Tutorial 4: In situ realization/characterization of temperature /heat flux sensors

B Garnier[1], F Lanzetta[2]

[1] Laboratoire de Thermocinétique UMR CNRS6607, Univ. Nantes, France
E-mail: bertrand.garnier@univ-nantes.fr
[2] FEMTO-ST, UMR 6174, CNRS-UFC-ENSMM-UTBM, Belfort, France
E-mail: francois.lanzetta@univ-fcomte.fr

Abstract. This tutorial is about temperature and heat flux measurement with thermocouples and can be seen as complementary information to lecture L5. Time constants, errors due to heat leakage through the connection wire of the thermocouples will be illustrated with experiments. Some rules will be explained to implement thermocouples in metallic sample in order to realize accurate and sensitive 1D heat flux sensors. Thin film heat flux sensors will also be discussed.

1. Introduction

One will expect from a temperature sensor to be 1) sensitive to temperature, 2) accurate and 3) with low inertia. The sensitivity is provided by the thermometric phenomena (see lecture L5 for sensitivity values). The accuracy comes on one hand from the calibration and measurement of the thermometric phenomena and on the other hand, from the correct mounting of the sensors. The first one is rather well known, the latter being very often ignored. The inertia of thermocouple is usually characterized by its time constant which depend also on the medium in which it is mounted.

In this tutorial, experiments will be performed in order to illustrate sensor time constants, errors due to incorrect mounting of thermocouples. Then the design of accurate 1D heat flux sensors will be presented.

2. Time constants of various thermocouples

The behavior of a sensor is characterized by its response to a disturbance in its surroundings. The response time of a temperature sensor, depends on the physical properties (density, specific heat, thermal conductivity), the transport properties of the fluid (turbulence, pressure, velocity and physical properties) and the thermal exchanges (radiation, convection, conduction) between the sensor and the surroundings [1-3]. A considerable amount of work has been carried out on the transient behavior of thermocouples and hot/cold wires (standard size, small and micro sizes) in flowing gases and liquids [4, 5].

Different dynamic characterization methods have been used to estimate response times:

- Standard immersion-plunge tests in liquids or gases [6],
- Current injection with sinusoidal, square-wave, 3w methods [3],
- Optical and chopped laser beam methods [7-10],
- Pulsed wire methods [11],
- Rocket plume-method [12],
- Convection method with fluid flows [10],

The thermometric device must show characteristics in order that interaction between sensor and medium reaches the equilibrium temperature in a sufficiently small time so that the temperature variations of the medium, during this same time, are negligible.

The thermal inertia is usually quantified by a characteristic time t_x which can be the time constant τ or time response t_r.

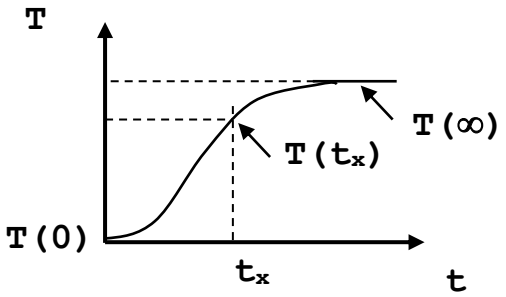


Figure 1: Typical temperature sensor response

Most of these works neglected the effects of conduction along the wires and radiation between the sensor external surface and the surroundings. Investigations have been devoted to the determination of the classical wire time constant τ considering convection heat transfer only:

$$\tau = \frac{\rho_w c_w d^2}{4 \lambda_g Nu} \quad (1)$$

Where d is the diameter of the sensor, ρ_w and c_w are the density and the specific heat of the sensor material, λ is the thermal conductivity of the fluid and Nu the Nusselt number.

If $T(0)$ is the initial temperature and $T(\infty)$ the equilibrium temperature, the time response t_x is defined such that :

$$\frac{T(\infty) - T(t_x)}{T(\infty) - T(0)} = x \quad (2)$$

- The time constant τ, is defined with $x = 1/e \cong 0{,}368$ $(e = 2{,}718...)$
- The $k.10^{-n}$ time response, t_r, is defined with $x = k.10^{-n}$.

