## HEAT AND MASS TRANSFER AND PROPERTIES
## OF WORKING FLUIDS AND MATERIALS

# A Technique for Scanning Probe Measurement
# of Temperature Fields in a Liquid Flow

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**Abstract**—For designing different heat and power equipment with a wide range of applications, it is necessary to measure the fields of thermophysical characteristics (temperature, pressure, velocities, etc.) in as much detail as possible. At the same time, the deployment of complex diagnostic methods is often impossible. Therefore, it is most practical to use movable probes that move in the flow and make measurements at separate points. The use of such scanning measurement methods is a complex task that requires the solution of many mechanical and thermophysical problems. The techniques of scanning probe measurements for determining thermal characteristics in the flows of various media are described. A review is given concerning the development of probe-based investigation methods since the 1960s. Joint probe developments concerning the probes made by the scientific group of the Engineering Thermophysics Department of the National Research University Moscow Power Engineering Institute and the Joint Institute for High Temperatures, Russian Academy of Sciences, for two-dimensional and three-dimensional temperature and velocity measurements in water and mercury flows are presented in detail. The experience in the development and use of scanning probes is summarized in three main designs, such as a hinged probe, a probe with eccentricity, and a longitudinal probe. Descriptions, methods of application, and the features of their operation are considered for these designs. The results obtained by using the probes of various designs in the course of experiments with water and mercury are considered. The choice of a required technique is substantiated depending on the preset conditions of the problem, such as the geometric characteristics of the investigated area, the presence of a magnetic field, the influence of thermal and gravity factors.

*Keywords:* probe measurements, probes of various designs, velocity and temperature fields, microthermocouples, liquid flow, invasive measurement method

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All the existing methods of temperature measurement in different tasks can be divided into three types: invasive (the methods that require direct contact), semiinvasive, and noninvasive methods. The noninvasive methods include infrared thermometry, absorption and emission spectroscopy, laser-spark fluorescence, refractive index measurements, etc. In the case of semiinvasive methods, one commonly uses thermosensitive labels and granules, thermoscopic bars and pyroscopes (Seeger cone). An extensive review of temperature measurement tools is presented in [1].

Despite all the obvious advantages of remote and indirect temperature measurements, there are situations wherein one cannot do without invasive methods, for example, when it is necessary to measure the temperature in a flow of opaque liquid. In such cases, it is advisable to use such sensors as thermocouples and resistance thermometers. They can be inserted into the wall to make measurements; however, limited information concerning the wall temperature rather than the temperature of the flow as a whole can be obtained. In addition, the introduction of thermocouples or other sensors into the wall can distort the obtained results to a great extent owing to the violation of the homogeneity of the wall material. In the case of such problems, the probe measurement technique is more preferable than the others.

## PROBE TECHNIQUE FOR MEASURING
## TEMPERATURE FIELDS

Temperature fields are measured using stationary or movable probes, at the end of which temperature sensors, such as thermoelectric converters and thermal transducers, are mounted. The transducer's sensing element (a thermocouple junction, thread or resistance temperature detector film) contacts with the studied
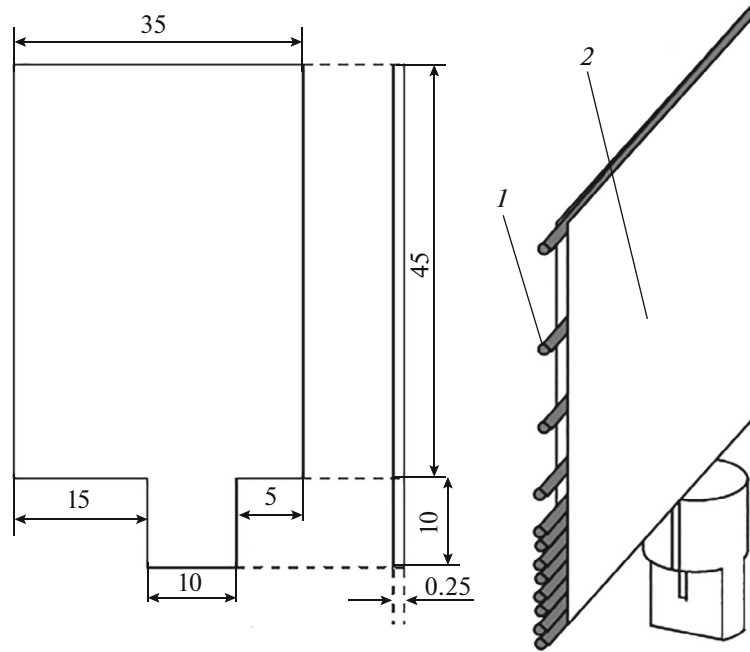
**Fig. 1.** Schematic diagram of a "thermocouple tower" probe (the sketch is restored from the data of [2]. (*1*) Thermocouples and (*2*) plate.

fluid directly or through an intermediate element, e.g., a thermal housing, sleeve, protective deposit, etc.

Commonly, for the manufacture of thermocouples, small-diameter wires made of materials having a



**Fig. 2.** Schematic diagram of a probe introduced into the flow through the side wall (the sketch is restored from the data of [5]). (*1*) Probe; (*2*) thermocouples; (*3*) potentiometer; *u*, *v*, and *w* are the components of the velocity vector; *B* is the magnetic field induction; *a* is the characteristic size; *z* is the longitudinal axis.

low thermal conductivity are used. The structural elements of the probe are placed in isothermal planes. The effect of radiation is reduced via reducing the size of a sensitive element (thermocouple junction) by covering it with materials having a low emissivity and with the help of shielding.

One of the initial stages of the development of the probe technique consists in the use of fixed immovable temperature sensors that are in direct contact with the flow [2–4]. For example, the authors of [2] used a probe design called a "thermocouple tower" (see Fig. 1) to measure radial temperature distribution in the case of KOH solution flowing in a round pipe. Figure 1 shows that the design has been developed in such a way as to conduct detailed measurements in the near-wall area. Using this probe, temperature profiles were measured both in the absence and in the presence of a magnetic field and at different angles between the direction of the magnetic field and the plane of the thermocouples. The authors of this technique have succeeded in fixing the deterioration of heat transfer with the imposition of a transverse magnetic field as well as other magnetohydrodynamic effects.

