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MICROTHERMOCOUPLES SENSORS FOR VELOCITY AND TEMPERATURE MEASUREMENTS IN GAS FLOW

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ABSTRACT
This paper presents the development of two classes of sensors based on microthermocouples with different wire diameters (from 7.6 µm to 25.4 µm). The first one uses the pulsed-wire technique for the couple velocity/temperature measurement. These sensors are used with three different techniques we developed in our laboratory: the time of flight method, the oscillation frequency method and the phase method. Because the purpose of this kind of sensor is to be introduced in different microdevices, it is realized with two thermocouple wires and does not use the micromaching technologies. Its working principle is close to that of the hot wire anemometer and it presents the same advantages such as very small dimensions and weak response time. The sensor is developed in order to measure flows and temperatures in microsystems like small channels (width < 500 µm), microtubes (diameter < 53 µm) and small structures (volume < 100 µm^3). The second class of sensors are based on the multi-wire thermocouple technique. In this paper we present a probe using two wires of same nature but different in diameter located close together at the measurement point. This probe is used to measure simultaneously the temperature and the velocity of flowing gas. Results will focus on oscillating flows of gas.

INTRODUCTION
In many industrial and medical applications, the determination of different flow parameters is required in order to control a process or to characterize with precision a fluid flow. For example, a great number of sensors have been made to detect a local velocity or a flow for gases or liquids, a local temperature or thermal properties or all others parameters like pressure or gas concentration. For each one of these sensors, a high sensitivity, a weak response time and small dimensions are performances to reach and particularly for the precedent parameter since the development of the microfluidic devices. Whatever the applications, an intrusive sensor needs to be developed to characterize micro-systems such as micropump and micromixer [1-3], heat exchanger [4, 5] or lab-on-chip device [6]. The micromachining techniques have allowed to realize sensors which the sensitive element can be introduced in the microsystem. For example, in the case of a flow velocity measurement for which thermal methods are frequently used, the heating element can be achieved by these techniques in the microsystem [7, 8]. This paper presents the experimental characterization of a new sensor realized with a micro-thermocouple for velocity and temperature measurements. Because the purpose of this sensor is to be introduced in different microdevices, it is realized with two thermocouple wires and does not use the micromachining technologies. Its working principle is close to that of the hot wire anemometer [9,10] and it presents the same advantages such as very small dimensions and weak response time.

The technique consists in heating the microthermocouple during a constant phase and letting it cool during a second phase which depends on the fluid velocity. An electronic command ensures the succession of these two phases and it becomes possible to connect the velocity information to the obtained signal frequency. The sensor is then used as an anemometer. Moreover, at the end of the cooling phase, the signal value corresponds to the local temperature of the fluid and this method presents thus the advantage to measure two local informations with only one probe.

MICROTHERMOANEMOMETER SENSOR

Description of the sensor

The sensitive element of the microsensor is a K type thermocouple (Chromel/Alumel) with a diameter of 25.4 µm. The measurement technique is based on the succession of an heating period and a cooling phase and is frequently used in the literature [11-14]. The block diagram of the sensor (called microthermoanemometer) and its associated electronic are represented in Figure 1.

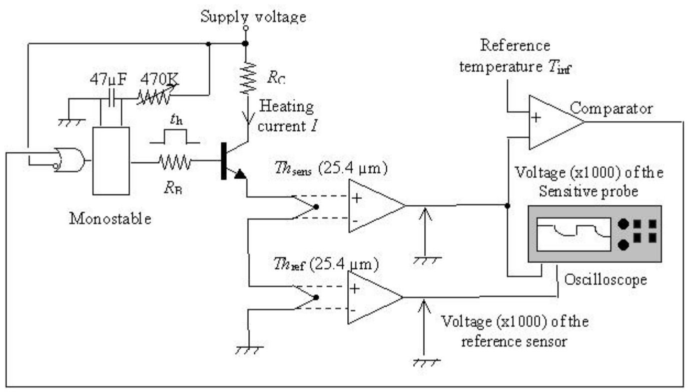


Figure 1 - Block diagram of the microthermoanemoter (µTA).

It contains a bipolar transistor to heat the thermocouple junction and to choose the current intensity with the resistors R_C and R_B, two instrumentation amplifiers, a comparator and a monostable to provide a current pulse. The microthermocouple is heated by Joule effect with the transistor during a constant duration t_h. During this phase, the temperature junction increases to reach a temperature T_{sup} higher than the fluid temperature T_f. This phase is then followed by a cooling phase and the time t_r necessary for the sensor to reach again the initial temperature T_f depends either on the fluid velocity or on the gas vacuum. In fact two thermocouples are used in this system. One of them, Th_{sens}, is introduced in the fluid whose we want to measure the velocity or the vacuum, and the second, Th_{ref}, is disposed in a closed volume to avoid the external disturbances. This probe does not influence the measurement principle but it can be used to give a reference signal. Indeed, the thermocouples being connected up in series, they are heated by the same intensity I which allows to observe the heating and cooling effects. Because the voltage values measured by the microthermocouples are very small, they are amplified by two precision instrumentation amplifiers (type AD624) with a gain amplification of 1000. The value issued from Th_{sens} is then compared to an adjustable reference value corresponding to a temperature close to the fluid temperature. If it becomes less than the reference value, the comparator commutes and provides a current pulse of duration t_h with the trigger input of the monostable. A new heating phase is thus restarted and the signal frequency measured on the microthermocouple Th_{sens} depends on the gas velocity or the gas vacuum. The choice of this reference is fundamental for the circuit functioning. First of all, this value has to be greater than the value corresponding to the fluid temperature to ensure the oscillations of the circuit but it must be very close to the fluid temperature to provide this information at the end of the cooling phase.

