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AIR-PERMEABLE HEAT FLOW AND TEMPERATURE SENSOR

Ua В роботі розглянуті шляхи побудови датчиків теплового потоку та розроблена конструкція повітропроникного датчика теплового потоку та температури. Принцип дії датчика базується на вимірюванні різниці температури за допомогою двох перетворювачів температури, розміщених на фіксованій відстані. Перевагою запропонованого датчика є можливість одночасного вимірювання теплового потоку та температури без застосування додаткових перетворювачів, а також повітро- та вологопроникність, що є критичним при вимірюванні параметрів біологічних об’єктів. Конструкція датчика розроблена з урахуванням можливості об’єднання окремих датчиків в єдину матрицю необхідної конфігурації

Для запропонованого датчика розроблена теплова модель, що може бути використана для інженерних розрахунків його параметрів, дослідження метрологічних характеристик та аналізу шляхів підвищення точності вимірювань.

Проведені дослідження повністю підтвердили адекватність розробленої теплової моделі та роботоздатність запропонованої конструкції датчика.

En The paper considers ways of designing heat flow sensors and developed the design of an air-permeable heat flow and temperature sensor. The operating principle of the sensor is based on measuring the temperature difference using two temperature transducers placed at a fixed distance. The advantage of the proposed sensor is the possibility of simultaneous measurement of heat flow and temperature without the use of additional transducers, as well as air and moisture permeability, which is critical when measuring the parameters of biological objects. The sensor is designed taking into account the possibility of combining individual sensors into a single matrix of the required configuration.

A thermal model has been developed for the sensor, which can be used for engineering calculations of its parameters, research of metrological characteristics and analysis of ways to improve the accuracy of measurements.

The research fully confirmed the correctness of the developed thermal model and the operability of the proposed sensor design.

Introduction

One of the most essential characteristics of the correct functioning of various biological and technical objects is their thermal regime. In most cases, the temperature at the surface or at characteristic points of the object is used to estimate it. However, in the presence of heat sources in the object, a more complete characteristic can be given by the heat flow emitted by the object.

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Currently, a fairly large number of heat flow meters are produced for the study of various enclosing structures in the construction industry. At the same time, obtaining such information for biological and complex technical objects is limited by insufficient development of special equipment for measuring heat flowers, in particular, due to the lack of required heat flow measuring sensors. Therefore, the development of such sensors is a rather urgent and promising task.

The problem formulation

To measure the heat flow, two main methods are used: optical and the measurement method using heat flow sensors.

Heat flow sensors can be divided into two classes:

– sensors measuring the heat flow by the emerging thermal EMF;
– sensors that measure heat flow by temperature difference using temperature sensors.

Typical heat flow sensor of thermal EMF consists of two substrates on which thermoelectrodes are located (as usual, film). An electrical contact is made between the thermoelectrodes of the two substrates. Due to the temperature difference between the thermoelectrodes, a thermal EMF is generated, which is proportional to the heat flow through the sensor. These sensors are adjacent to gradient sensors, in which the EMF arises due to the presence of a temperature gradient in the substance of the sensor [1, 2].

Sensors measuring heat flow by temperature difference have a similar design. They consist of one or two substrates, which are used to fix the temperature sensors at a distance. The value of the heat flow in such sensors is determined as a result of measuring the temperatures t_1 and t_2 by two temperature sensors located at a distance x perpendicular to the heat flow source:

$$P = -\lambda \frac{t_1 - t_2}{x} S , \qquad (1)$$

where λ – coefficient of thermal conductivity, $\mathrm{W/m \cdot K}$;

S – area through which heat flow passes.

Thermocouples and semiconductor sensors are usually used as temperature transmitters [3–5].

Usually the researcher is interested in both the heat flow and the temperature. Therefore, a complex sensor is required to measure both quantities. When using heat flow sensors based on the effect of the appearance of a thermal EMF a temperature sensor is additionally built in them, which complicates the design of the sensor. In this case, it is simpler to use sensors that measure the heat flow from the temperature difference. But such sensors are not mass-produced, which leads to the need for their development.