There is a similar technique but with the possibility of moving temperature sensors: a probe is inserted through the side wall of the channel into the flow of a heat-carrier [5, 6]. This technique allows one to measure the temperature distribution along over the radius (channel width) in a given section (Fig. 2) as well as to measure velocity fields, pressure fields, etc. In addition, using a similar technique, one can perform the studies at once in several sections along the length of
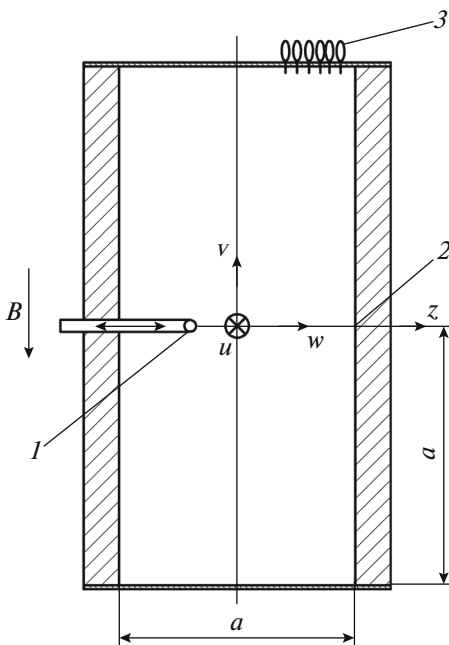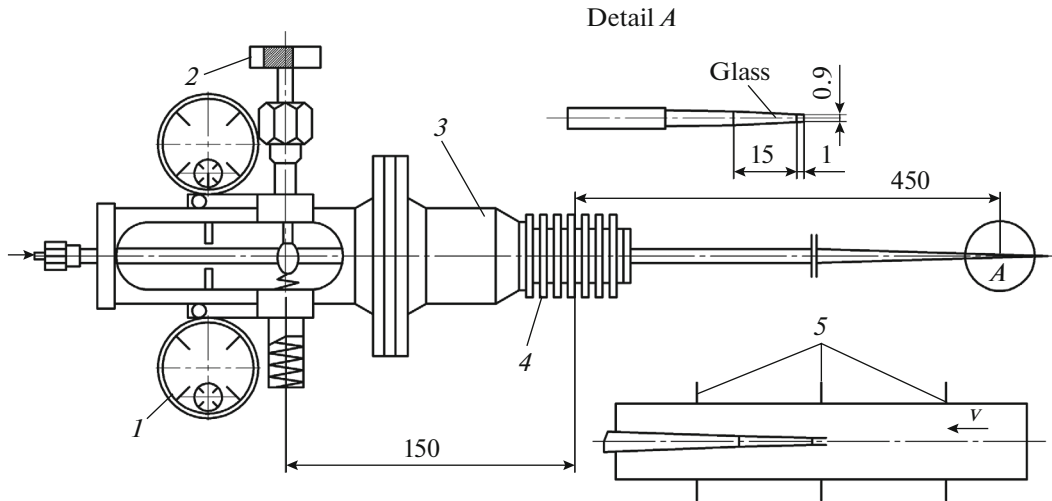
Detail *A*



**Fig. 3.** Hinged probe (the sketch is restored from the data of [18]). (*1*) Movement indicators; (*2*) microscrew; (*3*) centering surface; (*4*) bellows; (*5*) external electrodes.

the channel, since miniature sensors introduced through the wall do not make any significant disturbances in the flow. However, the use of this method is not sufficient for more detailed measurements in the cross section of the channel.

In parallel with the above-mentioned studies, the researchers at the Engineering Thermophysics Department of the National Research University Moscow Power Engineering Institute developed their own novel probe technique. The studies were carried out with several types of heat-carriers flowing in channels having different configurations and different geometric characteristics [7–17]. Further, we consider movable probes belonging to the main used types in more detail.

## HINGED PROBE OF A LEVER TYPE

Some studies with the use of hinged probes were published by the authors of [7, 18, 19], wherein the measurements were carried out in a flow of liquid metal. The used probe represents a lever that rotates around the hinge in such a way that, when one end of the lever moves with the help of a coordinate mechanism, its second end with a sensor (thermocouple) can be placed to a preset point of the experimental section (Fig. 3) [7].

Among foreign papers published at the same time, one should mention a publication [20], whose authors used the probe of the same design as the authors of [7, 18] to measure the flow velocity but replaced the thermocouple by a Pitot tube (Fig. 4).

Further, we consider in more detail the hinged probes that we used directly in this work. As in [7, 18–20], we take a design that represents a lever capable of turning around a hinge as the basis. The longer lever arm represents a rod having a variable cross-section,

on the tip of which a sensor is mounted (Fig. 5a). As the sensor, a thermocouple is usually used, the bead of which is attached using special adhesive compositions at the end of a stainless-steel capillary with an outer diameter of 0.3 mm, so that the thermocouple wires pass inside the capillary. The choice of adhesive composition depends on the aggressive properties of the used medium and on the temperature of the flow. The capillary, inside which there are thermocouple wires, is glued or welded into a capillary with a larger diameter (0.7 mm). The whole structure is fixed on the probe rod that is inserted through a bellows joint into the tested section towards the flow. Separately, it should be noted that, for the years in the course of which hinged probes were used, a lot of their modifications were developed with the use of different sensors to measure the flow temperature, velocity, etc. (Figs. 5b–5d).

