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HOT-WIRE PROBES FOR FLUID TEMPERATURE MEASUREMENTS

A b s t r a c t

Available hot-wire methods for turbulent temperature fields measurement are revived. The sensor sensitivity to velocity and temperature is analyzed in order to determine the optimal condition for simultaneous velocity and temperature fields measurements. Design of a unique five hot-wire probe, specified for simultaneous 3-D measurements of velocity and temperature fluctuations in a broad temperature variation range is also proposed.

SONDE SA ZAGRIJANIM VLAKNIMA ZA MJERENJE TEMPERATURE FLUIDA

I z v o d

U radu je dat pregled raspoloživih metoda mjerenja turbulentnih temperaturskih polja anemometarskim sondama sa zagrijanim vlaknom. Osjetljivost senzora na promjenu temperature i brzine je posebno

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analizirana u cilju odredjivanja optimalnih uslova za simultano mjerenje brzinskog i temperaturskog polja. Takodje je predložena i nova sonda sa pet zagrijanih vlakana, namijenjena simultanom 3-D mjerenju vektora brzine i temperature u širokom opsegu promjene intenziteta temperatuskog polja.

1. INTRODUCTION

Most of the flows in the nature and engineering practice are turbulent and characterized by non-isothermal temperature fields. In order to achieve high efficiency of different technical systems, suitable measuring instruments are needed. However, measurements of this kind are not always easy to perform. In comparison to isothermal flows, experiments in non-isothermal turbulence are very complex and rather rare. Since hot-wire anemometer is in fact an instrument that measures heat transfer flux from a very thin heated wire toward its environment, it is sensitive to superposed changes of both the velocity vector and temperature. This is the reason why employed methods for simultaneous fluctuating velocity and temperature measurements have to distinguish the changes in the wire cooling flux originating from the variations of fluid temperature and fluctuations of velocity vectors. In these situations, besides hot-wires specified for velocity measurement, probe must posses a separate wire for temperature sensing. The most common techniques are reviewed here, together with proposal of a currently developed five-wire probe.

All hot-wire anemometers utilize the mechanism of heated cylinder convection cooling by environmental flow. They operate in one of two available modes: "*constant temperature (CT)*" or "*constant current (CC)*". In the first mode electronic circuit maintains sensor temperature in the very close limits, by controlling its resistance. The second mode uses different electronic circuits to maintain approximately constant electric current that heats the wire.

A heat transfer relationship for a sensor of a hot-wire probe can be expressed as (*Perry 1982*)

$$\frac{E_W^2}{R_W} = (X + Y \cdot U^N) \cdot (R_W - R_A) + c_w \rho_w A_w l \frac{dR_w}{dt}, \tag{1}$$

where E_W is hot wire voltage, R_W hot wire resistance, U fluid velocity, X, Y and N constants that include the other relevant parameters like fluid and probe properties, while c_w, ρ_w, A_W and l are specific heat, density, cross section and length of the wire. Constants X, Y and N have to be determined experimentally for each probe, wire and flow conditions. In the first approximation, which is valid if the temperature difference $T - T_0$ is not to large, hot wire temperature and its electrical resistance can be related by a simple expression

$$R = R_0[1 + \alpha_0(T - T_0)], \tag{2}$$

where R_0 is the wire resistance at a given temperature T_0 and $\alpha_0 =$ const. Using this relation, the temperature difference between wire and surrounding fluid, $T_W - T_A$, can be expressed as

$$T_W - T_A = \frac{R_W - R_A}{\alpha_0 R_0}. \tag{3}$$

Having that in mind, the heat transfer relationship (1), for a CTA mode ($R_W =$ const) or for a steady state condition of both modes, can be expressed as

$$\frac{E_W^2}{R_W} = (A + B \cdot U^N) \cdot (T_W - T_A) \tag{4}$$

or

$$\frac{E_W^2}{R_W} = (X + Y \cdot U^N) \cdot (R_W - R_A), \tag{5}$$

where: $A = \alpha_0 R_0 X, B = \alpha_0 R_0 Y$. These two expressions are very convenient to analyze the sensitivity of wire voltage to velocity, temperature and other parameters changes.

