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HEAT FLOW DENSITY MEASUREMENT DURING NON-DESTRUCTIVE TESTING

The object of the study is the development of a device capable of accurately and reliably measuring heat flux density in various environments. The development of a heat flux density meter designed for non-destructive analysis of thermal processes in various fields of application is presented.

The developed device is intended for evaluating the thermal insulation condition of underground pipelines. The functionality of the heat flow device relies on comparing standard temperature values with experimental ones measured on the soil surface. To ensure accurate and reliable measurement of heat flux density, the basis is a thermoelectric battery converter, which uses the auxiliary wall method. The heat flow density measuring device is constructed in the shape of a restricted cylinder, with one base serving as the working surface, while the second base establishes thermal contact with the body at ambient temperature. Embedded heaters enable the generation of heat flow through the thermoelectric sensor in directions perpendicular to its base. For calibrating the heat flux device, experiments were conducted using a standard copper-constantan calibration table. Temperature increments were determined from thermo electromotive force, and tests were performed on an existing heating network. The conducted measurements validate the fundamental feasibility of employing the proposed device for implementing the non-destructive thermal testing method on underground heating mains.

The results of the experiment can be used not only for research, but also for monitoring and regulating processes in various fields of science and technology. The developed heat flux meter promises a significant contribution to the development of modern methods for analyzing thermal processes.

The dimensions of the thermoelectric battery converter are also determined and the coefficient (kq) should be in the range from 4.0 to 12.0 W/(m^2·mV), and the electrical resistance should be in the range of 12–20 kOhm

Keywords: heat flow meter, thermoelectric battery converter, copper-constantan thermocouple, non-destructive method

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1. Introduction

Devices for controlling and measuring heat flux density play a crucial role in addressing issues related to energy efficiency, energy conservation, and obtaining accurate data on the sources and quantitative values of heat losses. Consequently, the development and implementation of heat flux density devices for heat supply systems are of particular significance. The outcomes of numerous studies on the thermal insulation of underground heating networks indicate that the most effective approach is non-destructive testing, which involves comparing calculated and experimental values of temperature distribution on the ground surface above heating networks [1].

At present, in connection with solving the problems of energy and resource saving, the research and modernization of thermal power facilities and energy-intensive technologies have become especially important. In these conditions, measurements, operational control and regulation of thermal parameters, among which the heat flow, which has become as informative parameter as temperature, pressure, flow rate, etc., occupies a significant place, are of great importance. Measurements of heat fluxes characterizing heat leakages are carried out by direct method using contact heat flux meters of “auxiliary wall” type [2].

Heat networks are powerful sources of heat and create a temperature field different from the Earth’s own field. Any violation of the thermal insulation structure and operating modes immediately leads to an increase in the temperature background of the ground surface. Having data on the temperature field around the underground pipeline, it is possible to draw conclusions about the condition of the laying and the thermal insulation structure.

The starting point for any measuring device or system is often the thermoelectric converters, which serve as the primary means of gathering information about the measured values. The thermoelectric converter serves as the primary means for measuring temperature and heat flow [3].

In this case, details regarding flaws are conveyed through variations in both the temperature and intensity of the heat flow across the surface of the monitored object. These parameters are influenced by alterations in thermophysical and geometric properties.

Thermal methods of non-destructive testing are extensively employed for evaluating a variety of protective coatings and assessing the integrity of thermal insulation in underground pipelines, building structures, and similar applications. There are many methods of thermal non-destructive testing used in various industries to detect defects and assess the condition of materials:

– infrared thermography is based on the measurement of emitted infrared energy from the surface of an object. It allows the detection of various defects such as cracks, inclusions and thickness irregularities;

– ultrasonic inspection uses ultrasonic waves to detect internal defects such as cracks, inclusions and voids. Can be used to evaluate wall thickness and weld defects;

– electrothermal tomography is based on applying an alternating current to the material and analyzing the heat distribution. It is used to detect internal defects and assess wall thickness;

