Calibration of sensors for measurement of high-density heat fluxes

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Abstract Calibration methodology of heat flux sensors for measurement of high-density heat fluxes is suggested. The choice of reference emitter is substantiated and construction of Gardon’s heat flux sensor is described. The difference of suggested heat flux sensor is that it realize indirect measurement of heat flux density, which is based on registration of heating speed of cylinder with high heat capacity and of intensity of heat exchange with its sheath. Three cases of heat flux meter calibration methodology are described: calibration with help of black body model and assistive body with high heat capacity; with help of Stefan-Boltzmann law and black body model; with help of high intensive lamp and assistive body with high heat capacity. Experimental facilitate is suggested and it’s construction is described. Article presents also the results of experimental investigation for each case of calibration methodology. Presented calibration characteristics shows good accordance at wide range of temperatures and heat flux density.

Keywords: Heat flux meter calibration, high-density heat flux, radiometer, black body model

1 Introduction

When conducting test to assess fire resistance building structures of materials ignition test equipment and machinery operating at elevated temperatures certification of protective equipment and in the course of scientific research there is a need to measure heat flux density of which reaches 50 kW/m² [1-4]. Solid surfaces and flame heated to the temperatures of 10³ K can be the source of such density fluxes. Modern domestic normative documentation does not regulate the calibrations of heat flow sensors over 10 kW/m² [5,32], and in the register of State primary standards of Russia there are no standards for the density of radiation heat flux above 5 kW/m². The developments of sensors and stands for their , existing today, represent a variety of designs that Implement and various physical principles of heat flow conversion [6-12] allow to measure heat fluxes over a wide range of temperatures, but they do not meet international standards requiring testing at thermal flows of density 50 kW/m² [13, 14]. To provide the required heat flow capacity the US-based N/St laboratory has a standard operating at an intensity of 10 kW/m², it allows calibrating the heat flow sensors based on the relevant standards [15-17]. Thus the method of sensors calibration in the high temperatures region and finding a suitable standard for this is an actual problem for the metrological
provision of measuring the heat flows when fire modeling the solution of which will allow materials and protective equipment testing [18-20].

2 Methods

To calibrate the heat radiation receivers, it is necessary to heat flow source, creating a stable evenly, distributed flux of radiant, energy [21,33] as a source, models of absolutely black, body or incandescent lamps including halogen ones, can be used:

The use of models of an absolutely black body is associated with a number of difficulties. Today, models of an absolutely black body are serially produced for the calibration of pyrometers and other thermometric devices. In these models, the calibrated device targets the part of the cavity surface, the temperature of which is well known. Thus, it is necessary to ensure isometric city only in the sighting zone. A distinctive feature of the models for calibrating the heat flow meter is the need to provide isothermality, throughout the internal surface of the model.

This is due to the fact the main requirement in the construction of calibration equipment for devises measuring heat fluxes is obtaining a strictly directed, accurately measured uniform flow [22] according to the Stefan – Boltzmann law, this can be achieved only by isothermality of the entire internal surface of the cavity [23]. They provide this with a different cavity configuration, liquid thermostating, the use of a special distribution of heat flux density on the radiating surface by choosing the material of the cavity walls, which makes the instruments that are hard to replace [24,34]. The next drawback is screening. With a close location of the object and the radiator, the heat flux is reflected from the surface of the first and inserts a nonuniformity in the temperature field of the second, which causes large measurement errors. Besides, these errors also include self – oscillations pf the temperatures, created by the work of system, thermostating. Due to this shortages of the blackbody models, it is proposed to use high – power lamp as a source. Such lamps are characterized by a strong heating of tungsten filament high light output. The brightness temperature of such lamps reaches 2800 K. To increase the efficiency coming from the lamp, the flow is concentrated by means of a reflector. In order to study high – intensity heat fluxes, many fire laboratories research, centers and institutes (such as Line-France, SP-Sweden, TNO-Holland and VTT-Finland) radio meters, worked according to Gordon scheme [25] enough widely used.