It should be noted that the study of heat flows of biological objects using heat flow sensors has significant features associated with the fact that they should not disrupt natural heat exchange with the external environment and, in particular, the mode of moisture evaporation from the surface of the object under study, i.e. be air-permeable. In addition, since biological objects, especially warm-blooded ones, can have a number of localized heat sources, it is needed to use not a single sensor, but a matrix of sensors covering the required area and allowing them to be located on a surface of a complex configuration. The same requirements can be imposed on a number of technical objects, the functioning of which is associated with similar heat transfer processes. Existing heat flow sensors cannot provide air permeability and sectioning.

The purpose of this work is to develop and study a heat flow and temperature sensor using the determination of its value from the temperature difference measured by two sensors.

When developing the design of a heat flow and temperature sensor, it is necessary that it, if possible, have a minimal effect on the thermal regime of the object surface and meet the following requirements:

– air permeability;
– moisture permeability (for water vapour);
– mechanical strength;
– no longitudinal and transverse stretching;
– the possibility of combining individual sensors into a matrix of arbitrary dimensions (to study the distribution of heat flows and temperatures);
– electrical insulating properties that provide an insulation resistance of at least 5 megohm at a temperature of at least $40°C$ and relative humidity up to 80 %.

Development of heat flow sensor design

To build a heat flow sensor based on the selected method, it is necessary to fix two temperature sensors in its body at a distance from each other so that during measurement they are perpendicular to the heat flow source.

In accordance with the requirements put forward, a sensor design was developed, which cross-section is shown in Fig. 1.

The heat flow and temperature sensor is a square made of double-sided foil-clad fiberglass, in the centre of which a hole is drilled. In the centre of the hole on each side of the heat flow sensor there is one temperature sensor, which pins are soldered to the foil on fiberglass. For the possibility of connecting the sensors to each other using flexible connecting elements (for example, threads), 4 holes are drilled in the corners of the square. This makes it possible to form a matrix of the required dimensions from individual sensors.

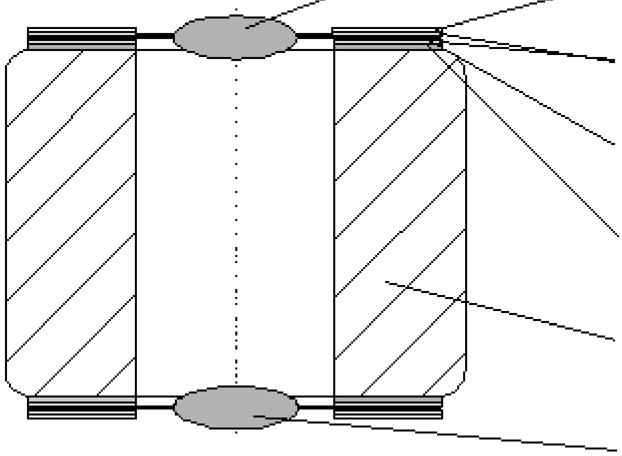

Fig. 1. Design of the heat flow sensor

The proposed sensor design is air and moisture permeable. Electrical insulation is provided by applying an epoxy electrical insulating varnish to the contact connections of the diodes after assembly and soldering of the lead wires.

The experimental prototype from a double-sided foil fiberglass with a thickness of 5,75 mm, in which centre a hole with a diameter of 3 mm was drilled was made for research.

The analysis carried out in [5] shows that achieving high technical and economic characteristics is possible when using semiconductor measuring sensors based on commercially available diodes and transistors for temperature measurement, in particular, rectifier diffusion silicon diodes of low power 2D104A in a plastic case with dimensions of $2\times2\times3$ mm. In the same source, a model was proposed for the temperature dependence of the voltage across the p-n junction when measuring the temperature along the straight direction of the current-voltage characteristic, which makes it possible to obtain temperature dependence close to linear in a rather wide temperature range with high stability.

Therefore, in the experimental prototype of heat flow sensor, two 2D104A diodes were used as temperature sensors.

