INVESTIGATION OF PARAMETERS OF AN INSTRUMENT FOR MEASURING HIGH-TEMPERATURE HEAT FLUXES

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Results of an experimental investigation of an instrument for measuring high-temperature heat fluxes with a density up to 800 kW/m^2 are presented.

One of the interesting and promising lines of investigations in the field of heat pipes is the creation and study of new designs of cooling devices intended to ensure prolonged operation of radiant heat flux sensors [1, 2] at temperatures up to 800-1500°C. First of all, such instruments are required when solving problems of technical diagnostics of boiler unit furnaces for their greater reliability and economical efficiency [3-5]. The importance and severity of diagnostics problems are conditioned by the fact that a furnace chamber is the element of a boiler which to the greatest extent determines its normal operation. The system of diagnostics makes it possible to optimize the temperature regime of radiation and convective heating surfaces, to decrease the intensity of corrosion, slagging, soiling, and to reduce the amount of dangerous and toxic discharge into the environment. Yet, among all the power unit elements, the furnace chamber of a boiler unit is least fitted with measuring devices, though the physicochemical processes in it are distinguished by the greatest intricacy, diversity, an extremely high temperature level, little study, and reproducibility. Temperature fields in boiler units are controlled solely when conducting special investigations.

At present, the moment I. I. Polzunov Central Boiler and Turbine Institute and a number of other organizations are engaged in works on determination and analysis of local conditions of a furnace process on an operating unit using mathematical modeling of the process of combustion and heat transfer in the furnace [6]. For purposes of diagnostics and control of the furnace process use is made of the results of measuring local heat transfer, for example, incident heat fluxes.

Essentially all basic indexes of heat transfer and normal operation of a furnace depend on the position of a flame in the furnace volume. It is precisely this factor to which all of the most serious deteriorations of the furnace process are related. Different direction and degree of flame displacement correspond to a different character of distribution of the incident flux (IF) on safety furnace walls, whose determination is just the problem of identifying the flame position. The work [6] reduces the identification of the position of a flame core along the furnace height to establishing the parameters A, α, B, and β of the distribution curve, which in its dimensionless form can be represented as

$$\tilde{q}_{\text{inc}} = Ae^{(-\alpha x)} - Be^{(-\beta x)}, \tag{1}$$

where $q_{\text{inc}} = q_{\text{inc}}/(\sigma_0 T^4_a)$, and $x = H/H_f$.

From the condition of the extremum of the function $q_{\text{inc}}(x)$ the location of the flame core along the furnace chamber height is found:

$$x_{\max} = \frac{\ln(A\alpha/B\beta)}{\alpha - \beta}. \tag{2}$$

Performing measurements of q_{inc} at four levels along the furnace height, it is not difficult on the basis of (1) to determine the parameters of the distribution function A, α, B, and β and to establish the flame displacement in any transverse direction.

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The temperature of the gases at the outlet from the furnace T''_f and its increments $\Delta T''_f$ in the form

$$T''_f = \sqrt[4]{q''_{inc}/(\sigma_0 a_t)} \quad \text{and} \quad \Delta T''_t = \sqrt[4]{\Delta q_{inc}/(\sigma_0 a_t)} \tag{3}$$

are determined from the measured q''_{inc} and prescribed a_f. Here $q_{inc} = a_f \sigma_0 T^4_{fl}$.

With current methods and instruments it is impossible to ensure prolonged measurements of the incident heat flux. The applied sensors have moderate sensitivity given the considerable overall dimensions. Water-cooled instruments require great capital outlays associated with the need for installation of long water pipelines. In addition, when turning off water cooling the instruments may break down.

The aim of the present work is to experimentally investigate parameters of heat pipes for cooling and thermostabilization of compact heat flux sensors designed to measure radiant energy at heat flux densities from 100 to 800 kW/m^2 and temperatures up to 1500°C.

To solve the stated problem, the Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer of the Academy of Sciences of Belarus" has worked up a special design of a heat pipe [7], which is the main element of an instrument for measuring high-temperature heat fluxes (Fig. 1). In the evaporator zone the heat pipe (HP) contains a socket for setting the heat flux sensor. At a certain length the HP evaporator is provided with heat insulation, which decreases heat influxes from the outside. Within the evaporating and transport zone of the HP there is a special tube for leading out measuring wires. Thus their superheating is ruled out. The HP condenser is fitted with brass or aluminum fins for releasing heat into the environment by natural air circulation. The charging union of the HP is protected by a special cap, which carries the connector for connecting the secondary measuring instrument.

