Dynamic characterization of a surface microthermocouple for non stationary temperature measurements

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Résumé

Ce travail porte sur la caractérisation dynamique d'un microthermocouple de surface destiné à la mesure de température en mode instationnaire. Le microthermocouple utilisé est de type K (Chromel /Alumel). La jonction chaude est réalisée à partir d'une couche de tungstène déposée sur un substrat de céramique. Ce film métallique est déposé par méthode PVD afin d'assurer une épaisseur constante et un bon maintien du dépôt. Deux méthodes sont utilisées pour la caractérisation dynamique : en mode convectif, la jonction est soumise à un flux de chaleur haché à l'aide d'un chopper alors qu'un pulse laser appliqué à la jonction permet de la caractériser en mode radiatif.

Abstract

This paper presents the dynamic characterization of a surface temperature sensor for non stationary measurements. The temperature sensor is a K type (Chromel/Alumel) wire microthermocouple which hot junction is obtained from a tungsten layer deposition on a ceramic tube. This thin film is realized by a PVD process which provides an uniform deposit and a high adhesion of the layer. Two characterization (convective and radiative) techniques are presented in this work. The first one consists in submitting the hot junction to a heat flow pulsed with a chopper while the second is based on laser pulses applied to the probe.

1. Introduction

Rapidly changing surface temperatures appear in many industrial and hostile environments like heat engines, transient flows, short flow duration facilities and chemical reactions. The temperature measurements involve sensors with low thermal inertia and fast response time in order to determine the heat transfer rates between the fluid and the wall. The thermocouple is the most widely electrical sensor in thermometry and it appears to be the simplest of electrical transducers. Thermocouples are inexpensive, small in size, rugged, and remarkably accurate when used with an understanding of their peculiarities. The technology used in this work for the sensor realization is similar to the thin film thermocouple. This well known technology [1-3] offers the same advantages of the wire thermocouples but it allows to reduce considerably the time constant of the sensor. The film thickness may be controlled with different micro fabrication processes and leads to layers with a very fast response time (few nanoseconds for a laser pulse focused on the junction) [4]. Moreover, different materials may be employed in the deposit which gives different thermal sensitivities [5]. In this work, we use two thermocouple wires whose the junction is realized by a metallic layer of tungsten. The junction thickness is smaller than a classical junction obtained by capacitive discharge in order to get a very well time behavior and to study unsteady temperature variations.

This paper deals of the characterization of this kind of sensor for two excitation modes (convective and radiative) for the experimental determination of the time constant.

2. Micro thermocouple Design

The technique used to realize the thermocouple probe consists of two wires inserted in a ceramic double core tube with length and external diameter depending on the experimentation. For our applications, the thermocouple is a K type thermocouple with two 25.4 µm diameter wires (Chromel and Alumel). In many cases, the junction is obtained by a sparking method with several condensers connected to the wires. The energy produced by the couple voltage – capacitance is sufficient to weld together the wires. The advantage of this technique is to obtain a junction diameter similar to the wires diameters [6]. In this work, the junction is obtained with a deposited thin film which reduces the junction size to achieve a fast response time and a high spatial resolution. These thin film temperature sensors present excellent heat transfer characteristics and are ideal for surface measurements. They are fabricated with lithographic technology on different substrates such as silicon or glass [7, 8]. The technology used is the Physical Vapor Deposition (PVD) process. It's a vacuum deposition technique where metal is vaporized in an atmosphere. The particles are deposited by either using a similar source material, or by introducing a reactive gas containing the desired reactants, which react with the metal from the PVD source. The metal deposit is obtained with a 0.8 µm thickness tungsten coat. Tungsten has the highest melting point among metals with temperature values ranging from 3115 to 3160 K. It has the lowest coefficient of thermal expansion and vapour pressure of all metals. Tungsten hot junction of the thermocouple forms a black surface and presents a good thermal absorptivity.

The thermocouple realization consists of two phases. First of all, the Chromel and Alumel wires are introduced to the ceramic tube with 20 mm length and 1.2 mm external diameter. Then, they are cut with a razor blade and covered by a cement in order to fix the wires and to stuff the empty place in the tube. After heating, the sensor surface is smoothed down to obtain a slightly corrugated surface in order to get a good bond of the metallic deposit. The second step consists of the thin film deposition with the PVD process. An example of the probe is represented Fig. 1 with the ceramic tube and the tungsten layer on its surface.