Design of Gordon classical sensor is follows: the sensitive element is a circular disc of constant to the center and cooled by a fluid, peripheries of which are fixed with copper wires. The heat flux, falling on the blackened disc, create a temperatur e difference between the center and the periphery of the sensitive element, which is proportional to the potential difference on the cobber wires. The obvious drawbacks of the classical design is liquid coding [26, 27]. Tests can be conducted under conditions in which the temperature of heat carrier changes in the supplying tubes or tender pressure conditions, in which the use of flexible hoses is impossible. Also, when experimenting with multiple sensors, the switching of all the lines is complicating many times. To measure the density of heat fluxes, in the present work the technique of indirect measurements based on the rate of heating of a heat – consuming cylinder and the intensity of its heat exchange with a shell is suggested [28]. To carry out the grading, a straightforward installation is used, the construction of which is shown in figure 1.
The basic construction of the plant is a source 1 and a receiver 2 of radiation located on an optical bench 3, a power source – a laboratory adjustable autotransformer 4, as well as meters and temperature transducer 5,6. The optical bench, is a chassis, the main elements on which are fixed with screws. As a source of radiation, several models are used: a model of an absolutely black body, and a high – power halogen lamp. The halogen lamp is connected to the LATR by means of an amper– meter of the type TS 4311. The ACT model consists of a cylindrical radiating cavity 1 (see figure 2), the walls of which are, made of high conductivity copper material. On the side wall and bottom of the convector radiator of nichrome wire 2 is mounted an auxiliary radiation receiver is a copper sample, weighing 280 grams, diameter of 39.5 mm and a thickness of 27.5 mm. A thermocouple of the XK type is attached to the sample.

The heat flow meter (see figure 3) consist of a sensor element 1, which nickel foil.
Figure 3. Heat flow meter (radio meter): 1 – sensing element; 2 – hole for the water; 3 – core; 4, 5, 9 – nuts and screws for fastening, 6 – lining, 7 – body, 8 – base.

The is fastened by means of screws 5 on a heat – consuming steel core 3 which, in turn, is fixed to the base 8 by means of screws 9 and 4, and separated from the housing 7 by insulation from the mineral wool 6. A stop wire is selected as a conductive relative to nickel. The body is made of polished stainless steel. The temperatures are judged by the readings of a digital voltmeter B7 – 21. On the progress of the experiment, different values of the heat flux were achieved by charging the distance between the components of the installation.

Calibration is carried out by successfully performing two stages. In the first stage to determine the heat flux created by the radiator, an auxiliary radiation receiver – a copper sample is used, which was installed to hear the radiator. Copper – calorimetric, substance with a well – known heat capacity, so it is expedient to choose this material. Before starting the calibration, the radiator is preheated before the steady – state values of the temperature and the outgoing radiant flux. At the same time, during the heating process, the radiator is closed by a metal screen to prevent the heat flow from entering the auxiliary sample.

After heating the radiator, the screen is removed, and a sample is placed at a distance of 5 mm from radiator. Under the influence of the heat flux from the radiator, the sample temperature is fixed for ten minutes. Then the sample is moved away from the radiator and freely cooled in the environment, the temperature and the time are again recorded. When performing measurements for the adequacy of the readings, the thermocouple is mounted at a distance of 1/3 from the surface of the sample to which radiation falls.

The heat balance of such a system is written by the equation.

\[
\begin{aligned}
Q - \text{is the heat flux incident on the surface of the cylinder, } W; \\
C_0 \frac{dT}{d\tau} + \sigma(T_0 - T_c) &= Q \\
C_0 \frac{dT}{d\tau} + \sigma(T_0 - T_c) &= 0
\end{aligned}
\]  

(1)

Q - is the heat flux incident on the surface of the cylinder, W; C_0 is a total heat capacity of the cylinder, J/K; \( \tau \) – time, s; \( \sigma \) is the conductivity from the cylinder to the environment due to convention and radiation, W/K; \( T_0, T_c \) – temperature of the object and the environment, K.