A control variable is integrated in the circuit to select the working of the oscillator. When this variable is activated, the signal extracted from the probe Th_{sens} corresponds to the fluid velocity and these informations are detected in the frequency variations. The inhibition of the control variable stops the oscillations and the value measured by the thermocouple corresponds then exactly to the fluid temperature. Two ways may be thus used to measure the fluid temperature: the first one with the inhibition of the oscillations for a functioning as a microthermocouple and the second at the end of the relaxation phase if the thermal inertia of the sensor is very weak.

Another advantage of this system is the possible thermal compensation of the sensor. Indeed, the second probe Th_{ref} is actually used as a reference signal but it can be used to give the reference voltage allowing the commutation of the comparator. Introduced in the flow and without electronic command, this microthermocouple may provide the voltage corresponding to the fluid temperature. It can so replace the actually voltage value which simulates this temperature and in this manner maintaining the oscillations of the circuit even if the fluid temperature increases.

Theory

The theoretical analysis is conducted through the dynamic behaviour of the resistive wire subjected to a periodic heating and cooling by forced convection. The two thermocouples wires are modeled by a single wire whose average thermo-physics characteristics are considered as constants. Thermocouple wires are assembled for forming a wire of length *2L* and diameter *d* placed in the fluid. The wire is heated by Joule effect by intensity of current *I* and dissipates the heat produced into the surrounding fluid of temperature T_f by convection. The air fluid characteristics are supposed constant. The one dimensional thermal balance interprets the equality between the accumulated power by the cylindrical volume of the wire and the sum of the following modes of the heat transfer: the convection through the boundary layer surrounding the wire, the conduction along the wires towards the support of the thermocouple, the radiation between the probe and the surrounding wall of the conduit, the internal heating by Joule effect.

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} - \frac{4\left(h_{cv}+h_{rad}\right)}{\rho c_p d}\left(T-T_f\right) + A\left[1+\alpha\left(T-T_f\right)\right]I^2 \qquad (1)$$

with $A = \left(\frac{4}{\pi d^2}\right)^2 \frac{\rho_0}{\rho\, c_p}$

Equation (1) interprets the thermal balance between a wire of circular section heated by Joule effect and the surrounding fluid and wall. This equation brings in two thermo-physics parameters representing the quality of the thermal exchange between the wire surface and the fluid: the convection coefficients h_{cv} and the linear radiative heat transfer coefficient $h_{rad.}$

Defining the convective time constant of the wire by the classical expression:

$$\tau_{cv} = \frac{\rho\, c_p d}{4 h_{cv}} = \frac{\rho\, c_p d^2}{4 \lambda_f Nu} \tag{2}$$

with

$$Nu = \frac{h_{cv}\, d}{\lambda_f} = C_1 + C_2\, Re^n \tag{3}$$

the Nusselt number of the flow where the Reynolds number Re is based on the wire diameter d and the local velocity V. Considering the relation valid for a Reynolds number $0.015 < \mathrm{Re} < 20$ for which the constants yield [23]:

$C_1 = 0.34$, $C_2 = 0.65$ and $n = 0.45$ (39)

The radiative time constant of wire is also defined by the expression:

$$\tau_{rad} = \frac{\rho\, c_p d}{4 h_{rad}} = \frac{\rho\, c_p d}{16 \varepsilon\, \sigma\, T_f^3} \tag{4}$$

with $h_{rad} = 4\varepsilon\, \sigma\, T_f^3$ the linear radiative heat transfer coefficient (the heating of the wire is very small, its surface temperature remains near to that of fluid flow).

Moreover, the time constant corresponding to the heating of the wire next to the heat accumulation by the Joule effect defined as:

$$\tau_{él} = \frac{1}{A\, \alpha\, I^2} \tag{5}$$

Finally, we call τ_g the global time constant of the sensor which can be defined by the relation:

$$\frac{1}{\tau_g} = \frac{1}{\tau_{cv}} + \frac{1}{\tau_{rad}} - \frac{1}{\tau_{él}} \tag{6}$$

Then equation (1) can be modified by introducing the global time constant τ_g:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} - \frac{T - T_f}{\tau_g} + A\, I^2 \tag{7}$$

The conduction effect along the wire can be neglected with respect to the convection for the aspect ratio L/d > 200 sufficiently large. Taking into account the simplifying hypotheses, the thermal balance finally written in the form of a differential equation of first degree whose solution gives the temperature profile of the wire during the heating and relaxation states of the wire:

$$\frac{dT}{dt} + \frac{T - T_f}{\tau_g} - A\, I^2 = 0 \tag{8}$$

Heating phase

The solution of the differential equation (8) describes the temperature rising of the wire during the time:

$$T(t) = T_f + A\, I^2 \tau_g + \left(T_{\inf} - T_f - A\, I^2 \tau_g\right) e^{\left(-\frac{t}{\tau_g}\right)} \tag{9}$$

with the initial condition : $T(t=0) = T_{\inf}$ (10)

T_{inf} is the reference temperature corresponding to the threshold temperature for heating the wire. The temperature T_{sup} can be expressed at the end of the heating period t_h. $T(t = t_h) = T_{sup}$ and equation (9) written as (11):

$$T_{\sup} = T_f + A\, I^2\, \tau_g + \left(T_{\inf} - T_f - A\, I^2 \tau_g\right) e^{\left(-\frac{t_h}{\tau_g}\right)} \tag{11}$$

