SENSORS FOR METERING HEAT FLUX AREA DENSITY AND
METROLOGICAL EQUIPMENT FOR THE HEAT FLUX DENSITY
MEASUREMENT

D O Doronin¹

¹Research and Production Company Etalon Joint-Stock Company, 175, Lermontov str.,
Omsk, 644009, Russia
E-mail: doronin@etalon.lan

Abstract. The demand in measuring and studies of heat conduction of various media is very urgent
now. This article considers the problem of heat conduction monitoring and measurement in various
media and materials in any industries and branches of science as well as metrological support of the
heat flux measurement equipment. The main study objects are both the sensors manufactured and
facilities onto which these sensors will be installed: different cladding structures of the buildings,
awnings, rocket fairings, boiler units, internal combustion engines. The Company develops and
manufactures different types of heat flux sensors: thermocouple, thin-film, heterogeneous gradient as
well as metrological equipment for the gauging calibration of the heat flux density measurement. The
calibration shall be performed using both referencing method in the unit and by fixed setting of the
heat flux in the unit. To manufacture heterogeneous heat flux gradient sensors (HHFGS) the Company
developed and designed a number of units: diffusion welding unit, HHFGS cutting unit. Rather good
quality HHFGS prototypes were obtained. At this stage the factory tests on the equipment for the heat
flux density measurement equipment are planned. A high-sensitivity heat flux sensor was produced,
now it is tested at the Construction Physics Research Institute (Moscow). It became possible to create
thin-film heat flux sensors with the sensitivity not worse than that of the sensors manufactured by
Captec Company (France). The Company has sufficient premises to supply the market with a wide
range of sensors, to master new sensor manufacture technologies which will enable their application
range.

Keywords – heat flux sensors, heat flux measurements, heat conduction, calibration equipment

1. Introduction

Heat flux density measurement is of great importance both for the experimental research and for the
commercial production. There are numerous instruments which assist in solving the heat flux density
measurement problems. These problems include measurement of local and integral heat flux to determine
heat losses, measurement of the material heat-protection and heat-transport properties, measurement of the
objects’ heat-emission [1,2,3].

There are different methods of obtaining information of heat flux:

1) Analytical methods based on the temperature measurement and numerical solution of the relevant
equation describing the process. Solution of the direct or inverse heat conduction problem.

2) Experimental methods based on the heat vs. physical value relationship.

A wide-spread method for the heat flux measurement is thermoelectric method. It is based on Seebeck
thermoelectric effect which consists in the fact that heating of two heterogeneous conductors’ junction
produces thermal electromotive force (TEMF) causing electrical current in the circuit.

The main heat-measurement objective is the development of such metering instruments which would
ensure the measurements locality, low heat resistance, high sensitivity, good result reproducibility and
having reliable metrological support [1,2,3].
Any metering instrument is based on the primary metering transducer which is the first element to take up the physical value in question. In our case this is primary heat-flux transducer (HFT) – heat-flux sensor (HFS). The heat flux in question is converted into the temperature difference; the temperature difference is converted into the thermoelectrical potential difference. The most popular HFT is auxiliary wall HFT. The auxiliary wall HFT operation principle consists in the measurement of the temperature difference arising when the heat flux passes through a finite thickness wall located on the heat flux route on the normal line to its direction, or the values of the temperature values of two parallel sections of the wall. An HFT has two mandatory elements: intrinsic wall where the temperature difference occurs and this difference meter (thermoelectric battery) [1, 2, 3].

2. **Problem Description**

The Company key objectives are:

- Supply a wide range of heat flux sensors to the consumer market.
- Development and manufacture of heat-flux sensors based on the new technologies.
- Holding internal factory acceptance tests of the sensors manufactured.
- Design of the units for the heat-flux sensor manufacture and metrological support.

3. **Theory**

**Manufacture of Thermocouple Heat-Flux Sensors**

Thermocouple heat-flux sensors are thermoelectric transducers operating on “auxiliary wall” principle. They consist of a battery of identical voltaic thermoelements (Figure 1) connected in parallel in terms of the heat flux being measured and in series in terms of the electrical signal generated. The sensor tightness in rigid or flexible version is ensured by the insulating sealant compound. These sensors are classified as lengthwise heat flux sensors [1, 2, 3].

