HOT-WIRE MEASUREMENTS WITH AUTOMATIC COMPENSATION OF AMBIENT TEMPERATURE CHANGES

by

Nikolay I. MIHEEV [a], ***Valeriy M. MOLOCHNIKOV*** [a], ***Dmitriy V. KRATIROV*** [b], ***Konstantin R. HAYRNASOV*** [a], ***and Philipp S. ZANKO*** [a*]

[a] Laboratory for Hydrodynamics and Heat Exchange, Academenergo, Kazan Science Center, Russian Academy of Sciences, Kazan, Russia
[b] Kazan National Research Technical University, Kazan, Russia

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A single sensor hot-wire device with automatic temperature compensation for velocity measurements is developed. Experience in measuring the velocity and temperature in a flow with variable temperature using self-made hot-wire equipment and probes is discussed. Results of the corresponding methodical experiments are presented.

Key words: *turbulence, hot wire, velocity, temperature compensation*

Introduction

Methods of turbulence measurements are of great importance for study, adjustment, prediction, and diagnostics of processes in various engineering applications. The hot-wire anemometer has been the main tool for such experiments till the end of the 20th century. But to tell the truth, the hot wire was not too comfortable for researchers. Inconveniences connected with hot wires are well-known: the necessary adjusting before measurements, the influence of the mean medium temperature on velocity measurements, the troublesome calibration of probes, *etc*. Also, hot wires were able to measure only local turbulent characteristics using one or at most a few probes. As a result, the hot wire has been supplanted by new techniques, such as LDV and PIV. The hot wire is not a popular commercial product anymore. Nevertheless, this instrument dominates a few niches in modern research. One of them is measuring complex turbulence characteristics such as vorticity using unique multi-sensor hot-wire probes [1, 2].

Also, there is a growing interest in designing of cheap self-made hot-wire turbulence measuring apparatus in several research groups across the world [3-5]. However, in addition to a hot-wire equipment one needs a compact device for spot welding and the correspondent instructions for making probes.

There are some educational issues as well. It is not easy to measure turbulence using a hot wire. As Kovasnay [6] wrote in his classic paper, "Nevertheless, it still has more of the caprice of an art, than the complete reliability of a convenient routine laboratory procedure". Undoubtedly, using of self-made equipment and probes could increase uncertainty in measure-

* Corresponding author; e-mail: zanko.philipp@gmail.com

ments but in many cases of practical importance it may be a reasonable choice for a qualified researcher.

In the present article we discuss our experience in measuring the velocity and temperature in a flow with variable temperature using self-made hot-wire equipment and probes.

Fluid temperature is not always constant during an experiment. For instance, the temperature of the air in a closed circuit wind tunnel will sometimes increase several degrees during operation. This leads to additional errors [7-11]. According to [12], an error of 1 to 2% per °C is introduced in the measurement of velocity due to the variation of the fluid temperature.

A lot of papers, among them [13-17], and even a special review [18] are devoted to the problem of compensating the velocity reading of a hot wire for varying fluid temperature. Broadly speaking, three variants of solving the problem are known: (1) manual adjustment of the hot resistance R_w to compensate for changes in T_a (obsolete), (2) automatic compensation using an additional temperature sensor incorporated into the Wheatstone bridge (a separate measurement of T_a is not necessary), and (3) analytical correction using a hot-wire heat-transfer relationship (a separate measurement of T_a is necessary, the hot-wire probe is operated at a fixed hot resistance R_w) [19-21].

One of the most efficient methods is using the second standard probe as a temperature sensor along with a resistor network. It was reported about maximal errors of only 1% in velocity by using this method when ambient temperature was varied by 20 °C [22].

Another interesting approach is a two-state hot-wire anemometer, which operates on the basis of a periodically changing heating level from a single sensor [23-26]. The flow velocity and temperature are determined using the steady-state output signals that correspond to two predefined levels of heating. The hot-wire anemometer must have the possibility to change the heating level of the sensor. The main disadvantage of the method is the fact that the temperature and velocity are estimated using the system of equations with high correlation between these equations. It is the so called ill-conditioned problem. This inevitably leads to relatively high error of measurements.

In this paper a single sensor hot-wire device with automatic temperature compensation for velocity measurements is presented. It makes unnecessary an additional sensor for temperature measurements and additional thermometric equipment.