A special feature of the developed structure is the fact that under all operating conditions it ensures effective cooling of the zone where the heat flux sensor is located, at the expense of a guaranteed supply of the heat-transfer agent to the superheating zone. For this purpose the HP condenser is located higher than the evaporator, and inside the condenser there is a vessel for collecting the condensate. The heat pipe is fitted with a condensate-pipe brought to a developed surface, which covers the sleeve for setting the heat flux sensor. In the given structure, under operating conditions in the cooling zone heat-transfer efficiency is attained, which is an order of magnitude greater than the efficiency in a single-phase water cooling. Technical characteristics of the developed device:

Parameter	**Characteristic**
Length of the heat pipe, mm	840
Height, mm	290
Weight, kg	5; 7
Diameter, mm:	
of the heat flux sensor	6
of the evaporator in the zone of setting of the sensor	19
Length of the evaporator, mm	410
Diameter of the heat insulation in the evaporation zone, mm	55
Material:	
of the HP body	Copper
of fins in the condenser zone	Brass, Aluminum
Heat transfer agent	Water
Fins:	
diameter, mm	120
thickness, mm	0.5; 1.0; 1.5
quantity, pieces	31; 40
Pitch of fins, mm	8

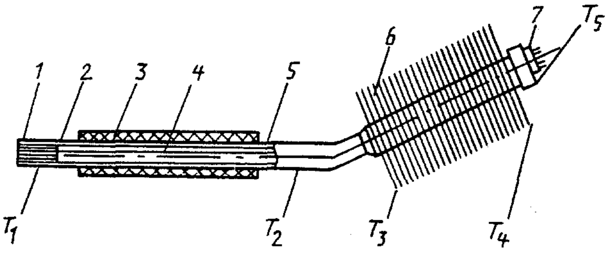

Fig. 1. Design of the heat pipe: 1) heat flux sensor; 2) heat pipe evaporator; 3) heat insulation; 4) tube for leading out measuring wires; 5) transport zone of the HP; 6) condenser; 7) connector for the measuring instrument.

TABLE 1. Temperature Distribution Over the Body of the Heat Pipe

HP No.	Supplied power, W	Heat flux density on the wall, W/cm^2	Temperature, °C				
			T_1	T_2	T_3	T_4	T_5
1	110	11,7	55	40	39	42	39
1	160	17,0	65	47	47	49	43
1	214	22,7	108	66	65	67	62
1	280	29,7	125	81	80	82	76
2	110	11,7	50	41	41	43	40
2	160	17,0	65	55	54	56	52
2	214	22,7	102	65	64	65	58
2	280	29,7	121	75	74	79	69
3	110	11,7	45	42	41	43	39
3	160	17,0	58	49	53	53	45
3	214	22,7	120	61	60	64	55
3	280	29,7	130	75	76	78	72
4	110	11,7	48	44	42	44	40
4	160	17,0	63	53	54	57	48
4	214	22,7	115	63	64	66	58
4	280	19.7	135	78	77	79	67

Under laboratory conditions, investigations of a set of heat pipes for full-scale tests have been performed. The first step of the investigations performed in the Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer of the Academy of Sciences of Belarus" consisted in checking the normal operation of the manufactured products under conditions which simulate the operating ones.

For this purpose, special electric heaters with controlled power were manufactured, which were set into a socket in the heat pipe evaporator. The socket diameter is 6 mm; its depth is 50 mm. The heater was provided with heat insulation to reduce heat losses. The power released in the heater was determined with an ordinary method by measuring the current and stress. Measurements were performed with supplied powers of 110, 160, 203, 214, and 280 W, the heat flux density on the heat-removing wall being respectively 11.7, 17.0, 21.5, 22.7, and 29.7 W/cm^2. Temperatures on the heat pipe body were measured using copper–constantan thermocouples. The locations of the thermocouples T_1, T_2, T_3, T_4, and T_5 are shown in Fig. 1.

Table 1 gives characteristic distributions of temperatures over the body of the heat pipe with various supplied powers and an ambient temperature of 20°C.

Figure 2 shows the dependences of the temperature in the zone of setting of the sensor T_1 and the temperature on the condensate fin of the HP T_4 on supplied power. From the plot it is seen that curve 1 has bends with the heat flux densities on the wall 17.0 and 22.7 W/cm^2. This is likely to be explained by a variation of the regimes of heat transfer in boiling of the heat-transfer agent on the developed surface covering the socket for setting the sensor.