![Thermoelectric Battery Schematic Diagram](image)

**Figure 1.** Thermoelectric Battery Schematic Diagram.

Our company manufactures HFS 0924, HFS 0925 (reference) heat-flux sensors intended as shop instrument for measuring thermal flux density during the test of various construction items and elements both in laboratory (using climatic chamber) and in environment conditions. The main thermocouple wire is made of constantan, bimetallic wire (main wire section with plating) is represented as copper electroplating [1,2,3].

The Company also designed and manufactured an experimental high-sensitivity heat-flux sensor for measuring low heat-flux densities (up to 10 W/m²).

**Manufacture of Thin-Film Heat-Flux Sensors**

Thin-film heat-flux sensor is a thin vacuum-metallized substrate. To provide temperature gradient overlaps made of low heat-conduction material are used, currently this material is POLIFIX 330 double-sided glue tape. Temperature-leveling surfaces are represented as foil-clad polyimide or copper foil (Figure 2).
The sensor operation consists in the fact that there are contacts with poor and good heat conduction. Heat flux line distribution is not symmetrical relative to the junction centre, the electrical charge is distributed along the heat flux line parallel to the poor-conduction substrate surface. The sensor is not based on the study of the temperature difference along the sensor thickness, it detects electrical potential tangential gradients produced by the heat flux [4].

The metal plating was performed using EVA-600 vacuum deposition unit as per magnetron deposition method. Substrate was made of sitall plate. Thermowires were made of chromium and nickel.

The advantages of this sensor compared with thermocouple sensors are: small dimensions, wider operating temperature and heat-flux density ranges.

**Manufacture of Heterogeneous Heat-Flux Gradient Sensors**

A Heterogeneous Heat-Flux Gradient Sensor (HHFGS) is a cross-type heat-flux sensor (Figure 3).

The HHFGS operation principle is based on cross-wise Seebeck thermoelectric effect – occurrence of thermal EMF with a field vector normal to the heat-flux vector, in the heat-conduction anisotropy, electric conductivity and thermoelectric coefficient. Transverse thermal EMF arises when the heat-flux vector does not match the crystal main axis with heat-conduction anisotropy and thermoelectric coefficients [5,6].

To manufacture the sensor, our Company designed and fabricated diffusion welding unit. The vacuum attained in the welding chamber is 16 Pa, with the maximum pressure acting on the workpiece to be welded equal to 10 tons, maximum temperature attained in the chamber of 597 °C, maximum briquette size of 35x35 mm.

To produce ready-made gradient heat-flux sensors the structure was cut on a special cutter into individual elements at 45° to the main crystal axes.

The Company produced a silicon- (Si) and aluminum- (Al) based GHFS (Fig. 4).
HHFGS has the following advantages: very high sensitivity of $300\ldots500$ mV/W, abnormally low time response $10^{4}\ldots10^{9}$ s making them virtually inertia-free for the study of most heat processes, operability under electromagnetic impacts and insensitivity to pressure drops, high thermal stability (up to $400{^\circ}C$ or more) which makes them an important diagnostic element at thermal power-engineering facilities [5,6].

**Metrological Equipment for Heat-Flux Density Meter Calibration**

The Company manufactures a range of metering instruments for the calibration of heat-flux density metering:

- **UTM–1** heat-metering unit is designed for the reproduction of heat-flux area density during the calibration of heat-flux area density meters by means of referencing in fixed-temperature mode. The unit provides calibration of heat-flux area density meter having different design (thermoelectric, voltaic, semiconductor etc.), different shapes and dimensions (within the working zone diameter of 300 mm), including those with the sensors with the design and shape different from the sensors against which they are referenced. The heat flux area density range produced in the heat-metering chamber is $20\ldots2000$ W/m$^2$.