The short arm of the lever is connected to the coordinate mechanism, which allows one to move the microthermocouple over the pipe section. The length
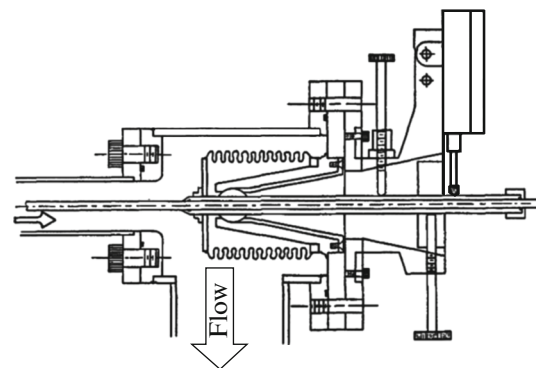


**Fig. 4.** Schematic diagram of a hinged probe (the sketch is restored from the data of [20]).
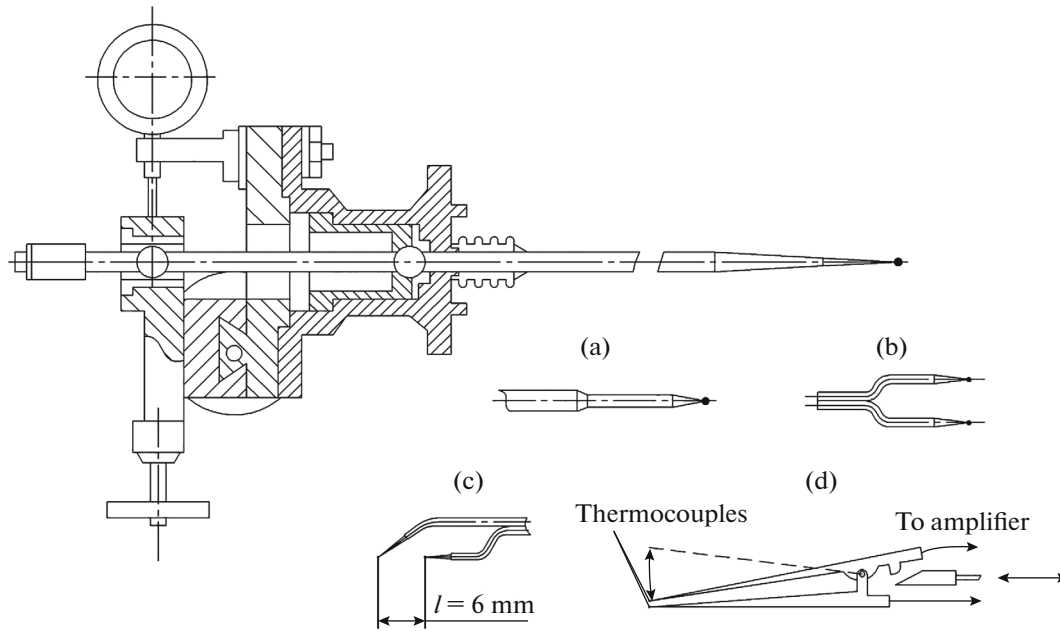
**Fig. 5.** Schematic diagram of a lever-type measuring probe. (a) Thermocouple for temperature measurement; (b) conduction velocity sensor [9]; (c) correlation velocity sensor [9, 10]; (d) sensor for measuring transverse velocity correlation [8].

of the probe rod is chosen in such a way so that the rod length is 15−20 times larger than the section of the channel. Thus, when the rod is rotated, the thermocouple moving along the radius remains in almost the same plane perpendicular to the axis of the channel.

The coordinate mechanism represents two micrometric screws, which allows one to move the end of the probe in two mutually perpendicular planes (horizontal and vertical ones) and to place it at any point of the cross section. Two electronic displacement indicators allow for the probe head to be placed into a preset position with an accuracy amounting to 10 μm. After



**Fig. 6.** Determination of the coordinate and the temperature of the wall.

the installation of the measuring probe at the experimental pipe section, a preliminary calibration of the coordinate mechanism of the probe is performed with the use of optical devices.

With the help of an electronic endoscope, it is visually monitored so that the probe is guaranteed to touch the wall just with a thermocouple in die positions. Further, the position of the wall is determined from the fracture of the temperature profile (Fig. 6). In Fig. 6, $r/r_0$ is the dimensionless radius of the tube (here $r$ is the current coordinate of the probe measured from the wall, $r_0$ is the radius of the tube) and $\theta$ is the dimensionless temperature that is expressed as

$$\theta = \frac{(t - t_{\mathrm{L}})\lambda}{q_{\mathrm{w}}d_{\mathrm{h}}},$$

where $t$ is the temperature in the current section, $t_{\mathrm{L}}$ is the bulk mean temperature of the liquid, $\lambda$ is the thermal conductivity of the heat-carrier, $q_{\mathrm{w}}$ is the heat flux density on the wall, and $d_{\mathrm{h}}$ is the hydraulic diameter of the channel.

For the flow of any configuration, the position of the probe sensor is determined with respect to the area of constant heat flux and to the area of constant magnetic field in case they are present.

