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SIMULATION OF SYSTEM FOR REPRODUCTION OF HIGH INTENSITY HEAT FLUX

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Abstract

Control of integral heat losses energy facilities during operation and fire tests are accompanied by an intensive heat transfer process in which the values of the surface heat flux reach about 200 kW/m^2. Measurement of the heat flux is carried out using contact (heat flux sensors) and contactless (radiometers of measuring instruments) sensors, which must be calibrated in the appropriate range.

The aim of the article is to analyze the ways of forming the thermal radiation heat flux in the range of values (1·-200) kW/m^2 and to determine the factors influencing the accuracy of reproduction of the unit of measurement. The main factors are the uniformity of the thermal field formed in the plane of the receiving surface of the measuring instrument, and the contribution of the convective component to the resulting heat flux.

The analysis of the heat field homogeneity on the heat sink surface was performed by computer simulation in the ANSYS package. In simulation studied the heat radiation intensity in a closed cavity at the variation of the distance between the heat radiation source and the heat sink surface at fixed cavity widths. For verification of the computer simulations results, experimental studies of the heat field distribution on the surface of the heat sink were performed using a multi-section heat flux sensor.

Keywords: heat flux; reproduction unit; computer simulation.

Introduction

Research and modernization of heat and power facilities, energy-intensive technologies, introduction of new energy efficiency measures are closely related to the measurement, operational control and regulation of thermal processes, the informative characteristic of which is heat flux. Reliable heat flux values are also important for reducing global energy consumption in the world, as they are a direct indicator of heat loss of facilities. Significant spread of surface heat flux direct measurement is appeared primarily due to its advantages such as the ability to measure, control and regulate the thermal processes of almost any object of any material, the condition of which can be assessed by uneven heat field distribution. In addition, the relevance of the reproduction of units of thermophysical quantities is reflected in the strategic document of the international organization Bureau International des Poids et Mesures in the framework of the metrology development program until 2027, which states that they are particularly valuable to support the climate and energy sectors [1].

In particular, an intensive process of heat transfer, in which the values of the surface heat flux reach about 200 kW/m2, which has a significant impact on the environment, accompanies the operation of energy facilities and fire tests [2, 3]. To control these parameters, measuring instruments are used, which must be calibrated in the appropriate range. Therefore, it is important to ensure the reproduction of the unit of measurement of surface heat flux density at high-intensity heat transfer.

Analysis of recent research and publications

Calibration of heat flux measuring devices for high-intensity heat transfer is preferably performed by the radiation method. Reproduction of the unit of measurement of surface density of a heat flux thus occurs by induction of thermal energy by sources of thermal radiation. As sources of thermal radiation can be used different versions of the model of blackbody [4] or emitters in the infrared region of the spectrum [5].

Thus, in the USA, radiation calibration systems use mainly emitters as the blackbody type of various configurations (developed by NIST) [6, 7]. The spherical emitter model is used to calibrate Gardon, Schmidt-Boelter sensors and thermal radiation receivers used in fire tests in the range of heat flux values from 2 kW/m^2 to 100 kW/m^2 [8]. With used of the radiator as a tubular model of blackbody create flux of thermal radiation to 50 kW/m^2 [8, 9].

In the Russian Federation for calibration of heat flux sensors in the range from 5 kW/m^2 to 2500 kW/m^2 the State standard of unit of radiation heat flux is created [10]. High-intensity heat fluxes are created by means of a high-pressure gas discharge lamp, and obtaining a uniform heat flux is ensured by the use of a quartz optical conductor, at the output of which a measuring radiometer-calorimeter and a test sensor are installed in series.

For calibration of thermal radiation receivers in the range from 10 W/m^2 to 10^5 W/m^2 in Ukraine the State standard of unit of energy illumination by incoherent radiation is appointed [11]. Calibration of working equipment takes place on a secondary standard, in which the value of the unit of measurement is reproduced in the range from 400 W/m^2 to 1360 W/m^2.

The design features of these standards, which have an output diaphragm size of the order of 8… 51 mm, do not allow calibration of measuring instruments whose heat-receiving surface diameter exceeds this size. It limits the use of a significant number of thermal radiation receivers and makes it impossible to calibrate contact-measuring instruments.

