WAYS OF INCREASING THE ACCURACY OF THERMOPHYSICAL MEASUREMENTS.
1. INCREASING THE ACCURACY OF CONVENTIONAL METHODS

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New methods are described that increase the accuracy and speed of thermophysical measurements. Principles of the design of appropriate instruments and primary measuring transducers are presented, and their metrological evaluation is given.

A lecture on the title topic was presented by the author at the recent International Thermophysical School in Tambov [1]. The content of the lecture is published as an abstract [2] which, certainly, does not give a full idea of the strengths and metrological feasibilities of the new methods and devices for thermophysical measurements. In view of the great interest in the lecture and the numerous letters that were received by the author later as well as many wishes, it seems useful to present more complete information to experimenters in thermal physics the form of several articles with a detailed bibliography of our relevant works.

As is known from the information theory of measuring devices, the attainable accuracy of measurements depends both on the level (power) of the measuring signal, the useful signal-to-noise ratio, and on which parameter of the measuring signal (amplitude, phase, or frequency) contains useful information. The outstanding American physicist L. Brillouin was the first to consider the problem of physical measurements within information theory in his well-known book [3]; the monograph by Russian Prof. P. V. Novitskii can also be recommended [4]. It was found that at a preset level of the measuring signal and preset measuring time, the (averaged) amplitude modulation (amplitude measuring methods) contained the least information and, consequently, gave the greatest measurement error. Under the same conditions, time (or phase) modulation (pulse, pulse-phase, and phase methods of measurement) increases the amount of information (the measurement error is decreased accordingly) $2\pi$ times, if external noise obeys a normal distribution law. Finally, frequency modulation (frequency methods of measurement) has the highest informative value in comparison with the previous methods, and primary frequency transducers provide the highest accuracy of measuring some physical quantities. It is also known that the accuracy of measurement of a physical quantity increases with the time of measurement (the time of continuous averaging of the recorded parameter of the measuring signal), but this increase is not infinite, as it cannot reach the accuracy of the (reference) standard measure that is embedded in the measuring instrument. A normal electromotive force (emf) element with a relative instability of $10^{-4}$ (guaranteed to four decimal places of emf) is ordinarily used in series-produced instruments; in series-produced phase, period and frequency meters measures of time intervals or frequencies are used whose stability is higher by two or more orders of magnitude. This is another important advantage of the frequency and phase methods of measurements over the amplitude methods. It should be noted that, other things being equal, for achievement of a preset accuracy of measurement, the frequency methods provide the shortest time of measurement (the fastest measurements), and the amplitude methods, the longest time (the slowest measurements).

In this connection, it is necessary to state that in contemporary experimental thermal physics the levels of accuracy and speed of measurement of thermal quantities and thermal properties are much lower in comparison with the levels achieved in other fields (for example, measurement of mechanical, electric, and acoustic parameters...
of compounds and many other physical quantities.) Analysis has shown that in experimental thermophysical studies, conventional amplitude methods that employ various kinds of measuring bridge are used, as a rule, which, as was stated above, give the worst results from the view point of accuracy. Phase methods of measurement are seldom used; frequency transducers of temperature and other thermal quantities are used sometimes, but they are ineffective, because they are based on the principle of electrical resonance, and in this case the accuracy of measurement of a physical quantity, for example, temperature, is determined not by the accuracy of measurement of frequency, which can be extraordinarily high, but by the quality of the resonance transducer. Experimenters often neglect this fact and in scientific papers they give underestimated measurement errors.

It should be noted that the accuracy of measurement of thermal properties is determined not only by the accuracy of measurement of the parameter of the appropriate sensor (for example, resistance of the thermistor, or emf of the thermocouple), but also by some other conditions connected with the peculiarities of thermal phenomena. Among these conditions we can mention the necessity to take account of thermal drift of the sensor, real conditions of thermal interaction of the sensor with the object of study, etc. Many authors have devoted their works to these matters; therefore, this problem will not be considered here, but our entire attention will be concentrated on the accuracy of measurement of the parameters of thermal sensors. The different methods will be comparatively estimated with measurement of temperature, its excessive value, and the rate of change as an example. At present, for this purpose thermocouples and thermistors are most widely used under ordinary conditions. In the former case temperature is inferred from the value of the thermal emf, i.e., only amplitude methods are used; in the latter case, temperature is found from the active resistance, its changes or contribution to the transfer function, and to the phase-frequency characteristic of a primary transducer with a thermistor as its component. Therefore, amplitude, phase, frequency, and other more complicated methods can be used in these cases. Thermistors seem preferable as thermal sensors, especially when high accuracy of measurements is required; they are gradually replacing thermocouples, especially in view of the fact that in recent years great achievements have been made in obtaining high stability of time and in decreasing the technological scatter of parameters of manufactured semiconductor thermistors.

First, we consider the possibility of increasing the accuracy of measurement of the parameters of sensors by conventional phase and frequency methods.

Phase Methods. They are as versatile as amplitude methods, since a phase meter can measure almost any physical quantity that can be measured by electrical methods. In this case the quantity measured can be transformed by a transducer into a phase shift or a time delay between two electrical (reference and measuring) signals. In this case the primary measuring transducer (sensor) is a phase-shifting circuit that switches on the thermosensitive element or a delay line that contains a radiator, a receiver of (ultrasonic, light, or radio) waves, and the object of study, through which sounding waves are transmitted.

If an a.c. bridge with a thermistor with resistance \( R(t) \) connected to one of its arms is used as a primary transducer, then by analysis of the argument of the transfer function of the bridge circuit, it is possible to calculate the bridge arms in such a way that the increment of the phase shift \( \Delta \phi \) of electrical oscillations at the input-output of the circuit is minimal with changes in \( R \), and the derivative \( d\phi/dR \) can be \( 1.5 \cdot 10^{-2} \) rad/\( \Omega \). Series-produced digital phase meters measure phase shift with an error of 0.1 of an angular degree (\( \pm 10^{-4} \)), which corresponds to relative measurement error \( \delta R/R = 7 \cdot 10^{-5} \). For example, for an STZ-14 thermistor it means that a series-produced phase meter can measure temperature with an error of \( 3 \cdot 10^{-3} \) K. This measurement error can also be achieved by amplitude measurement, but then it is close to the feasibility limit of the method.

The relatively high error of series-produced digital phase meters (such as the F2-34) mentioned above can be explained by the fact that these phase meters are intended for measuring phase shifts over a wide frequency range. For our purpose we can restrict ourselves to one or several fixed frequencies, for example, 1 or 5 MHz. For these frequencies there are highly stable generators, comparators, precision radiometers, and metrological aids. When phase meters are used at a fixed frequency, use can be made of high-quality circuits, principles of phase multiplication, etc., which provides accuracy in measuring phase shifts that is higher by several orders of magnitude and does not make the circuit design more complicated or increase the cost. Such a phase meter can contain a built-in generator of a harmonic signal which is a reference signal for the meter and is simultaneously fed to the