frac{\partial f}{\partial\theta}=\frac{\partial f}{\partial\mu}\frac{\partial\mu}{\partial\theta}=-\sin\theta\frac{\partial f}{\partial\mu}$; where φ and υ — orbital and azimuth angles; R_1 and R_2 — inner and outer radii of the ball zone; $Q(\mathrm{r},\varphi,\mu,\mathrm{t})$ — the function associated with the power of internal sources $q_\upsilon(\mathrm{r},\varphi,\mu,t)$ arising during calibration, the expression:

$$Q(\mathrm{r},\varphi,\mu,\mathrm{t})=\frac{q_\upsilon(\mathrm{r},\varphi,\mu,t)}{\lambda}, \qquad (2)$$

where λ is the coefficient of thermal conductivity.

Equation (1) must satisfy the initial condition

$$\mathrm{T}(\mathrm{r},\varphi,\mu,0)=f(\mathrm{r},\varphi,\mu). \qquad (3)$$

Boundary value conditions

$$\frac{\partial T(\mathrm{R}_1,\varphi,\mu,\mathrm{t})}{\partial r}=\frac{\alpha_1}{\lambda}\left[T(\mathrm{R}_1,\varphi,\mu,\mathrm{t})-\mathrm{T}^*_{1c}(\varphi,\mu,\mathrm{t})\right] \qquad (4)$$

$$\frac{\partial T(\mathrm{R}_2,\varphi,\mu,\mathrm{t})}{\partial r}=-\frac{\alpha_1}{\lambda}\left[T(\mathrm{R}_2,\varphi,\mu,\mathrm{t})-\mathrm{T}^*_{2c}(\varphi,\mu,\mathrm{t})\right] \qquad (5)$$

$$\frac{\partial T(\mathrm{r},\varphi,\mu,\mathrm{t})}{\partial\mu}=0 \qquad (6)$$

and the periodicity condition

$$T(\mathrm{r},\varphi,\mu,\mathrm{t})=\mathrm{T}(\mathrm{r},\varphi+2\pi,\mu,t), \qquad (7)$$

where α_1 and α_2 are the heat exchange coefficients of the inner and outer surfaces of the sensing element with the medium: $\mathrm{T}^*_{1c}(\varphi,\mu,\mathrm{t})$ and $\mathrm{T}^*_{2c}(\varphi,\mu,\mathrm{t})$ are the equivalent temperatures of the medium at the inner and outer surfaces.

We will replace the variable in this boundary problem:

$$z=\frac{\mu-\mu_1}{\mu_2-\mu_1}, \qquad (7^*)$$

where: $z=0$ at $\mu=\mu_1$, $z=1$ at $\mu=\mu_2$ and $\mu=\mu_1+\mathrm{z}(\mu_2-\mu_1)$.

Then equation (1) will take the form:

$$\frac{1}{a}\frac{\partial T}{\partial t}=\frac{1}{r^2}\ \{\frac{\partial}{\partial r}\left[r^2\frac{\partial T}{\partial r}\right]+\frac{\partial}{\partial\mu}\left[(1-\mu^2)\frac{\partial T}{\partial\mu}\right]+\frac{1}{1-\mu^2}\frac{\partial T^2}{\partial\varphi^2}\}+Q \qquad (8)$$

with range of change of variables: $t>0;\mathrm{R}_1<r<R_2;0<\varphi<2\pi;0<z<1.$