The aim of article

The aim of presented article is improving the calibration system of both contact and non-contact means of measuring the surface heat flux density of high intensity, including those with a heat-receiving surface size greater than 50 mm, by used simulation the working chamber of the reproduction unit in the range of values (1·-200) kW/m^2.

The main part

The formation of the heat radiation flux in the range of values (1·- 200) kW/m^2 is possible using a heat source with a temperature on the surface of the radiation body of at least 650…1100 K. High-temperature models of blackbody and thermal emitters possess this characteristic. Known designs of high-temperature blackbody models, as mentioned above, have a diameter of the output diaphragm of the order of 8… 51 mm [6-11], which is insufficient to calibrate heat flux sensors whose diameter exceeds the size of the output diaphragm of the source energy. Another source of high-intensity radiation is thermal emitters, the radiation spectrum of which lies in the near infrared region. In the Table 1 presented of the thermal emitters comparative characteristics [12].

Table 1

Comparative characteristics of the thermal emitters

Characteristics	Mirror incandescent lamps	Quartz halogen incandescent lamps	Quartz emitters with nichrome spiral	Tubular electric heaters
Emitter temperature, К	1400-2200	1260-2470	1030-1260	800-1030
Energy output, %: radiation convection	65-70 35-30	72-86 28-14	55-45 45-55	53-45 47-55
Maximum wavelength, microns	1,5-1,15	1,5-1,15	2,8-2,6	3,6-2,8

As can be seen from Table 1, due to the temperature at the surface of the emitter body these sources are appropriate the requirements for the formation of high-intensity flux. However, due to the redistribution of energy transfer methods, mirror and quartz halogen incandescent lamps have advantages. They have the lowest percentage of heat transfer by convection, which has a significant effect on the formation of a uniform heat flux field on the heat-receiving surface of the measuring instrument.

Therefore, the use of halogen incandescent lamps is promising as a source of high-intensity thermal radiation. Their advantages are the stability of the energy characteristics of the radiation, relatively small size, mechanical and thermal stability.

Given the choice of heat source, the formation of heat flux can be carried out according to the scheme shown in Fig. 1
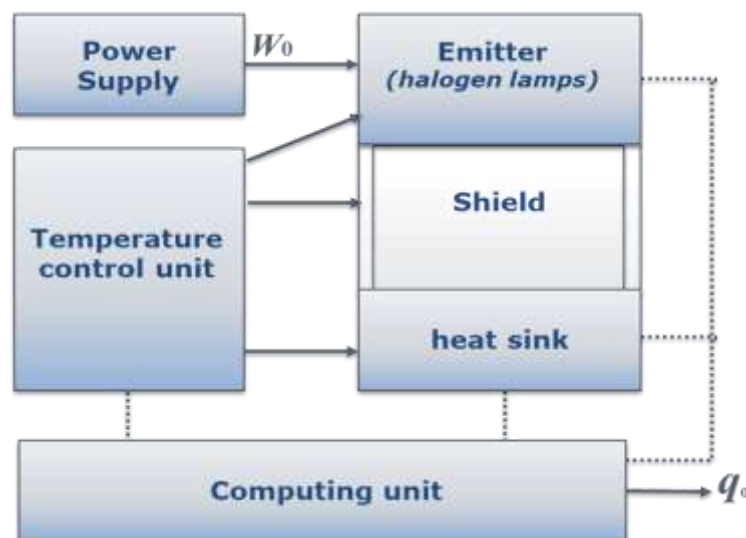

Fig. 1 Formation of a high-intensity radiation heat flux

This allows us to offer the implementation of the working chamber of system for reproduction unit of measuring value in the form of a closed space formed by two diffuse radiating surfaces: the emitter and sink of heat, and a protective shield consisting of four flat surfac-

es with mirror reflection [13]. The use of mirror surfaces of the screen will reduce the attenuation of the intensity of the flow of thermal radiation, which is an important factor in reproducing the values of the unit of measurement at the level of 200 kW/m^2. The accuracy of measurement in

devices of this type depends on the degree of hemisphericity of the incident radiation, the uniformity of the distribution of values of the heat flux entering the heat sink, as well as the contribution of the convective component to the resulting heat flux.

