DYNAMIC CALIBRATION OF CONTACT THERMOMETERS IN A LIQUID STREAM

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Results are presented for the dynamic calibration of temperature converters in a liquid stream using thermal heterogeneities produced in the water by pulses of infrared radiation of a neodymium laser.

A full description of the dynamic properties of a contact probe measuring the temperature of a nonstationary process is given by its transmission function [1], for an experimental determination of which one must know the form or spectrum of the input effect on the thermometer. In connection with the absence of a standard method of calibration it is carried out under the conditions which most fully simulate the conditions of employment of the thermometer [1-3]. Thus, if the thermometer is intended for the recording of temperature pulsations in a moving liquid it is calibrated in an analogous stream in which a controlled temperature process is created which provides a known form of input effect. In the present report the input effect on the thermometer is understood to be the space-time temperature distribution calculated or measured by a standard instrument in the region of the stream subsequently occupied by the thermometer. In such a determination the input effect characterizes the liquid temperature undistorted by the presence of the probe and does not take into account the distortions in the stream dynamics produced by the body of the probe or the conditions of heat exchange at the surface of the probe, but these factors enter into the description of the transmission function of the calibrated probe. If the dynamic properties of the probe do not remain unchanged during variations in the hydrodynamic parameters then they can be characterized by a family of transmission functions each of which is determined at fixed values of the principal criteria of similarity, in particular the Reynolds, Prandtl, and Peclet numbers.

The nonstationary controlled process required for calibration is organized with the help of a laminar stream modulated in temperature. The modulation of the stream consists in introducing into it dosed portions of energy determined by a modulating signal. In this case the device used for the stream modulation must not introduce into it hydrodynamic disturbances. The energy of the modulating signal is restricted by the condition of the absence of convective distortions of the stream.

The least distortions are observed in modulation of a stream by electromagnetic radiation of suitable wavelength absorbed by the liquid. A promising method is modulation using the infrared radiation of a neodymium laser which creates in the liquid a thermal marker [4, 5] in the form of a local region of increased temperature. Optical methods are used for the visualization of this marker; shadow methods in the presence of considerable temperature gradients in a small volume or interference methods with small gradients occupying a considerable region of the stream. Optical methods are contactless and inertialess and are suitable for quantitative temperature measurements, and therefore it is evidently feasible to use them for the creation of a standard apparatus in the dynamic calibration of contact thermometers. So that the standard apparatus will measure the temperature at the undistorted stream, the thermometer being calibrated is mounted downstream from the standard apparatus. Then the input effect at the thermometer will differ from that measured by the standard apparatus, since the temperature distribution of the modulated stream is a function of the coordinates and time. The degree of deformation of the input effect along the stream depends on the thermophysical properties of the liquid, the stream velocity, and the distance from the standard meter to that being calibrated and is characterized by the transmission function which

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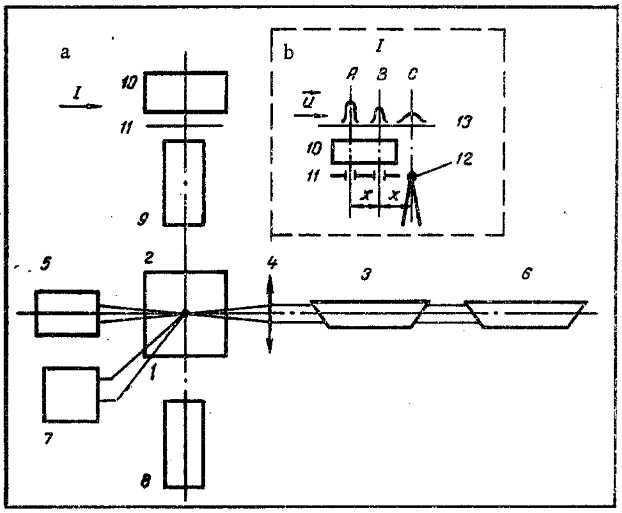

Fig. 1. Diagram of experimental apparatus for the dynamic calibration of contact thermometers in a liquid stream: 1) thermometer; 2) hydraulic channel or tank containing liquid; 3) neodymium laser; 4) spherical or cylindrical focusing lenses; 5) laser radiation converter; 6) adjusting He—Ne laser; 7) recording instrument; 8, 9) standard measumrent apparatus; 10) photoelectric recording unit; 12) image of thermometer on screen 11; 13) signals in sections of stream.