The quantities τ or t_r depend not only on the sensor but also on how it is mounted in or on the medium and how it is connected to the measurement device. So talking about time response of a sensor does not make senses if we don't consider the medium in or on it is mounted.

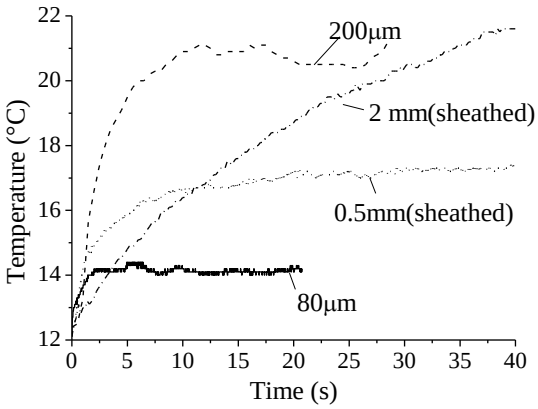


Figure 2: Temperature recording in quiet air

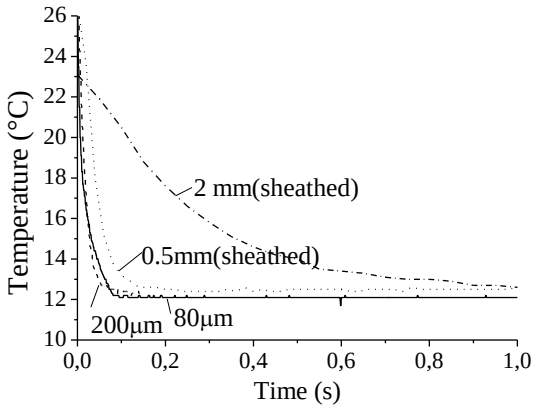


Figure 3: Temperature recording in stirred water (12°C)

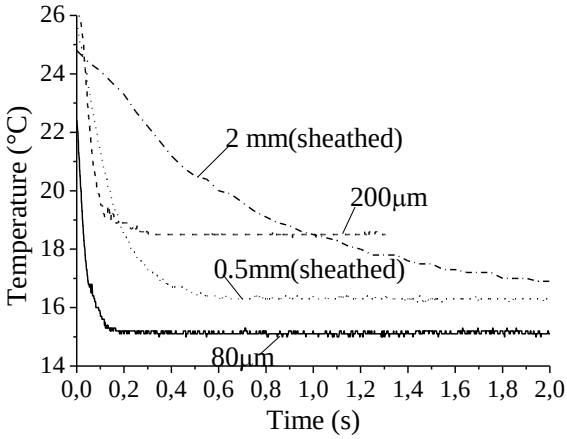


Figure 4 : Temperature recording in mercury (12°C)

In this tutorial, we investigate the time constants of thermocouples since this type of sensors is very common due to their easy mounting, fast response and low cost. Four type K thermocouples are considered with two diameters (80 and 200 µm) and with or without stainless steel sheath. They were plunged successively in three different mediums. Stirred water was provided by a built-in circulating pump of a temperature controlled water bath (at 12°C). A $5cm^3$ mercury beaker was maintained also at 12°C. The quiet air was the room air (at about 20°C). Figures 2 to 4 show the measured transient temperatures for the 4 thermocouples plunged in the three different mediums. The transient measurements are performed using a low voltage recorder (Yokogawa, 16 channels, 100 kHz).

Table 1: Time constants (ms) of common type K thermocouples with various diameters, with and without sheath and mounted in various medium.

Thermocouple→ Medium↓	No sheathed		Sheathed*	
	Φ = 0,08 mm	Φ = 0,2mm	Φ = 0,5 mm	Φ = 2,0 mm
quiet air	595	2330	30980	42720
mercury**	45.2	38.3	129.3	1208.5
stirred water	16.4	14.0	28.5	698.1

* : stainless steel sheathed thermocouple with junction welded at the extremity of the sheath
**: mercury k=8.3 $W.m^{-1}.K^{-1}$; c_p= 140 $J.kg^{-1}.K^{-1}$, ρ=13600$kg.m^{-3}$ (a= 4,36 $10^{-6}m^2.s^{-1}$); water (a= 1,68 $10^{-7}m^2.s^{-1}$)

The measurements clearly show the influence of the medium on the time constant of thermocouples. The time constants range from a few ms to several seconds. In addition, one can observe several features:

- As obtained with lumped capacitance model ($\tau=\rho c_p L/h$), the time constant decreases for increasing heat transfer coefficient. This can be observe when switching from quiet air to mercury and then to stirred water.
- The higher the diameter of the sensors, the higher the time constants are

Table 2 shows some additional values of time constant measured with various temperature sensors [13].