Structurally, halogen incandescent lamps can be used as a radiation source. They are made in the form of a cylindrical bulb of quartz glass with a diameter of 11 mm and a length of 110 mm, along the axis of which a spiral incandescent body made of tungsten wire is mounted. The power of the lamps is 1000 W at a surface temperature of 1173 K. To create uniform illumination in the working area, taking into account the geometric parameters of the lamps, in the field of the radiator are six lamps, which are placed in the terminals of the holder. Fig. 2 is shown a cross section of the proposed working chamber.

The emitter together with the shield form a cavity having the shape of a rectangular parallelepiped with a longitudinal size at the base of 120 mm, on all its surfaces a constant temperature T is maintained.

For calculation of the heat exchange by radiation and assess the degree of uniformity of the thermal field on the surface of the heat sink, it is necessary to know what part of the heat energy radiated by one surface (in our case, lamps) falls on another surface (heat sink).

For diffuse and reflective radiation surfaces, this information can be obtained by calculating the angular emission coefficients, and for mirror reflective surfaces it is necessary to determine a separate angular radiation coefficient taking into account multiple reflections from the mirror surfaces of the system [14].

The separate angular coefficient of thermal radiation for a closed system is determined by the equation:

$$\Phi = \varphi_0 + \sum_{i=1}^{4} \chi_i \cdot \varphi_{i-1},\qquad(1)$$

where φ_0 – angular coefficient of radiation between the surface of the plane in which the lamps are placed and the surface of the heat sink; χ_i – the reflection coefficient of the surface of the shield; φ_{i-1} – angular radiation coefficients between the shield surface and the heat sink surface.
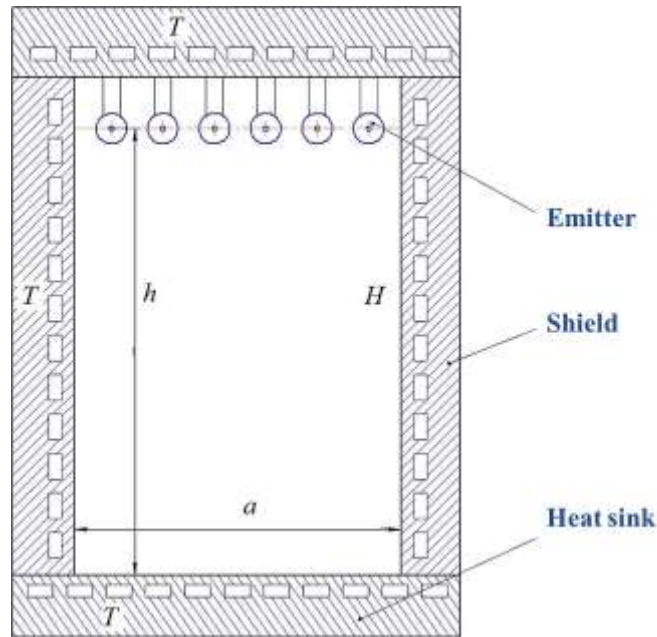

Fig. 2. Cross section of the measuring cell of the system that implements the radiation method of reproduction of high-intensity heat flux

The distribution of angular coefficients in the thermal radiation from the surface of the plane in which the lamps are placed to the surface of the heat sink is calculated on the basis of the expression [14]:

$$\varphi_0 = \frac{1}{2\pi}\left[\frac{a/H}{\sqrt{1+(a/H)^2}}\,arctg\left(\frac{b/H}{\sqrt{1+(a/H)^2}}\right) + \frac{b/H}{\sqrt{1+(b/H)^2}}\,arctg\left(\frac{a/H}{\sqrt{1+(b/H)^2}}\right)\right],\qquad(2)$$

where a – the coordinate that determines the position of the elementary site on the surface of the heat sink relative to the plane in which the emitter is located.

The distribution of local values of angular radiation coefficients of the inner surface of the shield with height His determined for the case of heat transfer between the elementary site on the heat sink surface and the each of surface areas of the four side faces by the equation [14]:

$$\varphi_{i-1} = \frac{1}{2\pi}\left[arctg\left(\frac{1}{d/b}\right) - \frac{d/b}{\sqrt{(H/b)^2 + (d/b)^2}} arctg\left(\frac{1}{\sqrt{(H/b)^2 + (d/b)^2}}\right)\right], \quad (3)$$

where d – the distance by which the elementary site on the surface of the heat sink is shifted from the side surface of the shield; b – the width of the inner surface of the shield.