Theoretical basis and philosophy for measurements

Consider a very fine wire heated by an electric current in a fluid flow. Evidently, the faster the fluid moves, the more intensive cooling of the wire we have. If the electric current follows changing of the heat transfer so that the temperature of the wire is always constant, we can consider the current as a measure for the fluid velocity. This is the idea of the constant temperature hot-wire anemometer (CTA) in brief.

Mathematically it could be expressed in the following way. Assume that the wire is in thermal equilibrium with its environment. Then, the electric power input is equal to the power loss caused by convective heat transfer [19]:

$$I^2R_w = \pi dl(T_w - T_a)h = (T_w - T_a)(A + BU^n), \tag{1}$$

where I [A] is the electric input current; R_w [Ω] – the resistance of the wire; d and l [m] – the diameter and the length of the wire respectively; h [W/°Cm^2] – the heat exchange coefficient of the wire; T_w and T_a [°C] are the temperatures of the wire and fluid, respectively, A, B, n – coefficients obtained from calibration; U [ms^{-1}] is the fluid velocity. Broadly speaking, h depends on the temperature difference ($T_w - T_a$), but in the case of small temperature changes (30-40 °C around room temperature) it is almost constant [21]. In the beginning of the 20th century Prof. L. King of McGill University, Canada, proposed to use a power function ($A + BU^n$) for approximation of calibration curves [27]. The exponent n in his formula was equal to 0.5. Today it is assumed that n is more likely close to 0.45 [28] or unknown.

Obviously, a drift of ambient fluid temperature T_a changes a calibration curve $I^2(U^n)$. It is always possible to perform a velocity calibration at a number of different fluid temperatures [29]. It is the most accurate and the most reliable approach. Unfortunately, it is also a very labour- and time-consuming procedure, not suitable for routine work. Another problem connected with changing fluid temperature is that an additional probe (or a coil of wire) and the corresponding thermometric apparatus are necessary for temperature measuring.

Using (1) a simple analytical correction formula for temperature effects can be obtained [21]:

$$I_r^2 = I_a^2 \frac{T_w - T_r}{T_w - T_a} \tag{2}$$

where T_r is the room temperature, T_a – the ambient temperature, and I_r (I_a) are the wire current at room (ambient) temperature.

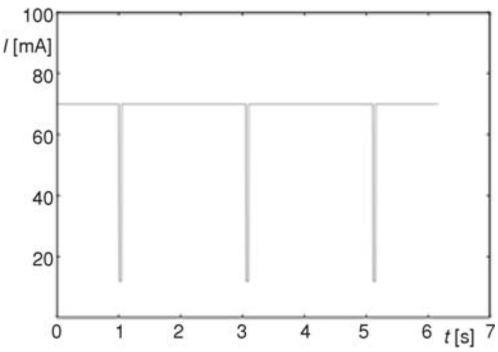

Figure 1. Oscillogram of velocity-temperature measurements

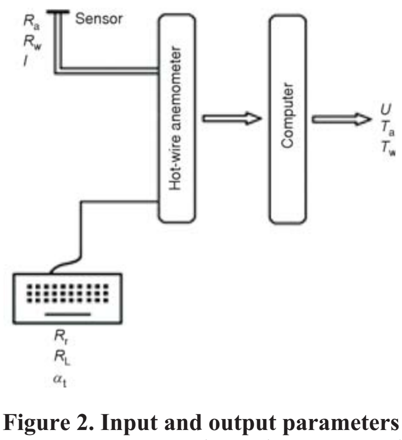

Figure 2. Input and output parameters
I – input current, R_a – wire resistance at ambient temperature, R_w – resistance of heated wire, R_L – cable resistance (0.5 Ω), R_r – wire resistance at room temperature (3.7 Ω), α_t – temperature coefficient of resistivity, T_w – hot wire temperature, T_a – cold wire temperature, U – velocity

Our single-sensor hot-wire device switches between two regimes – a velocity measuring regime (like a usual CTA) and a temperature measuring regime (the resistance-wire regime at a low overheat ratio) (fig. 1). After measuring the temperature, if it has been changed, the resistance R_w is corrected, so that ($T_w - T_a$) = const. In other words, it is the method of constant overheating relative to ambient temperature.

