Eurotherm Seminar 94
Advanced Spring School: Thermal Measurements & Inverse Techniques
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Lecture 5 -A

Measurements with contact in heat transfer: principles, implementation and pitfalls

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Lecture 5-A

Part 1 : F. Lanzetta

Measurements with contact : temperature and (micro)thermocouples

Part 2 : B. Garnier

Measurements with contact : temperature and heat flux

Lecture 5-A

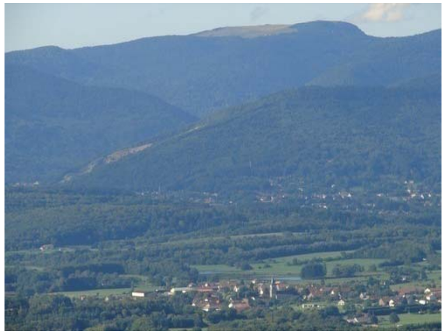
Part 1 : F. Lanzetta

Measurements with contact : temperature and (micro)thermocouples

BELFORT

Belfort's Lion
(A. Bartholdi)

Ballon d'Alsace - Vosges (1247 m)



Last week…

… and …

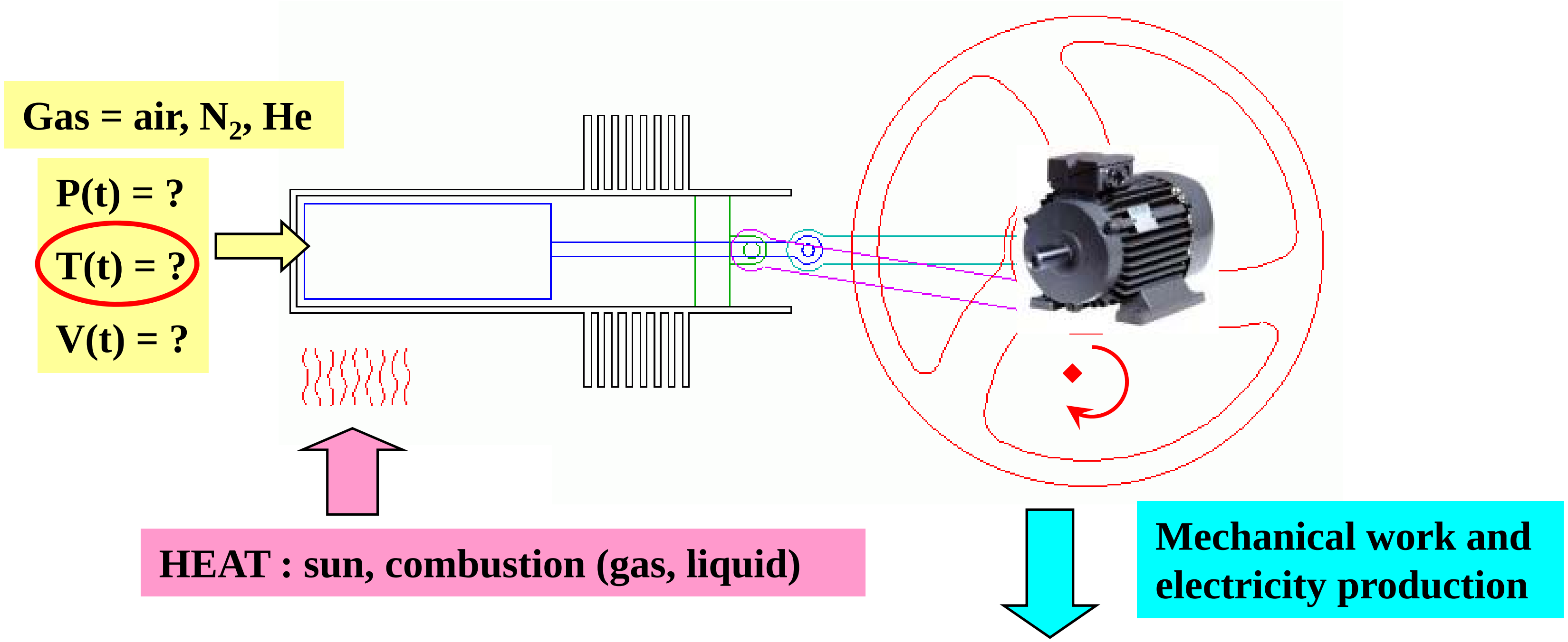
Next winter ?