One of the reliable ways to determine the wall coordinate, alongside with taking into account a fracture in the temperature profile, consists in using the symmetry of the temperature distribution or other characteristics with respect to the center of the section (Fig. 7).
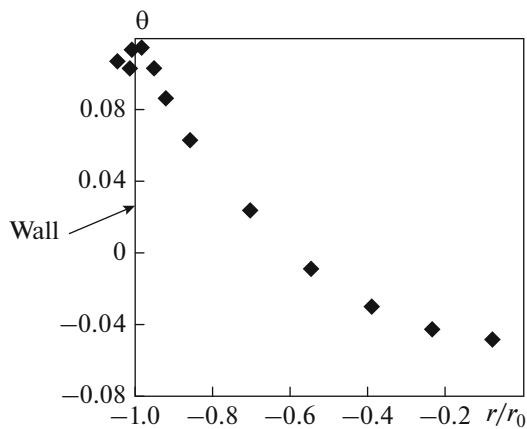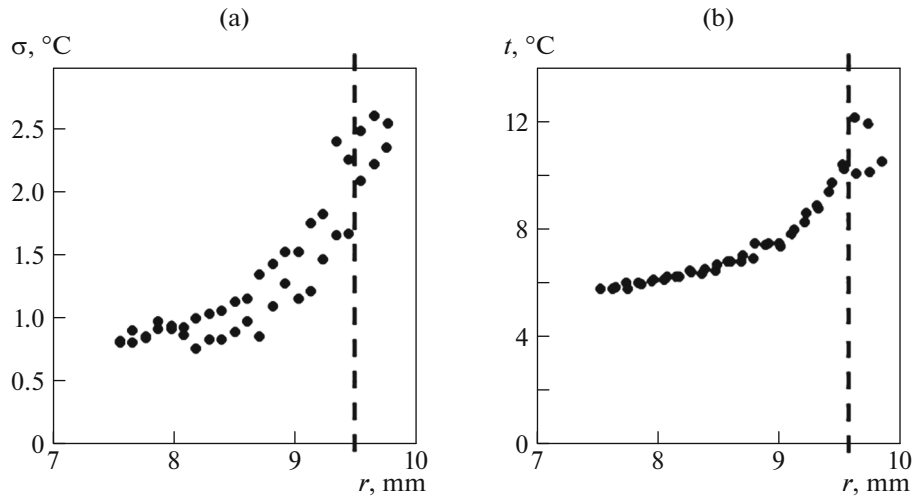
**Fig. 7.** Centering of a probe using the symmetry of temperature pulsation fields σ and the liquid dimensional temperature $t$.
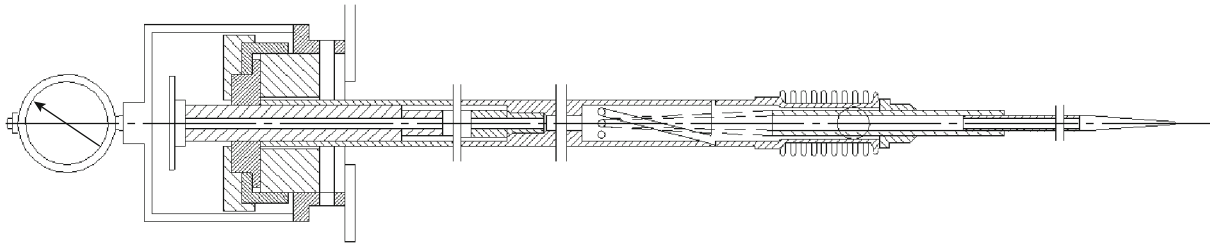


**Fig. 8.** Movable thermocouple (the sketch is restored from the data of [21]).

In some cases, an electro-contact method can be used in order to detect the contact between the wall and the probe tip, i.e., when the thermocouple touching the wall closes the electrical circuit.

We should separately mention an improved version of the probe that allows one to perform measurements in both the longitudinal and transverse directions. The same team of authors that participated in [18] carried out studies with the use of the probe in a sodium-potassium flow [21]. The authors have developed a device (Fig. 8) for moving the sensor, which includes a jack-type mechanism for longitudinal movement and a wedge-type mechanism for lateral movement. The probe of this design has made it possible to obtain a considerable amount of information while simultaneously maintaining a high sealing level of the experimental pipe section and observing safety under operation with toxic media.

## LONGITUDINAL PROBE
## WITH ECCENTRICITY

With the help of lever probes, it is possible to make measurements in only one preset fixed section. In order to measure local characteristics over the entire length of the flow, special longitudinal probes are required. The first longitudinal probes with eccentricity [11, 12] were designed to study the statistical characteristics (the intensity of temperature pulsations, autocorrelation functions, frequency spectra, etc.) depending on the longitudinal and transverse coordinates. The main parts of such a probe are two coaxial tubes that can rotate around their own axes and move along the flow either as a single whole or as one with respect to another (Fig. 9). There are holders glued to each of the tubes with the use of epoxy resin; bared microthermocouple beads are fixed at the ends of the holders using the same method as that used in the hinged probes. Such a design allows one to move simultaneously both thermocouples along the flow over the entire length of the heated section as well as to move the first thermocouple with respect to the second one up to a distance of 50 mm. With the help of a hinge, one can move sensors (thermocouples, etc.) over the cross section of the pipe and provide a maximum approach with respect to the wall. Just as in the case of hinged probes, the moment of contact is determined by a fracture on the temperature profile.

This design has several disadvantages, such as difficulties in the manufacture as well as a hazard of probe depressurization (owing to the presence of two stuffing
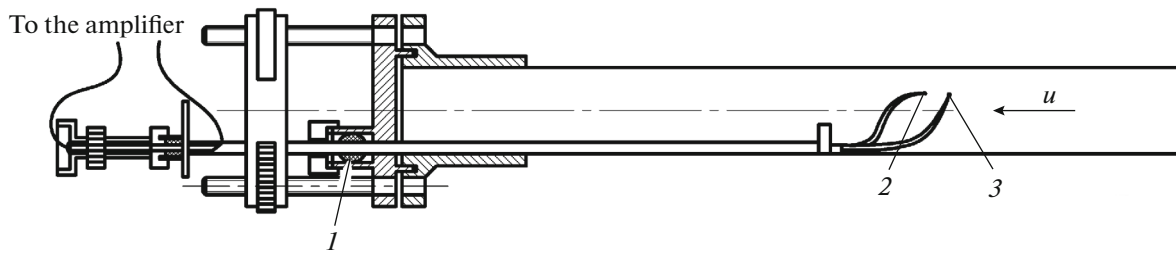
**Fig. 9.** Probe with eccentricity. (*1*) Seal and (*2, 3*) thermocouples.
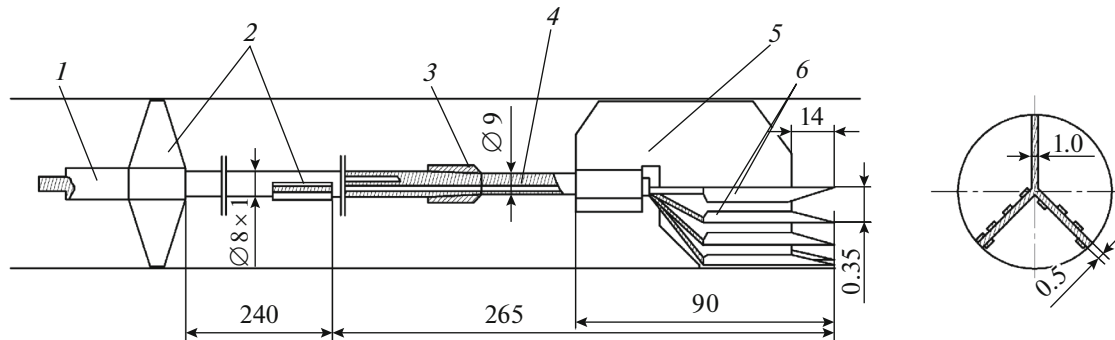