In order to automatically compensate changes of velocity readings due to temperature effects the device must be able to measure I, R_w, T_w, T_a (fig. 2). R_w is measured using a bridge circuit incorporated into the hot wire.

It is natural to determine the temperatures T_a and T_w using the wire resistance. It is common knowledge that the wire resistance R_w is a linear function of temperature:

$$R_w = R_r[1 + \alpha_t(T_w - T_r)] \tag{3}$$

where α_t [°C^{-1}] is the temperature coefficient of electrical resistance, and T_w [°C] – the wire temperature. The electrical resistance of a wire depends only on the geometrical dimensions and the material of the wire. It can be computed as:

$$R_r = \frac{4\rho_r l}{\pi d^2} \tag{4}$$

where R_r [Ω] is the resistance of a sensing element at room temperature (20 °C), and ρ_r [Ωm] – the electrical resistivity, .

Assume that $R_w(T_a)$ is determined using for example a temperature chamber. Then, by measuring the wire resistance at room temperature R_r one may calculate the temperature coefficient of resistivity α_t, the cold wire temperature T_a, and determine R_w which provides $(T_w - T_a) =$ = const.

In practice this approach which looks like the most natural is connected with large and not controlled uncertainty of measurements [30]. We cannot use a reference value of α_t taken from books. It must be determined experimentally for every probe or at least for every wire material. One needs to determine the resistance with high accuracy. Common testers are not suitable because they heat a wire and consequently change its resistance. Therefore, special and expensive equipment is necessary in order to measure the resistance correctly. It is not easy to estimate accurately the geometric sizes of a wire (wire length – about several mm, wire diameter – about several μm). Finally, measuring the wire resistance (without prongs and cables) is tricky. In principle, all these obstacles could be overcome but this leads to growth of measurement uncertainty which could be hardly estimated.

In this study another approach for determination of the hot wire temperature is applied [30]. Assume that a researcher has several calibration curves obtained at some temperatures including room temperature. Then the unknown temperature T_w can be determined with the help of a trial and error method. The criterion for the method implies that the calibration curves corrected in accordance with (2) must be as close to the calibration curve obtained at room temperature T_r as possible. Such an approach gives a capability to avoid all the difficulties connected with direct determination of the relation between R_w and T_w using formulas (3) and (4). The method's accuracy and cheap options of its realization are discussed in [31].

If you know the hot wire temperature T_w, it is easy to determine α_t and relation $R_w(T_w)$. This information is enough to provide automatic temperature compensation of velocity readings.

In summary, let us list our principles of hot-wire measurements:

(1) Instead of quests for higher accuracy of measurements (often illusive) it is better to use methods with known and/or controllable uncertainty.

(2) A researcher should duplicate measurements of the most important parameters with the aid of alternate tools if possible. For example, in this study the mass flow rate was measured using critical nozzles and a vortex flowmeter.

(3) In practice every piece of experimental data describes not an ideal scientific problem from textbooks but features of a certain experimental setup. A researcher should clarify these features (in reasonable limits) in order to understand their influence on modeling of an ideal problem. The concept of a hybrid (experiment-CFD) wind tunnel is a good idea [32].

(4) Every additional chance to estimate measurements' uncertainty should be used. For example, we may determine terms of the integral boundary equation in the case of measurements in a 2-D boundary layer and estimate the total uncertainty of an experimental model [33] (not realized in the present research).

Hot-wire device, probe, and experimental set-up

We have taken part in development of a common commercial CTA – IRVIS TA-5 [34]. Our new device is designed on the basis of a digital hot wire for registering vortices in *IRVIS* vortex flowmeters. The flowmeters are developed in Kazan, Russia, since 1990. They are successfully used in Russia, Ukraine, Kazakhstan, and Uzbekistan [35]. Preliminary methodical results obtained with the aid of our device have been published in [36]. Debugging of the device is not finished yet. Slight changes of the circuit are possible (fig. 3).