– magnetic particle inspection relies on the arrangement of magnetic particles that are administered onto the object's surface, particularly around identified flaws. This method is utilized for identifying cracks, weld imperfections, and other surface irregularities;

– radiography uses X-rays to create images of the internal structures of an object. It is used to detect inclusions, cracks, weld defects, etc.;

– eddy current testing is based on the induction of eddy currents in conductive materials under the influence of an alternating magnetic field. It is used to detect defects on the surface of materials;

– acoustic emission measures acoustic signals that are generated as a result of material deformation or fracture. It is used to monitor the condition of materials in real time;

– the method of induction heating is based on the measurement of changes in the electrical resistance of a material during induction heating. It is used to detect changes in material properties.

These methods can be used in various combinations depending on the specific requirements and characteristics of the controlled objects. Technologies in the field of non-destructive testing are constantly evolving, and new methods may appear over time.

Infrared thermography has a number of advantages and disadvantages over other methods of thermal non-destructive testing.

Advantages of infrared thermography:

1. Non-contact. Infrared thermography does not require direct contact with the surface of the object. This allows for remote monitoring, which is convenient when checking hard-to-reach or dangerous places.

2. Speed and efficiency. Infrared thermography can provide fast and effective detection of defects. It is capable of scanning large surfaces and processing data in real time.

3. Detection of hidden defects. It allows the detection of hidden defects such as material thickness irregularities or internal defects that may not be visible during visual inspection.

4. Capability of thermal conductivity evaluation. Allows evaluation of the thermal conductivity of a material, which can be useful for identifying defects related to thermal properties.

5. Real-time monitoring capability. It can be used to monitor changes in the thermal characteristics of an object in real time.

At present, heat networks with unsatisfactory condition of both thermal insulation structure and heat pipelines as a whole are operated for a long time. The foundation of the non-destructive testing method relies on standard temperature measurement tools, which often exhibit insufficient sensitivity for effectively addressing the diagnostic challenges at hand.

In this regard, the most important aspect of technical quality control is the use of effective control methods and devices. High-precision heat flow density meters allow to increase the efficiency of thermal engineering measurements at industrial facilities, to carry out diagnostics of facilities, to detect technological defects in time and promptly determine the causes of their occurrence.

2. Literature review and problem statement

Many heat flux sensors have been designed for different applications. For instance, in situations with elevated levels of flux and temperature, the authors of the paper [4] have developed resilient sensors capable of maintaining sensitivity across a broad operational range, reaching temperatures of up to 1,000 °C and flux levels in the thousands of W/m^2. The prototype high-temperature calibration system has effectively assessed Virginia Tech's HTHFS up to 900 °C, enhancing the sensor's precision in measuring heat flux at elevated temperatures. The characterization of the system confirmed that the thermal disruption induced by the HTHFS on the stainless steel hot plate is minor yet noteworthy. Employing the analytical model demonstrates a feasible approach to rectify thermal disturbances, yielding satisfactory outcomes. Analytical modeling becomes essential to address slight systematic disparities in heat flux encountered by the two sensors. Further investigation into the minor yet noteworthy thermal disruption induced by the sensors on the stainless steel hot plate is necessary to assess its potential impact on measurement accuracy and reliability, especially in practical applications where precise heat flux measurements are crucial.

The paper [5] presents the study that showcases the efficacy of heat flux sensors in addressing thermal measurement challenges, particularly in scenarios where certain specific areas are inaccessible to temperature sensors. Numerical experiments confirmed the advantage of incorporating heat flux data into an inverse heat conduction method to predict heat fluxes on a wall that is otherwise inaccessible. The proposed sensor is quite sensitive to the input heat flux value and possesses good accuracy. But there were unresolved issues related to other problems associated with the sensor such as the surface conditions and the temporal response of the cooling device were not considered in this work. While these issues may impact the repeatability and time response of the sensor to changes, they do not change the primary conclusions of this study.