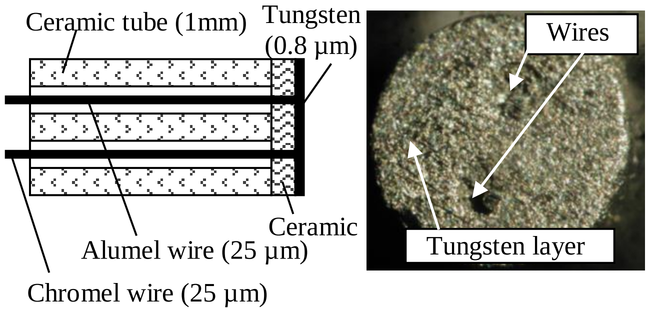

Fig. 1. Thermocouple design.

The total electrical resistance of the probe (thin film, wires and ceramic substrate) varies from 30 to 50 Ω for a Seebeck coefficient of 40 µV/°C at 20°C. All measurements were performed at sensor working temperature from 20 °C to 500 °C. The static response is not presented in this work but the sensor has been characterized with a standard K type thermocouple as reference. The thermocouples are introduced in an oven temperature regulated and their outputs are registered with a National Instrument data acquisition system (described later) and compared.

3. Experimental Setup

Before presenting the experimental results, we describe the test bench represented figure 2. This test bench is used for the dynamic characterization of the probes in convective mode. The square wave excitation technique is implemented in this work for the time constant determination. This technique being sensitive to the noise, a high excitation amplitude must be used. A hot air flow is introduced in a duct whose the extremity leads on a steel wheel with several holes. The rotational speed of the chopper is controlled with a Pulse Width Modulation generator which involves a variation of the frequency excitation and the air flow temperature may vary from 20°C to 600°C. In order to determinate the mean temperature of the flow a second K type thermocouple (125 µm diameter) is introduced in the duct. The sensor to characterize is placed just beyond the chopper and an optical sensor allows to measure the rotation speed of the wheel. Moreover, this test bench has the possibility to introduce a second air flow above the sensor whose the temperature is maintained constant.

The signals are registered with a data acquisition card from National Instrument Corporation driven by a software written in LabVIEW graphic language. The interface card allows the acquisition of different analog inputs (tension or thermocouples), the signal conditioning and the cold junction compensation for a scan rate of 200 kscan/s. Because the voltage values measured by the micro thermocouples are very small, they are amplified by a low noise amplifier integrated in the National Instrument system. More over, all the wires and the connections around the probe are protected to the temperature fluctuations by a ceramic cement.

The calibration methods consist of a series of heating and cooling histories performed by submitting the thermocouple to convective excitation mode. The thermocouple junction is exposed continuously to a constant cold air-stream at constant temperature. A second hot air flow excites periodically the thermocouple and creates a temperature fluctuation.

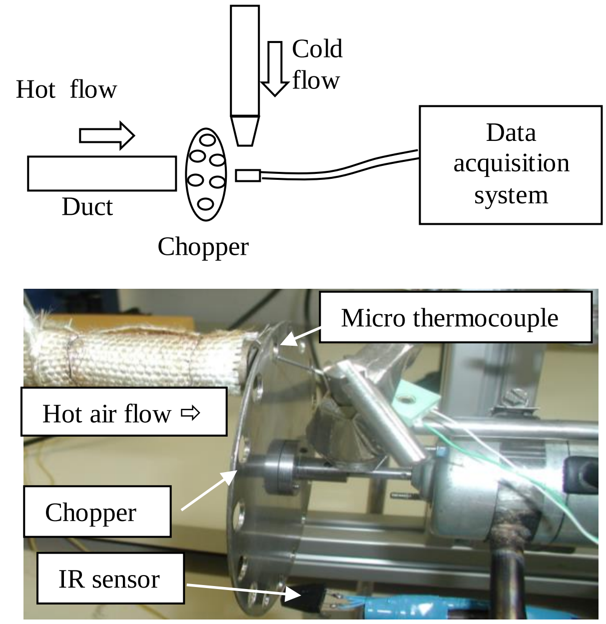

Fig. 2. Experimental setup used for the dynamic calibration.

4. Experimental Results

In a first step, the test bench is only used to produce a continuous hot flow pulsed with the chopper. Fig 3 shows the temperature variations of the sensor for different excitation frequencies and for a 420 °C continuous flow. The IR sensor provides a reference signal used only to control the excitation frequency compared to the microthermocouple signal. The microthermocouple and the IR sensor being fixed at different places around the chopper, the rising edge of this IR signal corresponds not necessarily to the beginning of a heating phase for the thermocouple.