On the Figure 3 presented the results of calculations in the radial direction of the angular radiation coefficients values according to equation (2). For the distribution of thermal radiation from the surface of the plane in which the lamps are placed to the heat sink surface, and the values of angular radiation coefficients according to equation (3) for thermal radiation propagation from and i-

th surface to the surface of the heat sink with variation in the relative height of the emitter cavity [13].

The results show that for a cavity with a square side at the base of 120 mm, taking into account that all side surfaces have the same geometry and thermophysical characteristics (in particular, for the surface of polished aluminum $\chi_i = 0,92$), the values of the angular coefficients and the separate angular coefficient are: $\varphi_0 = 0,11$; $\varphi_{i-1} = 0,096$; $\Phi = 0,484$.
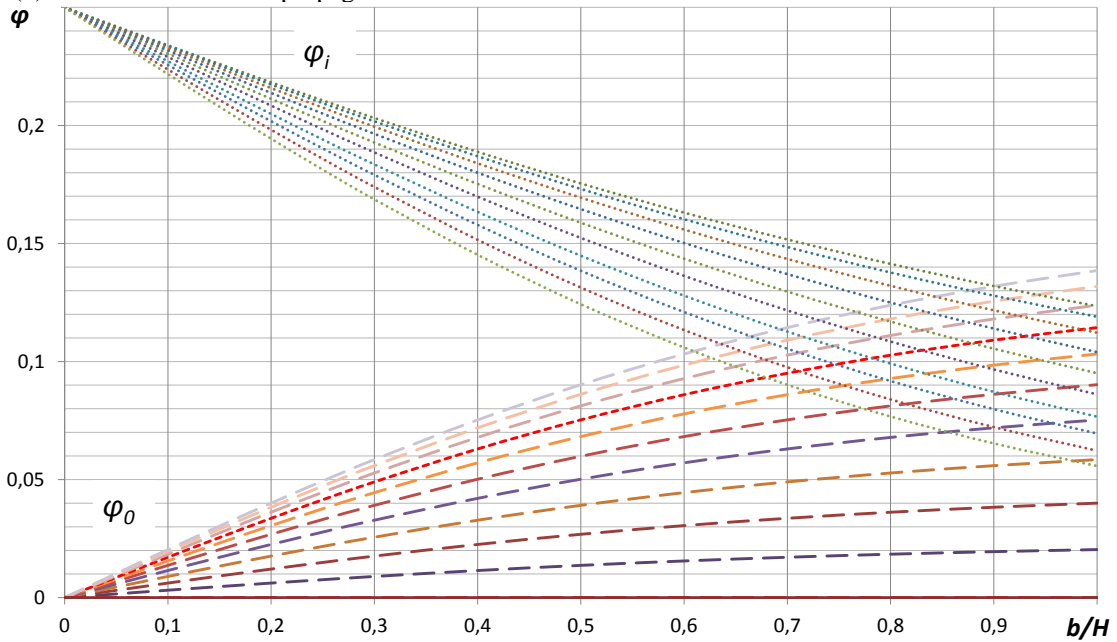

Fig. 3. Graphs of the distribution of the values of the angular coefficients of radiation on the surface of the heat sink with variations in the relative height of the emitter cavity

To establish the homogeneity of the field of heat radiation flux on the surface of the heat sink, it is necessary to determine the distribution of values of the surface density of thermal radiation. The initial value that characterizes the radiation field is the radiation intensity, which is a function of the coordinates and direction of radiation

propagation and characterizes the process of energy transfer by radiation. The mathematical model of the thermal field, which describes the process of energy transfer by radiation, is presented in the form of a vector field [15], which in the general case is written as:

$$\nabla\left(I(\mathbf{r},\mathbf{s})s\right) + (k+a)I\left(\mathbf{r},\mathbf{s}\right) = a\eta\frac{\sigma T^4}{\pi} + \frac{\chi}{4\pi}\int\limits_0^{4\pi} I\left(\mathbf{r},\mathbf{s}'\right)\Phi\left(\mathbf{s},\mathbf{s}'\right)d\Omega', \quad (4)$$

where $\mathbf{s}$ – the vector in the direction of which the radiation is considered; $\mathbf{s}'$– direction of scattering of radiation energy; a – absorption coefficient; η – refractive index; I – radiation intensity, which depends on the position of the point in the volume and the direction in which the radiation flux is considered; T – local point temperature in the volume; Φ – phase function (scattering indicator); Ω' – the body angle within which the flux of radiation energy is considered.