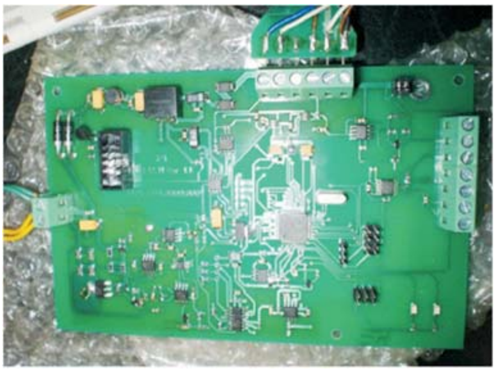

Figure 3. Hot-wire device for velocity-temperature measurements

Our hot wire is a CTA [37] with a digitally controlled bridge. Such kind of control allows to adjust the bridge automatically to any given temperature of the wire and provide reliable measurements of the electrical power dissipated in the wire. Only mean velocity is measured in these experiments, not instantaneous. The wire current can achieve a value of about 100 mA at the velocity measurement regime ('hot' wire) and it is quite small (10-12 mA) at the temperature measurement regime ('cold' wire). One has a capability to determine ambient temperature using the hot-wire bridge, because temperature of a thin wire is almost equal to the temperature of a medium. Usually the time of the temperature measurement is about 0.05 s and the period of a measurement cycle equals to 1-10 s (fig. 1). The time of the wire cooling depends on its diameter. For instance, a tungsten wire with the diameter of 5 μm could be cooled in 0.01 s. It is assumed that the temperature drift is relatively slow.

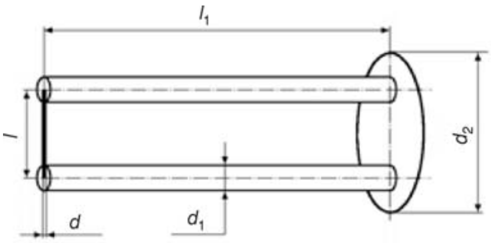

Figure 4. Design parameters of single-wire probe; $d = 6$ μm, $d_1 = 0.5$ mm, $d_2 = 2$ mm, $l \approx 2$ mm (calculated), $l_1 \approx 15$ mm

Common self-made single-wire velocity probes are used (fig. 4). The wire 3 of the sensing element with the diameter of 6 μm is made of annealed tungsten (no plating, unknown manufacturer). It is welded to the lead wires 4 made of stainless steel. Relation $R_w(T_a)$ for this type of wire is obtained in the temperature range of 0 °C to 60 °C with the help of a climate chamber. The function is found to be a linear one. The deviation of experimental points from the regression line is no greater than 0.2%. The wire length l is calculated using formula (4), electrical resistivity of tungsten at 20 °C, $\rho_r = 56 \cdot 10^{-9}$ Ωm [38], and resistance of the wire $R_r = 3.7$ Ω measured with the aid of DISA 55M hot-wire apparatus.

An experimental set-up is shown schematically in fig. 5. Air is heated by a heater (1). A flow conditioner (2) is used in order to decrease the effect of flow non-uniformity. A sin-

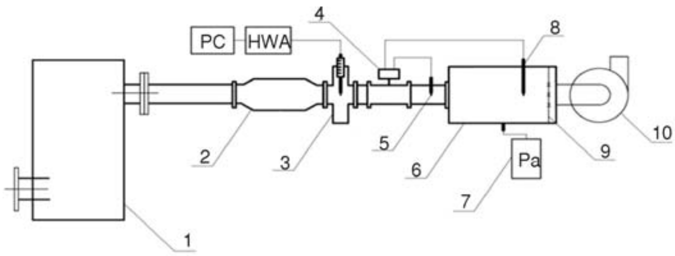

Figure 5. Scheme of experimental set-up:
1 – heater, 2 – flow conditioner, 3 – test section with velocity probe, 4 – vortex flowmeter IRVIS-RS4-Par, 5 – temperature probe Kvarts-DT.007, 6 – receiver, 7 – pressure probe PROMA-IDM, 8 – temperature probe Kvarts-DT.007, 9 – critical nozzles, 10 – turbo compressor

gle-wire probe is located in a 50 mm inner diameter test section (3). A vortex flowmeter IRVIS-RS4-Par (4) additionally measures flow rate and records readings of temperature probes Kvarts-DT.007 (5) and (8) located near the test section and near the critical nozzles. A turbo compressor (10) provides constant mass airflow rate (it sucks air) with the help of a set of critical nozzles (9). A receiver (6) installed after the test section damps pressure pulsations before the critical nozzles.