2. "CONSTANT-TEMPERATURE" (CT) OPERATIONAL MODE

For a CTA operational mode the sensor temperature T_W and, therefore, sensor resistance R_W are practically constant. It follows from (4) that wire voltage E_W will depend on fluid velocity U and its temperature T_A changes. Starting from (4), the following expressions for the sensitivities of hot-wires to temperature and velocity can be derived (*Elsner 1973* and *Bruun 1979*)

$$S_{WT}^{CT} = \frac{\partial E_W^{CT}}{\partial T_A} = -\frac{1}{2} \cdot \sqrt{\frac{R_W \cdot (A + B \cdot U^N)}{T_W - T_A}}, \tag{6}$$

$$S_{WU}^{CT} = \frac{\partial E_W^{CT}}{\partial U} = \frac{N \cdot B \cdot U^{(N-1)}}{2} \cdot \sqrt{\frac{R_W \cdot (T_W - T_A)}{A + B \cdot U^N}}, \tag{7}$$

and wire voltage E_W expressed as

$$dE_W^{CT} = S_{WU}^{CT} \cdot dU + S_{WT}^{CT} \cdot dT_A. \tag{8}$$

For a small velocity and temperature variations ($dU \sim u, dT_A \sim t_A$) the wire voltage fluctuation $dE_W \sim e_W$ will be

$$e_W^{CT} = S_{WU}^{CT} \cdot u + S_{WT}^{CT} \cdot t_A. \tag{9}$$

Formula (9) is not suitable, because it involves hot-wire voltage-drop e_W^{CT} that can not be directly measured. Instead, anemometer output voltage e^{CT}, which can be measured and is linear function of e_W^{CT} can be introduced in the response equation, giving:

$$e^{CT} = S_U^{CT} \cdot u + S_T^{CT} \cdot t_A, \tag{10}$$

$$S_U^{CT} = \frac{\partial E^{CT}}{\partial U}, \tag{11}$$

$$S_T^{CT} = \frac{\partial E^{CT}}{\partial T_A}. \tag{12}$$

It follows from (6-7) that for a constant fluid velocity, temperature sensitivity decreases and sensitivity to velocity increases with increasing $(T_W - T_A)$. It can be shown that ratio S_U^{CT}/S_T^{CT} is a function of overheats ratio R_W/R_A (*Bruun 1995*). Therefore, high overheat-ratio is reliable for measurement of velocity fluctuations, while low over-heat ratio provides high temperature sensitivity.

3. "CONSTANT CURRENT" (CC) OPERATIONAL MODE

Construction and design details of CCA mode were published even fifty years ago (*Kovasznay 1948, Betchov 1948a,b, Hinze 1959, Grant and Kronauer 1962,* etc.). In CC mode, wire operates at very low overheat ratio, behaving as resistance thermometer (so called resistance wire - RW in further text). The wire voltage E_W is sensitive to any variation of parameters relevant for heat exchange between the wire and environment, e.g. both the velocity and temperature fluctuations.

In order to find the wire voltage sensitivity to velocity and temperature changes, it is necessary to take into account that the wire resistance R_W, in expressions (4-5) is a variable to. Using the relation $R_W = E_W/I$, the following expression for the wire voltage can be derived from (5)

$$E_W = \frac{R_A(X + YU^N)I}{X + YU^N - I^2}. \tag{13}$$

Simple differentiating formula (13) can obtain the sensitivities to fluid velocity and temperature changes:

$$S_{WU}^{CC} = \frac{\partial E_W^{CC}}{\partial U} = -\frac{(N \cdot Y \cdot U^{(N-1)} \cdot I^3 \cdot R_A)}{(X + Y \cdot U^N - I^2)^2}, \tag{14}$$

$$S_{WT}^{CC} = \frac{\partial E_W^{CC}}{\partial T_A} = \frac{\alpha_0 R_0 I (X + YU^N)}{X + Y \cdot U^N - I^2}. \tag{15}$$