**Fig. 10.** Longitudinal probe for measuring the temperature fields (drawing recovered from [22]). (*1*) Pipe; (*2*) sealing nut; (*3*) seal; (*4*) rod with a longitudinal groove; (*5*) probe blades; (*6*) grooves.

box seals (see Fig. 9)) when operated in toxic media and in the environment of heat-carriers.

Due to these difficulties, the amount of experimental data measured using this probe is relatively small. However, with the help of this probe, information was obtained for the first time concerning the length of the pipe section wherein the thermal stabilization of the statistical characteristics of temperature fluctuations is observed in the flow of mercury [11]. This has made it possible to substantiate the choice of the length of a heated pipe section in the course of further experiments.

There is a modification of an eccentricity probe wherein only one thermocouple is installed for detailed measurements in the near-wall area. Further, temperature measurement results using the modernized probe [13, 14] are presented.

## LONGITUDINAL COMB-TYPE PROBE

One of the commonly used longitudinal-type probes is represented by a comb-type probe. The authors of [22] measured temperature distribution in a mercury flow using a longitudinal temperature probe (Fig. 10) that represents a set of thermocouples mounted on a plate at fixed distances from the wall and has translational and rotational degrees of freedom. Owing to such a design of the probe, data were obtained based on which the authors have been able to draw conclusions concerning the axial symmetry of the temperature field and the stabilization of the temperature profile along the length of the pipe and to be certain that there is no influence of natural convection.

Figure 11 shows a scheme of the probe that is used in the authors' experiments on studying the flow development along the length of the experimental pipe section.

The measuring element of the probe consists of five copper-constantan thermocouples with 50−70-μm diameter junctions (Fig. 11a), fixed with epoxy resin in glass capillaries with a diameter of 0.13 mm, which pass into capillaries made of stainless steel with a larger diameter (0.3 mm), and then 0.8 mm, thereby forming a holder. It is possible to manufacture the holder in such a way that the position of the extreme thermocouples is fixed for constant contact with the wall as was done when using the holder with ten thermocouples (Fig. 11b). The thermocouple holder is mounted on a rod. To fix the probe in the radial direction, centering rings ground in the inner surface of the pipe are used.

The coordinate mechanism provides the probe movement along the length of the heating zone and the rotation thereof around the longitudinal axis. Owing to this, it is possible to obtain a detailed temperature field in a preset section. The hermetic connection between the movable rod with a fixed flange is performed using a stuffing box seal. The coordinates of the thermocouple junctions are determined via a preliminary optical calibration using a cathetometer.
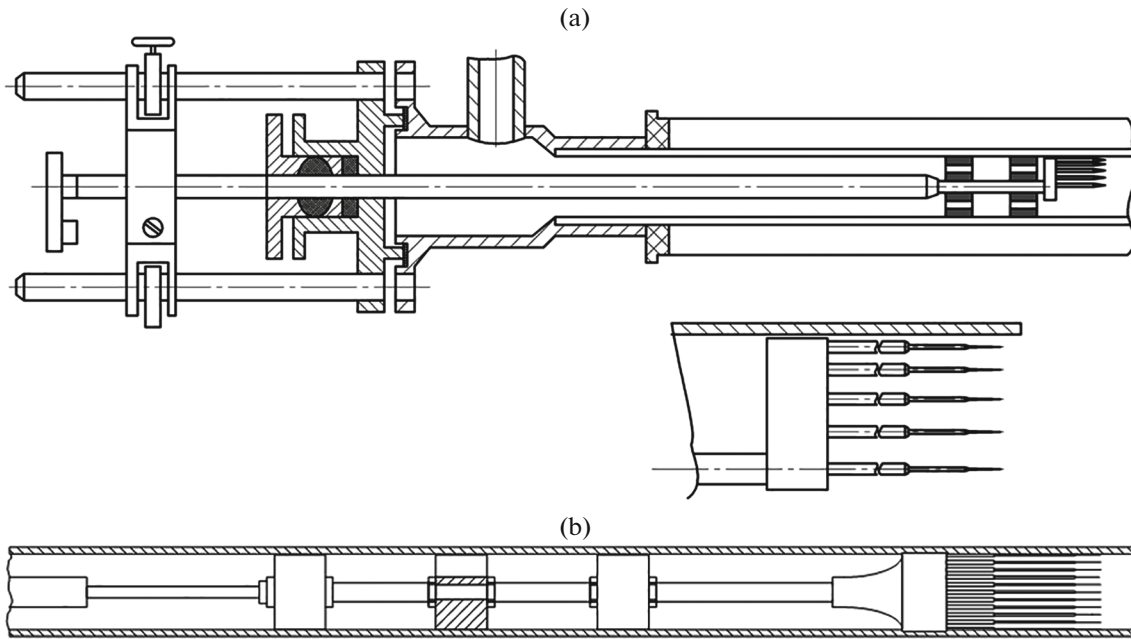
(a)



(b)

**Fig. 11.** Longitudinal probe "comb" in the pipe of the working section (a) with five thermocouples and (b) with ten thermocouples.