Boundary conditions and periodicity conditions will write down respectively

$$T(\mathrm{r},\varphi,\mathrm{z},0)=\mathrm{f}(\mathrm{r},\varphi,\mathrm{z}) \qquad (9)$$

$$\frac{\partial T(\mathrm{R}_1,\varphi,\mathrm{z},\mathrm{t})}{\partial r}=\frac{\alpha_1}{\lambda}\left[T(\mathrm{R}_1,\varphi,\mathrm{z},\mathrm{t})-\mathrm{T}^*_{1c}(\varphi,\mathrm{z},\mathrm{t})\right] \qquad (10)$$

$$\frac{\partial T(\mathrm{R}_1,\varphi,0,\mathrm{t})}{\partial r}=\frac{\alpha_1}{\lambda}\left[T(\mathrm{R}_1,\varphi,\mathrm{z},\mathrm{t})-\mathrm{T}^*_{1c}(\varphi,\mathrm{z},\mathrm{t})\right] \qquad (11)$$

$$\frac{\partial T(\mathrm{R}_1,\varphi,0,\mathrm{t})}{\partial \mathrm{z}}=0 \qquad (12)$$

$$T(\mathrm{r},\varphi,\mathrm{z},\mathrm{t})=\mathrm{T}(\mathrm{r},\kappa+2\pi,z,t). \qquad (13)$$

Apply successively to the boundary value problem (8)-(13) integral transformations of the form

$$T(\mathrm{r},\mathrm{z},\mathrm{t})=\int_0^{2\pi}T(\mathrm{r},\mathrm{z},\mathrm{t},\varphi)\,\Phi_n(\varphi)\,\mathrm{d}\varphi \qquad (14)$$

$$T(\mathrm{r,t}) = \int_0^1 T_n(\mathrm{r,z,t})\, \mathrm{K}_{2m}^{2n}(\mathrm{z})\, \mathrm{dz} \tag{15}$$

$$T_{nmk}(\mathrm{t}) = \int_R^{R_2} T_{nm}(\mathrm{r,t})\, \mathrm{R}_{km}(\beta_{km}\,\mathrm{r})\, \mathrm{r}^2\, dr \tag{16}$$

with conversion cores

$$\Phi_n = (\varphi) = \frac{1}{\sqrt{\pi}} \cos 2n\varphi \quad n = 0,1,2... \tag{17}$$

$$K_{2m}^{2n}(z) = \sqrt{\frac{4n+1}{2} \cdot \frac{(2\mathrm{n}-2\mathrm{m})!}{(2\mathrm{n}+2\mathrm{m})!}} P_{2m}^{2n}(\mathrm{t}) \quad n = 0,1,2... \quad m = 0,1,2... \tag{18}$$

$$R_{nm}(\beta_{km}\,\mathrm{r}) = \mathrm{c}_{1k} \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{r})}{\sqrt{r}} + c_{2k} \frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{r})}{\sqrt{r}} v, \tag{19}$$

where $P_{2m}^{2n}(\mathrm{z})$ - associated Legendre polynomial

$$P_{2m}^{2n}(\mathrm{z}) = (1-\mathrm{z}^2)^{2n/2} \frac{d^{2n}}{dz^{2n}} P_{2m}(\mathrm{z}), \tag{20}$$

$P_{2m}(\mathrm{z})$ - Legendre polynomials of degree 2m; $J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{r})$ and $N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{r})$ - accordingly, the Bessel and Neumann function (m+½) of order; $C_{1к}$ and $C_{2к}$ are determined from the following system of equations:

$$\begin{gathered} -c_k \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_1^{3/2}} + c_{1k} \frac{J'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_1^{1/2}} - c_{1k} \frac{\alpha_1}{\lambda} \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_1^{1/2}} - \\ -c_{2k} \frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_1^{3/2}} + c_{2k} \frac{N'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_1^{3/2}} - c_{2k} \frac{\alpha_1}{\lambda} \frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_1^{1/2}} = 0 \end{gathered} \tag{21}$$

$$\begin{gathered} -c_{1k} \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R^{2/3}} + c_{1k} \frac{J'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_1^{1/2}} - c_{1k} \frac{\alpha_2}{\lambda} \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_1^{1/2}} - \\ -c_{2k} \frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_2)}{2R_1^{3/2}} + c_{2k} \frac{N'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_2^{1/2}} - c_{2k} \frac{\alpha_2}{\lambda} \frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_2^{1/2}} = 0 \end{gathered} \tag{22}$$