In the left part of equation (4), the second term determines the degree of attenuation of the radiation intensity in the direction s due to the processes of absorption and scattering of radiation energy. In the right side of equation (4), the first term takes into account the amplification of the radiation intensity due to the radiation of the medium, and the second term with the subintegral function shows the contribution of radiation energy from other directions s due to radiation scattering.

The boundary conditions of equation (4) are given in the form of a connection between the values of radi-

ation intensity at the points on the boundary surface and the radiation characteristics of the surface. The intensity of effective surface radiation distributes in the direction of the internal normal to the surface, equal to the sum of the surface's own radiation and reflected from it radiation. The reflected radiation is expressed by the intensity of the radiation that reaches the surface point from all directions $\mathbf{s}'$ within the body angle [16]. In the case of a diffusion radiating and reflecting surface, the boundary conditions are described by the equation:

$$I_{cm} = \varepsilon I_{0,T_{cm}} + \frac{\chi}{\pi} \int_{2\pi} I_{env} \cos(\mathbf{s}',\mathbf{r}') d\Omega ,$$

where I_{cm} – the intensity of effective radiation from the wall surface; $I_{0,T_{cm}}$ – intensity of equilibrium radiation at wall surface temperature T_{cm}.

For determination of the intensity energy transfer of thermal radiation the method of discrete ordinates is used, in which not only spatial but also angular sampling of the radiation transfer equation is performed. In this method, the entire angular space is divided into a number of body angles, within which the radiation intensity is considered constant [17, 18]. The method of discrete ordinates was implemented using the ANSYS software package.

The simulation results are presented on Fig. 4. The distribution of the velocities of the internal environment indicates the presence of forced convection in the location of the heat source (see Fig. 4, a), but on the surface of the heat sink in the location of heat flow sensors convective heat transfer component is absent.
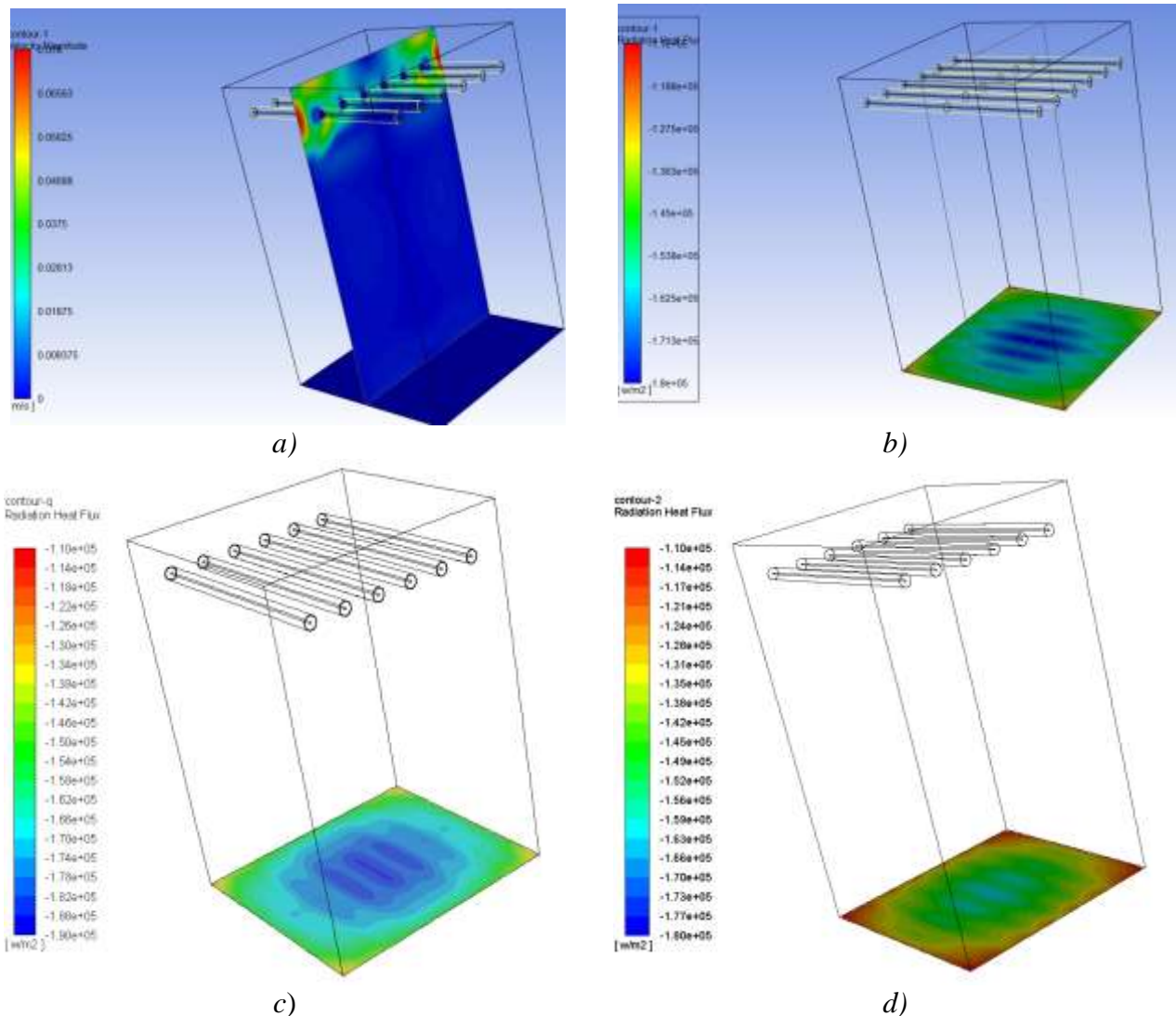