My researches deal with machines like :

1) Stirling engine, cogeneration systems, regenerators (exchangers)

Oscillating flows : pressure, temperature, volume, velocity =f(time)

Convection coefficient h_{cv}(◆) between gas/wall ? Nu(◆) = ?



Gas = air, N_2, He

P(t) = ?

T(t) = ?

V(t) = ?

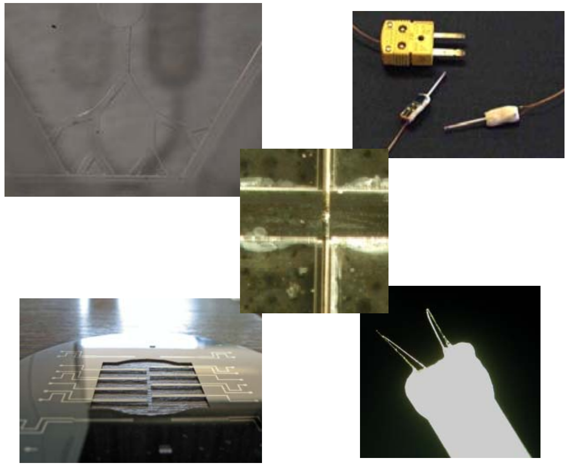
HEAT : sun, combustion (gas, liquid)

Mechanical work and electricity production

2) Development of Instruments :

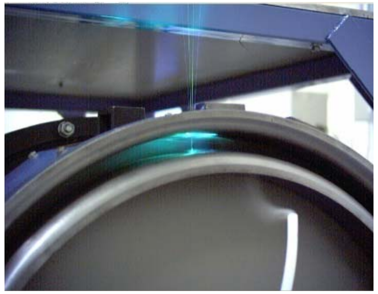
Temperature T(t) :

- microthermocouples,
- IR measurement



Fluid velocity V(t):

- optical methods (PIV, LDV, etc…)
- microthermocouples



Pressure P(t) :
commercial sensors

The (micro)thermocouple

Introduction

1 The (micro)sensor

2 Theoretical model for transient measurements

3 Dynamic characterization

- Convective calibration

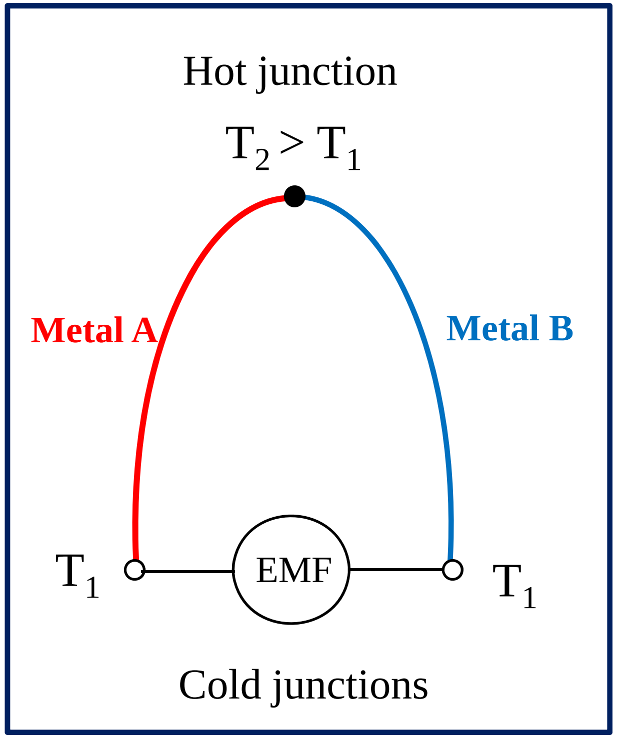
- Radiative calibration

- Shock tube calibration

Conclusion

How does a thermocouple work ?