Table 2 : Time constants from literature for various temperature sensors [13]

Sensor	Medium	Time constant (s)
mercury-in-glass thermometer ϕ=9mm	quiet air	450
mercury-in-glass thermometer ϕ=9mm	quiet water	4,8
metallic thermoresistances in a ceramic sheath ϕ=2mm	stirred water	0,5
sheathed thermocouples (ϕ =0.5mm) - thermocouple junction inside the insulation-	hot water	0,035
sheathed thermocouples (ϕ =0.5mm) – thermocouple junction welded on the sheath	hot water	0,015
Metallic thin film (a few μm thick) deposited on a substrate (thermocouple or thermoresistance)	-	a few tens of μs

3. Discussion about the time constant

Dahl and Fiock [14] and Alford and Heising [15] have discussed the problem of lead conduction from a spherical bead along the wires for a thermocouple cooled in a static gas from a temperature T_1 to a temperature T_2. The time constant τ includes the effect of convection and conduction:

$$\tau = \left(\frac{3\,h_{cv}}{\rho_w\, c_w\, d} + K_{cd} \right)^{-1} \tag{3}$$

Melvin [9] adopted a similar point of view in the precedent work and developed a simple approximate solution of the heat conduction equations integrating the heat transfer coefficient as the ratio between the thermal conductivity of the gas and the radius of the thermocouple junction. For gases of relatively low thermal conductivity the time constant of the thermocouple was expressed as:

$$\tau = \left(\frac{3\,\lambda_g}{\rho_w\, c_w\, d^2} \right)^{-1} \tag{4}$$

Benedict [16] established an expression of the time constant accounting convection, conduction and radiation:

$$\tau = \tau_C \frac{(1-\psi_w)}{1+\dfrac{4\beta\,\varepsilon_w}{T_g}} \tag{5}$$

Where ψ_w is a conduction correction factor [5, 17], β a radiation error factor [5], ε_w the thermocouple emissivity and T_g the gas temperature.

If the thermal environment includes effects of convection, conduction and radiation, the response of the sensor is not a first-order. Pandey [2] and Dantzig [18] suggested that a simple time constant can be expressed as:

$$\tau = C_1 + C_1\, h_{cv}^{-1} \tag{6}$$

where C_1 and C_2 are correlation constants dependent on the properties of the thermocouple and h_{cv} is the average heat transfer coefficient between the thermocouple external surface and the air flow.

Actually, the fact that different kinds of heat transfers are involved should lead to a global time-constant in which the different phenomena contributions are included [19, 20]. As a consequence, the ability of a thermocouple to follow any modification of its thermal equilibrium is resulting from a multi-ordered time response which more accessible experimental parameter remains the global time constant.

The multi-ordered temperature response of a thermocouple can be represented by the general relation [1]:

$$\frac{T_g - T}{T_g - T_i} = K_1 exp\left[-\frac{t}{\tau_1} \right] - K_2 exp\left[-\frac{t}{\tau_2} \right] - \cdots - K_n exp\left[-\frac{t}{\tau_n} \right] \tag{7}$$

Where T_i is the initial temperature, T_g is the fluid temperature. The value of the constants K_1, K_2, … , K_n as well as the time constants τ_1, τ_2, …, τ_n, depend on the heat flow pattern within the thermocouple and the surrounding fluid. Kerlin et al. [21] showed that the time constants τ_1 and τ_2 are most important. Cimermam [6] used the same result for real Pt-resistance temperature-sensor in dynamic measurement relative to natural and petroleum gas processes.