If the sensor, in the convective conditions, having thermo-physics characteristics such that $\tau_g << t_h$, then it attains its thermodynamic equilibrium and its temperature T_{sup} takes for value (Figure 48):

$$T_{\sup} \approx T_f + A\, I^2\, \tau_g \tag{12}$$

hence for a heating with respect to the average temperature of the flowing fluid:

$$T_{\sup} - T_f \approx A\, I^2\, \tau_g \tag{13}$$

Relaxation phase

The relaxation phenomenon, of duration t_r (Figure 48), is due to the cooling of the thermocouple wire caused by the fluid flowing at the velocity V. In this way the duration of dynamic cooling produces two informations relative to the local velocity of the flow, the temperature of the thermocouple when the regime of thermal equilibrium with the fluid is attained. The wire is cooled by forced convection from the new temperature T_{sup}, obtained at the end of heating period t_h. It tends towards the corresponding temperature T_{inf}, either to the threshold temperature where the voltage is fixed by the electronic system, or to the regime of thermal equilibrium if the inertia of the wire is sufficient. The differential equation which governs the relaxation phenomenon is obtained from the balance equation (8) for which the heating current is set to zero. So, for $I = 0$:

$$\frac{dT}{dt} + \frac{T - T_f}{\tau_g^*} = 0 \tag{14}$$

with the initial condition :

$$T(t = t_h) = T_{\sup} \tag{15}$$

and now the global time constant of the sensor becomes :

$$\frac{1}{\tau_g^*} = \frac{1}{\tau_{cv}} + \frac{1}{\tau_{rad}} \tag{16}$$

Considering equations (15) and (16), the solution of the wire temperature has the following expression:

$$T(t) = T_f + (T_{\sup} - T_f)\, e^{\left(-\frac{t-t_h}{\tau_g^*}\right)} \qquad (17)$$

From equation (17), the temperature T_{inf} corresponding to the threshold temperature attained by the sensor at the end of relaxation time t_r :

$$T(t = t_r) \equiv T_{\inf} = T_f + (T_{\sup} - T_f)\, e^{\left(-\frac{t_r-t_h}{\tau_g^*}\right)} \qquad (18)$$

Or on heating:

$$T_{\inf} - T_f = (T_{\sup} - T_f)\, e^{\left(-\frac{t_r-t_h}{\tau_g^*}\right)} \qquad (19)$$

From equation (19), we can express the relaxation time t_r at the end when the temperature tends towards the value T_{inf}. Then it occurs $T(t = t_r) = T_{\inf}$ and finally,

$$t_r = t_h - \tau_g^* \ln\left(\frac{T_{\inf} - T_f}{T_{\sup} - T_f}\right) \qquad (20)$$

Oscillation frequency

The sensor is heated by an electric current during a constant time t_h. Next it is cooled by convection during a variable time t_r which depends upon the nature of the flow and the fluid properties. The temperature then attains the threshold value T_{inf} fixed by the electronic system. A new heating is thus achieved. By this way the sensor is subjected to an oscillation whose frequency is proportional to the cooling and thus to the velocity of the flow as well. The oscillation frequency f of the sensor can be related by putting the heating time as a parameter fixed by the electronic system. So we get:

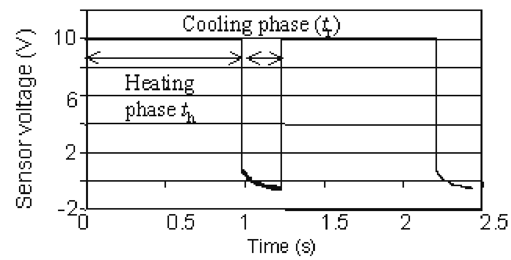
$$f = \frac{1}{t_h + t_r} = \frac{1}{2t_h - \tau_g^* \ln\left(\frac{T_{inf} - T_f}{T_{sup} - T_f}\right)} \qquad (21)$$

Finally the oscillation frequency of the sensor can be expressed as a function of the following parameters: flow velocity V and wires diameter d (taking place in the expressions of the time constant τ_g^* and τ_g), heating duration t_h, heating current I, relaxation heating $T_{inf} - T_f$.

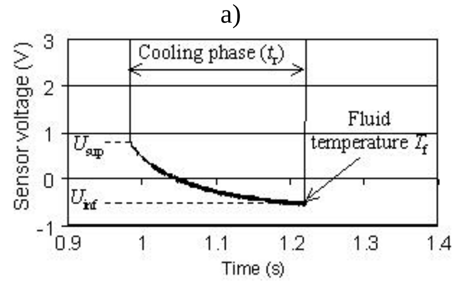
$$f = \left[2t_h - \tau_g^* \ln\left(\frac{T_{\inf} - T_f}{A I^2 \tau_g + (T_{\inf} - T_f - A I^2 \tau_g)\, e^{\left(-\frac{t_h}{\tau_g}\right)}}\right)\right]^{-1} \qquad (22)$$

Sensor response

An example of the sensor response is represented Figure.2. This curve is obtained without flow in the ambient conditions for a K type thermocouple of diameter 25.4 µm and an intensity I of 32 mA. The choice of the current pulse value results from a compromise between a significant heating duration to heat the junction and a weak response time in order to characterize rapid flow variations. It can be observed on this curve the two successive phases describing the measurement cycle. The heating phase is fixed at t_h = 1s. This phase corresponds to a amplifiers saturation for which the measured voltage is close to the alimentation value. The duration of the cooling phase depends in this case on natural convection and the obtained value is t_r = 0.24 s which corresponds to a signal frequency f = 806 mHz with:



a)



b)

Figure 2 - Sensor response in ambient conditions (a) and without flow (b) (I = 32 mA, t_h = 1s).