In 1821 T.J. Seebeck observed the existence of and electromotive force, EMF (V or µV) at the junction formed between two dissimilar metals (Seebeck effect) submitted to a temperature difference (T_2-T_1).



Seebeck effect is actually the combined result of two other phenomenon, Thomson and Peltier effects.

Peltier discovered that temperature gradients along conductors in a circuit generate an EMF.

Thomson observed the existence of an EMF due to the contact of two dissimilar metals and the junction temperature.

Thomson effect is normally much smaller in magnitude than the Peltier effect and can be minimized and disregarded with proper thermocouple design.

How does a thermocouple work ?

$$E_{AB}(T_2,T_1)=\underbrace{\Pi_{AB}^{T_1}-\Pi_{AB}^{T_2}}_{\text{Peltier effect}}+\underbrace{\int_{T_2}^{T_1}(\tau_A-\tau_B)dT}_{\text{Thomson effect}}$$

Seebeck effect

$$E_{AB}(T_1,T_2)=\sigma_{AB}(T_2-T_1)$$

$\blacklozenge_{AB}$ = Seebeck coefficient (µV.°C^{-1})

$$\sigma_{AB}=\frac{dE}{dT}$$

$\blacklozenge_{AB}$ depends on the two materials A and B

♦$_{AB}$ = Seebeck coefficient (µV.°C^{-1})

Material	Seebeck coefficient (µV°C^{-1})	Material	Seebeck coefficient (µV°C^{-1})
Bismuth	-72	Silver	6.5
Constantan	-35	Copper	6.5
Alumel	-17.3	Gold	6.5
Nickel	-15	Tungsten	7.5
Potassium	-9	Cadmium	7.5
Sodium	-2	Iron	18.5
Platinum	**0**	Chromel	21.7
Mercury	0.6	Nichrome	25
Carbon	3	Antimony	47
Aluminium	3.5	Germanium	300
Lead	4	Silicium	440
Tantalum	4.5	Tellurium	500
Rhodium	6	Sélenium	900