Two fine mesh screens are installed at the output of the heater (1) in order to prevent damaging of a thin hot wire by small solid particles. At large flow rates the heater and the screens cause noticeable increase of the hydraulic resistance of the set-up and the corresponding decrease of the mass flow rate in the test section in comparison with the flow rate provided by the critical nozzles. This leads to additional pressure loss in the test section and decrease of the air density. In order to take into account these effects the pressure in the receiver has been measured in a cold flow using a multifunctional pressure probe PROMA-IDM (7).

The temperature difference between the test section and the critical nozzles could achieve several tens of degrees Celsius due to large size of the receiver (6). For this reason the flow temperatures are measured simultaneously in both these regions using temperature probes Kvarts-DT.007 (5) and (8).

The flow conditioner has been developed in order to be used in combination with vortex flowmeters IRVIS [35]. The principle of operation of the device is the following (fig. 6). A non-uniform input velocity profile is destroyed due to the expansion passage (2) and the flow separation. Then the flow is intensively mixed. After that a new flow with an approximately uniform velocity profile is formed in the contraction passage (3). Results of methodical experiments with the flow conditioner are presented in [39].

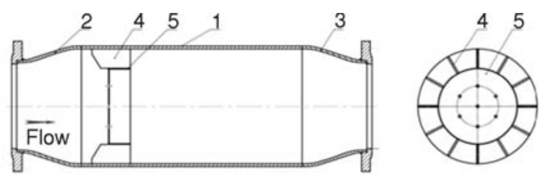

Figure 6. Flow conditioner scheme
1 – cowling, 2, 3 – conical passages, 4 – air directing vanes, 5 – cylinder with perforated bottom

Velocity and temperature profiles in the test section have been measured at a low nominal standard flow rate Q_n = 27 Nm^3/h (standard flow rate through a critical nozzle at standard conditions) using the same calibrated hot wire. In this case the profiles are expected to be some of the most non-uniform (fig. 7). During the measurement of the profiles the mean flow temperature in the test section determined with the help of a temperature probe Kvarts-DT.007 was almost constant (64.1-63.8 ºC). The origin of co-ordinates is located at the center of the cross-section of the pipe (X = 0 mm). The temperature probes underestimate the temperature in comparison with the hot wire at low flow rates, fig. 7(b). It is caused by a heat flux from the temperature probe to a metallic pipe wall and low heat exchange at such regimes in general.

Certified critical nozzles which guarantee constant value of a standard flow rate with an error no greater than 0.25% are used in the experiments. A multifunctional pressure probe PROMA-IDM has the allowable error limit of ±1% of the upper measurement limit for the current output. The characteristic time for the thermal inertia of a temperature probe Kvarts-DT.007 is no greater than 45 s. The temperature range is from –50 ºC to +150 ºC. The allowable error limit is ±0.5% of the measurement range. Vortex flowmeter IRVIS-RS4-Par can work in the temperature range from –40 ºC to +250 ºC. An error of the standard flow rate measuring is no greater than 1% at 0.2 Q_{min} ... Q_{max} and no greater than 1.3% at Q_{min} ... 0.2 Q_{max}.

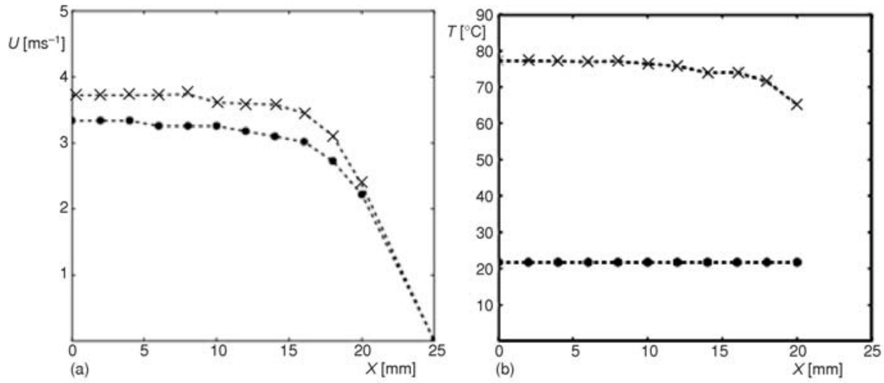

Figure 7. Velocity (a) and temperature (b) profiles in test section at nominal standard flow rate Q_n = 27 Nm^3/h; • – T_a = 21.7 ºC, × – T_a = 64 ºC

Two methods of "cold" wire calibration

The goal of the present experiments is to show that readings of the "hot" wire do not depend on a temperature drift. In order to demonstrate it the "cold" wire must be previously calibrated for temperature measurements with the help of a reference thermometer. The following problems or features of the setup should be mentioned:

(1) A "cold" wire measures temperature at a point, a temperature probe measures in fact the average temperature along a cross-section. A flow conditioner corrects a non-uniformity of the temperature profile and solves the problem to some extent.