Moreover, the temperature rising can be determinated by the voltage difference between the values U_{sup} at the beginning and U_{inf} at the end of this second phase. Taking into account the sensitivity of 40 µV.K^{-1} for a K type thermocouple and an amplification gain of 1000, the current pulse provides a difference voltage of 1.3 V which corresponds to a temperature difference of 33 °C. If the fluid velocity increases, the sensor is cooled by forced convection, the temperature rising decreases and the signal frequency increases.

Experiments

To study the sensor sensitivity to velocity variations, an experimental characterization has been developed in the laboratory. The calibration system is represented on Figure. 3. An air flow at ambient temperature is introduced with a compressor in a cylindrical tube of length 1.20 m and of diameter 10 mm. The flow is regulated with a mass flow rate (type Brooks) which is used as reference for the calibration. The microthermocouple Th_{sens} is then introduced in the tube extremity and placed on the central axis. The velocity range obtained with this tube and the mass flow rate is 0 – 3 m.s^{-1} which corresponds to a laminar flowing regime. The sensor being placed on the axis of the tube, the signal extracted from Th_{sens} depends directly on the maximum velocity of the flow. The calibration step consists in measuring the signal frequency for different velocity values.

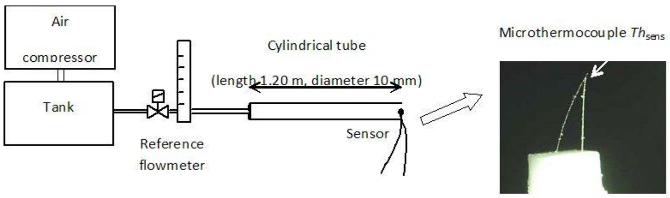


Figure 3 - Structure of the velocity calibration system.

The results presented on Figures 4 and 5 are obtained with a microthermocouple of diameter 25.4 µm and for different values of heating time and current intensities. They show the frequency variations of the sensor as a function of the flow velocity in the tube. In general manner, two different domains can be distinguished on theses curves. The first one is obtained for a velocity less than 0.14 m.s^{-1} for which the frequency variations are important and the sensitivity is high. This part corresponds to the maximum value of the sensitivity and to the functioning domain of the sensor. The microthermocouple junction is cooled by forced convection and the heat transfer with the fluid is effective. The second zone, beyond 0.14 m.s^{-1}, corresponds to a diminution of the sensor sensitivity until reaching a saturation zone for velocities higher than 1.5 m.s^{-1}. In this case, the temperature rising obtained by Joule effect is insufficient compared to heat transfer caused by the flow. For each one of these curves, the sensitivity has been computed in the linear zone in order to estimate the current intensity or heating time effects. The best results are obtained for an heating time of 0.6 s and it can be observed on the curves that the sensor sensitivity decreases when this parameter increases.

A very short heating duration limits the temperature rising of the junction and so decreases the radiation effects limiting the working of the sensor. The current study shows that the signal frequency decreases with the intensity of the current. The temperature rising being more important, the cooling duration to reach again the fluid temperature increases which causes a diminution of the frequency value. Moreover, we can observe on Figure 6 corresponding to the best results with t_h = 0.6 s, that the sensitivity increases with the intensity to reach a maximum value for I = 32 mA. Beyond this maximum the sensor sensitivity decreases or does not evolve anymore. For high current intensities, the radiation heat exchange become higher than of the convection and the junction cannot dissipate the heat produced by Joule effect.

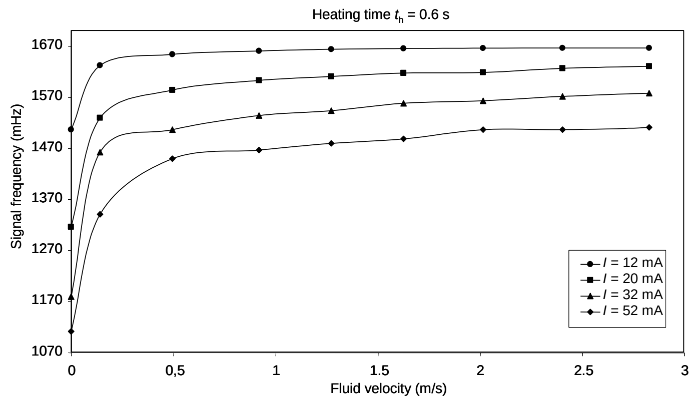


Figure 4 - Experimental variations of the signal frequency versus fluid velocity for different current intensities (heating time fixed at t_h = 0.6 s).