a)

b)

c)

d)

Fig. 4. The results of computer simulation of the system working chamber: the distribution of velocity in the internal environment (a); distribution of radiation heat flux density on the heat sink surface with variation of screen height H = 170 mm (b), H = 150 mm (c) and H = 190 mm (d)

Determination of the heat flux distribution on the heat sink surface is performed by varying the distance between the emitter and the heat-receiving surface of the heat sink at fixed dimensions of the cavity width, which is due to the design features of the applied incandescent lamps. The simulation results are presented for values of H=170 mm, 150 mm та 190 mm.

The obtained results showed that the value of the flux of thermal radiation in the Central zone of heat dissipation at H=170 mm (Fig.4, *b*) exceed 187 kW/m^2, and with approach to the side surfaces of the emitter the flux of thermal radiation decrease to 165 kW/m^2. In this case, the uneven distribution of the thermal field on the surface of the heat sink is 10%, and in the central zone limited by the area of 0.8L, the unevenness does not exceed 2%, which is a satisfactory result.

The results of the calculation for the screen height variant H = 150 mm (Fig. 4, c) show that the intensity of the thermal field on the surface of the heat sink increases to 190 kW/m^2 but also increases the unevenness of its distribution which reduces the size of the working area. At the same time, with screen height of H = 190 mm (Fig. 4, d) the most uniform distribution of the thermal radiation field can be provided, but the obtained intensity level does not allow to implement the unit of measurement at values close to 200 kW/m^2.

