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REMOTE DEVICE FOR MEASUREMENT OF HEAT FLUX AND SURFACE TEMPERATURE OF CEMENT KILNS

The paper deals with a development of physical and mathematical models of a remote thermoelectric device for measurement of heat flux and temperature with regard to specific features of heat exchange from the surface of cement kilns. The results of calculation of convective and radiant heat flux components with consideration of kiln rotation are presented. Such a remote measuring device has been designed and manufactured, as well as its experimental calibration has been made.
Key words: cement kiln, measuring device, thermoelectricity.

Introduction

General characterization of the problem. The specific feature of cement production process is high consumption of thermal and electrical energy [1]. Works [2-4] are concerned with the possibility of reducing energy expenditures for cement production through use of thermoelectric recuperators of waste heat from cement kilns. For creation of such recuperators it is vital to have information on the amount of thermal energy radiated by cement kiln surface, as well as on its temperature.

Moreover, in the process of production one must assure for certain time the necessary temperatures in cement passage zones. In so doing, it is important to control temperature conditions in these zones, as well as to measure heat losses from the kiln surface (Fig. 1) [1, 5].

Fig. 1. Outward appearance of a cement kiln [6].

There are devices for monitoring the amount of heat release from the surface of kilns [1, 5]. However, they do not assure sufficient precision of temperature and heat flux measurement [7, 8].

The purpose of this work is development of a device for precise contactless measurement of heat flux and surface temperature of cement kilns.

Physical and mathematical models of measuring device

Fig. 2 shows a physical model of a thermoelectric device for remote measurement of temperature and heat flux from the surface of cement kiln 1 of length c and radius a. Heat flux Q_0 from the surface of cement kiln with temperature T_0 and emissivity factor ε_1 is transferred to the environment with temperature T_a. At the distance b from the cement kiln there is a thermoelectric measuring device. Part of heat flux Q_1 from the cement kiln comes to a graphite receiving pad 2 of the device with emissivity factor ε_2. Heat flux passes through the receiving pad with surface temperature T_1 and through thermoelectric module 3 (T_2 is the hot side temperature of thermoelectric module; T_3 is the cold side temperature of thermoelectric module). The module converts thermal energy into electric energy W. The receiving pad and thermoelectric module are placed in thermally isolated package 4. Heat losses through isolation are Q_3. Removal of heat Q_2 from the thermoelectric module is done by liquid heat exchanger (T_4, T_5 are liquid temperatures at the inlet to and outlet of heat exchanger, respectively).

The rate of heat flux from the lateral surface of the cement kiln can be written as:

$$Q = Q_{rad} + Q_{conv}, \tag{1}$$

where Q_{rad} is radiation component of heat flux, Q_{conv} is convective component of heat flux.

According to the Stephan-Boltzmann law, a radiant heat exchange between two arbitrary grey surfaces is determined by the formula:

$$Q_{rad} = \sigma \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot (T_0^4 - T_1^4) \cdot S_1 \cdot \varphi_{1-2} = \sigma \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot (T_0^4 - T_1^4) \cdot S_2 \cdot \varphi_{2-1}, \tag{2}$$

where σ is the Stephan-Boltzmann constant, S_1 is the radiation surface area, S_2 is the receiving pad area, φ_{1-2}, φ_{2-1} are angular radiation coefficients.