Development of a thermal sensor model

To analyse the properties and optimize the parameters of the developed sensor, it is necessary to develop its thermal model. To do this, you need to mathematically pose the problem and find a particular solution of the main equation [6]:

$$c\rho\cdot\frac{\partial t}{d\tau}=q_v+\lambda\left(\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}+\frac{\partial^2 t}{\partial z^2}\right), \quad (2)$$

where c – heat capacity of matter, $\frac{J}{kg \cdot °C}$;

ρ – density of matter, $\frac{kg}{m^3}$;

t – temperature, $°C$;

τ – time, s;

q_v – volumetric power of heat sources, that is, the amount of heat released in volume per unit of time, $\frac{W}{m^2}$;

λ – coefficient of thermal conductivity, $\frac{W}{m \cdot °C}$;

x, y, z – coordinates.

When setting the problem, it is necessary to fix a certain geometric shape of a heat-conducting body, its physical properties and, in addition, to set boundary conditions. The boundary conditions include the initial temperature distribution (time boundary condition) and boundary conditions (spatial boundary conditions).

When making measurements with this sensor, it is assumed that the temperature of the investigated object and the ambient temperature are constant and do not change during the measurement time. Therefore, the sensor is in stationary temperature conditions.

The performed analysis showed that to construct a thermal model of a heat flow and temperature sensor, it is convenient to set the boundary conditions of the first kind. For stationary temperature conditions, setting the boundary conditions of the first kind will consist in setting the temperature at the boundary of the object under study and the sensor on the one hand and the temperature at the border of the sensor and the environment on the other hand.

This sensor has two sensitive elements - diodes (Fig. 1). One of them is in direct contact with the surface of the object under study (let's call it the 1st diode), the second is located at a distance from it (the 2nd diode). Heat transfer to each of them occurs in different ways. Let's consider the main ways of transferring heat to each of the diodes.

At temperatures in the range of $+10\ ...+100°C$, heat transfer by radiation is small and can be ignored. Heat transfer by convective heat exchange through an opening in the sensor body is also negligible. The decisive factor in heat transfer to the diodes of the sensor is thermal conductivity [6].

Since the sensor is in stationary temperature conditions, stationary thermal conductivity takes place.

The transfer of heat to the diode can be thought of as transferring heat through a set of flat plates of different thicknesses. If we exclude the narrow zone bordering the plate at the ends, then in practice, the temperature inside the plate can be considered to vary only along its thickness d_{pl}, i. e. classify the problem as one-dimensional (the temperature changes along the ***x*** coordinate, there are no ***y*** and ***z*** coordinates). Since there are no heat sources inside the sensor, we take $q_v = 0$ and, by the stationarity condition $\frac{\partial t}{\partial \tau} = 0$. Let us set the boundary conditions of the first kind:

– at $x=0$: $t=t_1$;
– at $x=\delta_{pl}$: $t=t_2$.

That is, the temperature on one surface of the plate is t_1, and on the second – t_2.

Then from (2) we obtain:

$$t = t_1 + \frac{t_2 - t_1}{\delta_{pl}} x . \tag{3}$$

Thus, a consequence of the assumed assumptions is the linear nature of the dependence of the temperature on the coordinate inside the plate (with the plate thermal conductivity $\lambda_{pl} = \text{const}$).

Let's calculate the amount of heat passing through the plate.

Considering that the temperature depends only on the ***x*** coordinate, and that $\frac{dt}{dx} = \frac{t_2 - t_1}{\delta_{pl}}$, we obtain an expression for the amount of heat passing through the entire plate:

$$Q = \frac{\lambda_{pl}}{\delta_{pl}} \left(t_1 - t_2 \right) \cdot S_{pl} \cdot \tau , \tag{4}$$

where S_{pl} – plate surface area.

The last expressions can be directly generalized to the case of a multilayer plate composed of homogeneous plates with thicknesses $\delta_1, \delta_2, \ldots, \delta_n$ and the corresponding heat conductivity coefficients $\lambda_1, \lambda_2, \ldots, \lambda_n$. Calculation of heat transfer through an air gap can be done in the same way as calculation of heat transfer through a plate.