It should be emphasized that, despite the presence of the centering rings, uncontrolled movements of the holder and the thermocouples of the "comb" in the radial direction are possible. These movements are small, but the uncertainty in the coordinates of thermocouples connected with the movements could be a source of a distortion for the temperature profiles. To estimate this uncertainty, the method shown in Fig. 12 was developed [15].

Based on preliminary calibration data, the authors believe that thermocouple beads are located at the points with coordinates $R_1-R_5$ ($R$ is the radial distance from the channel axis). If one assumes that the probe has shifted in the radial direction by a distance of $\Delta R$, then all the junctions of the thermocouples shift by the same distance and, therefore, they measure the temperature values that are marked in Fig. 12 with black dots. By connecting the measured temperature values with coordinates $R_1-R_5$, wherein, as it was mistakenly assumed, the junctions of the thermocouples are located, one obtains a distorted profile *2* instead of the true temperature profile *1* (see Fig. 12). The calculations have shown, under shifting the thermocouples by $\Delta R = \pm 0.1, \pm 0.2, \pm 0.3$ mm, the temperature profiles exhibit stretching (flattening) by 1.5, 3.2, 5.0%, respectively. The calculations were based on the temperature profiles obtained as a result of thorough measurements using a lever probe (see Fig. 5).

Figure 13 shows, as an example, the development of the temperature field along the length of a heated section of a round pipe.

## COMPARISON OF THE RESULTS OBTAINED USING PROBES OF DIFFERENT DESIGN

For each probe type, a different movement program exists. The general stage consists in the measurement of the operating conditions before the beginning of probe measurements in each section.

In the case of a lever probe, each time when the probe thermocouple moves to a new measurement point, input/output temperatures of the experimental section are measured, and the oscillogram of the probe thermocouple readings is registered (Fig. 14a). In the lower part of Fig. 14a, an example of the tem-
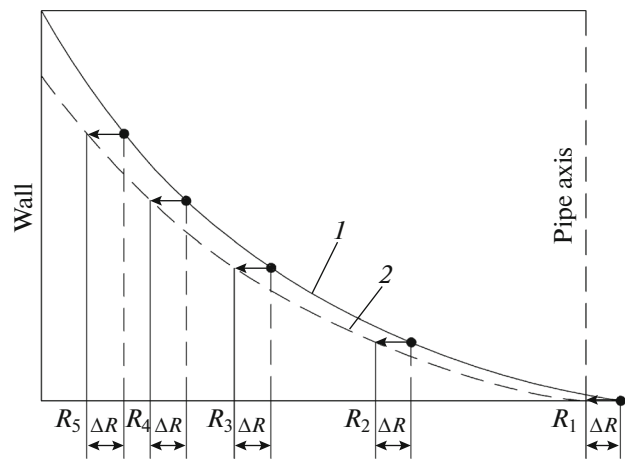


**Fig. 12.** Scheme for estimating the uncertainty of temperature profile measurements using a longitudinal probe. (*1*) True profile and (*2*) measured profile.
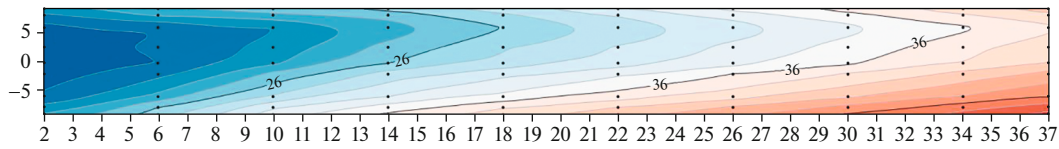
**Fig. 13.** Longitudinal temperature field, °C, in a round pipe.

(a)                                   (b)                                   (c)
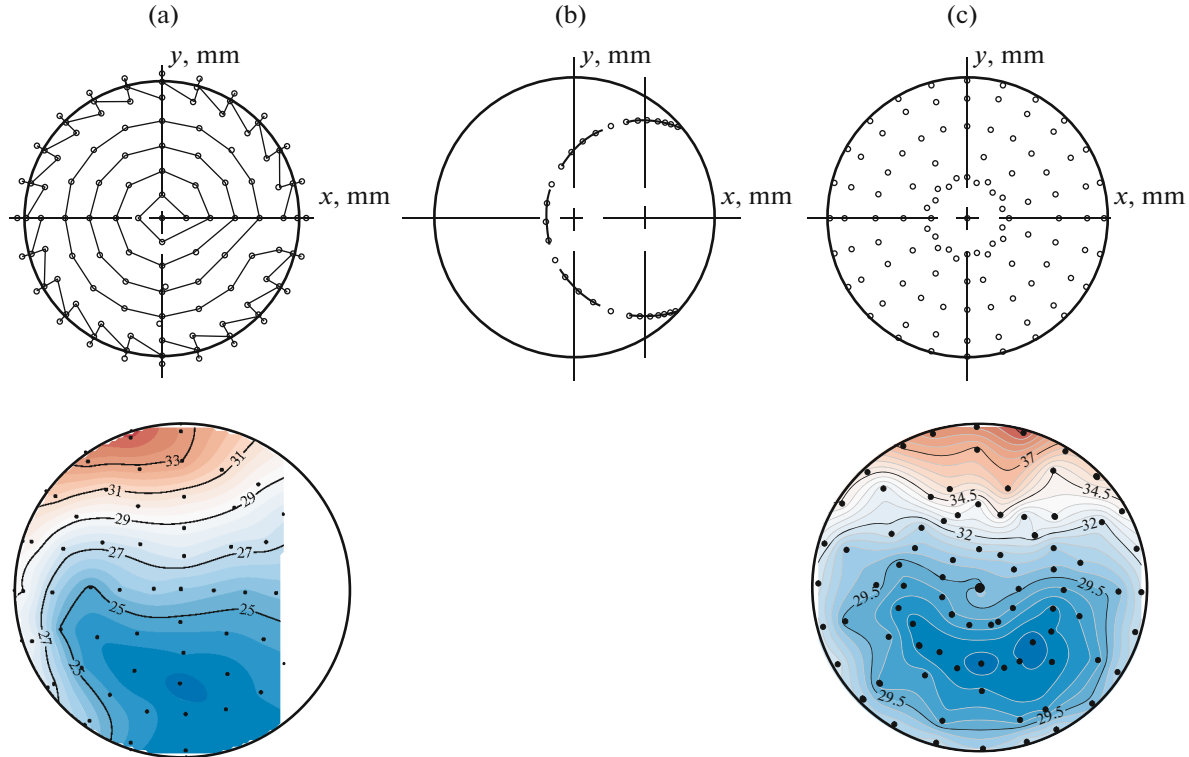