The paper [6] presents a small device with a fast response developed for checking and calibrating heat flow density sensors. The device was designed for heat flow density sensors with an area of 20 mm. It has a main measuring part, which consists of hot and cold plate within 30×30×30 mm. The device reacts quickly and reaches a steady state in about 40 minutes. The applicable heat flow density range from 0.65 kW/m^2 to 2.4 kW/m^2 has been confirmed. From a rough estimate of the uncertainty, it was found that the uncertainty of the sensitivity of the heat flow density sensor using this device was estimated at less than 10 % with a coverage factor of k=2. The heat loss was assumed to be equal to 20 W/m^2 depending on the temperature in each position. This is 0.8 % for 2.4 kW/m^2. The error of the burner area was calculated based on the reliability of the caliper, which was used to measure the size of the burner, and the repeatability of the measurement. For the heat flow, it was less than 0.01 %. Summing up, we can say that the error of the heat flow is less than 1 %. These results may be useful in that the steady-state measurement method created a device for calibrating heat flux sensors with fast response and can be applied over a wide range of heat flux densities.

The paper [7] presents calibration of thermopile heat flux sensors designed for such measurements in steady-state mode, where the heat flux is determined by the temperature difference in the direction of the insulation layer thickness. An experimental setup was built, which was used to calibrate sensors in stationary conditions at a heat flow density from 0.5 to 8 kW/m^2. The temperature of the sensor was monitored in the range from 30 to 110 °C, and the correlation of voltage and flow – based on theoretical dependence – was determined using a maximum likelihood estimate. During tests conducted at a consistent measuring temperature, researchers observed a linear correlation between voltage and heat flow. This phenomenon arises from the temperature-dependent nature of the Seebeck constants of thermoelectric materials, causing the voltage to rise as the measuring temperature increases. In every instance, a remarkably close match was observed between the measured and correlated values, with the overall uncertainty of the correlation estimated to be less than 5 % of the measured heat flux. The results of this study demonstrate that the relationship between voltage and flux is contingent upon the number of thermocouple junctions as well as the thermal conductivity and thickness of the insulating material that separates these junctions. In this paper, the calibration was performed within a specific temperature range (30 to 110 °C). Investigating the sensor's performance at lower or higher temperatures could help determine its applicability across a broader range of operating conditions.

The paper [8] presents a thin film of heat flux sensor that consists of a Wheatstone bridge applied on an aluminum oxide substrate with a thickness of 1 mm. This design is much easier to manufacture than other designs because a matrix of resistors is made, and not a matrix of thermocouples. Aluminum oxide was chosen by the authors because its thermal conductivity is relatively higher than that of some metals, so that the sensor does not change the thermal resistance and thus does not distort the measurement results, and also has good properties at high temperatures and is inexpensive. The thermo-sensitive element of this sensor was made of platinum, which was deposited by spraying. Platinum also has excellent high temperature properties, and the variation of its electrical resistance with temperature is well characterized. These results can be useful for improving the efficiency of heat flow operation. But there were unresolved issues related to the difficulties associated with the large amount of metal in the thermocouple, this reduces the temperature difference. It may also be possible to test sensor response by using a shock tube, but the heat transfer coefficient is unknown. At this point, numerical simulation may be the best option, at least for comparing designs.

The paper [9] presents the fabrication of the heat flux sensor with thin film thermal resistances, they used thin-film thermal-resistant materials, which were applied to a flexible thin polymer substrate (copper), instead of wire thermocouples welded to a metal sample. The advantage of using thin-film thermistors instead of wire thermocouples is less interference due to the smaller thickness of thin-film sensors (usually less than 1 µm) and a much better knowledge of the distances between the different heats resistances of thin films, which is precisely determined in the mask used to make the metal thin-film fabrication. The disparity between electrically dissipated heat flux and measured heat flux is reduced when using heat flux sensors equipped with thin film thermal resistances, with a discrepancy ranging between 1.5 % and 1.8 %. In contrast, the difference is higher with heat flux sensors containing thermocouples, ranging between 2.7 % and 4.1 %. It's noteworthy that due to the manufacturing process, this particular type of heat flux sensor can be easily produced. Moreover, the sensitivity of their temperature sensors can be adjusted by altering the supply voltage of the Wheatstone bridge, thereby regulating the current flowing through each thermal resistance element. While the sensor has been calibrated and tested, its long-term stability in various operating conditions or environments may still need to be verified. Factors such as drift in sensor readings over time could impact its reliability.