- **UTM–2** heat-metering unit is designed for the transmission of the heat-flux area density value using direct measurement of the heat-flux area density in fixed-temperature mode. The unit provides calibration of heat-flux area density meter having different design (thermoelectric, voltaic, semiconductor etc.), different shapes and dimensions (within the working zone diameter of 150 mm), including those with the sensors with the design and shape different from the sensors against which they are referenced. The heat flux area density range produced in the heat-metering chamber is $1\ldots3000$ W/m$^2$.

- **UTM–P** heat-metering unit is designed for the transmission of the heat-flux area density value using direct measurement of the heat-flux area density in fixed-temperature mode. The unit provides calibration of heat-flux area density meter having different design (thermoelectric, voltaic, semiconductor etc.), different shapes and dimensions (within the working zone diameter of 200 mm), including those with the sensors with the design and shape different from the reference sensors. The heat flux area density range produced in the heat-metering chamber is $100\ldots10000$ W/m$^2$.

- To gage HHFGS our Company developed and designed a special unit (Fig. 5).

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**Figure 4.** Schematic Diagram of the HHFGS Produced at NPP “Etalon” Company.

**Figure 5.** Schematic Diagram of the HHFGS Gauging Unit.

Legend: 1 – HHFGS to be calibrated; 2 – tube; 3 – housing; 4 – cover; 5 – holder; 6 – thermocouple; 7 – vacuum branch; 8 – heater.
The HHFGS to be gauged are installed onto the tube with the thermocouple. The cover is tightly closed and the working volume is vacuumed to eliminate convection heat-transfer between its elements. In the cover tight connections for the power-supply to the heater and signal reception from the gradient heat-flux sensor and thermocouple. The heat flux from the heater is transferred by emission radial to the outer walls. The thermocouple is used to determine the reference temperature [3,4]. The range of the heat-flux area density in the chamber is approximately 100…30000 W/m².

4. Experiment Results

High-Sensitivity Heat-Flux Sensor

The high-sensitivity heat-flux sensor was tested on UTM-1 heat-metering unit and is further tested at Construction Physics Research Institute (NIISF RAASN), Moscow. The sensor thermocouple materials are constantan-copper. Filling compound MG CHEMICALS 832HT. Sensor dimensions: 40x80 mm, thickness 2.8 mm.

The tests conducted on UTM-1 unit gave good sensitivity and reproducibility results, see Table 1.

| Heat Flux Density, [W/m²] | Sensitivity, [mV/(W/m²)] |
|-------------------------|--------------------------|
| 92.54                   | 0.242                    |
| 188.39                  | 0.241                    |
| 290.62                  | 0.240                    |
| 392.68                  | 0.239                    |

Based on the calculations made the sensitivity measurement error was less than 0.7 %. The sensor conversion ratio was 4.163 (W/m²)/mV.

Based on the preliminary tests conducted at the Construction Physics Research Institute the sensor we manufactured demonstrates a more stable behavior than its equivalents.

Thin-Film Heat Flux Sensor

Thin-film heat-flux sensors are manufactured on two substrate types: sitall (thickness 0.5 mm, foil-plated textile laminate 0.3 mm). The main thermowire is chromium (Cr) meander with the metallization thickness of 0.5 µm, as the second thermowire – nickel (Ni) with the metallization thickness of 1 µm. The sensitive element location area on the substrate was 40x50 mm (Fig.6).

As the overlaps to create the temperature gradient synthetic-rubber-based POLI-FIX 330 double-sided glue tape was used. Thickness 0.08 mm, heat conduction \( \lambda \leq 0.035 \text{ W/(m} \cdot \text{K)} \) at 0 °C. As temperature-leveling coatings 80 µm foil-clad polyimide was used, copper thickness 35 µm.

The tests were conducted on UTM-1 heat-metering unit. The sensor made on the textile laminate substrate demonstrated unsatisfactory results, with the sensitivity of 0.00158 mV/ (W/m²). The sensor made of sitall substrate gave better results: its sensitivity made 0.00338 mV/ (W/m²). These sensitivity readings are approximately equal to the sensitivity specifications of similar sensors manufactured by Captec Company (France) [4].