4. Errors due to heat losses through the connection wires of the thermocouples

To avoid temperature bias due heat loss along the thermocouples wires, one usually considers that a thermocouple has to be mounted along an isothermal line started from the junction and on a length equal to 100 times the metallic wire diameter ϕ of the thermocouple. If it is not the case, one may obtained heat loss which will change locally the temperature of thermocouple junction. In lecture L5 section 2.3, a thermal model was designed to study the effect of various parameters on this systematic error. In this section, an experiment will be used to quantify this temperature measurement error.

A PMMA sample of 76.8 mm diameter and 20mm thickness is instrumented with 7 type K thermocouples of diameter 0,2 mm as shown on fig. 5. Three thermocouples #1, #2 and# 3 are correctly mounted: starting from the junction, the thermocouples are along isothermal lines at least on a length of 20 mm. On the contrary, thermocouple #7 is perpendicular to the isothermal lines and thermocouples #4, #5 and #6 are close to the edge. Two temperature controlled thermal baths are used to prescribe a constant temperature difference (40°C) between each two sample faces

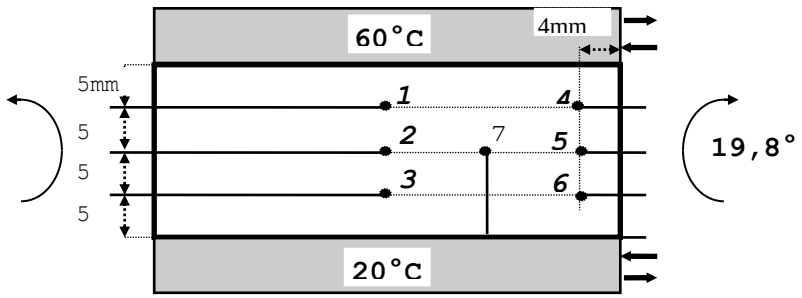


Figure 5: experimental setup with an instrumented PMMA sample

Table 3 : steady state temperature measurements from experimental setup of fig.5

δ*, mm	#	T , °C	#	T , °C	#	T , °C
5	*1*	49,9	*4*	43,5		
10	*2*	**40,5**	*5*	35,4	*7*	**34,8**
15	*3*	31,5	*6*	27,7		

δ: distance between thermocouple and the heated face*

From the measurement obtained with steady state, one can observe that:

- The temperature discrepancy between thermocouple perpendicular (#7) and parallel (#2) to the isothermal lines is very important (5,7°C !), this result from the heat losses through the metallic wire of thermocouple #7 inducing a local temperature decrease at its hot junction. This happens for a 0.2 mm thermocouple, one would have got much more error for metallic sheathed thermocouple where the metallic cross-section of the complete thermocouple is typically 6 times higher than the one of the bare thermocouples (thickness of metallic wall: *10 %*ϕ and metallic wire diameter *18 %*ϕ [22])

- Thermocouples #4, #5 and #6 are closed to the edge (4 mm only) , the connection wires being in the thermal boundary layer therefore they show lower temperature measurement, from 3.3 to 6.4°C less compared to the correct ones (#1, #2 and #3). As illustrated on fig. 6 , thermocouples

#4, #5 and #6 show however a linear distribution. So, one should remind that the fact that the temperature distribution is linear is not a criterion to say that temperature measurements are without bias. In fig.6, the temperature shift between the two sets of thermocouples is important, the slopes being slightly different.

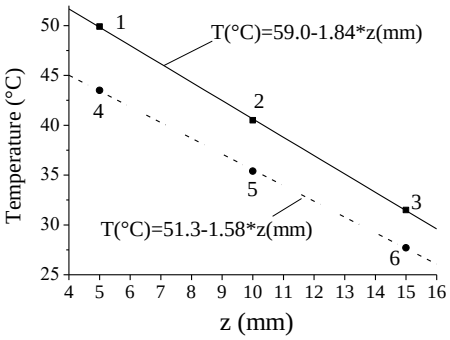


Figure 6: Temperature distributions within the PMMA sample (data from tab.2)

5. Heat flux sensor with wire thermocouples and thin film

Heat flux sensors (HFS) are very useful for the understanding and the control of the thermal phenomena coupled or not with other physical, chemical or mechanical processes. HFS should be judiciously designed to reduce source of bias in heat flux measurement while ensuring the highest sensitivity. The heat flux can be measured by direct methods (see lecture L5). However very often these sensors are mounted directly on the surface to characterize and the sensors create disturbance in the surface/environment heat exchange. There exists one type of HFS which was designed to limit this perturbation [23] especially for 1D transient measurement. As shown on fig.7, a set of microthermocouples is mounted inside the medium at different locations [23]. Practically there are welded on one of the two half shells (fig. 8 [24]).