Analyzing the small perturbation of the velocity and temperature around the mean values $\overline{U}, \overline{T_A}$ (*Hinze 1959, Wyngaard 1971, Fulachier 1978*) derived the following expressions:

$$S_{WU}^{CC} = \frac{\partial E_W^{CC}}{\partial U} = -\frac{N \cdot Y \cdot \overline{U}^{(N-1)} \cdot \overline{I}^3 \cdot \overline{R_W}}{\overline{R_A} \cdot (X + Y \cdot \overline{U}^N)^2}, \tag{16}$$

$$S_{WT}^{CC} = \frac{\partial E_W^{CC}}{\partial T_A} = \frac{\alpha_0 \cdot \overline{I} \cdot \overline{R_W} \cdot R_0}{\overline{R_A}} \tag{17}$$

which follow from (14-15) in combination with (5) for time mean values of fluid and probe properties. However, a small perturbation of output voltage e_W^{CC} of a CC wire can be described analogue to (10):

$$e_W^{CC} = S_{WU}^{CC} \cdot u + S_{WT}^{CC} \cdot t_a. \tag{18}$$

Expressions (16-17) show that minimizing velocity-temperature sensitivity ratio reduces contamination of the temperature signal by velocity fluctuations. Dividing (16) by (17) gives:

$$\frac{S_{WU}^{CC}}{S_{WT}^{CC}} = -\frac{N \cdot Y \cdot \overline{U}^{(N-1)} \cdot I^2 \cdot \overline{R_W}}{\alpha_0 \cdot R_0 \cdot (X + Y \cdot \overline{U}^N)^2}. \tag{19}$$

Wyngaard 1971 analyzed this problem and developed the non-dimensional expression for the same ratio:

$$\frac{S_{WU}^{CC}}{S_{WT}^{CC}} = -\frac{I^2 \cdot R_W \cdot 0.25 \cdot R_e^{0.45}}{\pi \cdot k \cdot l \cdot \overline{U} \cdot (0.24 + 0.56 \cdot R_e^{0.45})^2} =$$

$$= -\frac{\chi_W \cdot R_e^{0.45}}{\pi^2 \cdot k \cdot \overline{U} \cdot (0.24 + 0.56 \cdot R_e^{0.45})^2} \cdot \frac{I^2}{D^2}, \tag{20}$$

where χ_W is the wire specific resistance at operational temperature T_W. For a chosen diameter D, this ratio varies in proportion with I^2. Therefore, heating current I should be set to t he smallest acceptable intensity, to minimize the influence of fluid ve locity on the CC wire output signal. Simultaneously with reducing D, what is often needed to decrease thermal inertia, I should be additionally reduced proportionally to reduction of D, to maintain a specified S_T/S_U ratio. *Mestayer and Chambaud 1979* experimentally verified these conclusions.

However, technical reasons do not permit decreasing of I under some lower limit, imposed by electronic circuit for signal processing. The problems originate from two opposite criteria: necessity for low signal-to-noise ratio and the large amplification required for resistance-wire signals. *Tavoularis 1978, Peattie 1987, Haughdahl and Lienhard 1988* claimed that temperature measurements with resistance wires requires low drift, low-noise CC anemometers, with amplifiers giving typical gains of 1000-5000 through the whole frequency spectrum of interest. Advanced electronic technology satisfies these requirements, but still demands careful selection of electronic components and sophisticated design of electronic circuits. To achieve this goal, a variety of empirical data is needed.

Following (10-12), analogue expression arises for anemometer output voltage e^{CC}:

$$e^{CC} = S_U^{CC} \cdot u + S_T^{CC} \cdot t_A, \tag{21}$$

$$S_U^{CC} = \frac{\partial E^{CC}}{\partial U}, \tag{22}$$

$$S_T^{CC} = \frac{\partial E^{CC}}{\partial T}. \tag{23}$$

4. MEASUREMENT OF TEMPERATURE FLUCTUATIONS - THE RESISTANCE WIRE

At present, three general measurement approaches for fluid temperature fluctuations exist: single-wire multiple overheat ratio method, probes with dual constant-temperature wires and resistance-wire probe operated at CC mode.

The first method is founded by *Corrsin 1947, 1949* for fluid temperature measurements in the low-velocity flows, and accommodated by *Kovasznay 1950, 1953* for supersonic flows. It utilizes single CT-wire probe, assuming that expressions (10-12) describe the wire response. After simple mathematical operations, expression (10) gives

$$\frac{\overline{e^{CT^2}}}{S_T^{CC^2}} = \left(\frac{S_U^{CT}}{S_T^{CT}}\right)^2 \cdot \overline{u^2} + 2 \cdot \frac{S_U^{CT}}{S_T^{CT}} \cdot \overline{u \cdot t_A} + \overline{t_A^2}. \tag{24}$$