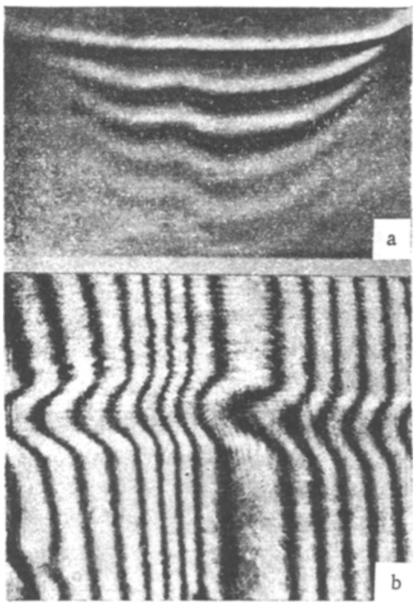

Fig. 2. Visualization of liquid flow in hydraulic chamber by the Töpler instrument (a) and in a convective jet by a Michelson interferometer (b).

connects the Fourier transforms of the temperature in the two sections of the stream. From this it follows that in comparing the readings of any two thermometers mounted at different sections of a nonstationary stream it is necessary to allow for the transmission function of the stream.

The transmission function of the stream and the spectra of the input effect on the thermometer during modulation of a laminar stream by laser radiation can be determined analytically. However, to increase the accuracy of the testimony of the contact thermometer it is advisable to determine their values experimentally at the moment of calibration of the temperature converter.

The method of such calibration consists in the following. Three sections A, B, and C distributed along the stream are chosen so that the segment AB = BC = x (Fig. 1b). The stream is modulated by a single pulse of radiation which creates in the liquid a temperature heterogeneity moving relative to the chosen sections. The temperature distribution in the heterogeneity is measured in each section: in sections A and B by the standard apparatus which records the result in the form of the functions f(t, 0) and g(t, x), respectively, and in section C by the thermometer being calibrated in the form of the function h(t, 2x), which corresponds to the average value of the temperature distribution. The spatial scale of the averaging is equal to the geometrical size of the sensing element, such as the diameter of a thermocouple junction. The functions f(t, 0) and g(t, x) must be obtained with the same scale of averaging as the function h(t, 2x). If the constancy of the stream velocity and the average temperature of the liquid is maintained during the calibration process (i.e., during the time of travel of the heterogeneity from A to C) then one can assume the equality of the transmission function of the stream in each of the

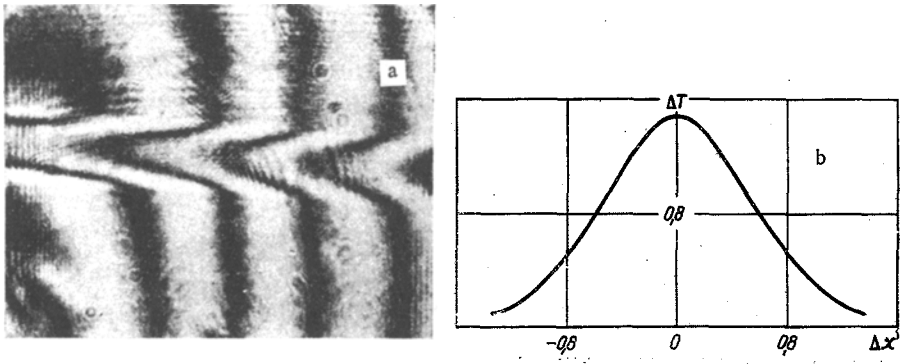

Fig. 3. Interferogram of temperature heterogeneity (a) and temperature profile established from it (b).

segments: $W_{AB} = W_{BC}$. Having determined the temperature spectra $F(j\omega)$, $G(j\omega)$, and $H(j\omega)$ at each section in the form of the Fourier integral of $f(t, 0)$, $g(t, x)$, and $h(t, 2x)$, respectively, and allowing for the inertialess nature of the standard apparatus one can determine both the transmission function of the stream in the measured segment and the transmission function of the thermometer being calibrated. Ultimately the transmission function of the thermometer was determined with an electronic computer from the equation

$$K(j\omega) = \frac{F(j\omega)\,H(j\omega)}{G^2(j\omega)}.$$

The calibration was carried out on the experimental apparatus whose diagram is presented in Fig. 1a. The thermometer 1, located in the liquid stream 2, was subjected to the effect of temperature heterogeneities produced when the liquid absorbed infrared radiation of the neodymium laser 3. The laser radiation was focused by the lens 4, in the region where the thermometer was located and was detected by the energy measuring device 5. The adjustment of the optical elements of system 1-5 was carried out using the He—Ne laser 6. The signal from the thermometer was recorded by the instrument 7 (an oscillograph or recording instrument). The optical axis of the standard apparatus 8-9, was orthogonal to the laser beam. A photoelectric recording unit 10-11, was used to record the heterogeneities.