The paper [10] presents calibration of the sensitivity of the heat flow density sensor in their work. They have developed a unique method of device calibration. The construction of these sensors comprises a copper plate measuring 52 mm in diameter and 20 mm in thickness. An experimental setup was designed and fabricated for calibrating the system under equilibrium conditions, with a heat flux ranging from 9 to 27 kW/m^2. The installation was exposed to temperatures of 70 and 260 °C. The resulting sensitivity value was within the limits. From the results, it can be concluded that increasing the number of thermocouples and the thickness of the inner layer of the sensor is very effective for the sensor sensitivity. However, measurement of heat flux under steady state conditions using guarded hot plate device takes much time. A way to overcome these difficulties is that small sensors having multiple junctions can be employed after proper calibration is tried in the present work.

To develop a device for measuring the heat flow, it is necessary to conduct research depending on the electrical parameters of the thermoelectric battery converter. These studies are carried out by conducting scientific research on the design and calibration of a heat flow measurement device.

3. The aim and objectives of the study

The aim of the study is to develop a heat flow measurement device for non-destructive testing of objects, to increase sensitivity and reduce the error of temperature measurement. This will help in detecting defects and malfunctions in materials and structures, such as network pipelines, heat leaks or insulation problems. This will allow for preventive maintenance and repairs, which helps to increase the service life and safety of facilities.

To achieve this aim, the following objectives were accomplished:

– to calibrate the thermoelectric converter of the heat flux meter;

– to investigate temperature changes in the sand layer.

4. Materials and methods

The object of the study is the development of a heat flow measurement device tailored for non-destructive testing of various objects, with a particular focus on enhancing sensitivity and minimizing temperature measurement errors. The hypothesis of the study: development of a novel heat flow measurement device will significantly enhance sensitivity and minimize temperature measurement errors, facilitating the non-destructive testing of objects. It is hypothesized that the improved accuracy and sensitivity of the device will enable more effective detection of defects and malfunctions in materials and structures, including network pipelines, heat leaks, and insulation issues. Consequently, the implementation of this technology will enable proactive preventive maintenance and repairs, ultimately leading to prolonged service life and enhanced safety of facilities. The work was supposed to develop a heat flux density meter and conduct experiments to calibrate the device by using a standard copper-constantan calibration table. In addition, it was assumed to investigate temperature changes in the sand layer. Simplifications made in the study were since at the location of heat network pipelines in the ground layer their top layer is covered with sand, a laboratory bench was equipped to determine the temperature change in the sand layer.

Among the various types of non-destructive testing, the thermal method of inspection holds a distinct position. Given that 65 to 95 % of the total energy in electronic equipment is eventually converted into thermal energy, this underscores the relevance of employing thermal methods for assessing the qualities of parameters, technical conditions, and the thermal energy released [9, 12].

In heat flux meters, the basis of all advances is the thermoelectric battery converter, where the auxiliary wall method is used. The essence of the method is that a wall with known thermal conductivity is placed in the path of the measured flow density. It remains to determine the temperature difference and calculate the flow using the equation (1) [12]:

$$q=\lambda\frac{\Delta t}{\delta}, \quad (1)$$

where q – heat flux density, λ – coefficient of thermal conductivity, Δt – temperature difference, δ – layer thickness.

The selection of this type T thermocouple is based on the following factors:

– wide temperature range: –200 °C...+350 °C;

– high sensitivity to temperature changes;

– copper and constantan have good chemical resistance, making this pair suitable for various operating conditions.