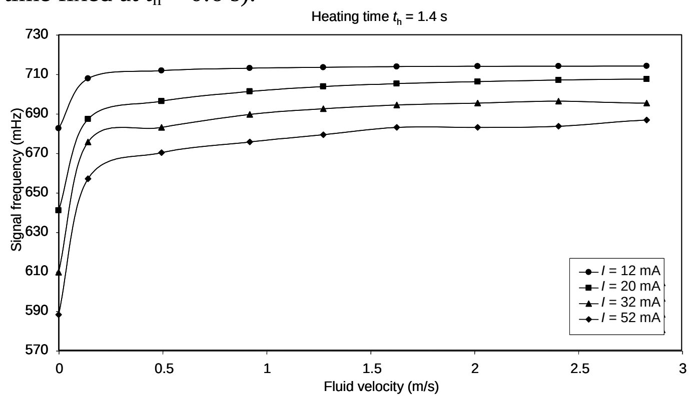


Figure 5 - Experimental variations of the signal frequency versus fluid velocity for different current intensities (heating time fixed at t_h = 1.4 s).

Comparison between µTA and LDV

This work compares two different methods for the velocity profiles measurement of an air jet at the outlet of a circular tube: the microthermocouple anemometer (µTA) and the Laser Doppler Anemometry (LDA) [15].

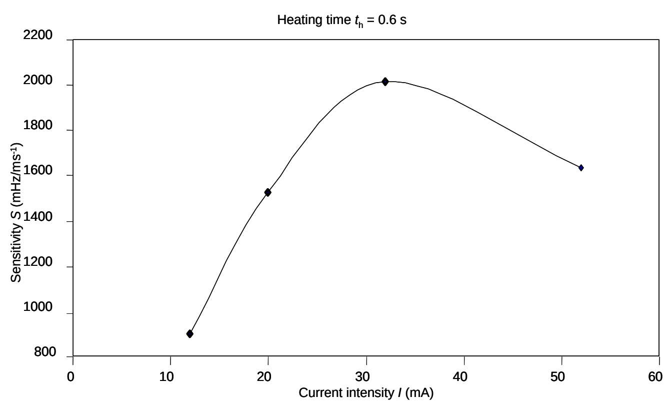


Figure 6 - Maximum values of velocity sensitivities for different current intensities (heating time t_h fixed at 0.6 s).

The microthermocouple anemometer consists of two type K (Chromel/Alumel) microthermocouples (25.4 µm diameter) used in an electronic oscillator. One is placed in the system and the other takes place in a reference volume. During a half period the two microthermocouples are heated to a suitable temperature above ambient. During the next half period, when the supply of current is interrupted, the microthermocouple placed in the system measures the flow while the other compensates for the ambient temperature changes. Cooling caused by experimental conditions under variable flow results in a change in the oscillator frequency. The sensor measures flows and temperatures simultaneously. The second method uses a classical Laser Doppler Anemometry to extract the velocity profiles and to be considered as reference measurements (Figure. 7). The flow measurements are in the range 0 to 5 $m.s^{-1}$.

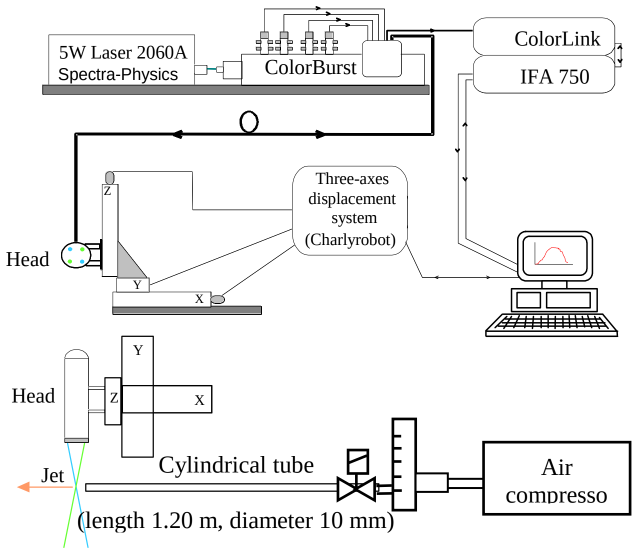


Figure 7 - Experimental setup

The micrthermanemometer measurements are made in the three directions (X,Y,Z) from the center-point of the test section with a measure each millimeter with the same three-axes displacement system (Figure 8). The frequency versus coordinate is obtained for each measurement point. The frequencies are then transformed into velocities by means of the calibration curve (Figure 4).

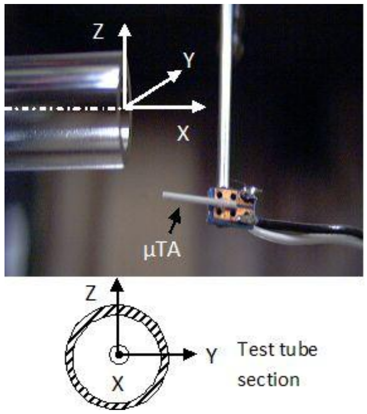


Figure 8 - Microthermocouple anemometer (µTA)

