DOI 10.1007/s11018-016-1024-z
Measurement Techniques, Vol. 59, No. 6, September, 2016

THERMOPHYSICAL MEASUREMENTS

THERMAL METHODS AND NON-DESTRUCTIVE TESTING INSTRUMENTATION

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UDC 536.33

This article describes several developed modifications to heat flux sensors. A common element in these devices is a specially designed thermopile sensor that acts as a thermoelectric converter of heat flow.

Keywords: *heat transfer system, heat flux, heat insulation, heat flux sensors, diagnostics, thermopile heat flux converter.*

At present in the Republic of Kazakhstan the level of deterioration of municipal heating networks is 63%; of electricity supply systems, 73%; and gas supply systems, 54%. Among the main tasks of urban public services is uninterrupted supply of heat and provision of hot water to each customer with minimal losses. In case of a heating pipeline accident and outpour of 10 tons of heat transfer agent at 100°C, up to 1 Gcal of heat may be lost. Timely diagnosis of underground heat transfer systems will not only quickly identify dangerous or potentially defective portions of the heating networks, but will also increase their service life and reduce losses in heat supply systems. In this regard, the creation and implementation of instruments for high precision measurement of localized heat loss and temperature control are urgent challenges for the utility services of the respective regions [1].

An extensive survey of underground heating systems has shown that all technical diagnostics requirements can be satisfied by the method of thermal non-destructive testing (TNT). The method is based on comparison of the calculated and experimental temperature distribution values on the ground surface above the heating systems [2]. It allows one to assess the condition of the pipes in heat networks and find heat transfer agent leakage sites without opening up the pipelines or interrupting their operation [3].

At the Karaganda State University, based on a thermopile heat flux converter, instruments for measuring the surface heat flux density, regardless of the environment, were developed and tested. In comparison with analogues, these devices have several advantages: high sensitivity; the possibility of total and continuous monitoring; efficiency in identifying heat transfer agent leaks [4].

Heat flux meter ITP-1M. Figure 1 shows the schematic of ITP-1M. The device consists of a receiving plate *4* in thermal contact with the active junctions, and a heating element *2* in thermal contact with the passive junctions of the thermopile heat flux converter *3*. Output signals from the converter *3* and the temperature dependent element *1* are fed to the electronic unit *5*. The housing of the device is in the form of a limited cylinder: one of its bases is the working surface, and the other is in thermal contact with the object the temperature of which is equal to the temperature of the environment. Built-in heaters provide heat flow through the thermoelectric sensor in directions perpendicular to its bases [5].

Before operation, the heat flux device is calibrated to the heat transfer system in a defect-free zone by measuring the controlled parameters directly above the pipe axis and outside the heat-affected zone. Electrical current is passed through

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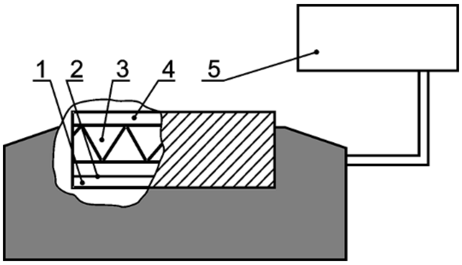

Fig. 1. Schematic of the ITP-1M heat flux meter: *1*) temperature-dependent element; *2*) heating element; *3*) thermopile heat flux converter; *4*) receiving plate; *5*) electronic unit.

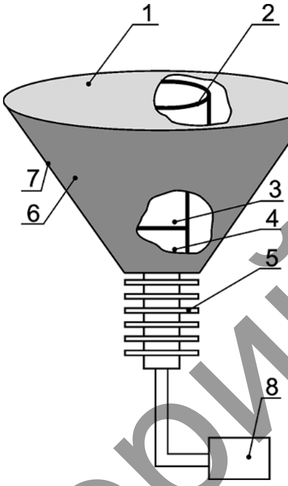

Fig. 2. Schematic of the ITP-2M heat flux meter: *1*) protective film; *2*) calibration coil; *3*) sensor; *4*) heat stabilizer; *5*) heat sink; *6*) heat insulator; *7*) lateral surface; *8*) electronic unit.

the heating element to provide a constant signal at the output from the battery converter. To investigate a possible defect of heating insulation in the heat pipeline, the current of the heating element is not regulated. Through combining the receiving plate of the device with the test area, internal insulation faults are discovered from the signal change at the output of the thermopile converter, and the size of the defect – from the value of this signal. The temperature of the heater is controlled by the temperature-dependent element.

Heat flux meter ITP-2M. Figure 2 shows the schematic of the modified meter ITP-2M. Heat flux enters through the protective film *1* onto the sensor *3*, the thermopile active junctions are in thermal contact with the protective film, the passive junctions – with the heat stabilizer *4*. Next, thermal energy is transferred to heat sink housings *5*. To eliminate heat transfer from the lateral surface, the sensor *3* is surrounded by a heat insulator *6*. The entire system is closed with a cone-shaped lateral surface *7* [6, 7].

A defect in the pipeline results in a sharp change in temperature, pointing to the zone of the pipe with damaged heat insulation or mechanical damage of the pipe material [8].

For preliminary calibration of the thermopile heat flux converter (Table 1), the authors carried out laboratory and field experiments, where Δt is the temperature difference between the investigated object and the surroundings; $\Delta\varepsilon$ is the thermo electromotive force difference (thermo EMF) between the investigated object and the surroundings; and α, α_{av} are the calculated and average calibration coefficients, respectively.