The basic design of the proposed heat flux meter is shown in Fig. 1. The heat flux meter operates using the method of auxiliary wall, the thermometric unit contains a thermoelectric heat flux density transducer based on a T-type (copper-constantan) thermoelectric sensor.

The thermoelectric battery converter is a flat structure 1 made of filling compound 3, within which thermopile batteries 2 are located. The thermopile is a combination of ascending and descending branches, and the space between them is filled with epoxy compound.

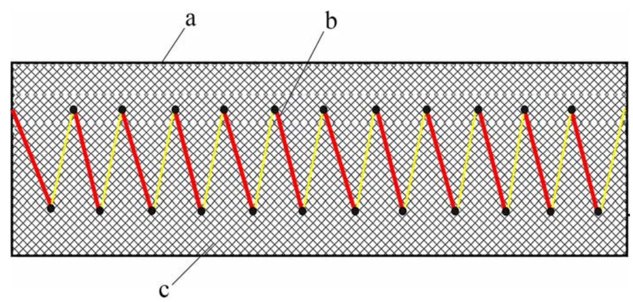

Fig. 1. Structure of thermoelectric converter: *a* — heat flow converter; *b* — thermoelectric battery; *c* — electrical insulation compound

The heat flow density measurement device comprises a thermometric unit and a compact electronic display device powered by an autonomous battery supply (Fig. 2). The thermoelectric heat flow converter comprises a thermometric unit, which utilizes a battery-powered thermoelectric converter as its foundation. The thermoelectric sensor is crafted in the shape of a bounded cylinder, with one base serving as the working surface while the second base establishes thermal contact with the body at ambient temperature. Embedded heaters enable the generation of heat flow through the thermoelectric sensor in directions perpendicular to its bases [13, 14].

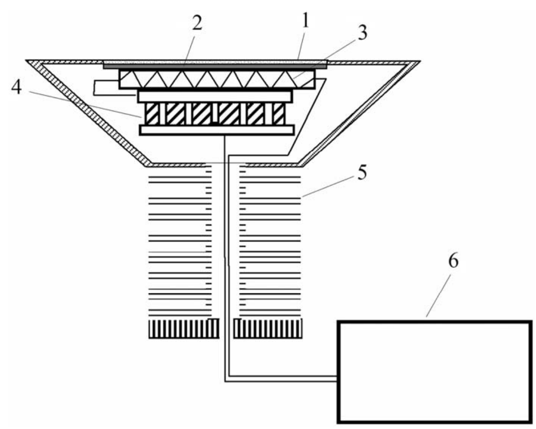

Fig. 2. Schematic representation of the device for measuring heat flow: 1 — insulating layer; 2 — heating element; 3 — thermoelectric heat flow converter; 4 — thermoelectric cooler; 5 — radiator; 6 — measurement unit

Thermoelectric converter of heat flux density consists of a sensitive element, as which, thermoelectric transducers are used, contacting through an exemplary heat conductive plate with a heater, which are placed in a heat insulating case.

A heating element 2 is installed on the insulated reference surface 1, which is brought into thermal contact with the "hot junction" of the thermoelectric converter 3. "Cold junctions" of the thermoelectric converter 3 are brought into thermal contact with "hot junctions" of the thermoelectric cooler 4. The "cold junctions" of the thermoelectric cooler are brought into thermal contact with the heat sink 5. At the same time, the "cold junctions" are brought into thermal contact with the device body having the ambient temperature. The output signal from the thermoelectric battery converter of the heat flow 3, the heating element 1 and the thermoelectric refrigerator 4 is supplied to the measuring unit 6.

The device for measuring the heat flow works as follows. An electric current of sufficient magnitude is applied to the heating element to ensure that the emitted power exceeds the potential heat flux from the object under investigation. A signal is generated at the output of the thermoelectric converter. In this scenario, the signal at the output of the thermoelectric converter will be directly proportional to the heat flux dissipated from the converter by the thermoelectric cooler, while the temperature of the heating element remains close to the ambient temperature. Thus, the device operates in its functional mode.