This result allows you to calculate the heat transfer from an object with a known temperature to a diode at a known ambient temperature.

Heat is transferred to the first diode directly from the investigated surface, as well as through the varnish – solder – diode leads. Since the first diode is in direct contact with the investigated surface and measurements are carried out after reaching a stationary temperature regime, its temperature can be taken equal to the temperature of this surface.

Heat is transferred to the second diode through a hole in the sensor body filled with air, as well as through the circuit of varnish – solder – foil – body – foil – solder – diode leads.

An expression was obtained that relates the temperature t_2 of the second diode with the temperature t_1 of the object under study, the ambient temperature t_{amb}, $(t_1 > t_{amb})$ and the parameters of the sensor when transferring heat through the hole (air gap) in the sensor body.

$$t_2 = t_1 - \frac{\lambda_d\left(\delta_h + 2\delta_f + \delta_s\right) + \dfrac{2}{3r^2}\left(\dfrac{l_d}{2}\right)\left(\dfrac{d_d}{2}\right)^2\left(\lambda_a - 2\lambda_d\right)}{\lambda_d\left(\delta_h + 2\delta_f + \delta_s\right) + \dfrac{4}{3r^2}\left(\dfrac{l_d}{2}\right)\left(\dfrac{d_d}{2}\right)^2\left(\lambda_a - 2\lambda_d\right)} \cdot \left(t_1 - t_{amb}\right). \tag{5}$$

From expression (5) it can be seen that the value of the temperature t_2 of the second diode depends on the parameters of the sensor: the thickness δ_h of the sensor body (in this case, it is fiberglass), the thickness of the foil layers δ_f and solder δ_s , the radius *r* of the hole in the sensor body, the geometric dimensions of the diodes (length l_d and diameter d_d), as well as thermal conductivity λ_d of the substance (compound) of the diode body and thermal conductivity λ_a of air.

Also, an expression was obtained that connects the temperature t_2' of the second diode with the temperature t_1 of the object under study, the ambient temperature t_{amb}, $(t_1 > t_{amb})$ and the parameters of the sensor when transferring heat through the circuit of varnish – solder – foil – body – foil – solder – diode leads.

$$t_2 = t_{amb} + \left(t_1 + t_{amb}\right) \frac{\dfrac{\dfrac{\delta_v}{\lambda_v \cdot S_v} + \dfrac{\delta_s}{2\lambda_s \cdot S_s}}{\dfrac{2\delta_v}{\lambda_v \cdot S_v} + \dfrac{2\delta_s}{2\lambda_s \cdot S_s} + \dfrac{4\delta_f}{\lambda_f\left(bc - \pi r^2\right)} + \dfrac{2\delta_b}{\lambda_b\left(bc - \pi r^2\right)}}}{\operatorname{ch}\left(l_l \cdot \sqrt{\dfrac{2 \cdot 0{,}062 \cdot \lambda_a \cdot \sqrt[3]{\Pr} \cdot \sqrt{\dfrac{\omega}{\upsilon \cdot l_l}} \cdot (a + \delta)}{\lambda_l \cdot a \cdot \delta_l}}\right)}. \tag{6}$$

From expression (6) it can be seen that the temperature of the second diode depends on the thicknesses $\delta_v, \delta_s, \delta_f, \delta_b$ and the thermal conductivities $\lambda_v, \lambda_s, \lambda_f, \lambda_b$ of the layers of varnish, solder, foil and body (fiberglass), the areas of the varnish layers S_v, solder S_s, sizes of sides *b* and *c* of the sensor, the radius *r* of the hole in its body, from the length l_l, the width *a*, the thickness δ_l and thermal conductivity λ_l of the diode leads, and also from the thermal conductivity λ_a of air, the viscosity υ and speed ω of the ambient air, Pr and t_1 number $\Pr$.