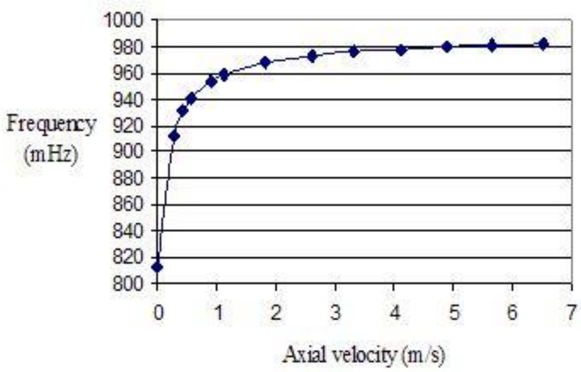
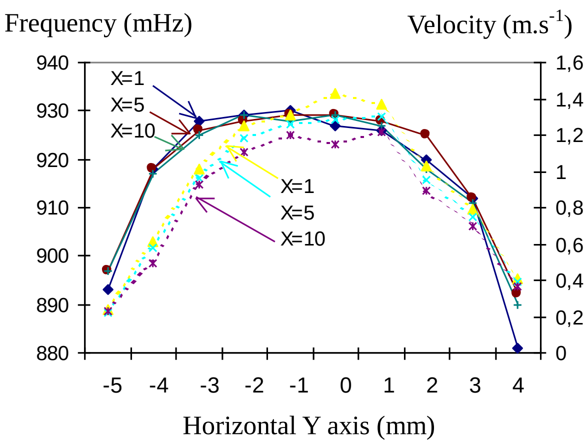
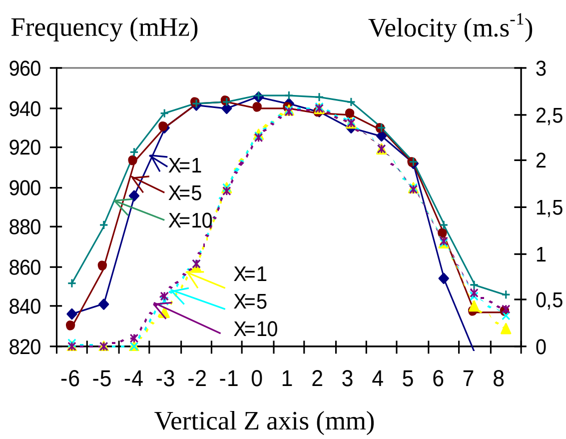


Figure 9 - Variation of the frequency versus axial velocity

Measurements resulting from the two methods described previously are then represented Figures 10a and 10b in order to compare the velocities profiles at the outlet of the tube for X = 1 mm, X = 5 mm and X = 10 mm. For the flow rate Qv_1 = 160 $L.h^{-1}$, the experimental results highlight a good agreement between the various profiles velocities. The velocities measured by LDA can then be used like reference in order to characterize the thermo anemometric probe. The flow rate Qv_2 = 370 $L.h^{-1}$ presents profiles with a dissymmetry more accentuated. In both cases, one notes a dissymmetry of measurements compared to the central axis of the tube which can come from the flow which is not perfectly symmetrical at the exit of the tube (effects of the turbulence). Moreover, shifts can also be introduced on the level of the adjustment of the origin of measurements related to a bad positioning of the probe or with the width of the zone of intersection of the beams.



a) Flow rate Qv_1 =160 L.h^{-1}



b) Flow rate Qv_2 =370 L.h^{-1}

Figure 10 - Comparison of the two methods for various horizontal planes: (- - -) LDA measurements and (—) µTA measurements.

MULTIWIRE SENSOR

Measuring fluid temperatures with a single thermocouple requires knowledge of the fluid velocity and fluid properties to determine the global heat transfer coefficient of the wire, integrating convection, conduction and radiation, and its natural frequency. In such a case, the thermal inertia of the thermocouples act as a first order low-pass filters attenuating the high frequency fluctuations. Another technique consists of temperature measurements with a probe using two [16-22] or three thermocouples [23, 24] of same nature but different in diameter located close together at the measurement point (Figure 11). This method was first used to characterize fluctuating gas flows for combusting flows. A two or multi thermocouple probe realizes simultaneously both the estimation of thermocouple time constants and the compensation of thermocouple response.

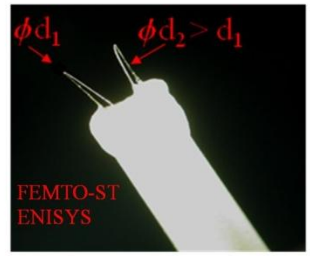


Figure 11 - Two-thermocouples probe with K (Chromel/Alumel) type wires [24].

Basic analysis of a two thermocouples probe

The basis analysis neglects the effects of the radiative and conductive environment in which the thermocouple junction is located and the effects of catalytic reaction on the thermocouple wire surface [16, 18].

The instantaneous heat balance written for each thermocouple permits to estimate the gas temperatures T_{g1} and T_{g2} function of the measured temperatures T_1 and T_2 and the time constants τ_1 and τ_1 respectively:

$$T_{g1} = T_1 + \tau_1 \frac{dT_1}{dt} \quad \text{and} \quad T_{g2} = T_2 + \tau_2 \frac{dT_2}{dt} \tag{23}$$

The two thermocouples are assumed to be exposed to identical flow conditions. Since the velocity V is the same for both thermocouple junction, the time constants can be written from Equation (2) as following:

$$\tau_1 = K\, d_1^{2-m}\, V^{-m} \quad \text{and} \quad \tau_2 = K\, d_2^{2-m}\, V^{-m} \tag{24}$$

K is a constant, d_1 and d_2 are the thermocouple junction diameters. m is an exponent function of the ratio between the Nusselt and Reynolds numbers and is generally assumed to lie in the range:

$$0.3 \le m \le 0.7 \tag{25}$$

From Equation (24) it can be defined a constant α as the ratio of the time constants:

$$\alpha = \frac{\tau_1}{\tau_2} = \left(\frac{d_1}{d_2}\right)^{2-m} \tag{26}$$

Frequency domain reconstruction:

The Fast Fourier Transform (FFT) of Equations (23) is used for reconstruction of signals from a two-thermocouple measuring rig [20-24] to obtain the following frequency domain equation, assuming $T_g = T_{g1} = T_{g2}$:

$$\overline{T}_g = \frac{\overline{T}_1\, \overline{T}_2 \quad \alpha - 1}{\alpha\, \overline{T}_1 - \overline{T}_2} \tag{27}$$

Where $\overline{T}$ denotes the FFT.