K type = Chromel/Alumel

♦ = 21.7-(-17.3) = **39** µV.°C^{-1} @ 0 °C

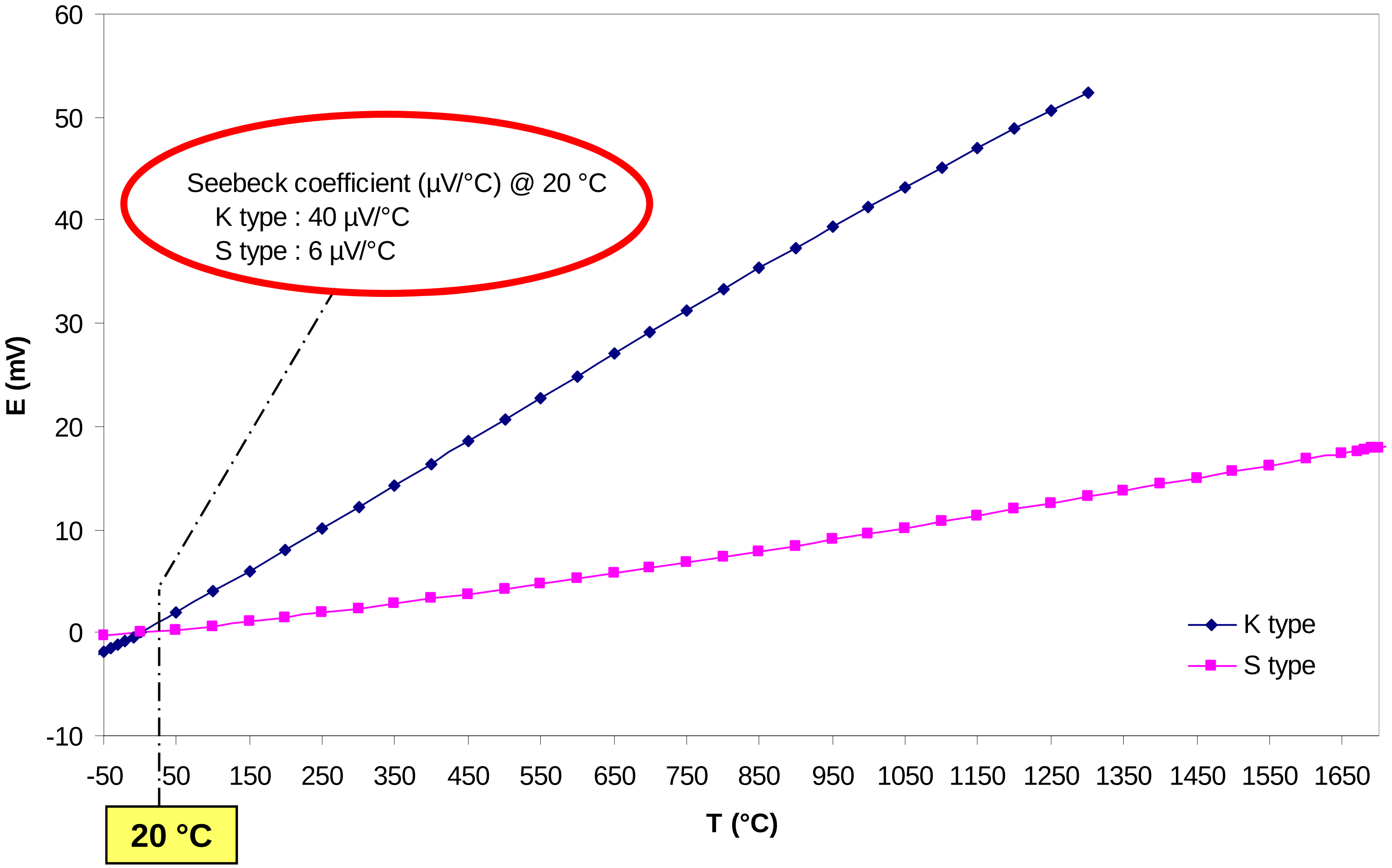
T type = Copper/Constantan

♦ = 1.7-(-37.3) = **49** µV.°C^{-1} @ 0 °C

« Metti^{5} » type = Nickel/Silicium

♦ = 440-(-15) = **455** µV.°C^{-1} @ 0 °C !!!

Seebeck coefficient versus temperature



Seebeck coefficient (µV/°C) @ 20 °C
K type : 40 µV/°C
S type : 6 µV/°C

20 °C

Electromotive force versus temperature for S type and K type thermocouples (ITS-90)

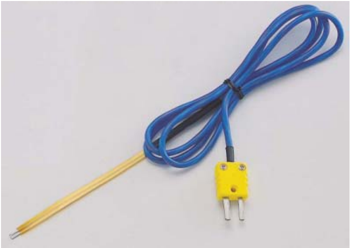
Advantages of Thermocouples

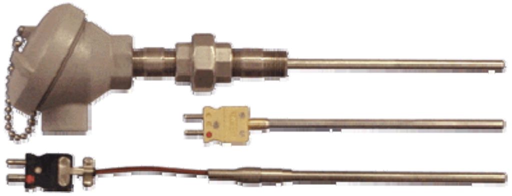
- Cheap
- Wide temperature range (–270 °C to 2100 °C)
- Small (…down to 0.5 µm)
- Easy to integrate into automated data systems