The eigenvalues are found from the equation:

$$\begin{gathered} \left[\frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_1^{3/2}} + \frac{J'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_2^{1/2}} - \frac{\alpha_1}{\lambda} \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_1^{1/2}} \right] \times \\ \times \left[\frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_2^{3/2}} + \frac{N'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_2^{1/2}} + \frac{\alpha_1}{\lambda} \frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_1^{1/2}} \right] - \\ - \left[-\frac{N_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_2^{3/2}} + \frac{N'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_1^{1/2}} - \frac{\alpha_2}{\lambda} \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_1^{1/2}} \right] \times \\ \times \left[-\frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{2R_2^{3/2}} + \frac{J'_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_1^{1/2}} + \frac{\alpha_2}{\lambda} \frac{J_{m+\frac{1}{2}}(\beta_{km}\,\mathrm{R}_1)}{R_2^{1/2}} \right] = 0 \end{gathered} \tag{23}$$

The conversion formulas for the transformation (14)-(16) have the form:

$$T_n(\mathrm{r},\varphi,\mu,t)=\sum_{n=0}^{\infty}T_n(\mathrm{r},\mu,\mathrm{t})\,\Phi_n(\varphi) \qquad (24)$$

$$T_{nm}(\mathrm{r},\mu,t)=\sum_{m=0}^{\infty}T_{nm}(\mathrm{r},\mathrm{t})\,\mathrm{K}_{2m}^{2n}(\mathrm{z}) \qquad (25)$$

$$T_{nmk}(\mathrm{r},t)=\sum_{k=0}^{\infty}T_{nmk}(\mathrm{t})\,\mathrm{R}_{km}(\beta_{km}\,\mathrm{r}) \qquad (26)$$

Then the solution of the boundary value problem (8)-(13) will be written as 24 and 25:

$$\begin{aligned}T(\mathrm{rt},\varphi,\mathrm{z},t)=&\sum_{n=0}^{\infty}\sum_{m=0}^{\infty}\sum_{k=0}^{\infty}\{\exp(-\alpha\beta_{km}^2\,\mathrm{t})\int_0^1\int_0^{2\pi}\int_{R_1}^{R_2}f(\mathrm{r},\varphi,\mathrm{z})\,\mathrm{r}^2\,\Phi_n(\varphi)K_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{km}\,\mathrm{r})\\&\mathrm{d}\varphi\,\mathrm{dzdr}+a\int_0^t[\int_0^1\int_0^{2\pi}\int_{R_1}^{R_2}Q(\mathrm{r},\varphi,\mathrm{z},\mathrm{t})r^2\Phi_n(\varphi)\,\mathrm{K}_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{r})\,\mathrm{d}\varphi\,\mathrm{dzdr}+\frac{R_2^2\alpha_2}{\lambda}\times\\&\times\mathrm{R}_{km}(\beta_{nm}\,\mathrm{R}_2)\int_0^1\int_0^{2\pi}\int_{R_1}^{R_2}T_{2c}^*(\varphi,\mathrm{z},\tau)r^2\Phi_n(\varphi)\,\mathrm{K}_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{r})\,\mathrm{d}\varphi\,\mathrm{dzdr}+\frac{R_1^2\alpha_1}{\lambda}\times\\&\times\mathrm{R}_{km}(\beta_{nm}\,\mathrm{R}_1)\int_0^1\int_0^{2\pi}\int_{R_1}^{R_2}T_{1c}^*(\varphi,\mathrm{z},\tau)r^2\,\mathrm{K}_{2m}^{2n}(\mathrm{z})\Phi(\varphi)\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{r})\,\mathrm{d}\varphi\,\mathrm{dzdr}]\exp[\,-\mathrm{a}\,\beta_{km}^2\times\\&\times(\mathrm{t}-\tau)]\,\mathrm{d}\tau\}\Phi_n(\varphi)\,\mathrm{K}_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{r})\end{aligned} \qquad (27)$$