For the first stage of calibration known the total heat capacity of the cylinder and the thermal conductivity from it to the medium. The total heat capacity can be determined by multiplying by the specific heat of the material used, or by measuring on the calorimeter. In addition, the dependence of the heat capacity of copper of temperature should be taken into account, since measurements are made over a wide range of temperatures. The value of the conductivity can be determined by free cooling of the cylinder in the
environment. With fixing the measurement of its temperature over time. As a result of the first stage of
calibration, the value of the conductivity $\sigma$ from the object to the medium is found from the system (1) and
determines the value, created by the heat flux radiator.

To check the value of the heat flux, the flux from the radiator is calculated based on the Stefan Boltzmann
law \[29, 30\].

$$Q = \sigma_0 \varepsilon_{\text{np}} \varphi S \left( \left( \frac{T}{100} \right)^4 - \left( \frac{T_{\text{e}}}{100} \right)^4 \right)$$  \tag{2}

Where $T$ - is radiator temperature and environment temperature, K; $\varepsilon_{\text{np}}$ - reduced degree of blackness, $\varphi$
- coefficient of mutual irradiation between the emitter and the surface, corresponding to the location of the
radiation receiver; $S$ – Heat exchange surface area, m$^2$; $\sigma_0$=5.67 - Absolutely black body radiation
coefficient, W/K$^4$m$^2$.

Coefficient of mutual irradiation for circles with general normal, located in parallel planes at distance $h$
between each other, is calculated according to the below mentioned formula (3).

$$\varphi = \frac{1}{2} \left( \frac{Z}{R} - \sqrt{Z^2 - 4R^2H^2} \right)$$  \tag{3}

Where,

$$R = \frac{r_2}{h} \cdot H = \frac{h}{r_1} \cdot Z = 1 + (1 + R^2)H^2$$

$r_1$ and $r_2$ - radiuses of source and radiation receiver, m.

Figure 4 is based on the results of the experiment and calculation (2). The graphs of the heat flux density
$q=Q/S$ on the electromotive force produced by the thermocouple fixed in the ACT are constructed. In this
case, the nominal static characteristic of a thermocouple of the HK type.

![Figure 4. Calibration according Stefan Boltzmann](image-url)

It can be seen from the figure 4 that the experiment fully confirms the Stefan-Boltzmann law in a wide
range of measuring temperatures.

On the second stage, a calibrated radiometer is installed on the optical bench instead of a copper cylinder,
the readings taken after the heat balance between the radiator and the radiometer.
3 Results and discussions
The emf values obtained from the radiometer are given in accordance with the values of the heat flux with the aid of the calibration coefficient K. For this, according to the obtained data, a graph of dependence of the heat flux density on the radiometer readings is plotted and there is the calibration coefficient K.

\[ \frac{Q}{S} = q = K\varepsilon T \]  

(4)

The values of the heat flux density \(q\) in the formula (4) can be obtained from the results of the first stage of Calibration with the radiator or according to the law of Stefan Boltzmann figure 5.

![Figure 5. Results of radiometer calibration](image)

4 Conclusion
Thus, in the present work, the radiometer has been calibrated in three different ways:
1) Based on the experimental measured flux from the ACT model to the auxiliary sample.
2) Using the flow calculated from the ACT model by Stefan-Boltzmann low.
3) Based on the experimental measured flux from the highly intense lamp to the auxiliary sample

Analyzing the obtained data, it is necessary to note the satisfactory convergence of the results of the calibrating the thermometer, including with theoretical laws. In the course of the experiment flows were achieved with a density of up to 50 kW/m². The carried out experimental researches confirm the high effectiveness of the proposed technique, and allow it to be recommended for the calibration of sensors for measuring high-density heat fluxes.

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