THERMOANEMOMETRIC SENSORS FOR STUDYING THREE-DIMENSIONAL STREAMS

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Experimental problems of liquid and gas mechanics require the study of nonsteady vector fields of three-dimensional nonisothermal streams, which are characterized by averaged and pulsation quantities. The methods of determining averaged quantities of one-dimensional and plane streams with pneumatic instruments, described in the monographs [1-10], are well entrenched in experimental practice. The possibilities of these instruments are limited, however. The thermoanemometric apparatus, possessing high sensitivity and the possibility of measuring pulsation characteristics in the frequency range above 100 kHz [11, 12], has become the most popular for studying turbulent streams.

The methods of determining pulsation quantities presented in the monographs [13-15] represent the development of this trend in measurement technology. Here the sensors of the thermoanemometric instruments always have been and remain the bottleneck in the experimental investigation of three-dimensional streams, since the demands on them are constantly growing and new spheres for their use are appearing [16].

The aim of the present review is to generalize the domestic and foreign experience involving this question in recent years.

The creation of multifilament thermoanemometer sensors for the study of three-dimensional streams is connected with the resolution of the conflicting demands of providing small size, good technological effectiveness, and high metrological characteristics. The existing sensors consist of a combination of several monofilament measurement elements which are on one holder and connected to the measurement channels of the instrument. In this case orthogonality of their arrangement simplifies the subsequent algorithms for determining the characteristics of the stream being studied [17].

The thermofilaments of the sensors are made of tungsten or platinum wire 5-60 μm in diameter [18]. A tungsten wire has a high mechanical strength, but it cannot be soldered and it lengthens considerably when heated above 320°C, which adversely affects the metrological characteristics of the sensor. A platinum wire is easily soldered with soft solder and it can be heated to 1000°C. It is possible to use platinum—rhodium and platinum—iridium wires. The thermofilaments are fastened to the holders of the sensor, which serve as current leads. They must be sufficiently rigid and, at the same time, introduce small aerodynamic disturbances. The best material for current leads is an alloy of silver and bronze, which assures that the sensor has a low inductance, although it is also possible to use stainless steel. The thermofilaments are fastened by soldering or welding them to the current leads. A drawback of the soldering process is the formation of bulges in the current leads at the welding sites, which cause additional disturbances in the stream being studied. A drawback of the welding process consists in the local changes occurring at the welding sites between the thermofilaments and the current leads, decreasing their mechanical strength. However, welding is the more universal means of fastening thermofilaments.

Several types of sensors are used in thermoanemometry. Cross-shaped sensors with two thermofilaments are used to study plane nonsteady streams [19-29]. The results of experimental investigations of these sensors are presented in [30]. The two thermofilaments of cross-shaped sensors are parallel to one plane and separated by less than 1 mm. A detailed analysis of the error in measuring with these sensors is given in [26, 27]. The measurement accuracy is also influenced by the downwash of the stream, its temperature variation, and contamination of the thermofilaments [31]. A variant of cross-shaped sensors is the orientable sensor with two thermofilaments [32]. Multifilament sensors for studying low-temperature, three-dimensional, nonsteady streams have no less than three thermofilaments [33-41], and the

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measurement accuracy depends on their size [42, 43]. A fourth filament operating in a low-heating mode is used to determine the temperature of the medium [44]. Since a large number of thermofilaments and current leads, influencing the measurement accuracy [45], are concentrated in the working volume of the sensor, knowledge of the physical processes of interaction of the stream with the sensor acquires importance [46]. The entry of one thermofilament of the sensor into the heated wake of another leads to a change in the value of its signal [47]. It has been established [48] that the mutual influence of the thermofilaments decreases as the distance between them increases. While noting the adverse influence of this effect on the measurement accuracy, we must point out the possibility of using it to determine the direction of a three-dimensional stream [49-54].

Pulsed filament sensors, in which the transmitting thermofilament is placed between two receiving filaments, comprise a special class. Heat pulsations, produced by electrical pulses in the middle thermofilament, are carried by the stream to one of the receiving filaments [55]. The results of theoretical and experimental investigations of these sensors are presented in [56, 57].

Besides the thermal wake of the thermofilaments, the aerodynamic disturbances of the stream caused by the current leads of the sensor affect the measurement accuracy. Flow over the leads by a high-velocity stream is accompanied by the formation of turbulent wakes which, intercepting the thermofilaments, affect their signals [58]. The sections of the thermofilaments adjoining the current leads are constantly in the regions of the stream disturbed by the holders. Wollaston thermofilaments are used to decrease this effect [59].

Pulsations in the velocity of the stream being studied cause vibration of elements of the sensor [60]. Vibration of its current leads is a cause of periodic variations of the electrical resistance of the thermofilaments and generates strain signals in them. The process of vibration of the thermofilaments themselves can be studied on the model of a string vibrating under a load. These vibrations result in variation of the velocity of stream motion relative to the thermofilaments and are reflected in the values of their signals. It has been established that wide-band turbulence causes less vibration of the thermofilaments of a sensor than narrow-band disturbances. In the fabrication of sensors special attention is paid to the straightness of the measurement thermofilaments, with which the local coordinate system is connected. A large sag in them may be due to technological factors, as well as to thermal linear expansion. The deviation of the thermofilaments from straight due to these factors, as well as their elastic deformation in the stream [61], affects the measurement accuracy [62]. These physical processes of interaction of the stream with the sensor limit the angle within which the velocity of a three-dimensional stream can be measured to 70°.