The discussion in this section will be about the location of the implemented thermocouples. The HFS should have at least 1 thermocouple if the 2nd boundary condition is well known otherwise at least 2 thermocouples are needed. Bourouga [25] has found that the first thermocouple should be located taking into account the following inequality:

$$10\, r \leq x_1 \leq 66\, r \qquad (8)$$

with r the radius of the hole where the thermocouple is mounted.

The first inequality ($10\, r \leq x_1$) comes from the fact that 96% of the temperature drop due to macroconstriction is within an hemisphere of radius $10\, r$ [26]. With this condition, the heat flux ϕ or temperature at the front face will not be affected by the presence of the first thermocouple.

The second inequality ($x_1 \leq 66\, r$) comes from inverse methods consideration. The computation time step Δt (supposed here equal to the experimental one) should not be too small to avoid too much sensitivity to measurement errors. Typically, the condition $a\Delta t/x_1^2 \geq 0.01$ should be respected [26], where a is the thermal diffusivity of the HFS material.
Therefore, one obtains :

$$x_1^2 \leq 100 a \Delta t \qquad (9)$$

The smallest possible Δt value which can be defined as the response time of a thermocouple which is also the characteristic time of the already described *10r* hemisphere. As shown by Cassagne [27], this characteristic time is defined by $\Delta t = 44r^2/a$ for a 95% development of the thermal constriction within the *10r* hemisphere. Using this Δt value in (9), one can obtained: $x_1 \leq 66\ r$
One should notice that for sensitivity enhancement during heat flux estimation, the first thermocouple should be as close as possible to the front face ($x_1 \approx 10\ r$).

For the second location (x_2) corresponding to the 2nd thermocouple or the 2nd boundary condition, its value should be as large as possible also for sensitivity concerns [5].

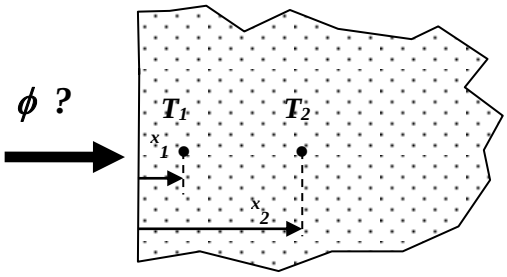


Figure 7: Heat flux sensor [23]

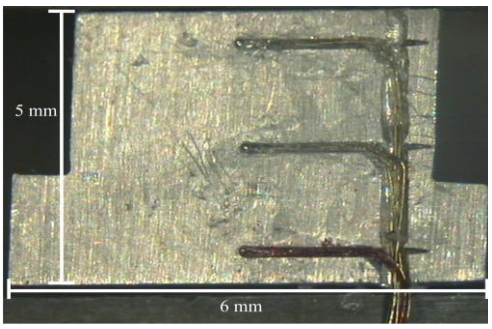


Figure 8: Heat flux sensor [24]

Recent developments in heat flux measurement concern thin film HFS with some advantages such as very accurate locations of the temperature sensors (fig. 9 [28]).

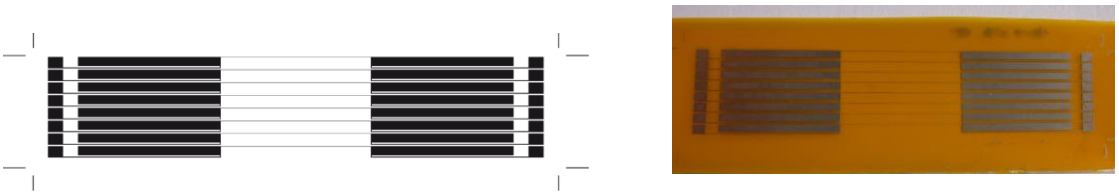


Figure 9: New HFS with thin film technology (wire thickness 30μm) [28]

5. Conclusion

In this tutorial, we have illustrated the role of the medium in the temperature sensor time constants and also the errors due to the sensor mounting. Temperature and heat flux sensors should be designed and mounted to minimize the various sources of errors and also to increase the sensitivity for heat flux estimation, some insights on the most favorable thermocouples location were presented.

