# THE STATE OF HEAT MEASUREMENT IN THE USSR

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By heat measurement is meant a set of methods and facilities for obtaining information on heat flux densities. The formal basis for this survey is that the scientific division headed by the author for over 30 years has coordinated work on that line in this country. Also, during the last 15 years, All-Union conferences have been held every 2 years at which heat measurement has been discussed. The last conference was held in September 1989, and its papers form the basis of the present survey.

Historically, heat measurements always coincided with temperature ones. In the early stages of heat measurement, no clear distinction was made between these two forms of measurement, which satisfied the general sensation of heat phenomena without distinction between the quantitative and qualitative aspects. At the end of the 16th Century, Galileo established that the intensities of these phenomena were qualitative and nonadditive. He was the first to put forward the concept of temperature, which we will use in various forms.

Professionalism played a large part in the practice of heat measurement, which brought about improvements in technology and metrology. That approach was evident from Fahrenheit's 1714 concept. Professionalism occurred in the quantitative heat measurements in calorimetry from the start of the 19th Century (Lavoisier and Laplace). Comprehensive professionalism in heat measurement is a relatively recent phenomenon.

In any measurement, the material basis is always provided by primary parameter sensors. Heat-flux sensors usually employ an auxiliary wall, across the faces of which one measures the temperature difference proportional to the heat-flux density, i.e., in essence such a device is a direct differential sensor, whose advantages have been pointed out by Lykov [1]. Even in the most simplified form of transformation sequence, the measured heat-flux density parameter is converted to a temperature difference, and that difference itself into a difference in the thermoelectric potentials or in thermosensitive resistances, which in a multistage conversion system are converted to some form of output information, from which one can judge the primary quantity. Many decades were required for measurements on electrical quantities to provide linearity in the latter part of such multistage systems. The metrological level for electrical measurements is higher by an order of magnitude than that in heat measurement, so the information correctness in the last stage of the metrological chain is beyond doubt.

The correctness is determined primarily by the primary-sensor performance, but there are error sources not only in the primary sensors but often also to no smaller extent in the other components in the measurement chain. Good conductors differ from insulators in conductivity by up to five orders of magnitude. For conductors of electricity, the difference is by 23 orders of magnitude. The conditions for thermal measurements are thus different from those for electricity as regards conductivity and insulation by 18 orders of magnitude. Therefore, heat measurement has a particular metrological level in each specific line, where there are the following ones to consider: 1) primary heat-flux sensors; 2) direct use of those sensors; 3) thermal radiation detectors; 4) heat loss meters; 5) heat diagnosis.

<u>Primary Sensors.</u> The industrial production of primary sensors began before the war, familiar objects being the Schmidt belt and Al'perovich disks. Advances in ways of making sensors for heat-flux density on the one hand were based on nontraditional phenomena and, on the other, on the improvement of traditional devices as regards metrological and technological characteristics, especially in relation to stability in properties and an extended range of sizes.

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The first line provides for various creative approaches and superficially gives the impression of fundamental research. Most papers on heat measurement belong to that line, and they often are distinguished by features in the tasks and methods.

In essence, these primary sensors are converters for some differential temperature parameter, so one naturally tends to use temperature measurements, while the derivation of differential characteristics is analytic or numerical. To many researchers, that approach appears easier and more readily understood, and ongoing computer advances have emphasized this. Such researchers include the teams directed by professors Alifanov [2], Dul'nev and Matsevityi [3], and Yaryshev [4]. In essence, the line involves not only classification and deeper understanding of existing processes, methods, and instruments, but also the definition of ways of obtaining new results.

During the last 5-10 years, many new designs have been suggested based not only on mathematical or computer analysis, but also on new phenomena or a profound physical analysis of phenomena in potential sensors. There are two ideas on those lines that deserve particular attention. One of them is associated with the thermo-emf for a pair of branches composed of material having the same composition but in different structural states, e.g., austenite-martensite. Measurements [5] have shown that the thermoelectric coefficients for some such pairs are some tens of microvolts per Kelvin, i.e., are only slightly inferior to the best alloy thermocouple values. Primary sensors can be based on them. Their technological and metrological characteristics have not yet been examined.

Another suggestion is to combine pyroelectric and thermoelectric sensors, which is due to V. L. Kremenchugskii. That combination improves the response rate by several orders of magnitude, which eliminates many difficulties associated with sensor lag. Some research results and applications of such sensors have appeared in the last two years [6].

The current state of the art in heat measurement requires not only leading-edge research such as has been described above, but also laborious routine and often thankless effort in the production of high-performance and technologically-stable sensors having the required features. The numbers made must also be sufficient to meet the rising demand. Here we may note particular advances made by a Special Designs Office [7] and by the Division of Heat Measurement at the Institute of Applied Electronics, Ukrainian Academy of Sciences. The designs office specializes in the production of semiconductor devices with high energy factors but with inferior stability. The Heat Measurement Division regularly produces metallic sensors with high stability and constant conversion factor but inferior to semiconductor ones in energy quality. The developments at these two organizations supplement one another in meeting scientific and engineering needs.