Then, the time domain representation is found by taking the inverse Fast Fourier Transform:

$$T_g = FFT^{-1}\left(\bar{T}_g\right) \qquad (28)$$

This method is simple but it presents the inconvenient to be dependent to singularities and noise.

Time domain reconstruction:

To reconstruct the time domain another technique consists in data smoothing, estimation of time domains and finally operates the reconstruction of solutions [16, 17, 19, 22, 23, 25]. The data smoothing is purchased after filtering with a low pass filter or with a sliding window on the data.

The next step consists in estimating the time constants τ_1 and τ_2, assuming $T_g = T_{g1} = T_{g2}$, by minimizing the time-average difference between the two reconstructed temperatures T_{g1}, T_{g2} and then $\left(T_{g1} - T_{g2}\right)^2$.

The mean squared error e for a data window is defined by:

$$e = \frac{1}{N}\sum_{i=1}^{N}\left(T_{g2}^{i} - T_{g1}^{i}\right)^2 \qquad (29)$$

N is the size of the window and the superscript i corresponds to the i^{th} term in the data array. Substituting equations (23) into equation (28), one obtains:

$$e = \frac{1}{N}\left[\begin{array}{c} \sum_{i=1}^{N}\left(T_2^i - T_1^i\right)^2 + \tau_1^2 \sum_{i=1}^{N}\left(\frac{dT_1^i}{dt}\right)^2 \\ + \tau_2^2 \sum_{i=1}^{N}\left(\frac{dT_2^i}{dt}\right)^2 - 2\tau_1 \sum_{i=1}^{N}\left(\frac{dT_1^i}{dt}\left(T_2^i - T_1^i\right)\right) \\ + 2\tau_2 \sum_{i=1}^{N}\left(\frac{dT_2^i}{dt}\left(T_2^i - T_1^i\right)\right) - 2\tau_1\tau_2 \sum_{i=1}^{N}\left(\frac{dT_1^i}{dt}\frac{dT_2^i}{dt}\right) \end{array}\right] \qquad (30)$$

Considering equation (26), differentiating equation (30) with respect to τ_1 and τ_2 and setting to zero to find the minimum gives two simultaneous equations which can be solved to obtain the time constants:

$$\tau_2 = \frac{\sum_{i=1}^{N}\left[\alpha \frac{dT_1^i}{dt}\left(T_2^i - T_1^i\right) - \frac{dT_2^i}{dt}\left(T_2^i - T_1^i\right)\right]}{\sum_{i=1}^{N}\left[\alpha^2\left(\frac{dT_1^i}{dt}\right)^2 + \left(\frac{dT_1^i}{dt}\right)^2 - 2\,\alpha\left(\frac{dT_1^i}{dt}\right)\left(\frac{dT_2^i}{dt}\right)\right]} \qquad (31)$$

$$\tau_1 = \alpha\,\tau_2 \qquad (32)$$

Finally, after determining the two time constants τ_1 and τ_2, the temperatures T_{g1} and T_{g2} are calculated from Equation (23).

Fluid velocity measurement with a two-thermocouple probe.

The goal of this technique is to measure the temperature and the velocity of the periodic flow inside an engine (Stirling machine in our case) with different two-microthermocouple probes [24]. Once the time constants τ_1 and τ_2 are determined, it is possible to extract the value of the fluid velocity V from Equations (23), and:

$$V = \left(\frac{\tau_2}{K\,d_2^{2-m}}\right)^{-1/m} = \left(\frac{\tau_1}{K\,d_1^{2-m}}\right)^{-1/m} \qquad (33)$$

The experimental apparatus consists of a rigid circular tube with a diameter of 10 mm. A sinusoidal flow is generated by the way of a compression cylinder, a piston and a crankshaft with adjustable stroke lengths. The crankshaft is driven by a dc electric motor with variable speed. In the present experiments, oscillating frequencies vary from 1 to 10 Hz. With this maximal frequency and the diameter of the tube the mean flow can be considered laminar. The sinusoidal pulsating flow in a rigid circular tube may be described by the frequency of pulsation, the mean-flow velocity and temperature and the magnitude of the harmonic velocity and temperature. The reconstructed signal from the two wire microthermocouple probe allows the determination of the temperature of the fluid. The frequency response of the fine-wire thermocouples can be described as a first-order lag system in the presence of convective heat transfer only without radiation and negligible conduction along the wires. For this last point, each thermocouple presents the ratio wire length on diameter greater than 200 (Figure 11) and thus, the conduction can be effectively neglected.

Figures 12 to 14 give the temperature measurements with the three different probes composed by the wires with 7.6 µm, 12.7 µm, 25.4 µm and 53 µm diameters. After having smoothing the curves, we calculate the mean time constant on a cycle for each thermocouple with Equations 31 and 32.

The results are given in Table 1. They show that the smallest sensors answer with a very small response time. Table 2 gives the values of flow velocities calculated by Equation (31). The values are relatively close. They show a difference of 4 % between the extreme values.