Research of heat flow and temperature sensor

When determining the value of the heat flux with this sensor, it is assumed that the heat from the object is transferred to the second diode through the hole in the body and in formula (1), the cross-sectional area of the hole is substituted as the area, and the thermal conductivity of the air filling this hole is substituted as the thermal conductivity.

Thus, the heat transfer through the sensor body and its terminals is not taken into account when determining the heat flux values, which leads to an error, the value of which depends on the temperature difference t_2 and t_2'. Let us write the last expression, taking into account the error due to heat transfer through the sensor body and the diode leads:

$$P + \Delta P = \lambda_a \frac{t_1 - (t_2 + \Delta t_2)}{x} S , \tag{7}$$

where $\Delta t_2 = t_2 - t_2'$ – absolute error in measuring the temperature of the second diode due to additional heat transfer through the leads;

x – distance between diodes.

Then the expression for the relative error in determining the heat flux γ_b due to additional heat transfer through the sensor body and the diode leads can be written as:

$$\gamma_b = \frac{\Delta P}{P} = \frac{t_2 - t_2'}{(t_1 - t_2)} . \tag{8}$$

The error γ_b does not depend on the change in the ambient air temperature and at a typical value of the object temperature $t_1 = 34\,°C$ and the ambient temperature $t_{amb} = 20\,°C$ its value is –1,6%.

The analysis showed that at small values of the body thickness, the temperature rise t_2' over the temperature t_2 is more significant and decreases with increasing δ_b. Consequently, the value of the error in determining the heat flux γ_b decreases with increasing δ_b, which is confirmed by the graph in Fig. 2. Moreover, in the section from 2 to 4,5 mm, the change in the error occurs especially quickly, and at large values of δ_b, the change is smoother. This allows us to recommend values greater than 4,5 mm for the selection of the sensor body thickness, which will reduce the error due to heat transfer through the body.

The value of the heat flux measured with this sensor is determined by the temperature of the second diode and depends on the diameter of the hole in the converter body.