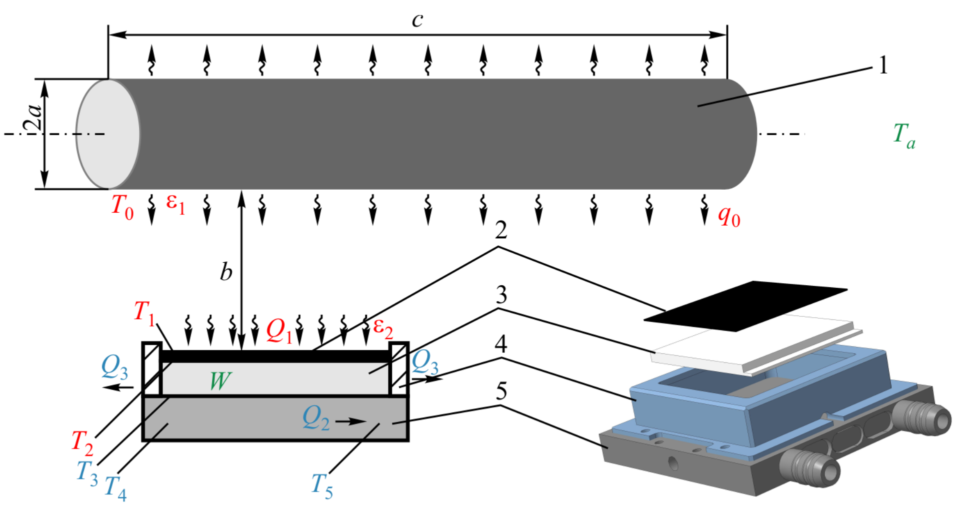

Fig. 2. A physical model of thermoelectric measuring device: 1 – cement kiln, 2 – graphite coating of receiving pad, 3 – thermoelectric module, 4 – package, 5 – liquid heat exchanger.

To determine component of heat flux that is passed to the receiving pad of the measuring device from the surface of cement kiln by radiation, it is necessary to calculate the angular radiation coefficients using the following expressions:

$$\varphi_{1-2} = \frac{1}{S_1} \cdot \iint\limits_{S_1 S_2} \frac{\cos\alpha_1 \cdot \cos\alpha_2}{\pi \cdot r^2} dS_1 dS_2, \tag{3}$$

$$\varphi_{2-1} = \frac{1}{S_2} \cdot \iint\limits_{S_1 S_2} \frac{\cos\alpha_1 \cdot \cos\alpha_2}{\pi \cdot r^2} dS_1 dS_2 = \frac{S_1}{S_2}\varphi_{1-2}, \tag{4}$$

where α_1, α_2 are the angles between the radiation direction and the normal to surfaces S_1 and S_2, respectively, r is the distance between the two surfaces.

For the case of a radiant heat exchange between the cylinder surface and the flat pad the following equation is valid:

$$\varphi_{2-1} = \frac{2}{\pi \cdot B} \cdot \left\{ \text{ctg}\frac{C}{\sqrt{B^2-1}} + C \cdot \left[\frac{X^2 - 2\cdot B}{X \cdot Y} \cdot \text{ctg}\frac{X}{Y}\sqrt{\frac{B-1}{B+1}} - \text{ctg}\sqrt{\frac{B-1}{B+1}} \right] \right\}, \tag{5}$$

where $B = \frac{b}{a}$, $C = \frac{c}{a}$, $X = \sqrt{(1+B^2)^2 + C^2}$, $Y = \sqrt{(1-B^2)^2 + C^2}$, c is the length of cement kiln 1, a is its radius, b is the distance from the kiln surface to the receiving pad.

Thus, total heat flux from cement kiln surface to a rectangular receiving pad of thermoelectric measuring device is determined by the expression:

$$Q = \sigma \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot (T_0^4 - T_1^4) \cdot S_2 \cdot \frac{2}{\pi \cdot B} \cdot \left\{ \text{ctg}\frac{C}{\sqrt{B^2-1}} + C \cdot \left[\frac{X^2 - 2\cdot B}{X \cdot Y} \cdot \text{ctg}\frac{X}{Y}\sqrt{\frac{B-1}{B+1}} - \text{ctg}\sqrt{\frac{B-1}{B+1}} \right] \right\}. \tag{6}$$

For the calculation of a convective component of heat flux from cement kiln surface [4] it is necessary to determine the Nusselt criterion which in free convection is a function of the Prandtl and Grashof criteria and depends on the body shape parameter.

$$\frac{\alpha l}{\kappa} = f\left(\text{Pr; Gr; body shape}\right), \tag{7}$$

$$\frac{\nu}{a} = Pr, \;\; \frac{gl^3}{\nu^2}\beta\Delta t = Gr \tag{8}$$

here β is coefficient of volume expansion of the medium; Δt is thermal head.