The second step of the investigations was performed in cooperation with the Institute of Technical Thermal Physics of the Academy of Sciences of Ukraine [8]. The given step involved fitting the heat pipes with special sensor-detectors of thermal radiation made in the form of cavity models of a black body with absorptivity no less than 0.95 [9]. The sensor

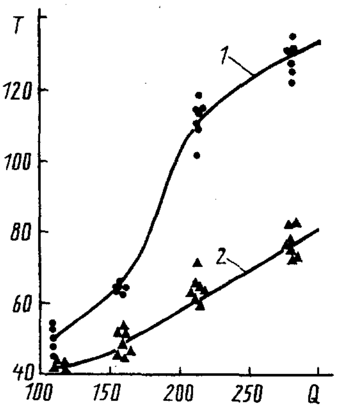

Fig. 2. Dependence of the heat pipe temperature on the supplied power: 1) temperature in the zone of setting of the sensor; 2) temperature on the condenser fin. T, °C; Q, W.

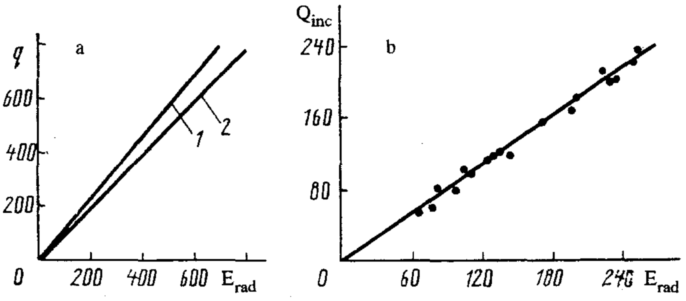

Fig. 3. Calibration dependences of the instruments on the density of the incident heat flux: a) calibration from the mirror paraboloid, b) from the radiating plate. q, Q_{inc}, kW/m^2, E_{rad}, mV.

is made in the form of a thermoelectric temperature transducer provided with hot and cold junctions. The sensor dimensions corresponded to those of the socket in the heat pipe evaporator. The diameter of the sensor inlet was 4.5 mm. The sensors were provided with built-in electric heaters for self-calibration directly on the object under operating conditions.

Tests and calibration of the instruments including HP with the sensors were performed on a plant, comprising a mirror paraboloid 1.5 m in diameter with focal distance 640 mm, at a load up to 1 MW/m^2 under conditions of convective cooling by air. During the tests the densities of the heat fluxes from $100 \cdot 10^3$ to $800 \cdot 10^3$ W/m^2 were overlapped. It turned out that the instruments ensure a linear dependence of the measured signal on the density of the heat flux detected by the sensor. Figure 3a gives the data on the calibration of two instruments. Numbering of the straight lines on the plot corresponds to the numbers of the investigated instruments.

The investigations performed have shown that the heat pipes successfully cool the heat flux sensor in the measured heat flux range. The sensing element retains normal operation after its short-term heating to a temperature of 300°C. Variation in the temperature of the sensing element body insignificantly increases the measurement error, which is within 8%.

Figure 3b gives the results of calibration measurements for one of the instruments made in the Scientific and Technical Association of the Central Boiler and Turbine Institute in the range of lower densities of the incident heat flux.

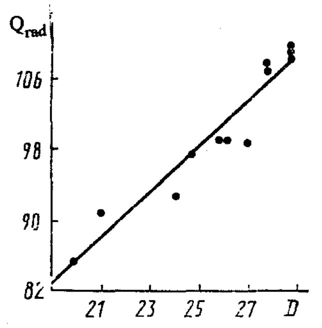

Fig. 4

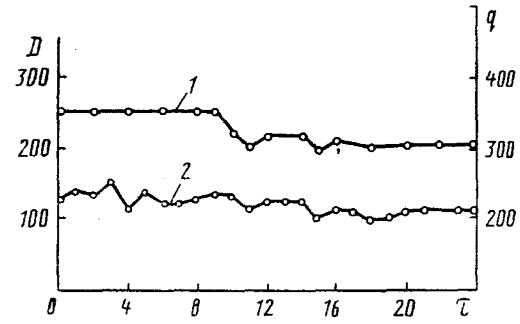

Fig. 5

Fig. 4. Heat flux incident on the furnace chamber walls vs load of the DKVR-35-39 gas boiler. D, t/h.

Fig. 5. Results of full-scale tests of the instruments for measuring heat fluxes on the BKZ-420-140 PG2 pulverized-coal fired boiler: dependence of the fuel rate D (1) and the incident heat flux density in the boiler furnace (2) on time. τ, h.

The calibration was performed from the radiation of a nickel plate, whose emissivity is known and is close to unity. The plate temperature was varied from 800 to 1200°C. It is evident from the plot that the calibration of the instrument is of a linear character which enables us to extrapolate it to larger values of the recorded heat fluxes. In calibrating the distance between the radiating and absorbing surfaces was 20 mm. The instrument sensitivity was $9 \cdot 10^{-7}$ V·m^2/W.