For a 10 Hz frequency, the thermocouple detects a variation of 18 °C just behind the chopper. This amplitude decreases with the frequency to reach approximately 5 °C at 300 Hz. The mean temperature of the flow is given by the reference thermocouple (before the chopper) and may be compared to the mean temperature measured by the sensor. The rotation of the steel wheel generates a diminution of this level as shown in Fig. 3 for the 100 Hz frequency.

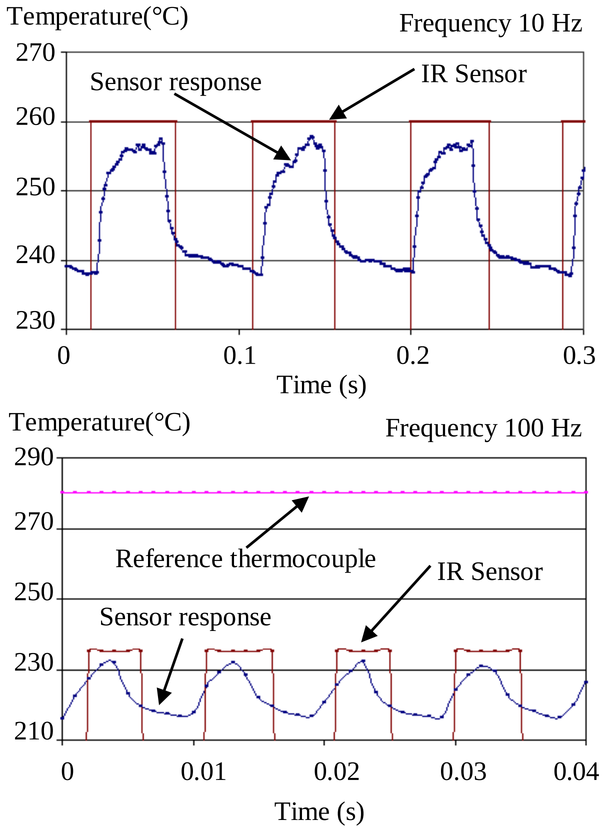

Fig. 3. Dynamic response of the sensor (hot flow).

The frequency effects may be observed on Fig. 4. It represents the temperature variations obtained with the sensor for different frequencies of the chopper rotation. A classical diminution of the temperature amplitude with the frequency is demonstrated. However, these variations do not allow to determinate easily the order of the system. Three different domains can be distinguished on theses curves. The first one corresponds to a linear zone with a sensitivity of 3 dB/octave (from 0 to 10 Hz). A second zone (10-100 Hz) is a constant zone with no variations of the amplitude and the third (100-200 Hz) corresponds to a slope curve of 6 dB/octave which is equivalent to a one order system. A –3 dB cut off frequency may be defined for this system for a 5 Hz frequency.

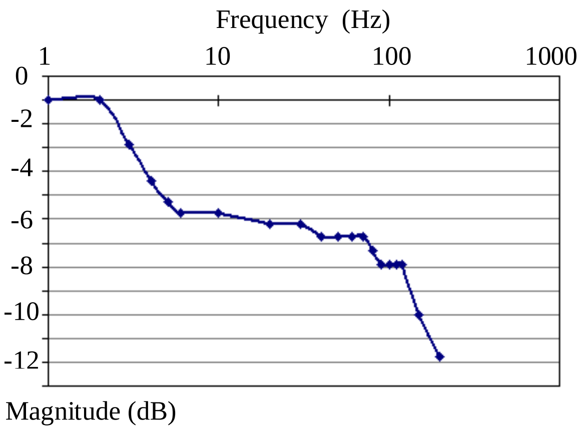

Fig. 4. Frequency response of the sensor.

This sensor can not be approximate to a first order system which can generate mistake for the constant time determination. For first-order systems, this one is identified by measuring the time that corresponds to 63.2 percent of the final value. In many cases, this particular value is used even if the order is different from one which is not significant. Another way to characterize the sensor time behavior regardless the system order is to measure the time taken to increase from 10 to 90 percent of the final value (rising time). It is this value which is measured in our experiments to avoid the determination of the system order. The principle is represented Fig. 5 for the 10 Hz frequency in convective mode. The rising time tr_{conv} of the microthermocouple is about 10 ms which is significantly superior to the classical K type thermocouple wires performed by the authors [6].