For verification of the computer simulations results experimental studies of the distribution of the surface density of the heat radiation flux on the surface of the heat sink were performed. The study was performed using a multi-section heat flow sensor, the sensitive area of which consists of 11 sections. Each of the sections has potential-wiring wires to record signals in the area bounded by one section. Thus, the distribution of the surface heat flux density on the heat-receiving surface of the measuring instrument at the exposure to thermal radiation is determined. On the Fig. 5 presented the experimental data in the form of the value of the surface heat flux density obtained at three given values of thermal radiation power. The markers on the graphs indicate the experimental data and a solid line shows the results of computer simulations.
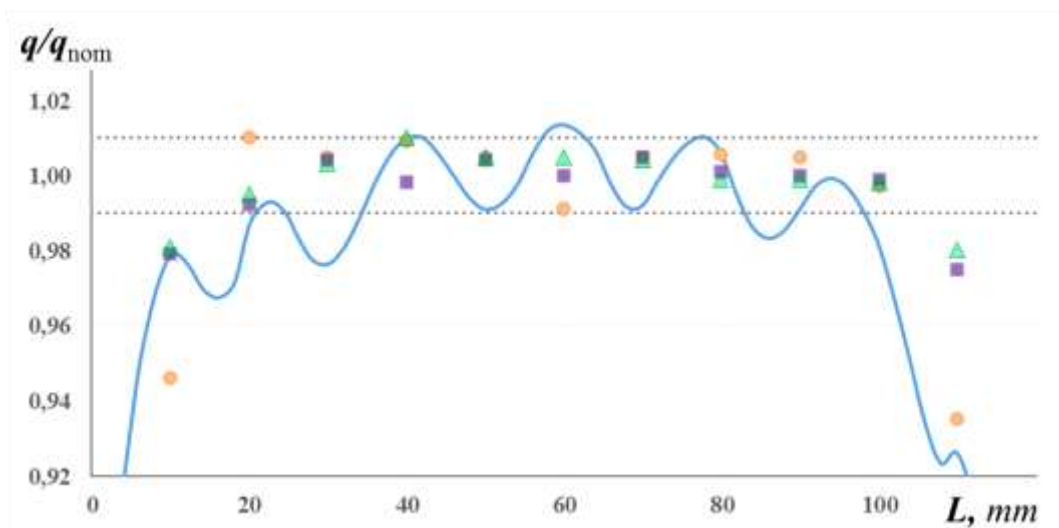

Fig. 5 Experimental data of the heat flux density distribution on the surface of the heat sink: markers indicate the results obtained during a series of experimental studies, a solid line - the results of computer simulations

As can be seen from Fig. 5, the consistency of computer simulation data with experimental ones is quite satisfactory. Thus, the relative deviation of the numerical model does not exceed 3%.

On the Fig. 6 showed the proposed design of the measuring cell, which provides reproduction of high-intensity heat flux. The main elements of the measuring cell are the emitter, thermostatic shied and heat sink.

The emitter together with the shield form a radiating cavity. The inner surface of the cavity is made of polished aluminum, the heat sink is made of aluminum alloy. The emitter, heat sink and shield are flat heat exchangers having internal milled channels for refrigerant circulation. The temperature on all internal surfaces of the measuring cavity and heat sink is maintained the same by means of the thermostat system of the thermal block.

On the inner surface of the emitter, there are holders with contact terminals for the connection of the heat source.

As mentioned above, as a emitter of thermal energy used halogen incandescent lamps that generate a stream of thermal radiation in the near infrared region of the spectrum.

The power of thermal radiation of the required level is set by adjusting the power of the lamps using a stabilization system of a given voltage. The stabilization system includes a voltage sensor supplied to the lamp contacts, a regulator and a triacs unit, which form a control system.
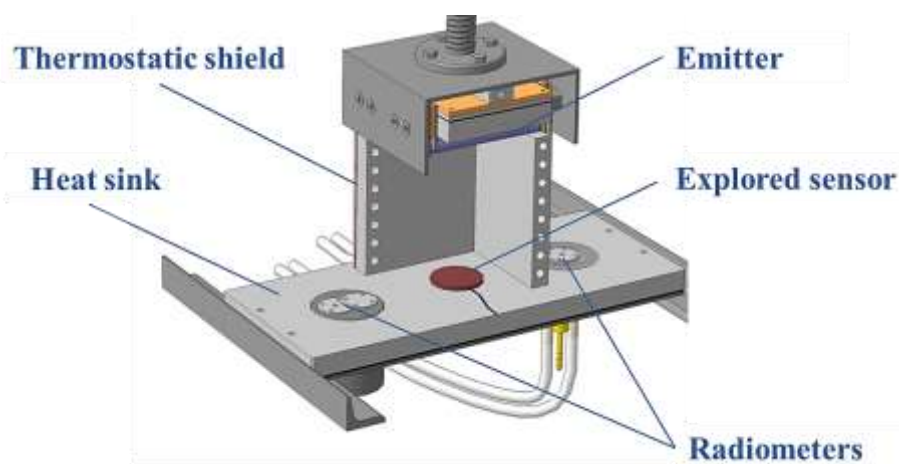
Fig. 6. Design of a measuring cell for reproduction of high-intensity heat flux

The working surface of the heat sink has the shape of a rectangle, in the central zone of which the location of the studied heat flux sensors is provided, and at a certain distance from the central zone on both sides, holes are made for placing the heat radiation receivers.