Full-scale tests of the created instrument were also conducted. Measurements of the incident heat fluxes were performed in the furnace chamber of a DKVR-35-39 boiler in the combustion of natural gas. The measurements lasted continuously for 6 h. A KSP-4 recording potentiometer served as a secondary instrument. To record the "cold" surface of the thermoelectric sensor, a PP-63 portable potentiometer was used. As tests have shown, the stabilization time for a signal is about 30 sec. The measurements show that the temperature of the "cold" surface of the detector varies about 40°C, that of the "hot" one – about 150°C.

For measuring, the sensor was inserted into the furnace chamber through a small port on the lateral wall at a fin surface level of water-wall tubes.

Figure 4 presents the data obtained on the density distribution of the incident radiation fluxes depending on the load of the boiler unit. As is evident from the plot, the data are generalized by a linear dependence accurate to $\pm 10\%$, which is quite consistent with the accuracy with which the steam rate was measured.

The produced instrument has also undergone full-scale tests on the BKZ-420 boiler at the Ust'-Ilim Heat and Electric Power Plant. The KSP-4 recording potentiometer and the V-7 digital millivoltmeter were used as secondary instruments. The setting of the sensor was performed in the same manner as in the case described before. Measurements were performed in both the lower and upper zones of the furnace. The outdoor air temperature was 36°C, the flame temperature in the zone of setting of the sensors was 1300-1600°C, the temperature of fins did not exceed 84°C. The measured density of the heat flux ranged up to 410 kW/m^2, the measuring element sensitivity being 300-600 mV. The continuous operation time for the instrument on the boiler was 2 months, the total test time – 11 months.

Figure 5 shows the results of continuous full-scale tests. Measurements were performed for a day on the BKZ-420-140 PG2 pulverized-coal fired boiler. The sensors were set into small ports in the boiler walls at a height 12.8 m from the lower furnace level. The flame temperature in this zone ranged up to 1300°C. The sensor sensitivity depending on the heat flux density ranged from 190 to 220 mV.

It is evident from the plots that in accordance with the variation in the rate of the fuel supplied to the furnace the density of the incident heat flux varies. Pulsations of curve 2 in time are mainly due to the variation in the fuel rate and the movement of the flame in a horizontal direction.

Owing to the performed investigations and full-scale tests, it may be concluded that the instrument developed on the basis of a heat pipe can be applied profitably to measuring radiant heat fluxes incident on the water-cooled surfaces of the furnace chamber for a long time and yield results necessary for the diagnostics of boiler units.

NOTATION

q_{inc}, Q_{inc}, incident heat flux density; A, α, B, β, x, dimensionless parameters; T_a, adiabatic combustion temperature of fuel; H_i, instantaneous height of furnace chamber; H, full height of furnace chamber; T''_f, temperature of gases at the furnace outlet; $\Delta T''_f$, increment in the temperature of gases at the furnace outlet; a_f, emissivity of furnace; T_f, temperature of flame; σ_0, Stefan–Boltzmann constant; T, temperature on the heat pipe body; Q, supplied power; E_{rad}, sensitivity of sensor; D, hourly rate of fuel supplied to the boiler furnace; τ, time.

LITERATURE CITED

1. Heat Flux Sensor, Author's Certificate No. 562,737 USSR.
2. Heat Flux Sensor, Author's Certificate No. 640,146 USSR.
3. A. G. Blokh, O. A. Gerashchenko, Yu. A. Zhuravlev, et al., Prom. Teplotekh., **9**, No. 1, 84-89 (1987).
4. V. V. Klyuev (ed.), Hardware for Diagnosis (Handbook) [in Russian], Moscow (1989).
5. A. G. Blokh, Yu. A. Zhuravlev, O. A. Gerashchenko, et al., Achievements in the Field of Radiative Heat Transfer, Key-Note Papers at the All-Union Conf. on Radiative Heat Transfer in Technology and Engineering, Minsk (1987), pp. 30-40.
6. A. G. Blokh, Yu. A. Zhuravlev, and L. N. Ryzhkov, Heat Transfer by Radiation (Handbook) [in Russian], Moscow (1991).
7. Heat Pipe, Author's Certificate No. 994,898 USSR.
8. A. A. Dolinskii, V. N. Karandeev, and S. A. Sazhina, Testing and Calibration of Thermal Radiation Receivers with Heat Pipes: Report of the Institute of Technical Thermal Physics of the Academy of Sciences of Ukraine [in Russian], Kiev (1990).
9. Method of Producing Thermoelectric Heat Flux Sensors, Author's Certificate, No. 718,731 USSR.