(2) The metallic receiver (figs. 5 and 6) is large and heavy, its internal diameter is about 0.3 m. It is connected with the chosen size and number of the critical nozzles. The receiver and the set-up as a whole have a high thermal inertia. It takes too much time to achieve a real stationary thermal regime (T_a = const). So, the experiments were conducted under non-stationary thermal conditions.

(3) Also, due to its very large size the receiver has a higher thermal inertia than other parts of the set-up. As a result, air temperature in the test section may differ considerably from the temperature near the critical nozzles (several tens of degrees). This means that the volumetric flow rate near the nozzles and at the measuring cross-section may be different because the air density is different. The mass flow rate is naturally the same in accordance with the law of conservation of mass.

(4) Relatively high flow temperature leads to air heating before the critical nozzles and changing of the mass flow rate. Let us consider this phenomenon in detail.

The mass flow rate at the critical cross-section of a nozzle at room temperature equals to:

$$\dot{m}_r = \rho_r A c_r \tag{5}$$

where $\dot{m}_t$ [kgs^{-1}] is a mass flow rate of air at room temperature, ρ_r [kgm^{-3}] – the air density at room temperature, A [m^2] – the area of the nozzle throat, and c_r [ms^{-1}] – the speed of sound at the nozzle throat at room temperature. If the flow temperature near nozzles T_{noz} differs from 20 ºC, it has an influence on the density ρ and the sound velocity c which can be expressed as:

$$\rho = \frac{pM}{RT_{noz}} \tag{6}$$

where p [Pa] is the air pressure, M [kgmol^{-1}] – the molar mass, R = 8.314 J/molK – the universal gas constant (the specific gas constant of dry air is R/M = 287 J/(kgK)), and

$$c = \sqrt{\frac{\gamma \mathrm{R} T_{\mathrm{noz}}}{M}} \tag{7}$$

where γ is the heat capacity ratio ($\gamma = 7/5$ for air). That is, if $T_{\mathrm{noz}} > T_{\mathrm{r}}$ ($T_{\mathrm{r}} = 293,16$ K), then a mass flow rate through a nozzle decreases:

$$\frac{\dot{m}}{\dot{m}_{\mathrm{r}}} = \frac{\rho A c}{\rho_{\mathrm{r}} A c_{\mathrm{r}}} \sqrt{\frac{T_{\mathrm{r}}}{T_{\mathrm{noz}}}} \tag{8}$$

and the corresponding actual volumetric flow rate increases:

$$\frac{Q_{\mathrm{noz}}}{Q_{\mathrm{r}}} = \frac{Ac}{Ac_{\mathrm{r}}} \sqrt{\frac{T_{\mathrm{noz}}}{T_{\mathrm{r}}}} \tag{9}$$

Pressure p is constant in this case because the pressure at a subsonic nozzle exit equals to ambient pressure.

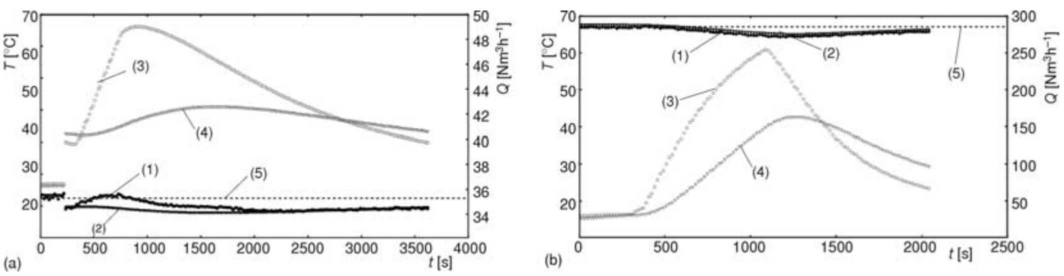

Figure 8. Standard flow rate and temperature at Q_{n} = 35.3 Nm^3/h (a) and Q_{n} = 285.2 Nm^3/h (b); (1) – standard flow rate measured by flowmeter, [Nm^3/h]; (2) – standard flow rate calculated using temperature near critical nozzles, [Nm^3/h]; (3) – temperature in test section, [ºC]; (4) – temperature near critical nozzles, [ºC]; (5) – nominal standard flow rate Q_{n}, [Nm^3/h]