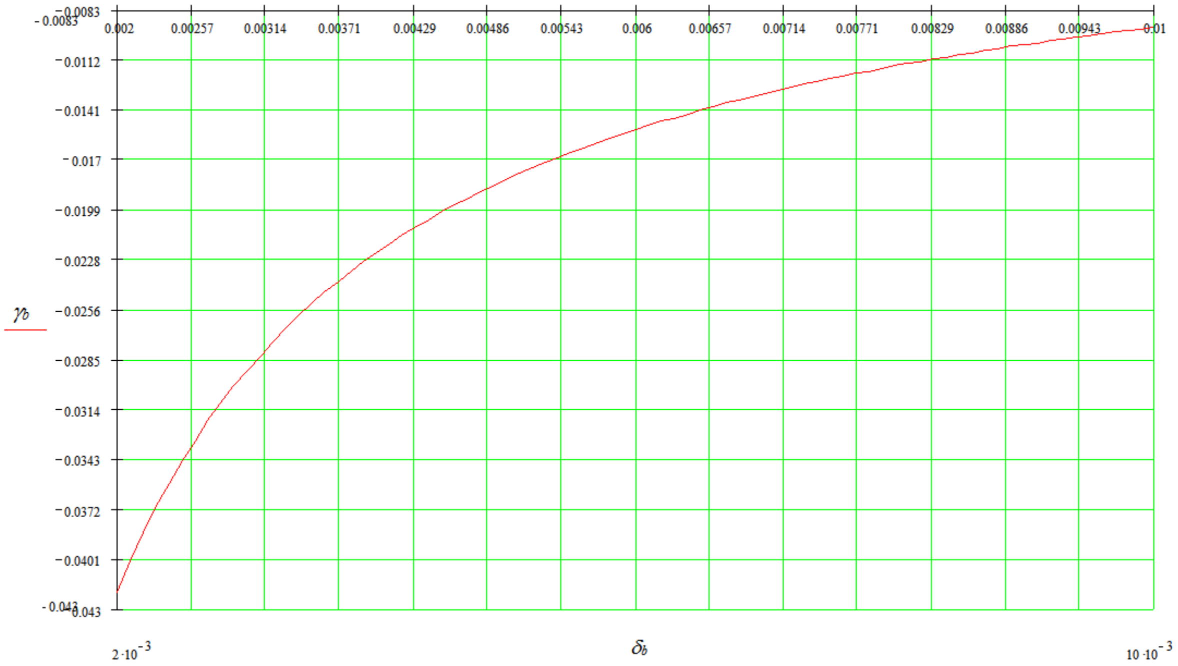

Fig. 2. Dependence of the error on the thickness δ_b of the sensor body

Fig. 3 and Fig. 4 show graphs of temperature dependences t_2 and t_2' on the hole diameter *d* in the sensor body.

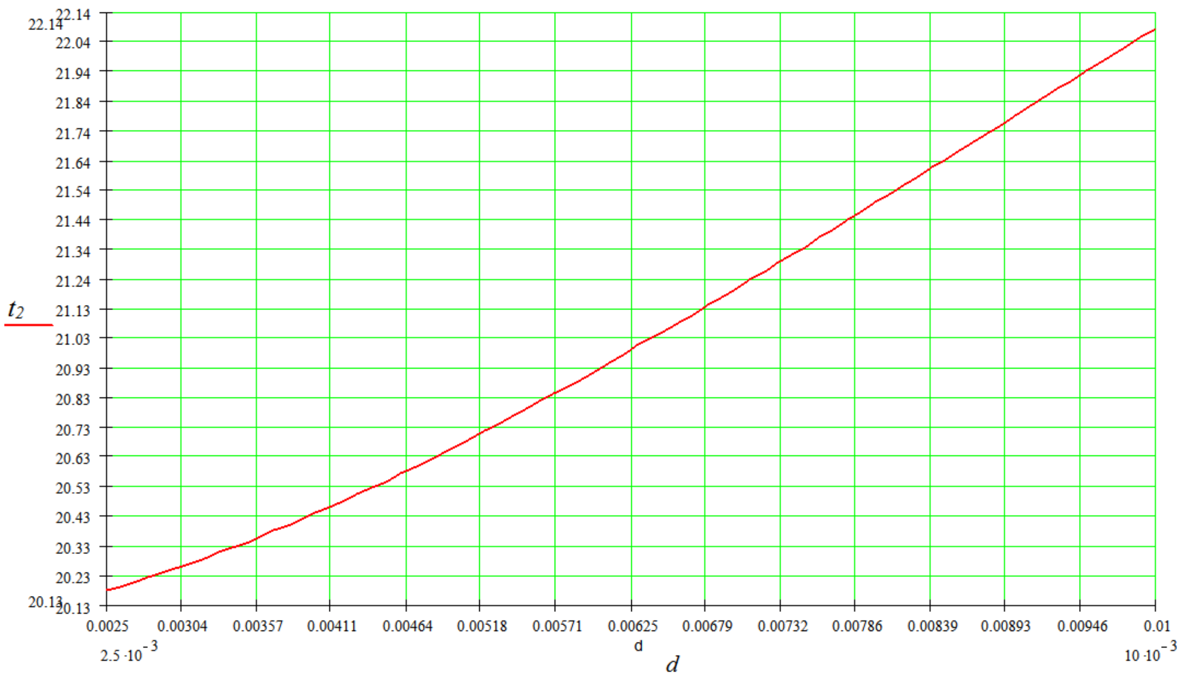

Fig. 3. Dependence of temperature t_2 on the diameter *d* of the hole in the sensor body