The operation of a sensor with an oblique thermofilament which rotates about the longitudinal axis of the holder is accompanied by a smaller number of the adverse effects described above. This explains its great popularity [63-93]. The main difficulty in the construction of this sensor is the creation of the unit accomplishing the transmission of the signal from its rotating to its fixed part, since the amount of electrical interference caused by this unit in the measurement circuit is close to the value of the useful signal of the thermofilament [74]. The problem can be solved by building the electronic circuit of the thermoanemometer in the form of one microcircuit and mounting it on the rotating part of the sensor [75].

Rotating and swiveling sensors with oblique thermofilaments must be differentiated. In the latter the rotation of the sensor is possible owing to the flexibility of the lead. One-channel thermoanemometers are widely used to measure the average and instantaneous velocities of a one-dimensional stream. The use of these instruments together with swiveling sensors is the simplest and most accessible means of studying steady three-dimensional streams.

Sensors with different angles of inclination of the thermofilaments are used to make measurements. An angle of inclination of 54°44' assures orthogonality of the positions of the thermofilament when it is turned by 120° about the axis of the sensor, which simplifies subsequent treatment of the signal. Sensors with an angle of inclination of 45° have become popular [77]. Since a change of 5° in this angle has a pronounced influence on the value of the thermofilament signal, its deviation from the nominal value because of inaccuracy in fabricating the sensor increases the measurement error [78]. Its size also depends on the angular interval in which the velocity vector of the stream lies relative to the sensor. The influence of the angle of inclination and the swivel of its thermofilament on the measurement accuracy is given in [79-80]. It should be mentioned that the direction of a stream can be measured with an orientable sensor with one thermofilament from the maximum of its signal [67] or the characteristic features of its calibration curves [94].

Each thermofilament of a sensor, being cooled by the three components of the stream velocity vector, yields a nonlinear signal. The connection between the effective component of the stream velocity vector and the value of the signal of a thermofilament was derived theoretically by King [95] and obtained empirically by Kramers [13]. The influence of various experimental conditions on the fulfillment of these relations was discussed in detail in [96]. Attempts to transform them appeared, giving rise to the necessity of finding the analytic relation which would yield the smallest disagreement with experimental results [81]. Measurement of the average velocity of a one-dimensional stream required preliminary velocity calibration, in which the values of the coefficients and the exponent of the Kramers relation were not used for its determination. The measurement of the components of the average velocity vector of a three-dimensional stream and its turbulent characteristic presumes the subsequent application of various algorithms using these quantities. For this each thermofilament of the sensor must have a velocity and angular calibration [82], from which the coefficients and exponents in the Kramers relation, as well as the coefficient of sensitivity of a thermofilament of the sensor to the longitudinal component of the velocity vector, are calculated by the method of least squares. The initial section of a calibration function differs considerably from the rest of the curve and it is advisable to treat it separately. Investigations of the stability of the readings of sensors over 92 h of operation have shown that the values of the calibration quantities vary in the process of operation as a consequence of the drift of the calibration functions of thermofilaments caused by the variation of their physicomechanical properties. Since the entire stream cools each thermofilament of the sensor, a system of equations must be solved to determine the components of the velocity vector. If one uses a sensor with three thermofilaments, the system of equations contains up to 12 calibration quantities, which are time-dependent variable parameters of these equations. For a sensor with one thermofilament the number of variable parameters is reduced to four, which is an important advantage for it, since the measurement error is lowered. Calculation algorithms are presented in [17, 59] which use the signals of sensors with several orthogonally arranged thermofilaments or swiveling sensors with an angle of inclination of 54°44'. Measurements must be made in six positions to treat the signal of a swiveling sensor with an arbitrary angle of inclination of the thermofilament [76]. However, this method lets one allow for the angle of inclination of the thermofilament in the calculation algorithm itself, and this lowers the error caused by its departure from the assigned value. There is a method of measuring with a swiveling sensor with measurements made in eight positions [85]. Electronic linearization of the signals of the thermofilaments is used to increase the velocity sensitivity of the thermoanemometer in the range of high velocities of the stream being studied. Algorithms employing linearized functions yield insignificant discrepancies of the resulting values from the true quantities [20]. An important defect of sensors with two and three thermofilaments is the ambiguity in the determination of the direction of the stream velocity vector in space. Thus, in a plane stream the signals of two thermofilaments correspond to four positions, while in a three-dimensional stream they correspond to eight positions of the velocity vector. Knowledge of the quadrant in which the stream velocity vector is probably located simplifies the measurement of its direction [73]. To eliminate the ambiguity of a stream velocity vector with an unknown direction one can introduce three additional thermofilaments into the multifilament sensor with subsequent analysis of their signals [37]. This problem is solved analogously by a rotating sensor with a slanting thermofilament [64]. The signs of the components of the stream velocity vector can be determined by dynamic-pressure sensors which can be oriented along the coordinate axes [38].

Thermoanemometric sensors have also obtained wide popularity thanks to the possibility of measuring turbulent streams in a small volume, comparable with the microscale of the turbulence [97-106]. Individual measurement methods allow one to avoid using the calibration quantities of the Kramers relation and thereby eliminate the influence of their drift [15, 55, 77]. The use of computer systems for the treatment of transformed signals of sensors considerably broadens the possibilities of experimental measurements [16, 107, 108].

The above questions constitute a circle of knotty problems in the fabrication, investigation, and use of sensors of thermoanemometric systems.

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