Assuming constant values of $\overline{u^2}, \overline{u \cdot t_A}$ and $\overline{t_A^2}$. The probe has to be exposed to the same flow field at minimum three different overheat ratios to provide the signals that can be used for evaluation of the second-order velocity and temperature statistics ($\overline{u^2}, \overline{u \cdot t_A}$ and $\overline{t_A^2}$). *Kovasznay 1953, Arya and Plate 1969* and *Fulachier and Dumas 1976* improved the measurement accuracy by increasing number of wire overheat ratios and using the least square fit methods. Although very simple to use, multiple overheat ratio method does not permit simultaneous measurement of velocity and temperature fluctuations. Therefore evaluation of the higher cross-correlation and joint probability density distributions is not possible. Also, measurement results are very sensitive to small changes of wire sensitivities S_U and S_T during data acquisition interval. Therefore, this technique is not practically reliable.

Corrsin 1949 used dual CT-wire method to measure temperature. Probe possessed two parallel CT wires, operated at different overheat ratios, what resulted in different sensitivities S_U and S_T to velocity and temperature fluctuations. Using (4) and assuming identical properties of both hot-wires (except overheat ratios) *Sakao 1973* derived a linear expression for U^N, which does not depend on the fluid temperature T_A. Solving for U^N the temperature T_A can be found from equation (4) applied for any of the two wires. Main disadvantage of this method lays in the assumption of identical wires, what is practically impossible:

calibration constants A and B will be different for different sensors. Problem is resolved by assuming equal values for exponent N only, which is close to the truth: experimental findings showed that its value is ~ 0.5. In such case, (4) can be transformed and rewritten for each wire, giving the system of two non-linear simultaneous equations, which can be solved for U^N and T_A. *Lienhard and Helland 1989* reported signal interpretation algorithm, similar to previous. In this case, elimination of fluid velocity U results with the cubic, instead of second-order, equation. Experimental comparison of their dual CT wire technique with resistance-wire method verified clear advantages of the last. Performances of the parallel-wires CT probe were better only in the low-level turbulence flows with high-enough temperature fluctuations. However, spectral measurements revealed that parallel-wire probes suffer from the severe noise problems when the fluctuations of temperature signals are small. In these situations, resistance-wire method should be used. *Blair and Bennett 1987* extended the parallel-wires to X-probe, by adding the third wire in the middle-section of X-wires.

Deficiencies of the multi-overheat-ratio techniques and dual CT-wire methods make resistance-wire the most common method for measurement of fluid temperature fluctuations. These probes contain platinum or platinum-alloy wires, covered by a thick sheet of silver, which are commercially available at very small diameters, down to 0.25 □m. The probe is made by soldering the wire to the prongs and then removing the silver coat from the middle part to expose it to the surrounding fluid. Unfortunately, such thin wires are extremely weak to aerodynamics and mechanics shocks, causing that most users make resistance-wire probes by themselves. These sensors, known as "cold-wires", operate at low overheat ratios in CC mode that provide high sensitivity to temperature fluctuations and low sensitivity to velocity changes. The sensor resistance is not constant and a first order differential equation for R_w can be derived from heat transfer relationship (1) in the form

$$M\frac{dR_w}{dt} + R_w = \varphi(t), \tag{25}$$

$$M = \frac{\rho_w c_w A_w l}{\alpha_0 R_0 (X + YU^N - I^2)}, \tag{26}$$

$$\varphi(t) = \frac{(X + YU^N)}{(X + YU^N - I^2)} R_A \tag{27}$$

where M is the time constant of response of R_w to the forcing function $\varphi(t)$.

To achieve high measurement accuracy, "cold-wire" must satisfy a variety of criteria. The most important is fast wire response to temperature fluctuations, which originates from thermal inertia of a CC wire. As for all dynamic measuring instruments, it is represented by the time constant M. It can be also expressed (see *Bruun 1995*) as

$$M \cong \frac{\rho_W \cdot c_W \cdot D^2}{4 \cdot k \cdot Nu}, \tag{28}$$

for a sensor of diameter D and low overheat ratio $(R_W/R_A \to 1)$, where k is thermal conductivity of the fluid and Nu is Nusselt number. This equation agrees well with measured values for $D \geq 1\mu m$. However, *LaRue, Deaton and Gibson 1975, Hojstrup, Rasmussen, and Larsen 1976, Antonia, Chambers, Sokolov and Van Atta 1981* found that for thinner wires values of M calculated using (27) are larger than measured, giving smaller cut-off frequency $f_C = 1(2\pi M)$.