Thermal resistance in gases is determined by the resistance of a narrow near-surface gas layer where molecular friction prevails. Therefore, a system of motion equations will comprise only four independent variables instead of five (a, $g\rho\beta\Delta t$, μ, l). This yields only one governing criterion:

$$Pr\;Gr = \frac{gl^3}{a\nu}\beta\Delta t. \tag{9}$$

Formulae for the calculation of heat exchange coefficient in this case are as below:

a) at $10^{-3} < Pr\;Gr < 5 \cdot 10^2$

$$\alpha = A_1 \left(\frac{\Delta t}{2a^5} \right)^{1/3}, \tag{10}$$

b) at $5 \cdot 10^2 < Pr\;Gr < 2 \cdot 10^7$

$$\alpha = A_2\left(\frac{\Delta t}{2a}\right)^{1/4}, \qquad (11)$$

c) at $Pr\ Gr > 2\cdot 10^7$

$$\alpha = A_3 \Delta t^{1/3}. \qquad (12)$$

For the air at the average temperature $T_{av} = \frac{1}{2}\left(T_1 + T_0\right)$ the values of coefficients A_{1-3} are as follows: $A_1 = 0.28$, $A_2 = 1.07$, $A_3 = 1.05$.

Thus, $Pr\ Gr = 1.3\cdot 10^{12}$, and, accordingly, $\alpha = 6.8$ W/(m^2·K).

However, in the above variant of heat exchange due to free convection the cement kiln rotation, that is the presence of forced convective heat exchange, is disregarded. The effect of forced convection may prove to be essential. In the Couette-Taylor problems, such a rotation is taken into account through dimensionless parameters, namely the Reynolds number Reh, characterizing forced flow, or the Taylor number. Here, for the calculations a modified Taylor number is used as below

$$Ta_m = \frac{\Omega^2 d^2 \delta^3}{2\nu\left(d+\delta\right)}\left(\frac{1697}{\pi^4}C\right), \qquad (13)$$

where Ω is angular velocity of rotation,

$$C = 0.0571\left(1 - 0.652\frac{2\delta}{d}\right) + 0.00056\left(1 - 0.652\frac{2\delta}{d}\right)^{-1}. \qquad (14)$$

Prior to origination of secondary flows ($Ta_m < 1700$), the Nusselt number Nu^* is defined by equality

$$Nu^* = 2 \qquad (15)$$

and does not depend on the properties of gas, the dimensions and rotation rate of the cylinder.

In the origination of macroeddy secondary flows, one must take into account the Taylor number. In the range $Ta_m \approx 1700\ldots10^5$ the coefficient of heat exchange for the air is defined by the empirical formula

$$Nu^* = 0.128 Ta_m^{0.367}; \qquad (16)$$

in the range $Ta_m \approx 10^4\ldots2\cdot10^8$

$$Nu^* = 0.42 Ta_m^{0.25} Pr^{0.25}; \qquad (17)$$

in the range $Ta_m \approx 10^7\ldots2\cdot10^9$

$$Nu^* = 0.28 Ta_m^{0.285}. \qquad (18)$$

Thus, account of kiln rotation yields increase in coefficient of heat exchange due to convection by a factor of 2.2.

Moreover, to perform precise measurements, it is also important to take into account the convective component of the heat flux that comes to the receiving surface of the measuring device Q'_{conv}. It can be taken into account by the formulae for solid wall thermal conductivity by introducing the equivalent thermal conductivity coefficient of the air gap.

The equivalent thermal conductivity coefficient of the air gap, with neglect of heat transfer due to radiation from one wall to another, is defined by the formula

$$\kappa_{eq} = \varepsilon_{conv}\kappa, \tag{19}$$

where κ is thermal conductivity coefficient of the medium filling the gap, with the average temperature of the latter (0.0355 W/(m·K) for the air at temperature 150 °C), $\varepsilon_{conv} = f\ (Pr\ Gr)$ is coefficient taking into account the effect of conversion.