**Fig. 14.** Trajectory of the passing through the pipe section by the probes of different types and the examples of obtained temperature fields. (a) Hinged probe; (b) probe with eccentricity; and (c) longitudinal probe.

perature fields obtained using a hinged lever probe is shown. The empty space on the graph of the temperature field can be explained by the fact that the temperature measurements were carried out using a correlation velocity sensor [9, 10], the design of which makes it difficult to approach the wall in some sections of the channel.

Figure 14b shows the movement trajectory of the sensor of the probe with eccentricity. The probe is installed in the working area not in the center in such a way as to investigate the viscous sublayer in detail passing along a preset route marked with a dotted line, therefore the grid of points is thickened therein. Just as it is in the case of a hinged probe, it is necessary in the course of the measurements to register the temperature at the inlet and outlet of the channel as well as the oscillograms of the thermocouple probe readings.

The longitudinal comb-type probe (Fig. 14c) automatically moves along the length of the experimental section, passing through several sections. In each section, the probe rotates around its axis, and thermo-

couple readings are registered at each turn (up to ten thermocouples were used in the authors' experiments). Thus, the entire cross section of the pipe is examined (see the bottom of Fig. 14c).

In the study of hydrodynamics and heat transfer for a liquid flowing in the channels of different shapes and under the action of various factors, such as application of a heat flux or of a magnetic field (electrically conductive liquid), detailed information is required concerning the main characteristics of hydrodynamics and heat transfer depending on the length and the cross section of the channel. Therefore, the use of different probes allows one to get closer to obtaining the most complete information. For different reasons, it is not always possible to implement such an approach in practice. By comparing the results of the measurement of the parameters performed using different methods, one can obtain additional information about which methods of measurement are more worthwhile to use in the specified conditions, in the channels of different shapes, etc.
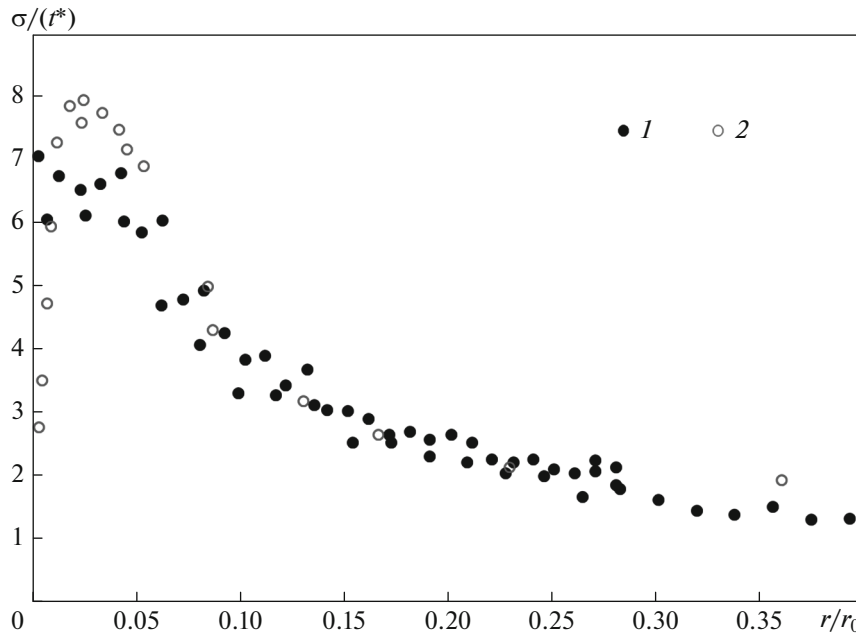
**Fig. 15.** Comparison of the intensity distributions of temperature pulsations (*1*) obtained using a hinged probe and (*2*) that obtained using a probe with eccentricity. (*1*) $q_w = 20$ kW/m$^2$, Re = 6000; (*2*) $q_w = 22$ kW/m$^2$, Re = 7500.

As an example, data obtained using different methods are compared. The probe shown in Fig. 9 has been developed, in particular, for detailed measurements in the near-wall area of flows [13, 14], including a viscous sublayer. Figure 15 shows the distribution of the intensity of temperature fluctuations $\sigma$ along the dimensionless pipe radius $r/r_0$ obtained using an eccentricity probe compared with that for a hinged probe. In order to compare the intensities of the temperature pulsations, the data were made dimensionless using a technique described in [13] according to the following relationship:

$$\bar{\sigma} = \sigma/t^*,$$

where $t^*$ is the dynamic temperature calculated according to the following formula:

$$t^* = q_w/(\rho c_p u^*).$$

Here $u^* = \sqrt{\tau_w/\rho}$ is the dynamic velocity; $\tau_w$ is the shearing stress on the wall; and $\nu$, $\rho$, and $c_p$ are the kinematic viscosity coefficient, density, and heat capacity of the liquid, respectively.

As can be seen from Fig. 15, the obtained results are in good agreement between each other within the error of measurements, except for the near-wall region, where, owing to the size of the thermocouple bead of the hinged probe, it is impossible to come close enough to the wall. In the case of a probe with eccentricity, such a problem does not arise owing to the trajectory of its movement. Thus, in the course of measuring with the use of a hinged probe, a space-averaged value of temperature fluctuations in the near-wall region, rather than a local one, can be obtained. This example suggests that it is possible in some cases to confine oneself to the use of a hinge-type probe, since it is easy in operation and allows one to study substantially asymmetric flows.