The sensor characteristics enable one to measure flux densities between $10^{-3}$ and $2 \cdot 10^{6}$ $W/m^2$ at temperatures between 4.2 and 1000 K. They all have metrological support, and the errors to not exceed ±5%. As a rule, the calibration error is 2-3%, but appropriate physicotechnical conditions can reduce it to 1-1.5% in the near future and ultimately to 0.2%.

At present, about a dozen organizatons produce these sensors. In Kiev alone, apart from the Institute of Applied Electronics of the Ukrainian Academy of Sciences, there are two divisions at the Institute of Thermophysics, Ukrainian Academy of Sciences, the Food Industry Institute [8], two departments at Chernovitsii University, Leningrad Refrigeration Industry Institute, and certain others. That advance in numbers favors progress in heat measurement and supports active cooperation. Unfortunately, the coordination between those researches could be better.

The total number of sensors produced per year is estimated as 10,000, of which up to 90% are made by the Special Designs Office at Tomsk Polytechnic and the Institute of Applied Electronics named above. To determine whether this is adequate, we give data on the production of primary sensors in the USA [9]. The total number of all sensors produced in a year exceeds a billion, of which over 25% are meant for temperature and thermal measurements. The annual rise in sensing-element production is 25-40%. The number of firms that produce primary sensors exceeds 1500, and the total number of types is up to 3000. In that impressive variety, one can see the lines for our future plans, in particular in the production of thermal sensors.

Direct Sensor Use. Direct use of routinely manufactured sensors on the one hand requires adequate knowledge and skill in the user. Incorrect direct use may increase the error of measurement by a substantial factor. On the other hand, direct use imposes certain specifications on the primary features.

The first steps in the data chain are the heat-flux density, temperature difference, and differences in electrical potential or resistance, all of which as a rule are nonlinear. Sometimes, these nonlinearities can balance one another quite fully. For example, the nonlinearity in the thermal conductivity of constantan is balanced over a fairly wide temperature range by the nonlinearity in the temperature dependence of the thermoelectric coefficient. In galvanic sensing elements, the nonlinearity can additionally be controlled by varying the relative coating thickness. The total range in which one can control the heat-measurement parameters for primary sensors is fairly wide. To a first approximation, one can take the number of forms of basic material as about a dozen (constantan, copel, nichrome, chromel, etc.). The number of possible materials for the coating is also restricted to about the same (copper, nickel, antimony, bismuth, iron, etc.).

If one takes the number of possible steps in the relative coating thickness also as 10, then in the simplest case of a single-layer coating, the number of possibilities exceeds $10^3$. With the more complicated variations possible with multilayer coatings, each increase in the number of layers raises the total number of variations by two orders of magnitude. In the three-layer case, the number of possibilities rises to $10^7$, which represents a fairly complicated task, although modern computers can handle it. Such a study has been undertaken in the Heat Measurement Division at the Institute of Applied Electronics.

When sensors are used at temperatures very different from room values, specifications are imposed on the thermal expansion and elastic modulus, particularly when the sensors are to be used at cryogenic temperatures or under vacuum. An example where all these requirements are met is provided by the PTP-13.

The temperature and heat-flux ranges providing effective measurement are given above. To provide these characteristics, the Heat Measurement Division has made sensors with areas from 0.3 to 1000 $cm^2$ and thicknesses from 1 to 7 mm. Some sensors have been used in numbers up to several hundreds in the last three years, including in the Buran space ship and the destroyed fourth reactor at Chernobyl.

Thermal Radiation Detectors. The importance of these in economy is evident from the fact that monitoring and automatic control alone for boilers at power stations would require over 20,000 specialized sensors, and the same devices but in even larger numbers would be needed for heating boilers, coking ovens, open-hearth furnaces, converters, and other plant. Combustion in aviation and space engineering, engineering heating monitoring involving ovens and greenhouses, all require reliable monitoring and thermal radiation measurement. The demand for sensors in the country exceeds $10^5$, which remains largely unsatisfied. Existing developments meet the demand by not more than 1%.

In the USSR, about 10 organizations are concerned with developing these detectors. Mostly, they are for metrological or meteorological purposes.

The best results have been obtained at the All-Union Physical Investigations Research Institute, the All-Union Technical Physics and Electronics Research Institute, the Voeikov State Hydrophysical Observatory (Leningrad), and the Metrology Cooperative in Kharkov. There, the certified errors have been reduced to 1%. The measurable flux densities extend to $10^6$ $W/m^2$. Practical detectors for measuring up to 30 $kW/m^2$ under vacuum and ones working up to $10^6$ and up to $10^7$ $W/m^2$ have been devised in the Heat Measurement Division at the Institute of Applied Electronics, and they have certified errors at the ±8% level. At present, those devices give a spread in measurements on identical quantities of not more than 1%, so it should be possible to reduce the errors to ±2-3%.

Temperature-dependent heaters with electronic controls have been built in the division to stabilize the temperatures of the sensors, which provide systematic errors in thermostatic control of not more than 0.25 K. That control means that an insulated thermostat has a random error of not more than 2.5 mK. That result is of interest to many researchers.