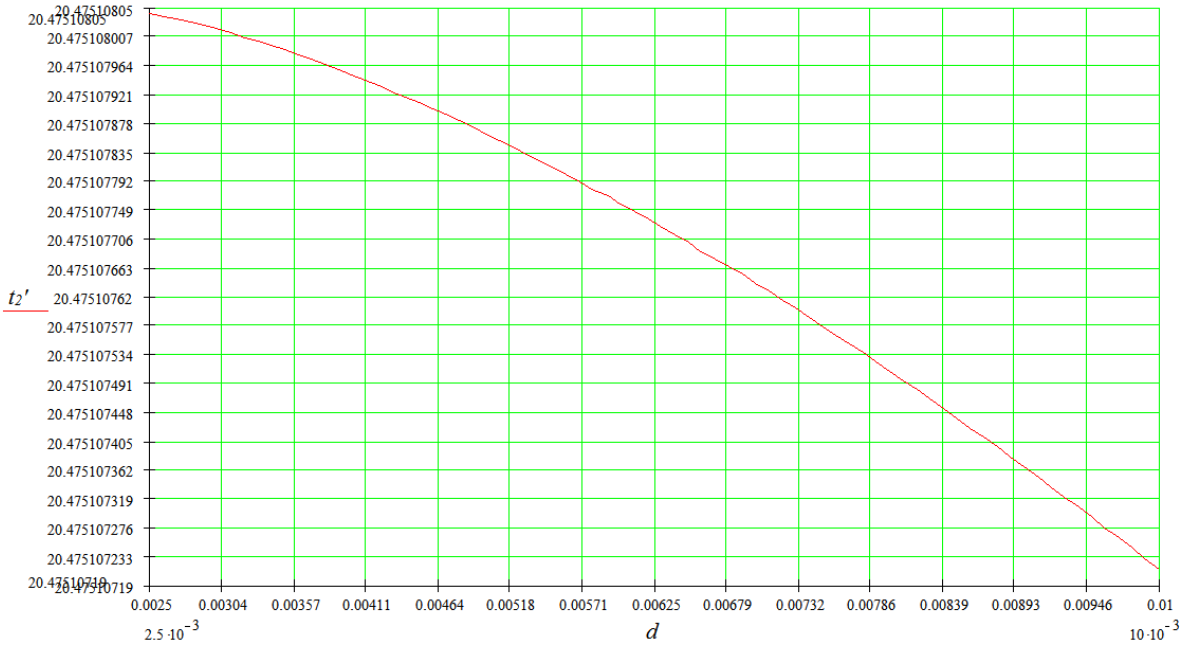

Fig. 4. Dependence of temperature t_2' on the diameter *d* of the hole in the sensor housing

It can be seen from the graphs, that with an increase in the hole diameter, the value of the temperature t_2 increases and the value of the temperature t_2' decreases. The increase in temperature t_2 is explained by the fact that with an increase in the hole diameter, the area of the object that gives off heat to the air gap increases, or, in other words, the area *S* increases, and the thermal resistance of the air gap decreases. A decrease in the value of t_2' is explained by the fact that with an increase in the diameter of the hole, the length of the leads located in the air gap increases, and, therefore, the outflow of heat from them increases.

When the hole diameter is less than 4,1 mm, the temperature of the second diode is determined by heat transfer through the body, since $t_2' > t_2$. When the hole diameter is 4,1 mm, the temperatures t_2 and t_2' are equal, and when the hole diameter is more than 4,1 mm, the value of temperature of the second diode is determined by the heat transfer through the air gap. Therefore, there is no error in determining the heat flux due to additional heat transfer to the second diode at hole diameters greater than 4,1 mm.

Thus, we can conclude that the diameter of the sensor hole should be chosen at least 4,1 mm.

The temperature values of the second diode and, accordingly, the heat flux also depend on the thermal conductivity coefficient of the sensor body, which determines the heat transfer through the body.

Fig. 5 shows a graph of the dependence of temperatures t_2 and t_2' on the thermal conductivity λ_b of the sensor body material.

It can be seen from the graph in Figure 5 that the temperature t_2' increases linearly with an increase in the value of λ_b, and the temperature t_2 does not depend on the value of λ_b.