However, another situation is possible, when the probe of one of the designs generates a disturbance in the flow and distorts the flow pattern under study. As already mentioned, the measurements of the main hydrodynamic and heat-transfer characteristics along the length are not less important than the measurements over the cross section. However, it is necessary to use comb-type probes that have a rather massive structure with respect to the cross section of the experimental pipe section. Figure 16 shows the distribution of the dimensionless temperature over the perimeter of the section (angle $\varphi$) obtained using longitudinal and hinged probes.

In practice, the use of dimensional wall temperature for comparing the profiles and other distributions in a flow is difficult, since it is not always possible to maintain a constant flow temperature at the channel inlet and outlet or to maintain the experimental conditions in general. In the authors' opinion, a more convenient parameter can be represented by the dimensionless wall temperature (inverse Nusselt number), which is expressed as

$$\theta_w = \frac{(t_w - t_L)\lambda}{q_w d_h},$$
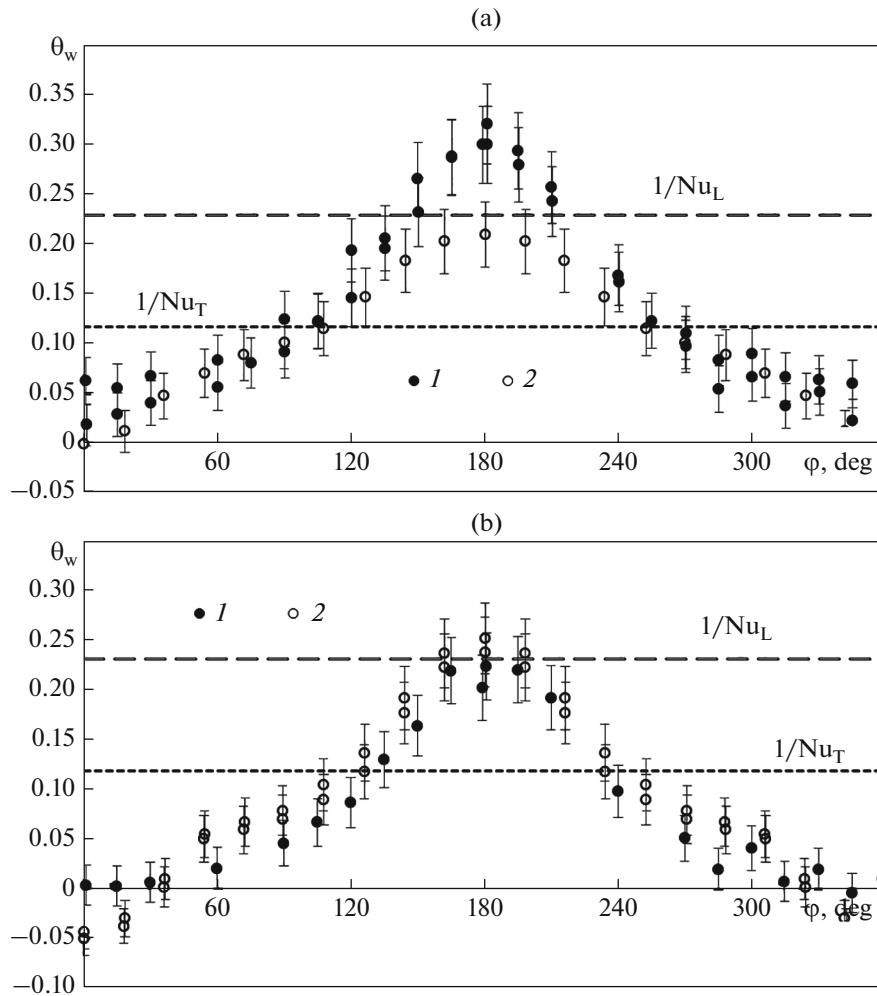
where $t_w$ is the wall temperature.

**Fig. 16.** Distribution of the dimensionless temperature $\theta_w$ around the perimeter of a round pipe inclined at an angle of 30° with respect to the horizon, in the section located at a distance of 37 calibers from the inlet into the channel, obtained (*1*) using a comb-type probe and (*2*) using a hinged probe (*2*). (a) $q_w = 15$ kW/m$^2$, Re $= 10^4$; (b) $= 50$ kW/m$^2$, Re $= 2 \times 10^4$; Nu$_L$ and Nu$_T$ are the laminar and turbulent Nusselt numbers.

The results shown in Fig. 16a exhibit a good coincidence on average, but there is a significant difference in local values near the upper generatrix of the tube. This, in the opinion of the authors, indicates that the longitudinal "comb" probe (which is more cumbersome than the hinged probe) introduces some distortions into the structure of the heat-carrier flow. However, this does not mean that the comb-type probe is absolutely not applicable. Thus, in the case of the doubled flow rate, these data coincide with each other even when heat fluxes are significant (see Fig. 16b).

## CONCLUSIONS

(1) The scanning probe measurement technique allows one to obtain complete information with any detailed degree concerning the structure of liquid flows in the channels having different shapes. To solve different problems, the probes of different designs are used.

(2) The most universal probe is a lever probe. With minimal modifications, it can be used for measurements in channels with different shapes. Two-dimensional fields obtained with its help serve as reliable data for the verification of numerical methods, whose use allows one to further obtain a complete picture of a three-dimensional field.

(3) The probes with eccentricity are optimally suitable for studying near-wall areas in channels, the flow wherein is symmetrical. Their significant disadvantages consist in a geometrically restricted area of measurements as well as in fundamental impossibility to operate in the flows that are substantially inhomogeneous over the cross section.

(4) The longitudinal probes are capable of giving the most complete picture; however, their bulkiness com-

plicates the interpretation of the results and requires an independent confirmation of the obtained data.

(5) The determination of the universal applicability range of probes having different design for various applications is a complicated problem. In planning experiments, it is necessary, if possible, to use probes having different design as well as to compare the obtained data with each other, with the results of independent studies, and with known regularities.

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