The heat release in the sensor element of the device is caused by its heating during calibration by electric current and during absorption of incident radiation. The function in solution (27) is related to the power of internal sources arising during calibration, according to formula (2) by the following expression:

$$Q(\mathrm{r},\varphi,\mathrm{z},\mathrm{t})=\frac{q_\upsilon(\mathrm{r},\varphi,\mathrm{z},\mathrm{t})}{\lambda}. \qquad (28)$$

The equivalent temperature of the medium is related to the local hemispherical irradiance by the expression:

$$T_c^*(\varphi,\mathrm{z},\mathrm{t})=\mathrm{T}_c(\varphi,\mathrm{z},\mathrm{t})+\frac{\eta E(\varphi,\mathrm{z},\mathrm{t})}{\alpha}. \qquad (29)$$

For excess temperature $\theta(\mathrm{r},\varphi,\mathrm{z},\mathrm{t})=\mathrm{T}(\mathrm{r},\varphi,\mathrm{z},\mathrm{t})-\mathrm{T}_c(\varphi,\mathrm{z},\mathrm{t})$ at $T_c(\varphi,\mathrm{z},\mathrm{t})=f(\mathrm{r},\varphi,\mathrm{z})$, taking into account (28) and (29), expression (27) will take the following form:

$$\begin{aligned}\theta(\mathrm{r},\varphi,\mathrm{z},t)=&\sum_{n=0}^{\infty}\sum_{m=0}^{\infty}\sum_{k=0}^{\infty}\frac{a}{\lambda}\{\int_0^t\int_0^{\pi}\int_{R_1}^{R_2}\mathrm{q}_\upsilon(\mathrm{r},\varphi,\mathrm{z},\tau)\,\mathrm{r}^2\,\Phi_n(\varphi)K_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{r})\times\\&\times\mathrm{d}\varphi\,\mathrm{dzdr}+\eta R_2^2\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{R}_2)\int_0^1\int_0^{2\pi}\int_{R_1}^{R_2}\mathrm{E}_2(\varphi,\mathrm{z},\tau)r^2\Phi_n(\varphi)\,\mathrm{K}_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{r})\times\\&\times\mathrm{d}\varphi\,\mathrm{dzdr}+\eta R_1^2\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{R}_2)\int_0^1\int_0^{2\pi}\int_{R_1}^{R_2}\mathrm{E}_1(\varphi,\mathrm{z},\tau)r^2\Phi_n(\varphi)\,\mathrm{K}_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{km}\,\mathrm{r})\times\\&\mathrm{d}\varphi\,\mathrm{dzdr}]\exp[\,-\mathrm{a}\,\beta_{km}^2(\mathrm{t}-\tau)]\,\mathrm{d}\tau\}\Phi_n(\varphi)\,\mathrm{K}_{2m}^{2n}(\mathrm{z})\,\mathrm{R}_{km}(\beta_{nm}\,\mathrm{r})\end{aligned} \qquad (30)$$

where $E_1(\varphi,\mathrm{z},\mathrm{t})$ and $E_2(\varphi,\mathrm{z},\mathrm{t})$ - local hemispherical irradiances of concave and convex surfaces of the spherical zone.

Expression (30) is applicable for both convex and concave sensing elements. In this case, one of the terms containing $E_1(\varphi,\mathrm{z},\mathrm{t})$ or $E_2(\varphi,\mathrm{z},\mathrm{t})$ will be zero.