References

[1] Manual on the use of thermocouples in temperature measurement, American Society for Testing and Materials, ASTM, Fourth Edition, 1993.
[2] D.K. Pandey *Journal Phys. E:Sci. Instrum.*, 18 (1985) 712–713
[3] J. Lemay, A. Benaissa, R.A. Antonia, *Experim. Thermal and Fluid Science*, 27 (2003) 133-143
[4] N.P. Bailey, *Mech. Engng*., 53 (1931) 797-804.
[5] M.D. Scadron, I. Warshawski, NACA, T.N., 2599 (1952)
[6] F. Cimerman, B. Blagojevic, I. Bajsic, *Sensors and Actuators A*, 96 (2002) 1-13
[7] P. Castellini P., G.L. Rossi, *Rev. Sci. Instrum.*, 67 (7), 1 (1996), 2595-2601.
[8] N.G. Kokodi, V.A. Timanjuk, *LFNM'2001*, 22-24 May, Kharkiv, Ukraine, (2001)

[9] A. Melvin, *Brit. J. Appl. Phys.* (J. Phys. D.), 2 (1969) 1339-1343.
[10] F. Lanzetta, Etude des transferts de chaleur instationnaires au sein d'une machine frigorifique de Stirling, Ph. D. thesis, University of Franche-Comté, France, (1997).
[11] Grignon M., Mathioulakis E., Ngae P., Poloniecki J.G. *Int. J. Heat Mass Transfer* 41 (1998) 3121-3129.
[12] X. Qiang, *Meas. Sci. Technol*., 14 (2003) 1381-1386.
[13] Techniques de l'Ingénieur, traité Mesures et Contrôle R 2 515 1-43
[14] A.I. Dahl, E.F. Fiock, J. Res. Natn. Bur. Stand. 45 (1950) 292-298.
[15] J.S. Alford, C.R. Heising Trans. *Am. Soc. Mech. Engrs*., 75 (1953) 7-14.
[16] R.P. Benedict R.P., *Fundamentals of Temperature, Pressure, and Flow Measurements*, 3d ed. Wiley, New-York, 1984.
[17] K. Farahmand, J.W. Kaufman, *Experimental Heat Transfer*, 14, (2001), 107-118.
[18] J.A. Dantzig, *Rev. Sci. Instrum*., 56 (5) (1985) 723-725.
[19] L. Paranthoen, J.C. Lecordier, *Rev. Gén. Therm.* 35 (1996) 283-308.
[20] H. Sbaibi, Modélisation et étude expérimentale de capteurs thermiques, Ph. D. Thesis, University of Rouen, France, (1987).
[21] T.W. Kerlin, L.F. Miller, H.M. Hashemian, ISA Trans., 17, 4 (1980) 71-88.
[22] Thermocoax, Documentation Products www.thermocoax.com 2011
[23] J.P. Bardon, Y. Jarny, "Procédé et dispositif de mesure en régime transitoire de température et flux surfacique" Patent n° 94.01996, Feb. 22nd1994
[24] A. Sorin; F. Bouloc; B. Bourouga ; P. Anthoine, *Int. J. Thermal Sci.* 47 12 (2008) 1665-1675
[25] B. Bourouga, V. Goizet, J.P. Bardon, *Int. J. Therm. Sci.* 39(2000) 96-109.
[26] J.P. Bardon, M. Raynaud, Y. Scudeller, *Rev. Gen. Therm.* (HS95) 34 (1995) 15-35
[27] B.Cassagne , J.P. Bardon and J.V.Beck 1986 8th *Int. Heat Transfer Conf*., San Fransisco, Vol.2 pp.483-488.
[28] B. Azerou, B.Garnier, J. Launay, A. Lahmar, Congrès SFT, Perpignan, France, 25-27mai 2011