The device for measuring heat flow is first brought to an area of the object under investigation where no defects are suspected. Subsequently, the device is positioned over the suspected defect area. The presence of a defect is determined by observing changes in the signal output from the thermoelectric converter [15].

The principle of operation of the instrument is based on the replacement of the effect of incident radiation by the effect of Joule heat generated in the calorimetric load when an electric current is passed during calibration. The role of the calorimetric load is performed by the heating element [16].

A laboratory stand was also equipped to conduct an experiment with this device for measuring heat flow (Fig. 3).

Fig. 3. Laboratory stand

5. Results of research of the device for measuring heat flow

5. 1. Results of calibration of the heat flux meter

For calibration of the device for measuring heat flow density, the receiver of the device was placed in the reservoir of the laboratory thermostat with liquid (water). The HFM-MG-4 "POTOK" meter was used as standard device (the temperature receiver of this device was also placed in water). Since the receiver of the device for measuring heat flow is made of copper-constantan conductors, its readings were compared with those of the copper-constantan thermocouple (Table 1).

Table 1

Table of calibration of the heat flux meter

Thermostat temperature, *t*, °C	Temperature determined by HFM-MG-4 "POTOK" meter, *t*, °C	EMF of copper-constantan thermocouple, *E*, mV	Indicator of the device for measuring heat flow density (EMF), *E*, mV
10	10	0.45	2.3
12	12	0.52	5.5
14	14	0.58	11.1
16	16	0.64	16.2
18	18	0.71	21.4
20	20	0.79	27
22	22	0.85	33.3
24	24	0.92	39.7
25	25	0.97	45.7
27	27	1.05	51.5
28	28	1.12	57.4
30	30	1.21	63.9
32	32	1.31	69.8
34	34	1.37	75.6
36	36	1.45	81.9
38	38	1.51	87.9
40	40	1.61	94
42	42	1.69	99.9
44	44	1.80	106.2
46	46	1.87	112.1
48	48	2.77	118.3
50	50	2.82	124.3

5. 2. Investigation of temperature change in the sand layer

Since at the location of heat network pipelines in the ground layer their top layer is covered with sand, a laboratory bench was equipped to determine the temperature change in the sand layer. The diameter of the sand fraction was 0.1–0.3 mm. The object under study (sand) was placed in a plastic container with a height of 300 mm, width of 150 mm and length of 150 mm.

A heating tube was placed in the bottom of the container. Heated water from the laboratory thermostat was supplied to the tube. The temperature change in the layer of bulk materials was controlled by the device for measuring heat flow density, HFM-MG-4 "POTOK" meter and digital multimeter. In this multimeter, a chromel-alumel thermocouple was used as a receiver. To test the bench to determine the temperature change in the sand layer, receivers were placed at different distances from the heat pipe in the sand layer and the temperature change was determined as a function of time (Fig. 4). The temperature of water supplied from the thermostat to the pipe to transfer heat to the sand layer was 80 °C.

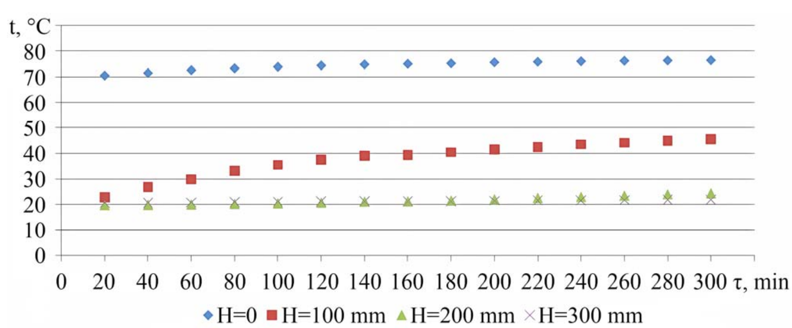

Fig. 4. Temperature change in the sand layer depending on time

In Fig. 4, H=0 is the obtained results when placing the receivers on the surface of the heat pipe; H=100 mm, H=200 mm, H=300 mm are the obtained results when placing the receivers at a distance of 100 mm to 300 mm from the heat pipe in the corresponding layer of the heat pipe.