The division has also built sensors for power boilers, which have passed tests lasting over 5000 h at power stations. That instrument has not yet been applied and awaits its time.

Heat-Loss Meters. In energy-saving programs, heat losses play the most important part. Industrial and domestic buildings alone every year dissipate to the environment heat equivalent to combustion of 600 million tons of coal equivalent. There are also losses from the insulation on pipelines and plant, undue heat leaks in refrigerated rooms, and so on, which are not so impressive, but which also correspond to many dozens of millions of coal equivalent. Heat-loss monitoring is therefore very important. Monitoring energy loss is not of itself energy saving, but it is entirely necessary in any approach to it. To meet the associated needs, several organizations have built instruments for measuring heat loss.

The developments at the Heat Measuring Division are representative in that respect: the ITP-12 and ITP-13, which have the following characteristics:

ITP-12

| | |
|---|---|
| Flux density limit, $W/m^2$ | 999 |
| Reading step, $W/m^2$ | 1 |
| Additional error due to change in air temperature around the conversion and measurement device by 10 K, % | 0.1 |
| Settling time, min | 3.5 |
| Power supply RTs 85Kh batteries (four) | |
| Dimensions, mm: | |
| heat flux converter | 33 × 10 × 1.5 |
| signal conversion and measurement device | 150 × 75 × 35 |

ITP-13

| | |
|---|---|
| Limiting flux densities, $W/m^2$ | 5000 and 15,000 |
| Scale division, $W/m^2$ | 100, 300 |
| Basic error, % | ±3.5 |
| Additional error from change in air temperature around converson and measurement device by 10 K, % | not more than 1 |
| Insulation surface temperature, K | not more than 573 |
| Settling time, min | 3.5 |
| Power supply 316 battery (three) | |
| Dimensions, mm: | |
| heat flux converter, diameter | ∅ 10 × 1.65 |
| conversion and measurement device | 215 × 115 × 85 |

As a rule, heat losses and leaks inevitably occur on account of free convection, for which harmonic processes are characteristic. Microprocessors are incorporated to provide averaged values [10].

Heat-Measuring Instruments for Nondestructive Testing. Nondestructive testing is a necessary stage in making new materials and components. Performance in their use is supported in engineering in particular by the organization of on-line monitoring for thermophysical characteristics and strength aspects correlated with them, as well as by the detection of internal defects.

Thermal nondestructive methods have advantages over others, such as acoustic, ultrasonic, and x-ray ones: high sensitivity to changes in thermophysical and geometrical characteristics, scope for operating without an external energy source, heat-leak detection, and safety.

Many industrial tasks can be handled by thermal methods, which are sometimes the only ones available, e.g., in multilayer composite monitoring, observing unglued areas or exfoliation in protective coatings, faults in cemented joints, etc.

It is difficult to observe such defects by traditional methods because there is no absorption of ionizing radiation in nonmetallic layers, or because of the heavy absorption of ultrasound in friable materials, or because electromagnetic methods cannot be used.

Most thermal test systems involve contactless heating and also contactless surface-temperature measurement from the thermal radiation [11, 12]. A major disadvantage is that the resolving power is reduced if there are local emissivity variations, since such areas give rise to temperature differences on contactless heating without relation to defects. When the radiation temperatures are observed with a radiometer, thermal-vision system, or other such detector, the values differ from other defect-free parts, so one cannot identify temperature differences with defects.

One usually needs two-sided access to eliminate the effects of emissivity on the monitoring results.

This shortcoming has been eliminated in the contact methods developed in the Division of Heat Measurement at the Institute of Applied Electronics [13].

The contact method has been implemented in a series of instruments (DT-2, DT-5, DT-9, UTKM-1, and UTKM-2).

Basic components in each case are a thermal probe and electronic equipment connected to it by a cable, with the equipment in a portable case.

The probe includes a sensor, electric heater, and temperature converter, which constitute the thermal measurement head, and a mechanism for applying pressure, which applies a force constant in magnitude and direction pressing the head to the surface.

The electronic equipment consists of an analog-digital converter, synchronizer, thermal-head temperature regulator, and power supply.

The necessary temperature difference between the head and the environment is specified and kept constant by the regulator, which employs a differential thermocouple, whose working junction is in the body of the head and the cold junctions are in the socket on the probe cable.

The probe is brought into contact with the object, and the heat flux from the heater is directed into the object and is measured by the sensor. The flux density is governed by the thermophysical characteristics. A defect such as a continuity fault alters the effective characteristics substantially relative to a good or standard part, which can be detected from the change in flux density.

The instruments have digital readout (UTKM-1 and UTKM-2), the measured quantity being the ratio of the heat-flux densities on the monitored area and on a standard specimen in percent, or else are fitted with sound and light signals indicating defects (DT-2, DT-5, and DT-9).

Methods of conducting tests with these instruments have been devised on standard specimens and on standard and defective items composed of cemented joints in metals, composites, protective coatings, honeycomb structures, etc. The readings have been related to the thermal activity of the material and to the defect sizes and depths, as well as the presence of moisture in honeycomb structures.

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