The evaluation formulae for the determination of coefficient of convection:

a) at $10^4 < Pr\ Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n < 10^7$

$$\varepsilon_{conv} = 0.062\left[Pr\ Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n\right]^{1/3}; \tag{20}$$

b) at $10^7 < Pr\ Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n < 10^{10}$

$$\varepsilon_{conv} = 0.22\left[Pr\ Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n\right]^{1/4}, \tag{21}$$

where δ is layer thickness, L_1/L_2 is the ratio between the length of convective flux path from the lower heater surface to the cooler and the height of this path, d is the diameter of the heater. For an inclined cylinder layer $L_1/L_2 = 1$, $k = 3$, $n = 0$. For a horizontal cylinder layer $\frac{L_1}{L_2} = \frac{\pi r + \delta}{d + \delta}$, $k = 3$, $n = 0$.

With the value of $Pr\ Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n$ complex $< 10^3$, the effect of convection in the gap is practically absent, so in the calculation of heat exchange only thermal conductivity component is taken into account.

In the calculation of criteria, the value of average temperature $T_{av} = \frac{1}{2}\left(T_1 + T_0\right)$ is used. For this case the value of $Pr\ Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n = 7.6\cdot10^5$, and $\varepsilon_{conv} = 2.62$. Accordingly, $\kappa_{eq} = 0.093$ W/(m·K), and heat flux due to convection from the lateral surface of the kiln to the receiving surface of the measuring device will depend on the steady-state temperature T_1.

Description of measuring device design

Outward appearance of thermoelectric measuring device is shown in Fig. 3.

Measuring head 1 with a thermoelectric device for temperature and heat flux measurement is arranged on the telescopic mast 2 which allows control of measuring head elevation. The telescopic mast 2 is fixed to the package of control and measuring unit 5 with a collet clamp 3. Removable supports 6 assure steady state position of the measuring device.

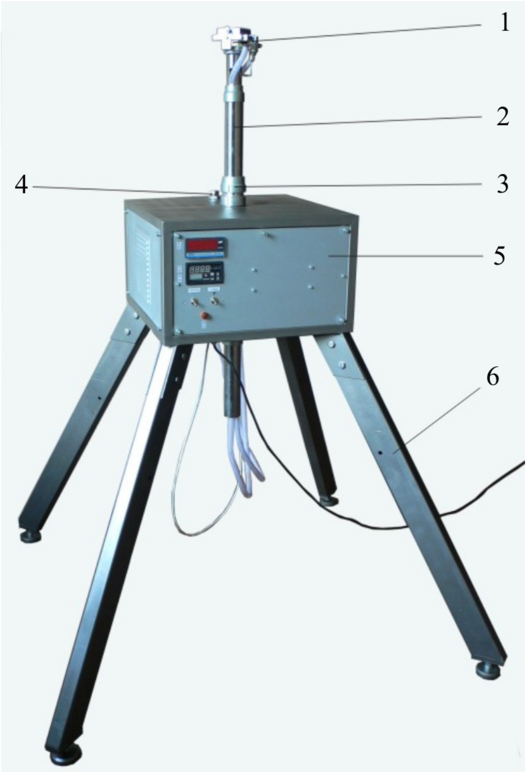

Fig. 3. Outward appearance of the measuring device: 1 –measuring head, 2 – telescopic mast, 3 – mast collet clamp, 4 – filler neck of expansion tank, 5 – control and measurement unit, 6 – supports.

Heat flux measuring device consists of a heat meter located on the heat exchanger for rejection of heat. Temperature sensor is fixed on the heat exchanger close to the heat meter's passive side. The heat exchanger is connected to liquid heat rejection circuit by liquid heat carrier. Distilled water can be used as cooling liquid. The temperature of liquid in cooling circuit is maintained by a two-channel temperature controller, where one channel maintains constant heat carrier temperature in the heat meter circuit, and the other channel is used to measure the temperature of passive heat meter side. Miniature resistance thermometers with a nominal static characteristic 100 Pt serve as temperature sensors. Heat meter signal is measured by a digital voltmeter. Heat meter together with temperature sensor and heat exchanger form a measuring head.

Fig. 4. Outward appearance of the measuring head.

The outward appearance of the measuring head is shown in Fig. 4. Liquid cooling circuit comprises also an expansion tank with water reserve about 4 l, allowing reduction of temperature fluctuations in operation of temperature control. As circuit coolers, 10 thermoelectric modules are used that work in maximum cooling capacity mode. Heat from the modules is rejected by means of heat exchangers with forced air cooling by two fans. The thermoelectric modules are powered by pulse current.