The vortex flowmeter which calculates a flow rate using the vortex shedding frequency around a bluff body and the temperature measured by a temperature probe at the test section does not reproduce the expected behavior at low flow rates (Q_{n} = 13, 35, and 56 Nm^3/h), as shown in fig. 8(a). In our opinion, wrong readings of the flowmeter could be explained by underestimation of temperature by the temperature probe at low flow rates, fig. 7(b). A vortex flowmeter measures velocity directly. The flow rate needs to be calculated using the measured temperature. Underestimated temperature leads to overestimated density and an overestimated value of the mass flow rate pU. On the contrary, readings of the vortex flowmeter are correct at large flow rates fig. 8(b). Because of this we assume that readings of the temperature probe at the maximal flow rate (Q_{n} = 285,2 Nm^3/h) are the most reliable.

In order to minimize the thermal inertia of the temperature probe the air flow has been maintained at almost stationary thermal regime (temperature in the test section was approximately constant). Results of temperature measurements in the test section obtained with the help of the "cold" wire and the external temperature probe are shown in fig. 9. A temperature coefficient of the wire resistance α_{t} expresses the relationship between the wire resistance and the flow temperature. The value of the coefficient is chosen in order to make equal the maximal flow temperatures registered by the "cold" wire and an external temperature probe. If you know the "cold" wire resistance at room temperature and the "hot" wire resistance at the maximal ambient temperature it is possible to calculate α_t using formula (3). The value obtained is $\alpha_t = 0.00377$ °C^{-1}.

Another approach to the "cold" wire calibration is based on determination of the "hot" wire temperature using a trial and error method *(see section Theoretical basis and philosophy for measurements)*. In this case the "cold" wire has been switched off and the hot-wire device has been switched to the common CTA regime ($T_w - T_a \neq$ const, $T_w =$ const). An air flow is gradually heated and cooled in the temperature range of 30 ºC to 40 ºC at the following flow rates: Q_n = 27, 83, and 185 Nm^3/h (fig. 10). Such a temperature drift has practically no effect on the mass flow rate through the critical nozzles. The values of electric current at the same ambient temperature for heating and for cooling are different (the difference is about 1 mA). It is connected with a higher thermal inertia of the temperature probe in comparison with a hot wire. The mean of these two values is used for calculations.

Calibration curves obtained at a few ambient temperatures are shown in fig. 11. As would be expected, less electric current is needed to maintain the constant temperature (or resistance) of the hot wire at higher ambient temperature. Room temperature equals to 19.5 ºC. The hot wire temperature T_w is determined directly using the following steps:

(1) A power function approximating the base calibration curve (T_a = 19.5 ºC) is found: $I^2 = 2312 + 1212U^{0.45}$.
(2) A first estimate (too high) for T_w is chosen: T_w = 300 ºC.
(3) All samples are reduced to room temperature by application of (2) using the respective ambient temperatures.
(4) The standard deviation of the complete "corrected" data set is calculated and noted.
(5) The estimate for T_w is lowered by one tenth of a degree.
(6) Steps (3) to (5) are repeated until the standard deviation starts to increase.

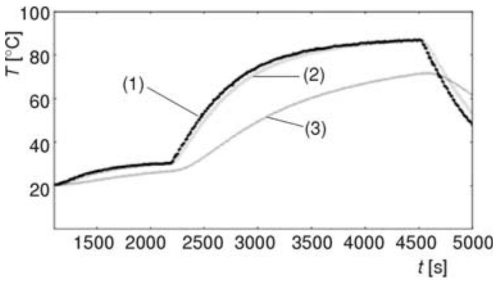

Figure 9. Calibration of "cold" wire using reference thermometer (Q_n = 285.2 Nm^3/h); (1) – temperature in test section measured by "cold" wire, [ºC]; (2) – temperature in test section measured by reference thermometer, [ºC]; (3) – temperature near critical nozzles, [ºC]