Two copper-constantan thermocouples, which had junctions not exceeding 0.3 mm in diameter and wires 0.08 mm in diameter, were used successively as the thermometers calibrated in the experiments. Both thermocouple junctions ("cold" and "hot") were placed in the stream, but the temperature heterogeneity interacted only with the hot junction. In this way the constant component of the thermoelectromotive force was reduced and disturbances were decreased. A low-frequency S1-19B oscillograph and N-327-3 recorder were used as the recording instrument.

The calibration was conducted in fresh distilled water* in a flat channel 15×35 mm^2 in size and in a convective jet produced by an electric heater in a water tank of 1 liter capacity. The hydraulic channel and the tank were equipped with optical windows of K-8 glass. The stream velocity in the hydraulic channel was regulated in the range of v = 0-100 cm/sec using valves, while in the convective jet the velocity v = 0-2 cm/sec was varied by the power supplied to the heater (in Fig. 1a the velocity vector is directed perpendicular to the plane of the drawing). The average water temperature in the stream was 20°C and in the convective jet 20-40°C.

A neodymium glass laser operating in a mode of free modulation and emitting an energy of about 1 J in a pulse at the wavelength of 1.06 μ in a solid angle of 0.001 sr was used for the formation of temperature heterogeneities in the stream. The laser operated under conditions of single pulses or a series of pulses with a frequency of 2 Hz. The laser radiation was focused with glass lenses: a spherical lens with a focal distance of 0.5 m or a cylindrical lens with a focal distance of 0.1 m. In the latter case a plane heat source, corresponding to the theoretical model in the calculations, was produced in the water. The stability of the energy of the laser radiation from flash to flash was monitored with a IKT-1M convector of the calorimetric type.

*Such water contains the least amount of dissolved gases and suspended particles and has the high transparency which is necessary so that cavitation does not arise during its pulsed heating by laser radiation.

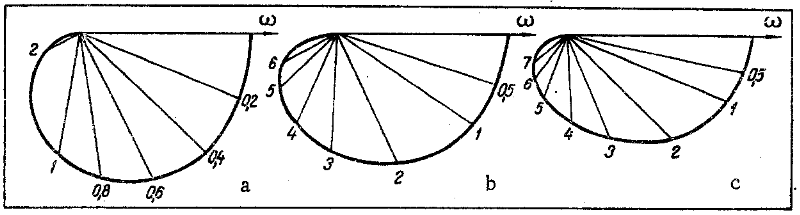

Fig. 4. Calibration characteristics of thermocouples in a convective jet (a) and in a stream (b) and transmission function of the stream (c).

The standard apparatus for the measurement of the temperature pulsations contained interchangeable units of a Töpler instrument with an illumination section using an incandescent lamp and of a Michelson laser interferometer. The standard apparatus was equipped with motion picture equipment and a unit for the photoelectric recording of the variation in illumination in the shadow pattern or the shift of the bands in the interference pattern. The photoelectric recording unit was assembled on the FÉU-51 photomultiplier 10, in front of whose cathode was mounted the opaque screen 11, which coincides with the image plane of the shadow or interference pattern and has two openings whose diameters are equal to the image of the diameter of the thermometer sensor on the screen 12 (Fig. 1b). This achieves the equality of the spatial averaging of the temperature measurements of the standard apparatus and the thermometer being calibrated. The openings are located along the image of the stream with the distance Mx between the first and second openings along the stream being equal to the distance between the thermometer image 12, and the second opening (Fig. 1b) in accordance with the adopted method of calibration with respect to the measurements of the temperature distribution in three sections of the stream, where M is the image scale.

The movement of the image of the temperature heterogeneity on the screen relative to the openings leads to a redistribution of the illumination and the amount of light energy incident on the photocathode, and the temperature distribution at the two sections A and B of the stream, averaged by the openings in the screen, is successively reproduced at the output of the photomultiplier. Knowing the distance between the openings and the image scale one can simultaneously determine the average stream velocity from the time interval between the signals. It is obvious that the distance between the openings must be greater than the image of the heterogeneity on the screen.