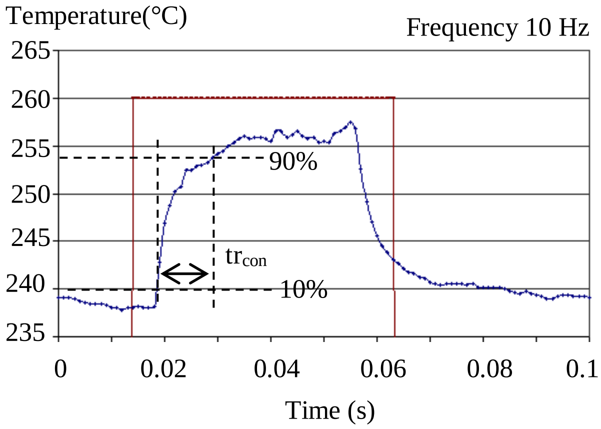

Fig. 5. Determination of the sensor rising time.

An other way to characterize the microthermocouple in convective mode is to use a second air flow on the junction. The sensor is then submitted to a periodic hot flow (created with the chopper) supperposed to a continous flow at ambiant temperature. An example of the sensor response is represented Fig. 6. with a 420 °C hot flow temperature at the beginning of the test bench and a 22 °C cold flow. In these conditions, the sensor is submitted to a succesion of a heating and cooling phases by forced convection.

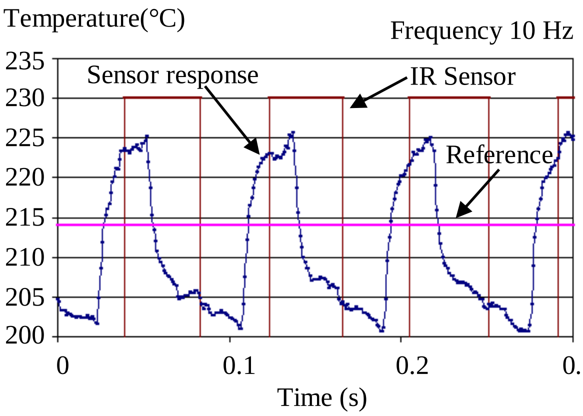

Fig. 6. Dynamic response of the sensor (hot and cold flows).

A decreasing of the mean temperature related to the cold flow is observed while the temperature variations increase. The rise time is about 12 ms which is comparable to the results obtained in natural convection.

5. Radiative characterization

Fig. 7 describes the technique used to characterize the microthermocouple in radiative mode. The sensor is excited by a single laser pulse with a duration of 6 ns and an energy of 108 mJ produced by a YAG laser (wavelength : 538 nm). The laser beam is focused on the junction with an optical lens and the measured signal is registered with the data acquisition system operating at the maximum sample rate (200 kHz). This maximum value is necessary to record without errors the response. The sensor output is connected directly to the card acquisition for amplification and signal conditioning.

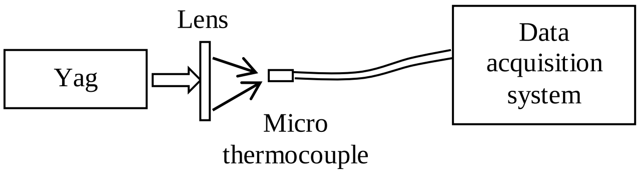

Fig. 7. Radiative characterization.

Fig. 8 shows an example of the microthermocouple response to the laser pulse. It corresponds to the temperature rising caused by the laser pulse on the junction. We can observe that this value is low (approximately 16°C) and depends on the energy density focused on the junction.