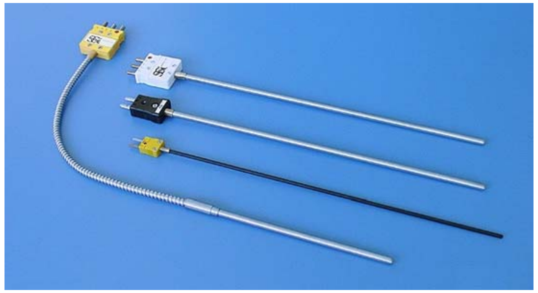
Disadvantages of Thermocouples

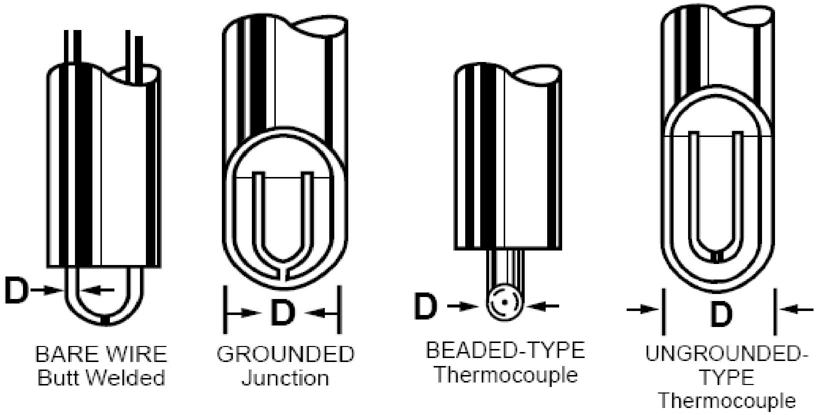
- Small signals, limited temperature resolution (from 0.1 to 1 K)
- Thermocouple wires must extend from the measurement point to the readout. Signal generated wherever wires pass through a thermal gradient.
- At higher temperatures, thermocouples may undergo chemical and physical changes, leading to loss of calibration.
- Recalibration of certain types of thermocouples or in certain applications is very difficult.

Commercial thermocouples









From thermocouples to microthermocouples…

Temperature fluctuations measurement = microthermocouples

Micronic and sub-micronic thermocouples

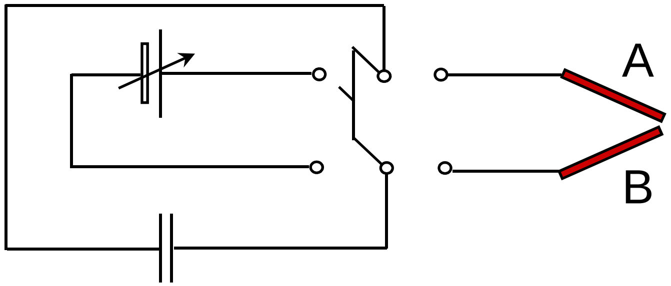
- S type : Platinum/Platinum-Rhodium 10% : **6 µV/°C** at 20 °C
  - **diameters = 0.5 ; 1.27 and 5.3 µm**
- K type : Chromel/Alumel : **40 µV/°C** at 20 °C
  - **diameters = 7.6 ; 12.7 ; 25.4 ; 53 µm**

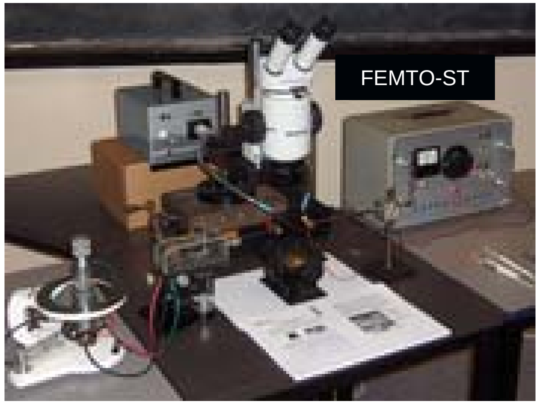
Spatial resolution and dynamic response

Dynamic calibration methods : time constant ?