To obtain an expression that can be used in solving practical problems, we restrict ourselves to the first term of the series in expression (30), i.e. we set *n = m = k =0*. Then the kernels of the corresponding integral transformations will take the following form based on expressions (17)-(19):

$$\Phi_0(\varphi) = \frac{1}{\sqrt{\pi}} \quad (31)$$

$$R_{20}^{20}(z) = \sqrt{\frac{1}{2}} \quad (32)$$

$$R_{00}(\beta_{00}\,\mathrm{r}) = \frac{1}{r}\sqrt{\frac{2}{\pi\beta_{00}}}(\mathrm{c}_{10}\sin\beta_{00}\,\mathrm{r} - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{r}) \quad (33)$$

The expression (31) in this case after the transition from *zkμ* in accordance with the formula (7*) can be written separately for heating with electric current and radiation:

$$\theta_э(\mathrm{r,t}) = \frac{a(\mathrm{c}_{10}\sin\beta_{00}\,\mathrm{r} - \mathrm{c}_{20}\sin\beta_{00}\,\mathrm{r})}{\lambda\pi^2\beta_{00}\,\mathrm{r}(\mu_1-\mu_2)}\int_0^t \exp\left[-a\beta_{00}^2(\mathrm{t}-\tau)\right]\times \int_0^{2\pi}\int_{\mu_1}^{\mu_2}\int_{R_1}^{R_2} q_\upsilon(\mathrm{r},\varphi,\mu,\tau)\,\mathrm{r}(\mathrm{c}_{10}\sin\beta_{00}\,\mathrm{r} - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{r})\,\mathrm{d}\varphi d\mu d\tau \quad (34)$$

$$\theta_{n1}(\mathrm{r,t}) = \frac{\sqrt{2}\eta R_1(\mathrm{c}_{10}\sin\beta_{00}R_1 - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{R}_1)(\mathrm{c}_{10}\sin\beta_{00}\,\mathrm{r} - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{r})}{\lambda\pi^{5/2}\beta_{00}^{3/2}r(\mu_2-\mu_1)}\times \int_0^t \exp\left[-a\beta_{00}^2(\mathrm{t}-\tau)\right]\int_0^{2\pi}\int_{\mu_1}^{\mu_2}\int_{R_1}^{R_2} E_1(\varphi,\mu,\tau)\,\mathrm{r}(\mathrm{c}_{10}\sin\beta_{00}\,\mathrm{r} - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{r})\,\mathrm{d}\varphi d\mu drd\tau \quad (35)$$

$$\theta_{n2}(\mathrm{r,t}) = \frac{\sqrt{2}\eta_a R_2(\mathrm{c}_{10}\sin\beta_{00}R_2 - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{R}_2)(\mathrm{c}_{10}\sin\beta_{00}\,\mathrm{r} - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{r})}{\lambda\pi^{5/2}\beta_{00}^{3/2}r(\mu_2-\mu_1)}\times \int_0^t \exp\left[-a\beta_{00}^2(\mathrm{t}-\tau)\right]\int_0^{2\pi}\int_{\mu_1}^{\mu_2}\int_{R_1}^{R_2} E_{12}(\varphi,\mu,\tau)\,\mathrm{r}(\mathrm{c}_{10}\sin\beta_{00}\,\mathrm{r} - \mathrm{c}_{20}\cos\beta_{00}\,\mathrm{r})\,\mathrm{d}\varphi d\mu drd\tau \quad (36)$$

where $Q_{n1}(\mathrm{r,t})$ and $Q_{n2}(\mathrm{r,t})$ — excessive temperatures of the sensing element in the form of a spherical zone during irradiation of concave and convex surfaces.

Thus, in the first approximation, consideration of a complex model of a multilayer sensor element of the receiver can be replaced by consideration of a simpler model of a homogeneous sensor element of the appropriate shape. This simplification makes it possible to obtain working formulas for determining the energy parameters of radiation from considering the temperature field of the sensing element.

Conclusion

The solution of the thermal conductivity equation describing the temperature field of the sensing element in the form of a hemisphere and a spherical zone, due to the nonequivalence of heat losses during irradiation and calibration by electric current, is obtained. Taking into account this systematic error makes it possible to increase the accuracy of measuring the energy parameters of radiation. These solutions of the equations formed the basis of the designs of devices for measuring heat flow.