This design of the thermal unit provides for the possibility of studying the metrological characteristics of measuring instruments by both the absolute method and the method of sequential comparison.

Conclusions

The method of formation of heat radiation flux in the range of values (1- 200) kW/m^2 analyzed and the main influence factors on the accuracy of reproduction of the unit of measurement are determined. The main influence factors are the uniformity of the thermal field formed in the plane of the receiving surface of the measuring instrument, and the contribution of the convective component to the resulting heat flux.

Computer simulation of the heat transfer in the closed cavity of the working chamber of high-intensity heat flux showed the presence of forced convection in the location of the heat source and the insignificant contribution of the convective component. The uneven distribution of the thermal field on the surface of the heat sink in the central zone limited by the area of 0.8L does not exceed 2%, which is a satisfactory result. For verification of the computer simulations results experimental studies of the distribution of the surface density of the heat radiation flux on the surface of the heat sink were performed.

One of the main of design feature of the simulated measuring chamber of the system is that there is a zone for location of the studied heat flux sensors and heat radiation receivers. This opens the possibility for the study of metrological characteristics of measuring instruments by both the absolute method and the method of sequential comparison.

Анотація

Контроль інтегральних теплових втрат енергооб'єктів при експлуатації і вогневих випробуваннях супроводжуються інтенсивним процесом теплообміну, при якому значення поверхневого теплового потоку досягають близько 200 кВт / м^2. Вимірювання теплового потоку здійснюється за допомогою контактних (датчики теплового потоку) і безконтактних (радіометри засобів вимірювань) датчиків, які необхідно калібрувати у відповідному діапазоні. Метою статті є аналіз способів формування теплового потоку теплового випромінювання в діапазоні значень (1 – 200) кВт / м^2 і визначення факторів, що впливають на точність відтворення одиниці вимірювання. Основними факторами є однорідність теплового поля, що формується в площині приймальні поверхні вимірювального приладу, і внесок конвективної складової в результуючий тепловий потік. Аналіз однорідності теплового поля на поверхні радіатора проводився за допомогою комп'ютерного моделювання в пакеті ANSYS. В ході моделювання досліджувалася інтенсивність теплового випромінювання в замкнутій порожнині при зміні відстані між джерелом теплового випромінювання і поверхнею радіатора при фіксованій ширині порожнини. Для перевірки результатів комп'ютерного моделювання були проведені експериментальні дослідження розподілу теплового поля на поверхні радіатора за допомогою багатосекційного датчика теплового потоку.

Ключові слова: тепловий потік, блок відтворення, комп'ютерне моделювання

Аннотация

Контроль интегральных тепловых потерь энергообъектов при эксплуатации и огневые испытания сопровождаются интенсивным процессом теплообмена, при котором значения поверхностного теплового потока достигают около 200 кВт / м^2. Измерение теплового потока осуществляется с помощью контактных (датчики теплового потока) и бесконтактных (радиометры средств измерений) датчиков, которые необходимо калибровать в соответствующем диапазоне. Целью статьи является анализ способов формирования теплового потока теплового излучения в диапазоне значений (1 – 200) кВт / м^2 и определение факторов, влияющих на точность воспроизведения единицы измерения. Основными факторами являются однородность теплового поля, формируемого в

плоскости приемной поверхности измерительного прибора, и вклад конвективной составляющей в результирующий тепловой поток. Анализ однородности теплового поля на поверхности радиатора проводился с помощью компьютерного моделирования в пакете ANSYS. В ходе моделирования исследовалась интенсивность теплового излучения в замкнутой полости при изменении расстояния между источником теплового излучения и поверхностью радиатора при фиксированной ширине полости. Для проверки результатов компьютерного моделирования были проведены экспериментальные исследования распределения теплового поля на поверхности радиатора с помощью многосекционного датчика теплового потока.

Ключевые слова: тепловой поток, блок воспроизведения, компьютерное моделирование

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