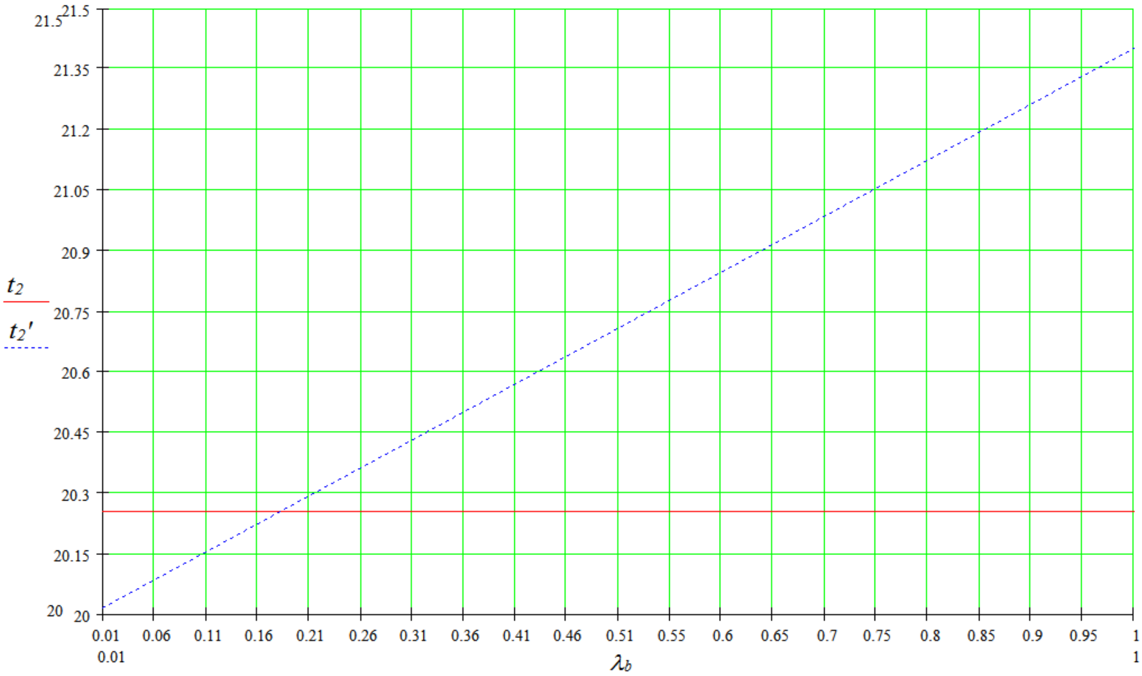

Fig. 5. Dependence of temperatures t_2 and t_2' on the thermal conductivity λ_b of the sensor body material

At values of the thermal conductivity coefficient less than $0{,}185\frac{W}{m\cdot°C}$, the temperature t_2 is higher than the temperature t_2' and the heat transfer to the second diode through the air gap is greater than through the body, and the error $\gamma_b = 0$. At $\lambda_b = 0{,}185\frac{W}{m\cdot°C}$, the temperatures t_2 and t_2' are equal, that is, through the air gap and through the body, the second diode receives the same amount of heat. At values of λ_b more than $0{,}185\frac{W}{m\cdot°C}\cdot t_2 > t_2$, and an error occurs due to additional heat transfer through the body, which increases with an increase in the value of the thermal conductivity coefficient.

At values of $\lambda_b < 0{,}185$, the sensor will affect the object under study, making it difficult for heat to flow out. Therefore, the optimal value of the thermal conductivity coefficient of the sensor body will be $0{,}185\frac{W}{m\cdot°C}$. Ebonite can be recommended as a material for the sensor body, which has a thermal conductivity coefficient of $0{,}17\frac{W}{m\cdot°C}$.

To check the results of theoretical studies of the thermal model of the converter, two experimental samples of temperature and heat flux converters were tested.

The experiments have confirmed that the developed sensors can be used to measure temperature with an error of no more than $0{,}1°C$.

Tests of the sensors in the mode of measuring the heat flux showed that the difference between the values of the heat flux determined experimentally and the values calculated using the thermal model does not exceed 0,85%.

Conclusions

The developed air-permeable heat flow and temperature sensors can be used to study the thermal regimes of various objects and the proposed thermal model of the sensor can be used for engineering calculations of its parameters, study of metrological characteristics and analysis of ways to improve the measurement accuracy.

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