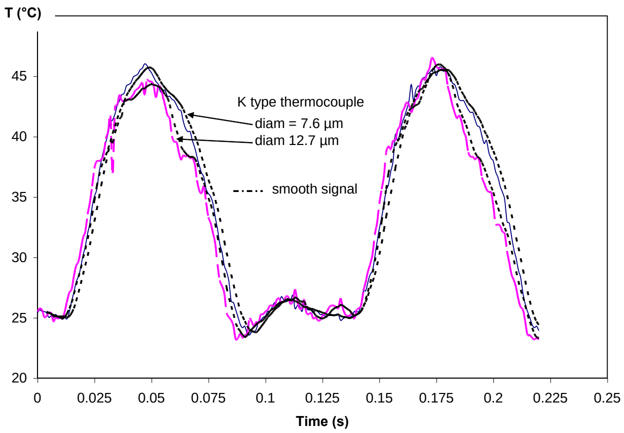


Figure 12 - Measurements with a 7.6/12.7 µm probe (Frequency = 8 Hz).

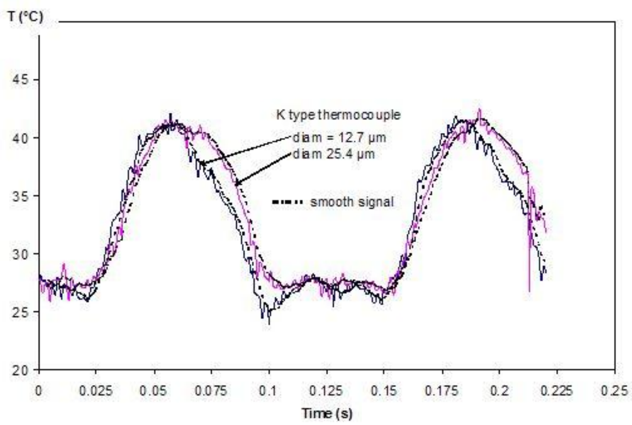


Figure 13 - Measurements with a 12.7/25.4 µm probe (Frequency = 8 Hz).

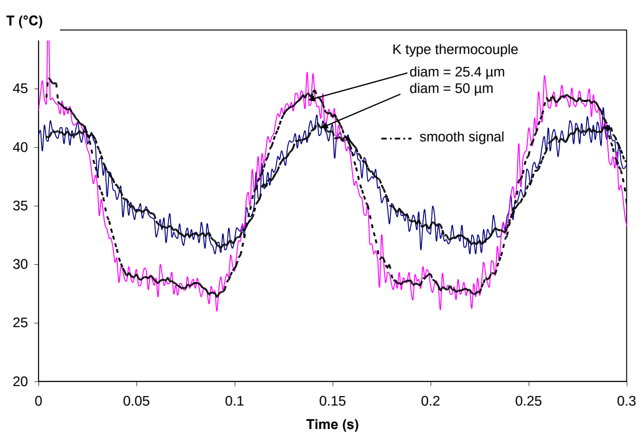


Figure 14 - Measurements with a 25.4/53 µm probe (Frequency = 8 Hz).

Table 1 - Experimental time constants.

d (µm)	τ (ms)
7.6	5.2
12.7	12
25.4	34
50	91

Table 2 - Velocity calculated by Eq. (33).
Thermocouple: K type (Chromel/Alumel): ρ = 8600 kg.m^{-3}; c = 480 J.kg^{-1}.K^{-1};
Fluid = air (35°C): λ = 0.0268 W.m^{-1}.K^{-1}; ρ = 1.146 kg.m^{-3}; μ=1.78.10^{-5} Pa.s

$\frac{d_2}{d_1}$	$\alpha = \frac{\tau_1}{\tau_2}$	$\alpha = \left(\frac{d_1}{d_2}\right)^{2-m}$	V (m.s^{-1})
7.6 / 12.7	2.30	2.20	0.86
12.7 / 25.4	2.83	2.90	0.83
25.4 / 50	2.68	2.83	0.86

CONCLUSION AND PERSPECTIVES

The purpose of this work was to present measurements of temperature and velocities in the same time with small size sensors using microthermocouples.

In a first approach we realized a fluid flow sensor (called microthermoanemometer) based on the hot wire anemometer principle and using microthermocouples of very small diameter. This sensor presents several advantages such as weak response time, a non intrusive sensor and different flow parameters determination. From voltage study the local temperature information can be deduced while the signal frequency allows to access to the information of local fluid velocity. Moreover, the fact to not use micromachining techniques for the sensor realization presents the advantage to introduce the probe in different places in a system and to establish local measurements. The developed sensor is still a prototype and several modifications may be taken into account to improve its performances. Heating time and current intensity, wires diameters are fundamental parameters in the sensor behavior and need to be optimized for the future sensor development. The experimental characterization has shown that the optimum functioning is obtained with weak heating duration for velocity measurements. The sensitivity increases with the current intensity but presents a maximum for 32 mA. It has been established that the sensor has a good sensitivity for velocity and particularly for velocities less than 0.14 m.s^{-1}. Lastly the miniaturization of the probe will be continued in testing others thermocouples diameters like 12.7 and 7.6 µm for K type and 5.3, 1.27 and 0.5 µm for S type.

In a second approach, we developed a sensor with two microthermocouples with different diameters. The velocity measurement was also set up to observe the velocities and temperatures of a gas flow over a frequency range 0 – 10 Hz. These probes are built with very thin thermocouple wires with 7.6 µm, 12.7 µm 25.4 µm and 53 µm diameters. We plan to test larger rotational frequencies (50 Hz) with higher fluid temperature and different gas like helium and hydrogen.

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