Heterogeneous Heat-Flux Gradient Sensor
Si-Al-based heat-flux gradient sensor was manufactured using a diffusion welding unit at NPP Etalon Company. The following materials were used for the sensor manufacture:

- КДБ-12 silicon plates, diameter 100 mm, thickness 500 µm, orientation (100), with two-sided polishing
- A5 grade aluminum foil, thickness 0.2 mm, T-hard

Si and Al plates were cut into rectangular plates 35x34 mm. Then they were alternately laid into the vacuum chamber for diffusion welding.

The diffusion welding mode:

The pressure onto the workpiece was about 30 atm., chamber pressure – 10 Pa, initial heating was performed up to 558 ºC, the entire workpiece residence time at this temperature was 10 minutes, then the workpiece was heated to 577 ºC. After the workpiece shrinkage to 20 µm the heating was stopped. The heating time was 52 minutes, cool-down time – 54 minutes. When the temperature in the vacuum chamber was 150 ºC, air was injected and the welded workpiece was removed.

For subsequent soldering of the leads to the sensitive elements the workpiece was coated with chemical-grade nickel.

To produce finished heat-flux gradient sensors the structure was cut into individual elements at 45 ºC to the main Si crystal axes, for cutting a special tool was used. As a result sensors shown in Fig. 7 were produced. The sensor width was 6 mm, thickness 1 mm.

![Figure 7. HHFGS Pilot Samples.](image)

Preliminary tests at UTM-1 heat-metering unit showed the dependence of the thermal EMF on the heat-flux density. For further analysis of the HHFGS’s produced tests at large heat-flux density values at HHFGS calibration units will be held.

5. Discussion of Results

The high-sensitivity heat-flux at the initial research stage came up to expectations, particularly: it enabled attaining the sensor high sensitivity with minor error and the linearity of its signal as function of time. Its disadvantage is large dimensions which may be an issue in case of its use under certain conditions.

During the design and manufacture of the thin-film sensor at this stage it became possible to obtain optimum structure of the sensitive element and thermowire metallization modes. The studies conducted demonstrated that the substrate material is very important for the sensor. In the future the manufacture of a thin-film HFS on a flexible basis is planned which will enable making it a more universal metering instrument. The sensor sensitivity improvement at the expense of applying other metals for thermowires and contact heat-insulation is also planned [5].

At the Unit developed for HHFGS diffusion welding, rather good HHFGS pilot samples were used [5]. The Unit enables rather fine tuning of all the parameters for diffusion welding as well as monitoring of the welding process. The welding modes will have to be worked out. The materials pre-welding treatment is critical: depending on their treatment degree and quality the welding modes and workpiece quality will change, the diffusion does not cover the entire surface of the elements [5].

6. Conclusions

1. High-sensitivity heat-flux sensor after improvements (dimension reduction, sensitivity raising) together with the metrological equipment will enable reliable check of the cladding structure heat conduction as well as monitoring of low heat fluxes which is necessary for the structures’ commissioning. This sensor is
different from its peers by the low output data error, it will enable on-site metering of heat fluxes with high accuracy.

2. Further upgrade and studies of the HHFGS gauging unit. The Unit advantages are stable maintaining of the heat flux in the wide temperature range which enables the sensor gauging in severe conditions.

3. Further upgrade and research of fine-film heat-flux sensors will enable creating flexible sensors with rather a good sensitivity for their use in the laboratories and in various industries where heat fluxes need to be measured in non-conventional conditions and to measure radiation heat flux.

4. HHFGS diffusion welding unit enables producing high-quality HHFGS which will allow their mass-scale production. The following activities are planned: HHFGS manufacture from other silicon and aluminum grades, sensor encapsulation, performance characteristics studies in HHFGS gauging unit. The sensor high sensitivity will enable their application without auxiliary signal amplification equipment. Due to a very low thermal inertia indicator it would be possible to instantaneously read the heat flux value in the sensor location area. The wide operating temperature range will enable its use in extreme conditions which is impossible for the most sensors produced worldwide. Due to their characteristics the sensors will find their application in high-energy industries as well as in aerospace industry.

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