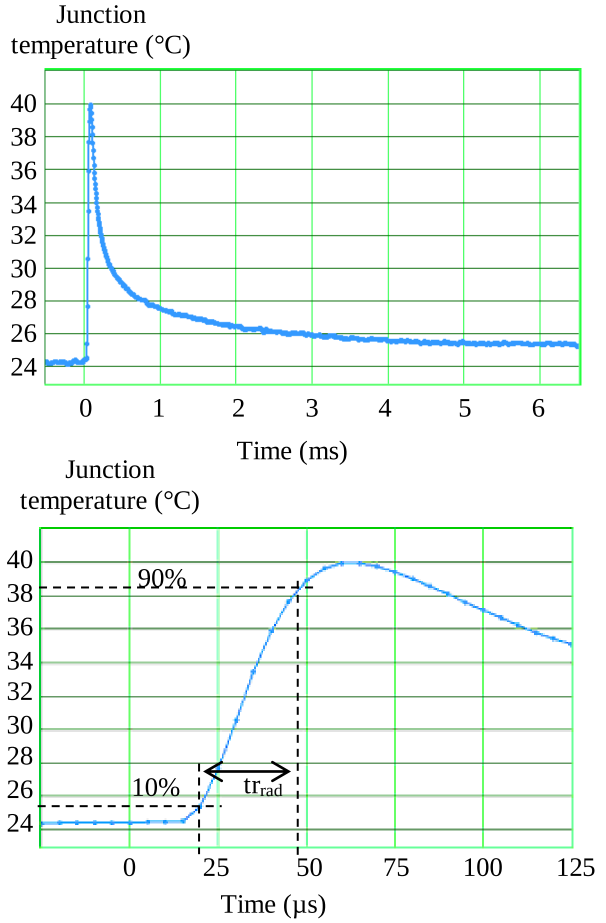

Fig. 8 : Microthermocouple response to a laser pulse

The rising time tr_{rad} has to be determined to characterize the system in radiative mode. This value is about 30 µs. It corresponds to the response of the probe (tungsten film, ceramic tube and connections) and is different of the layer response which is much smaller. It must be noticed that time constant also decreases for increasing of the laser power. The laser beam being focused on the junction with an high energy density, the rising time obtained in radiative mode is smaller than this constant in convective mode.

These results may be compared with the time constants obtained for different process [9,10] or with the wire technology thermocouple [6]. The best values are given for S type thermocouples (1.27 and 0.5 µm diameter) and for constant time corresponding respectively to 180 µs and 70 µs.

6. Conclusion

A thermal device which consists of 0.8 µm tungsten junction of K type micro thermocouple has been fabricated and characterized. Rise times of 30 µs and 10 ms respectively in radiative and convective modes have been measured. This first study demonstrates the feasibility of this kind of sensor with a high local resolution and fast response time. Future works lead on testing new materials and different junction layers in order to improve the response time. The uncertainty of measurements must be taken into account with the noise level (few mV) and the possibility to get a temperature difference between the connections at the sensor output.

A theoretical study has to be developed to characterize the system order and to simulate the dynamic behavior of the sensor [11], [12]. These techniques (mathematical model and electrical analogy) determinate the time constant and reconstruct the real signal when a sensor is characterized with a large time constant.

References

[1] J.C. Godefroy, C. Gageant, D. Francis, M. Portat, "Thin film temperature sensors deposited by radio frequency cathodic sputtering", Journal of Vacuum Science and Technology A, Vol. 5, pp 2917-2923, 1987.

[2] K.G. Kreider "Thin-film transparent thermocouples", Sensors and actuators A, Vol. 34 N°2, pp. 95-99, 1992.

[3] J.F. Lei, H. A. Will, "Thin film thermocouples and strain gauge technologies for engine applications", Sensors and actuators A, Vol. 65, pp. 187-193, 1998.

[4] Y. Heichal, S. Chandra, E. Bordatchev, "A fast-response thin film thermocouple to measure rapid surface temperature changes", Experimental Thermal and Fluid Science, Vol. 30, pp 153-159, 2005.

[5] T.M. Berlicki, E. Murawski, M. Muszynski, S.J. Osagnik, E.L. Prociow, "Thin film thermocouples of Ge doped with Au and B", Sensors and Actuators A, Vol. 50, pp. 183-186, 1995.

[6] J.P. Prenel, F. Lanzetta, B. Serio, E. Gavignet, Y. Bailly, P. Nika, L. Thiery "Thermal sensor : Applications to temperature and fluidic measurements", Encyclopedia of sensors, Vol. 10, pp. 217-245, 2006.

[7] D.P. Brunco, M.O. Thompson, C.E. Otis and P.M. Goodwin, "Temperature measurements of polyimide during KrF excimer laser ablation", Journal of Applied Physics, Vol. 72, pp. 4344–4350, 1992.

[8] D. Debey, R. Bluhm, N. Habets and H. Kurz, "Fabrication of planar thermocouples for real-time measurements of temperature profiles in polymer melts", Sensors and Actuators, Vol. 58, pp. 179–184, 1997.
[9] B. Revaz, R. Flukiger, J. Carron and M. Rappaz, "A device for measurements of the temperature response to single discharges with high local resolution and fast response time", Sensors and Actuators, Vol. 118, pp. 238–243, 2005.
[10] H. Choi, X. Li, "Fabrication and application of micro thin film thermocouples for transient temperature measurement in nanosecond pulsed laser micromachining of Nickel", Sensors and Actuators, Vol. 136, pp. 118–124, 2007.
[11] N.G. Kokody, V.A. Timanjuk, "Mathematical modeling in measuring methods of optical radiation pulses", Proceedings of 3rd International Workshop Laser and Fiber-Optical Networks Modeling, 2001, pp. 147-149.
[12] B. Sarnes, E. Schrufer, "Determination of the time behavior of thermocouples for sensor speedup and medium supervison", Estonian Journal of Engineering, Vol. 13, pp. 295-309, 2007.

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