Control and measurement unit is shown in Fig. 5.

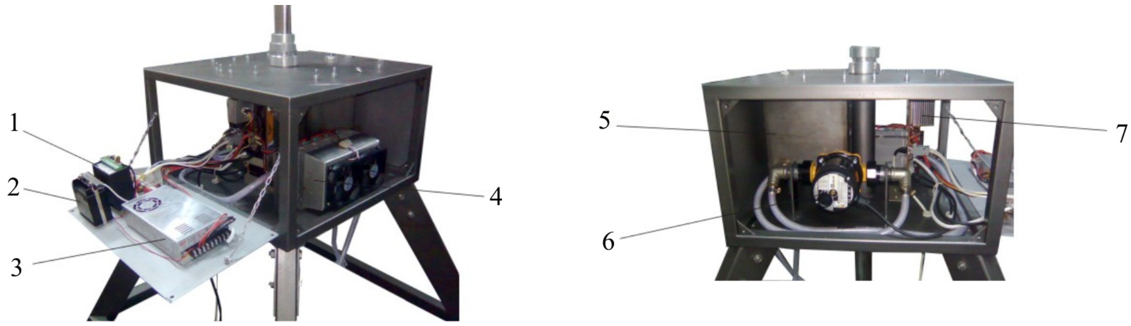

Fig. 5. Arrangement of component parts inside control unit. 1 – digital voltmeter, 2 – thermal controller, 3 – supply unit, 4 –thermoelectric water cooler in cooling circuit, 5 – expansion tank, 6 – circulating pump, 7 – power switch of thermal control system.

The power of radiation heat and the temperature of object under study are determined by the results of measuring the thermopower of thermoelectric module and its hot side temperature. The module is preliminarily calibrated. For this purpose, the emissivity factor of receiving pad is determined by experiment, and thermal flux radiated by the object and the object temperature are calculated using Eqs. (22), (24).

Calibration of a device for measuring the temperature and heat flux from the heated surface

For calibration of temperature and heat flux measuring device a special bench is used with a heater whose thermal radiation is similar to radiation from the heated cement kiln. The experimentally obtained volt-watt and volt-degree characteristics of thermoelectric meter are shown in Figs. 6, 7.

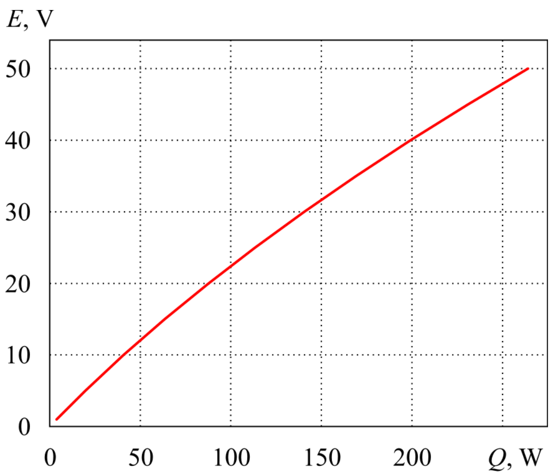

Fig. 6. Volt-watt characteristic of measuring device.

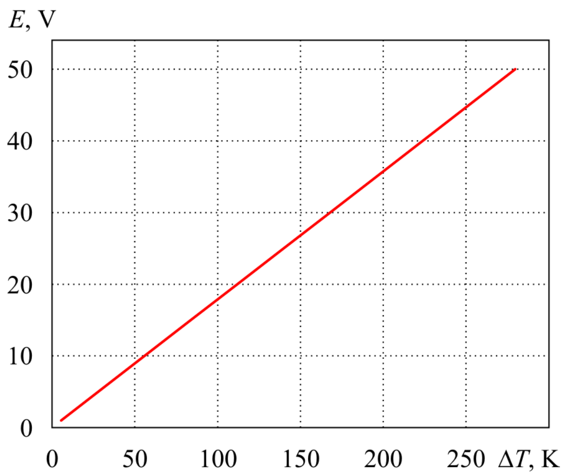

Fig. 7. Volt-degree characteristic of thermoelectric converter.