In subsequent studies, the device was used to conduct tests on the ground heating network (Table 2). The heat main under consideration was investigated in winter. Temperature changes in its insulation and outer layer (metal protective part) were investigated on the heating main.

Table 2

Experimental values of temperature along the length of the heating network

Length of heating network, mm	Temperature of heating network, °C (internal environment temperature 9.3 °C)	Temperature of heating network, °C (external environment temperature 13.5 °C)
500	14.5	18.1
1,000	13.3	17.8
1,500	14.1	17.2
2,000	12.9	16.4
2,500	14.8	18.6

Since the temperature of the pipeline at the entrance to the building was measured when supplying heat to consumers, this device was used to take measurements along the length of the pipeline every 500 mm. Total measurements along the heating network amounted to 2500 mm.

6. Discussion of the results of determining temperature change in different media using a device for measuring heat flow density

Table 1 indicates that the measurements obtained from the heat flow density measurement device are consistently slightly higher than those recorded by the single-split thermocouple. This indicates an increase in the sensitivity of the device. It follows from the results of the experiment that when the water temperature changes by 2 °C, the change in the electromotive force, determined by the device for measuring heat flow density, was an interval of approximately 5.7–6.4 mV.

From the results of temperature changes in the sand layer, shown in Fig. 2, it follows that according to the data obtained every 20 minutes of the time interval, the temperature determined by the receiver located on the surface of the pipe (H=0) changed from 70.5 °C to 76.4 °C, and at a distance of 100 mm from the heat exchanger temperature in the sand layer changed from 22.8 °C to 45.6 °C. At 200 mm (19.9 °C to 24.5 °C) and 300 mm (20.7 °C to 22 °C) away from the heat exchanger, the temperature did not change much.

Table 2 indicates that the temperature variation at the examined points along the above-ground heat network remains relatively consistent, based on the findings of the conducted study. From these data, it was found that the pipe, its isolated and external protective part were not defective.

The research data can be used in the work on the use of the non-destructive testing method for registering disturbances introduced by internal defects in the regular nature of the propagation of heat flows in the object of control.

We have previously developed several modifications of heat flow devices [17]. The peculiarity of the developed device in comparison with the existing ones is the increase in reliability, sensitivity, efficiency, compactness during operation.

The limitations of the prototype device for measuring heat flow include the size or shape that needs to be measured.

The main disadvantage of the operation is that the device can be sensitive to changes in the microclimate, such as temperature and humidity, which can lead to distortion of measurement results.

The main difficulties in research arise in the manufacture of a thermoelectric battery converter. To solve this problem, it is necessary to increase the sensitivity of the device by increasing the number of hot junctions in the thermal battery per unit area of the sensing element. This is also facilitated by an increase in the temperature of the hot junctions of the thermal battery due to a decrease in the heat capacity of the thermal battery and a decrease in heat dissipation along its branches.

7. Conclusions

1. The basic design and results of calibration of the device for measuring the heat flow are described. The obtained data indicate that, in contrast to the standard calibration values of a copper-constantan thermocouple, the readings from the device exceed the norm by approximately 30 times. This discrepancy is attributed to the device's heightened sensitivity in measuring heat flux, wherein the total thermal electromotive force (EMF) within the thermopile circuit is N times greater than in an individual thermoelectric converter. Consequently, the sensor's sensitivity is enhanced.

2. The calculation of all the data necessary to achieve the required sensitivity for accurately measuring the indicated flow density revealed that the heat-sensitive element should be constructed with a height of 1.5 mm and a receiving area diameter of 80 mm, using a wire with a cross-section of 0.05 mm. In this configuration, the operating coefficient of the converter (kq) should fall within the range of 4.0 to 12.0 W/(m^2·mV), while the electrical resistance of the converter should be between 12 and 20 kOhm.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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