The standard apparatus is also designed for the visual observation of the motion of temperature heterogeneities during monitoring of the laminar state of the stream. Photographs of the shadow pattern of the liquid flow in the hydraulic channel visualized by pulses of laser radiation following with a frequency of 2 Hz (a) and an interferogram of a convective jet with a temperature heterogeneity moving in it (b) are presented in Fig. 2. In Fig. 2a it is seen that the flow of the stream over the thermocouple junction has a laminar nature. This is also indicated by the local Reynolds number $Re \leqslant 3$ calculated in the region of the junction for a stream velocity of 1 cm/sec. An example of an interferogram of a heterogeneity (a) and the temperature profile (b) established from it using the well-known equations is presented in Fig. 3. The photography of the heterogeneity was conducted 1.5 sec after its formation, hence the temperature profile is close to a Gaussian distribution with an amplitude $\Delta T = 1.5°C$ for a half-width of 1 mm and a dispersion of 36 mm^2.

In calibrating a thermometer by such temperature pulsations in a stream it is important to determine the effect of the physical parameters of the liquid and the dynamic properties of the stream on the form of the calibration characteristic of the thermometer. The optimum calibration conditions lead to the degeneration of the Fourier number $Fo < 1$, while the Peclet number for water will be $Pe > 1$ so that the heat exchange between the medium and the thermocouple has a convective nature. The Prandtl number in the working temperature range varies in the range $Pr = 4\text{-}12$ and at 20°C it equals 7. The dimensionless heat exchange coefficient calculated from these numbers is sufficiently small ($Nu = 3.2$). The Reynolds number has the greatest effect on this coefficient and consequently on the transmission function of the thermometer. Therefore in the calibration one must determine a family of transmission functions $K(j\omega) = \Phi(Re, Pr)$, found for discrete values of Pr and continuous values of Re, if the hydrodynamic parameters vary within wide limits under the working conditions of employment of the thermometer.

The results of the calculations, obtained using an electronic computer, are presented in Fig. 4 in the form of examples of the calibration characteristics of two thermocouples of equal inertia in streams of different velocity. The dynamic characteristics of the thermocouples are given in polar coordinates, where the radius is proportional to the amplitude and the angle is proportional to the phase. The first thermocouple (Fig. 4a) was calibrated in a convective stream at a heater power of 1.7 W and a jet velocity of 1.2 cm/sec at an average liquid temperature of 22°C. The working frequency range is 0-0.3 Hz, the drop in the amplitude-frequency characteristic starts at a frequency of 0.15 Hz, and it is 20 dB per decade. The second thermocouple (Fig. 4b) was calibrated in the hydrodynamic channel at a stream velocity of 1.5 cm/sec and an average temperature of 20°C. This thermocouple is less inertial (working frequencies 0-1 Hz) and the drop in the characteristic starts at a frequency of 0.5 Hz with the same steepness as for the first thermocouple. The transmission function of the stream on a segment $x = 0.35$ cm at a velocity of 0.7 cm/sec is presented in Fig. 4c. At this flow velocity the transmission function of the stream is analogous to the transmission function of the thermocouple in Fig. 4b but with a smaller phase lag. From this it is evident that the transmission function of the stream must be taken into account in calibrating the thermometers.

If a thermocouple certified in this way at an average temperature of 20°C is used in a working temperature range of 5-40°C the measurement error of this thermocouple will reach ± 25% because of variation in the heat exchange coefficient. The systematic error in the certification itself for calibration of a thermocouple in a modulated stream reaches 1% for temperature pulsations with an amplitude of 1°C. To increase the accuracy of the certification it is necessary to allow for the variation in the heat exchange coefficient during calibration in a modulated stream. More rigid requirements are set with respect to the constancy of the stream velocity. A velocity instability of 2% introduced a systematic certification error of 1%.

NOTATION

x	is the distance between sections A, B, and C along stream;
$f(t, 0)$, $g(t, x)$	are the temperature distribution functions in heterogeneity recorded by standard apparatus at sections A and B, respectively;
$h(t, 2x)$	is the temperature distribution function recorded by thermometer at section C;
W_{AB}, W_{BC}	are the transmission functions of stream in segments AB and BC;
$F(j\omega)$, $G(j\omega)$, $H(j\omega)$	are temperature spectra at sections A, B, and C of stream, respectively;
$K(j\omega)$	is the transmission function of thermometer;
ΔT	is the amplitude of temperature pulsations;
Fo, Pe, Pr, Nu, Re	are the Fourier, Peclet, Prandtl, Nusselt, and Reynolds numbers.

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