The developed heat flow device of a given shape allows you to pinpoint and diagnose in advance the condition of pipes of heating networks, search for places of coolant leakage, without opening pipelines and stopping their operation.

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Жылу ағыны құрылғыларының жұмысын құрудың теориялық негіздері

Көптеген зерттеулер жылу желілері мен технологиялық объектілерді техникалық диагностикалаудың барлық талаптарын бұзбайтын бақылау әдістері қанағаттандыратынын көрсетеді. Бұзбайтын бақылау әдістері процестердің температуралық күйін бақылауға және автоматтандырылған тіркеуге негізделген. Әзірленген құрылғы жерасты құбырларының жылу оқшаулау күйін талдауға арналған. Жылу ағынын өлшеуге арналған аспаптарды әзірлеу және зерттеу сезімтал элементтің температура өрісін міндетті түрде қарастыруды талап етеді, яғни берілген шеттік жағдайларда белгілі бір пішіндегі дене үшін жылу өткізгіштіктің дифференциалдық теңдеуін шешуді талап етеді. Жалпы жағдайда сезімтал элементтер көп қабатты: қарамен жабылған жабын, калориметриялық жүктеме, термосезгіш элементтер, лак және желіммен қабатталған ауыспалы қабаттар. Яғни, сезімтал элементтер сәулеленген бетке перпендикуляр бағытта да, параллель бағытта да біртекті емес. Бірінші жағдайда біртекті еместігі сезімтал элементтің көпқабаттылығымен байланысты. Мақалада сәулелену және электр тогын калибрлеу кезінде жылу шығынының эквиваленттілігіне байланысты жарты шар және шар аймағы түріндегі сезімтал элементтің температура өрісін сипаттайтын жылу өткізгіштік теңдеуінің шешімдері сипатталған. Осы жүйелі қателікті есепке алу сәулеленудің энергетикалық параметрлерін өлшеу дәлдігін арттыруға мүмкіндік береді. Теңдеулердің бұл шешімдері жылу ағынын өлшеуге арналған құралдың құрылымына негіз болды.

Кілт сөздер: жылу ағыны, жылу ағынын өлшеуге арналған құрылғы, сезімтал элемент, сезімтал элементтің температура өрісі.

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Теоретические основы построения работы приборов теплового потока

Многочисленные исследования показывают, что наиболее всем требованиям технической диагностики тепловых сетей и технологических объектов удовлетворяют методы неразрушающего контроля. Методы неразрушающего контроля основаны на наблюдении и автоматизированной регистрации за температурным состоянием процессов. Разработанный прибор предназначен для анализа состояния тепловой изоляции подземных трубопроводов. Разработка и исследование приборов для измерения теплового потока требуют обязательного рассмотрения температурного поля чувствительного элемента, то есть решения дифференциального уравнения теплопроводности для тела определенной формы при заданных краевых условиях. В общем случае чувствительные элементы многослойны: черное покрытие, калориметрическая нагрузка, термочувствительные элементы, чередующиеся лаковые и клеевые прослойки. То есть чувствительные элементы неоднородны, как в направлении, перпендикулярном облучаемой поверхности, так и в параллельном. Неоднородность в первом случае обусловлена многослойностью чувствительного элемента. В статье описано решение уравнения теплопроводности, описывающее температурное поле чувствительного элемента в форме полусферы и шаровой зоны, обусловленное неэквивалентностью тепловых потерь при облучении и калибровке электрическим током. Учёт данной систематической погрешности позволяет повысить точность измерения энергетических параметров излучения. Данные решения уравнения легли в основу конструкций прибора для измерения теплового потока.

Ключевые слова: тепловой поток, прибор для измерения теплового потока, чувствительный элемент, температурное поле чувствительного элемента.

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