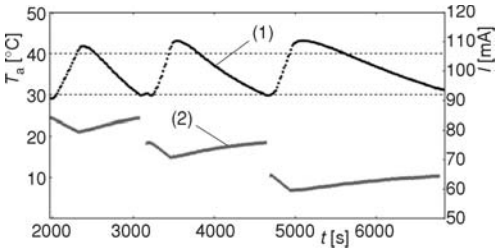

Figure 10. Temperature regimes and electric current through hot wire of common CTA; (1) – air temperature in test section T_a, [ºC]; (2) – electric current through hot wire I [mA]

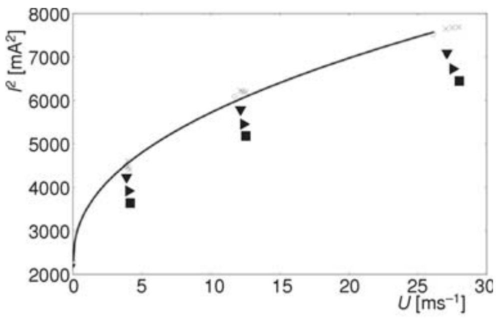

Figure 11. Calibration curves at various ambient temperatures before (○ – T_a = 19.5 ºC; ▾ – T_a = 30.0 ºC; ▸ – T_a = 35.0 ºC; ■ – T_a = 40.0 ºC) and after (x) correction

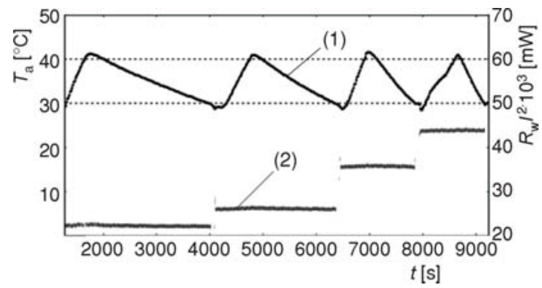

Figure 12. Temperature regimes and output signal of hot-wire device at constant temperature difference regime ($T_w - T_a$ = const); (1) – air temperature in test section T_a, [°C]; (2) – output electric power of hot wire $R_w I^2$, [mW]

The temperature of the hot wire determined with the help of this procedure was equal to 146.6 °C. This value is close to the alternate value 150.0 °C which was obtained using the temperature coefficient of the wire resistance α_t = 0.00377 °C^{-1} determined by the first method of the "cold" wire calibration.

Calibration curves at various ambient temperatures before and after the correction in accordance with expression (2) at T_w = = 146.6 °C are presented in fig. 11. The base calibration curve (room temperature) is shown using a solid line. The deviation of corrected experimental points from the approximating curve is about 0.64-0.80 m/s.

Measurements in flow with constant mass flow rate and changing temperature

An output velocity signal of our hot-wire device with a calibrated 'cold' wire at different constant standard flow rates (13; 27; 83 and 185 Nm^3/h) is presented in fig. 12. The device operates in the constant temperature difference regime ($T_w - T_a$ = const). Evidently, the velocity readings practically do not depend on ambient temperature. The relative deviation of the output signal from the corresponding calibration value increases with decrease of the flow rate. The maximal deviation is no greater than 3,3% (Q_n = 13 Nm^3/h).

This work is a good illustration of the famous phrase, "*the devil is in the details*": simple physical idea of experiments contrasts sharply with many complex external factors and phenomena which a researcher must take into account. A numerical modeling of the experimental set-up would be very useful for planning the experiments and understanding the results.

Conclusions

A single sensor hot-wire device with automatic temperature compensation for velocity measurements is presented. The device is able to measure quasi-simultaneously the temperature and velocity at the "cold" wire and the "hot" wire regimes, correspondingly. Two practical methods of a "cold" wire calibration are described in detail. It is demonstrated that the hot wire can measure velocity correctly in a flow with a temperature drift up to 40 °C. Probably, the upper temperature limit could be even up to 50-60 °C, but it was not verified by measurements due to limitations of the experimental set-up. Though only mean velocity is measured in the present work the hot wire is able to measure instantaneous velocity as well.

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Nomenclature

Acronyms

PIV – particle image velocimetry
LDV – laser doppler velocimetry
CTA – constant temperature anemometer

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