LaRue, Deaton and Gibson 1975, Paranthoen, Lecordier and Petit 1982 and others noticed that cold-wire changes its response function and increase the time - constant M depending on the running time, due to dust depositions. They can be cor-rected to nearly the initial value of new wire by ultrasonic cleaning or washing in the Javel water.

Although not very accurate at small diameters, exp. (28) gives general directions for choosing the cold-wire diameter, showing that wire frequency-response depends strongly on its diameter. For example, a 0.63 μm platinum wire gives a cut-off frequency of 10 kHz for the airflow velocity around 10 m/s. However, decreasing of a wire diameter will improve its response, but also decrease its mechanical strength what could result in fragility. Therefore, a compromise between these two properties is needed. On the other hand, the required value of the cold-wire time constant also depends on the flow regime, as well as on the measured flow parameter.

Experimental testing of cold-wire response is possible by placing the wire in an isothermal flow of constant velocity and varying the electrical heating current I. At present, two general approaches are available. The first provides internal wire heating only, using sinusoidal variation of I at different frequencies (*LaRue, Deaton and Gibson 1975, Bremhorst and Krebs 1976 and Bremhorst and Graham 1990*). *LaRue, Deaton* *and Gibson 1975, Bradbury and Castro 1972 and Hishida and Nagano 1978* applied a stepwise (square wave) increase of the heating current. Both internal heating methods have negligible influences on the prong temperature and measured responses mainly represent isolated wire element itself. Whatever of the two methods is applied, the experiments clearly demonstrate the increase of cut-off frequency with increasing the fluid velocity and decreasing the wire diameter.

In contrast to the first approach, external-heating techniques measures common response of the resistance wire and its prongs. For this purpose, a chopped laser-beam can be applied (*Fiedler 1978, Weeks, Beck and Joshi 1988*) or a heat radiant flux (*Smits, Perry and Hoffmann 1978*). Both of these methods sometimes do not expose the wire prongs to the identical temperature fluctuations as the sensing element, what decreases their reliability. Experiments showed that they enable wire response measurement only for large aspect ratios of the wires: l/D> 1000. *Antonia, Chambers, Sokolov and Van Atta 1981,* as well as *Shah and Antonia 1986,* applied an additional external-heating technique, using pulsed wire, placed upstream and perpendicularly oriented to the resistance wire axis.

Practically, it is more useful to evaluate the total response of complete resistance-wire probe, including both the wire and its prongs. This can be achieved only by external heating methods, which generate temperature fluctuations, by an upstream wire heated by sinusoidal current (*Paranthoen, Petit and Lecordier 1982 and Petit, Paranthoen, Lecordier and Gajan 1985*). A strong sound field can be also used (Hojstrup, Rasmussen. and Larsen 1977).

The compromise between the wire mechanical strength and corresponding response is rather rare. Therefore, a sensor with non-adequate response to temperature fluctuations sometimes has to be used, supported with some frequency-compensation technique. Whether compensation is needed or not, depends on the sensitivity of measured flow quantity on the cold-wire diameter. In general, the value of M should be adjusted in the flows with large variations of mean velocity, flows with high turbulence levels and for spectral and dissipation measurements.

Multiplying equation (25) by the electric current I, having in mind that $E_w = R_A I$, the following equation can be obtained

$$M\frac{dE_w}{dt} + E_w = IR_A\frac{(X + YU^N)}{X + YU^N - I^2)} \tag{29}$$

If the current I is sufficiently small, what should be achieved in CC mode in order to get high temperature sensitivity (expression (20)), this equation can be simplified to

$$M\frac{dE_w}{dt} + E_w = IR_A = E_A \tag{30}$$

Assuming that the value of M is known (in the ideal case close to zero), instantaneous value of E_A (and therefore T_A) can be obtained from this expression using the measured value of E_w. The time constant M is a function of flow velocity U (expression (26)) and it can vary by a factor of four in the range of 0 - 5 m/s, so it is necessary to adjust the value of M for different velocity ranges.