Experimental volt-watt characteristic of measuring device is described by a polynomial of the kind:

$$Q = A_1 \cdot E + A_2 \cdot E^2, \quad (22)$$

where Q is thermal flux [W], E is thermopower [V], A_1 = 3.788 [W/V], A_2 = 0.03 [W/V^2].

The temperature of heat meter's receiving pad (in Kelvin degrees) is determined as

$$T_1 = 273.15 + t_{heater} + \Delta T, \quad (23)$$

where t_{heater} are readings of thermal controller channel 1 in degrees Celsius, ΔT is temperature difference on thermoelectric converter.

Using volt-degree calibration of thermoelectric converter, temperature difference in the heat meter is determined as:

$$\Delta T = A_3 \cdot E_{heater}, \quad (24)$$

where E_{heater} are voltmeter readings [V], A_3 = 5.59446 [K/V].

Based on (1) – (4), we obtain the object temperature:

$$T_0 = \sqrt[4]{\frac{A_1 \cdot E_{heater} + A_2 \cdot E_{heater}^2}{\sigma \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot S} + (273.15 + t_{heater} + A_3 \cdot E_{heater})^4}. \quad (25)$$

If the exact value of coefficient ε_1 s unknown, the object temperature can be determined more precisely by performing calibration. For this purpose it is necessary to determine the value of object temperature by an external device and compare heat meter signal to this value. In this way one can determine the generalized constants. In this case:

$$T_0 = \sqrt[4]{k \cdot E_{heater} \cdot (E_{heater} + A_1 / A_2) + (273.15 + t_{htater} + A_3 \cdot E_{heater})^4}. \quad (26)$$

At $T_0 = T$ we obtain the value for k – a generalized coefficient of heat exchange

$$k = \frac{T^4 - (273.15 + t_{heater} + A_3 \cdot E_{heater})^4}{E_{heater} \cdot (E_{heater} + A_1 / A_2)} = \text{const}, \quad (27)$$

where T is an actual value of absolute object temperature measured independently.

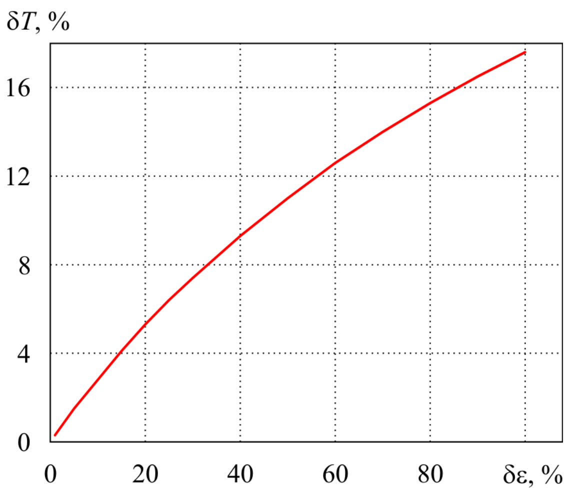

Fig. 8. Dependence of the error in measuring object temperature δT on the error in determination of emissivity factor δε.

Moreover, estimates have been made of the impact of error in determination of measured surface emissivity factor on the accuracy of its temperature measurement. It has been established that a relative error in temperature measurement depends to a small extent on the accuracy of determination of surface emissivity factor (Fig. 8). Thus, to assure temperature measurement accuracy 10 %, it is sufficient to know surface emissivity factor to an accuracy of 44 %.

Conclusions

1. Physical and mathematical models of thermoelectric device for remote measurement of heat flux and temperature for cement kilns have been developed.

2. The impact of convective and radiant components of heat flux for a rotating cement kiln has been calculated. It has been established that the contribution of convective component of the flux does not exceed 30 % of its total value.
3. A thermoelectric device for remote measurement of heat flux and temperature of cement kiln surface has been designed and manufactured.
4. The volt-watt and volt-degree calibrations of such thermoelectric measuring device have been experimentally obtained.
5. Calculations of the error in object temperature measurement versus the error in determination of its emissivity factor have been performed. It is established that to provide temperature measurement accuracy 10 %, it is sufficient to know surface emissivity factor to an accuracy of 44 %.

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