TABLE 1. Calibration Table

No.	Δt, °C	$\Delta\varepsilon$, mV	α, mV/°C	α_{av}, mV/°C
1	0	0	0	0.7824
2	5	4	0.80	
3	7	5.9	0.8428	
4	10	8.1	0.8100	
5	15	12	0.80	
6	20	15.4	0.7700	
7	25	19.2	0.7680	
8	30	22.8	0.7600	
9	35	26.2	0.7485	
10	40	29.7	0.7425	

Calibration results of copper-constant thermocouples were compared with table values for standard thermocouples. Based on thermo EMF values, the temperatures at local points were determined. The tested device operated in the range of 50–1000 W/m^2, which is consistent with normative heat losses. Signal recording time did not exceed 1 min.

Using the standard method, the authors found the measurement error for the thermopile converter. The thermocouples were connected differentially, i.e., for calculations it is sufficient to obtain a set of time-dependent temperature readings from one of the thermopiles [9, 10]. The difference of temperatures measured with the first thermopile is ($T_1 - T$), the second thermopile – ($T - T_2$), and $T_1 > T > T_2$, where T is the measured temperature. Then, we record thermo EMF of the thermopiles as

$$\varepsilon_1 = n_1 k(T_1 - T); \quad \varepsilon_2 = n_2 k(T_2 - T),$$

where n_1 and n_2 are the number of thermocouples in each thermopile, and k is the Seebeck coefficient of the thermocouple.

If the measured temperature is known and equal to T_0, then

$$\varepsilon_{10} = n_1 k(T_1 - T_0); \quad \varepsilon_{20} = n_2 k(T_0 - T_2).$$

Assuming the temperature T_0 is the critical baseline value and $\varepsilon_{10} = \varepsilon_{20}$, we get

$$T_0 = (n_1 T_1 + n_2 T_2)/(n_1 + n_2).$$

When the thermopiles are connected in differential mode, the voltage drop on the recording device is

$$U = (\varepsilon_1 - \varepsilon_2)R/(r_1 + r_2 + R),$$

where r_1 and r_2 represent the resistance of the thermopiles, and R is the input impedance of the recording device.

To find the measured temperature, we use

$$T = T_0 - U/a,$$

where $a = k(n_1 + n_2)R/(r_1 + r_2 + R)$.

When the thermopiles are connected in series,

$$T = U/a - T_0.$$

Such mode of connecting the thermopiles increases measurement accuracy by compensating for the effect of surrounding temperature. In fact, only the difference between the reference and the test temperatures is measured.

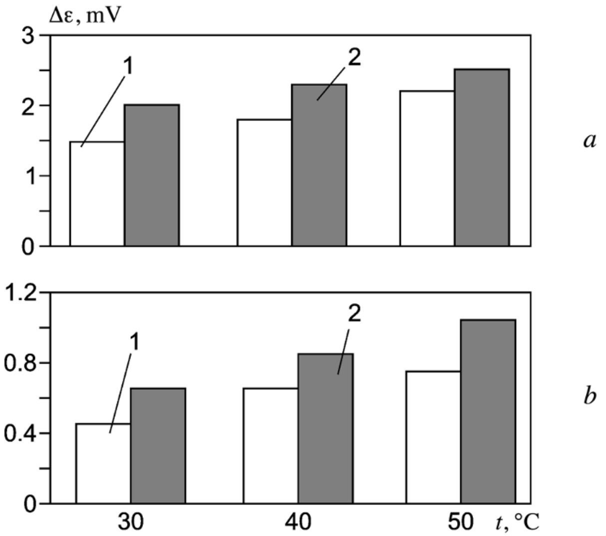

Fig. 3. Thermo EMF as a function of temperature *t* of the heat transfer agent in the heating system for *h* = 10 and 30 cm (*a*, *b*, respectively) in a defect-free system (*1*) and in case of damaged heat insulation (*2*).

The error in calculating heat flux density during calibration equals

$$\sigma_q = \sqrt{4\sigma_i^2 + \sigma_r^2 + \sigma_s^2},$$

where σ_i, σ_r, and σ_s are errors in the value of current at calibration, the Ohmic resistance of the heating coil, and the sensor area, respectively ($\sigma_i = \pm 0.05\%$, $\sigma_r = \pm 0.02\%$, $\sigma_s = \pm 0.04\%$, $\sigma_q = \pm 0.11\%$).

The results obtained were verified in an experimental model of an underground heat insulating structure. Experimental measurements were conducted at the nodes of grids applied on the soil surface at 200 mm intervals. The heat transfer agent temperature (process water) in the pipe was monitored with a thermostat in the range of 30–50°C. The thickness of the soil *h* was varied in the range of 10–30 cm. Preliminary studies were carried out both in a defect-free mode, and by simulating leakage of the heat transfer agent in some parts of the pipeline (Fig. 3).

The results of the experiments showed a temperature rise on the surface of the ground in the leakage zones.

ITP-1M and ITP-2M are indicators of the state of underground heat transfer pipes based on the nature of heat flux changes or the temperature of the surface soil above the studied heat transfer pipe. When diagnosing, the operator moves the device along the heating line collecting readings needed to calculate the heat flux density or temperature above the axis of the heating pipe. The data are compared to the standard, plots are constructed for the specific heat transfer system. This information allows one to detect leakage zones and insulation damage.

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