An adequate approach for automatic compensation of time constant M to variable fluid velocity U assumes application of dual hot-wires probe. One sensor operates in CC mode and measures temperature, while the other operates in CT mode in order to measure velocity. In this case, the information of measured instant fluid velocity $U(t)$ enables correction of time constant M.

Hishida and Nagano 1978, Tsuji, Nagano and Tagawa 1992 and *Wroblewski and Eeibeck 1991* derived theoretical compensation methods for $M = M(U)$, while an empirical correction method for time constant $M = M(U)$ dependency on velocity was developed by *Bremhorst and Graham 1990.* Thermal inertia of cold wire attenuates its amplitude response at high frequency fluctuations of fluid temperature by a factor of $1/\sqrt{(1 + f^2M^2)}$ (see *Bradshaw 1971,* for example). Corresponding compensation technique can be developed using analogue electronic circuit that contains amplifier with variable gain. Its amplification of signal amplitude rises (up to some limit set by the amplifier-circuit components) with the signal frequency by a factor $\sqrt{(1 + f^2M^2)}$ that is inversely proportional to the corresponding factor of signal attenuation at high frequencies by sensor thermal inertia. *Weeks, Beck and Joshi 1988* reported a reliable automatic compensation technique for M. They applied a special electronic device that feeds the output from the velocity (CT) sensor through an analogue switch, which selects the most adequate resistor among eight available. Such circuit represents dependency of M on the instant fluid velocity magnitude U by an eight-step function. However, at present, it is more suitable to perform this correction digitally. It is faster, more reliable and enable easy implementation of arbitrary function for $M = M(U)$.

5. SIMULTANEOUS MEASUREMENT OF VELOCITY AND TEMPERATURE

Contemporary hot-wire probes for simultaneous measurements of fluid temperature and velocity fluctuations contain a resistance wire and one or more CT sensors. CC wire is employed for temperature measurement, while the CT wires measure velocity components. Various dual-sensor configurations were reported. The simplest probes, containing a velocity wire with a joined temperature-sensing wire, were applied starting from *Chevray and Tutu 1972* and up to the later studies of *Antonia, Chambers, Sokolov and Van Atta 1981, Hishida and Nagano 1988, Weeks, Beck and Joshi 1988, Bremhorst and Graham 1990* etc. Hot-wire probes for 2-D measurement of velocity field simultaneously with temperature fluctuations contain two CT wires and a resistance-wire for temperature measurements (fig. 1). Among the firsts to report contemporary probe of this type were *Bourke and Pulling*

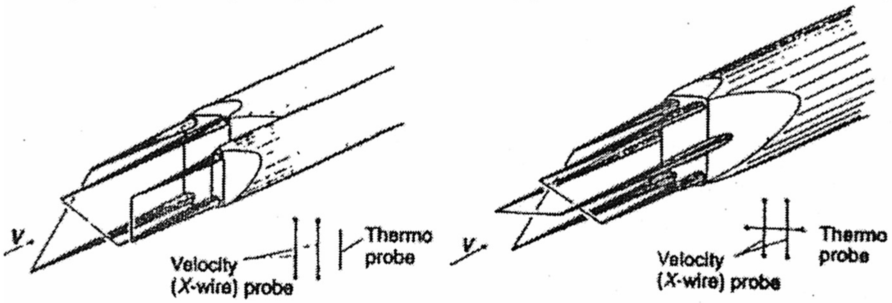

Fig. 1: Probes for simultaneous velocity (two CT wires) and temperature (RW) measurement. Source: Fiedler 1978.

1970, Pessoni and Chao 1974, etc. The newer improved triple-wire techniques were applied by *Subramaniam and Antonia 1981, Gibson and Veriopulos 1984, Graham and Bremhorst 1990/1991*, etc. The most complex probes with three wires for velocity measurement and a resistance wire were rarely used, because of complicated time consuming calibration procedures (see *Fabris 1978/1983a,b, Frota and Moffat 1982*).

6. A QUADRUPLE VELOCITY PROBE WITH A TEMPERATURE SENSOR

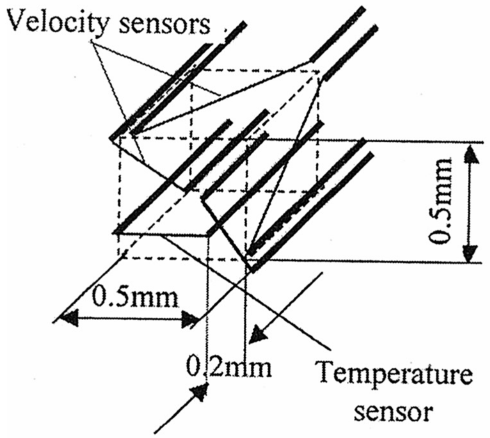

Fig. 2: A sketch of $VTP-4q+1$ hot-wire probe, designed to measure the temperature and 3-D velocity field.

Unique probe $VTP-4q+1$ (fig. 2), specified for simultaneous measurement of fluid temperature and 3-D velocity fluctuations, is currently being developed at the University of Montenegro. Four CT wires measure velocity, while the fifth resistance wire senses temperature. The probe is built using existing technology for fabrication of vorticity probe with 12 wires (*Vukoslavčević, Wallace and Balint 1991*) and probe $VP-8qd$ (*Vukoslavčević* and *Petrović 1996*).

Choice of suitable probe configuration and good angular resolution is based on previous analysis of *Vukoslavčević and Petrović 1997a, 1998b.* Recently developed probes for vorticity measurement enabled more sophisticated analysis of probe geometry influence on the measurement accuracy of fluid velocity and vorticity field (*Vukoslavčević and Wallace 1996, Vukoslavčević and Petrović 1997b, 1998a*). The first attempt with probe of this configuration was made by *Vukoslavcevic* and tested by *Wallace 1992* at University of Maryland (USA). Unfortunately due to the inadequate position of temperature sensor, the signal was contaminated by the influence of velocity hot-wire sensors.

The probe is designed to measure the turbulent velocity field in a broad temperature range up to 500^0C. Tungsten 2.5 μm wire, used for the previous probes, is not adequate because it oxides at around 300^0C. It is replaced by Platinum-10fix the prongs in desired positions, suitable for room temperature, is also replaced by high temperature epoxy as well as connectors, insulation etc.

It is clear from expression (28) that a small sensor diameter is needed to get high frequency response of a temperature sensor. The sensor diameter as small as 0.6 μm is usually used for a single temperature probes. Such small sensors are very fragile what is a serious problem for a complex structure like the probe shown in fig.2. To replace the sensor placed in the middle of the probe, surrounded by four velocity sensors, without damaging them is a tedious job. In order to reduce the possibilities of sensors braking, 2.5 μm wire is used what requires a compensation of time constant M as a function of fluid velocity U. That is possible in the case of the probe capable of simultaneous temperature and velocity measurements as it is the quintuple hot-wire probe $VTP-4q+1$.

The thermal contamination of different sensor signals is characteristics of all multisensor probes. It is a very serious problem for the cold-wire sensor that can be badly contaminated by the hot-wire velocity sensors. The contamination of the *Wallace 1992* probe was of the same order as it was the temperature signal itself. One possible way to avoid it is to get the cold sensor in front of the hot velocity sensors for a small distance Δx. In the case of $VTP-4q+1$ probe this distance is 0.2 mm.

The probe dimensions are of the same order as one of the array of 12-sensor vorticity probe (*Vukoslavčević and Wallace 1996*). It means that it meets the same resolution criteria as vorticity probes what are capable of measuring the most of turbulent structure in a low speed wind tunnel.

7. CONCLUSIONS

Hot-wire anemometer is the unique instrument capable of simultaneous measurement of temperature and velocity in the flows heated up to 800^0C, at frequency of up to few hundred kHz. Hot-wire probes can be made very small being able to measure the smallest turbulent structure. Different probes and method suitable of temperature and simultaneous temperature and velocity measurements are presented. A designed of a special $VTP-4q+1$ probe capable of simultaneous 3-D velocity and temperature field is proposed. The probe measuring volume is a cube of $(0.5\text{mm})^3$, while additional minimization is still possible. The developing of the probe is in progress and it is expected that the probe will be capable of simultaneous measuring of velocity and temperature field up to 500^0C. *Besides the Shehata A. M. and McEligot 1996* this is the first attempt to measure the velocity and temperature field simultaneously under such high fluid temperature. Further plans also include extending the method for optimizing the sampling parameters of velocity measuring on the probe $VTP-4q+1$. Besides sampling optimization of velocity signals, the output voltages of resistance wire will be also included.

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