- convective calibration
- radiative excitation
- shock tube

1 The (micro)sensor

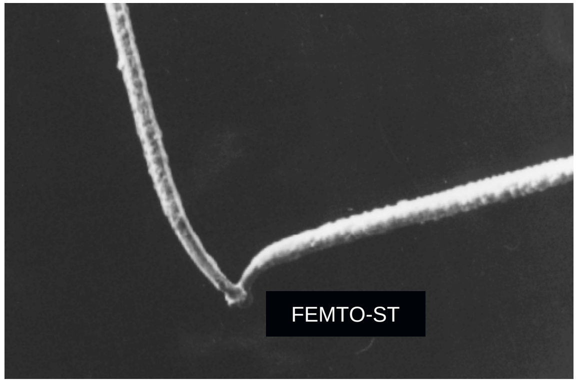




Circuit for beading by condenser-discharge method

tension : 0 - 250 V

capacitance : 0 - 5 µF

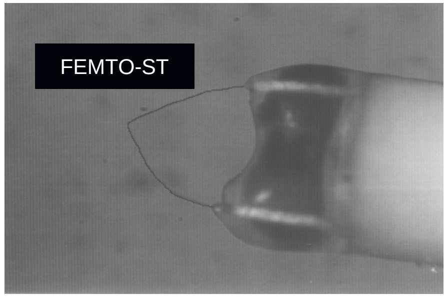


junction

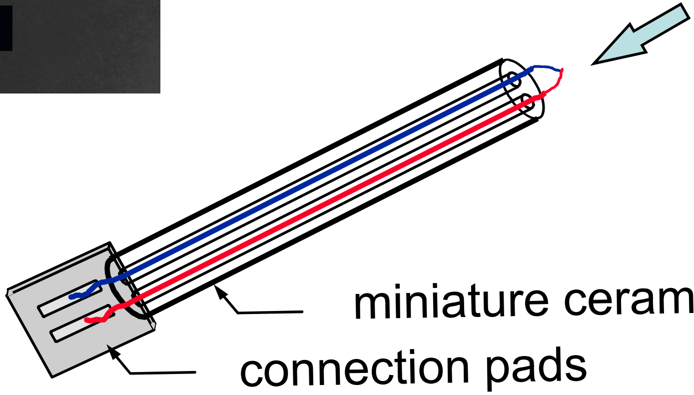
S type thermocouple

ϕ 1.27 µm

6 µV/°C at 20 °C



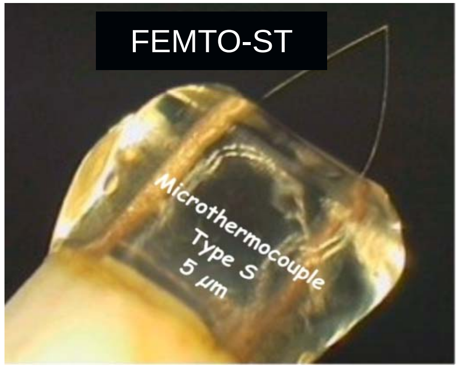
probe

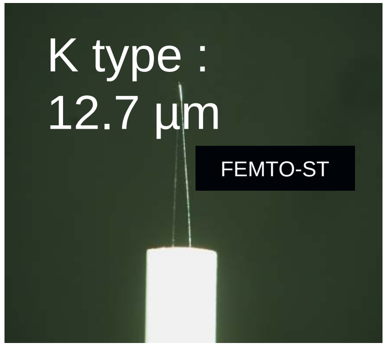


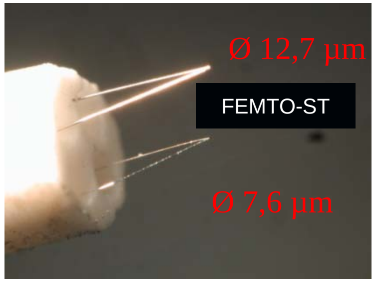
miniature ceramic insulator

connection pads

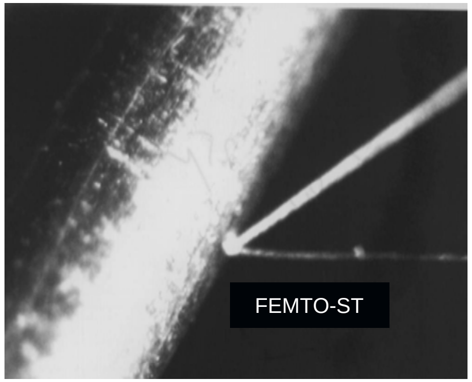
Different microthermocouples



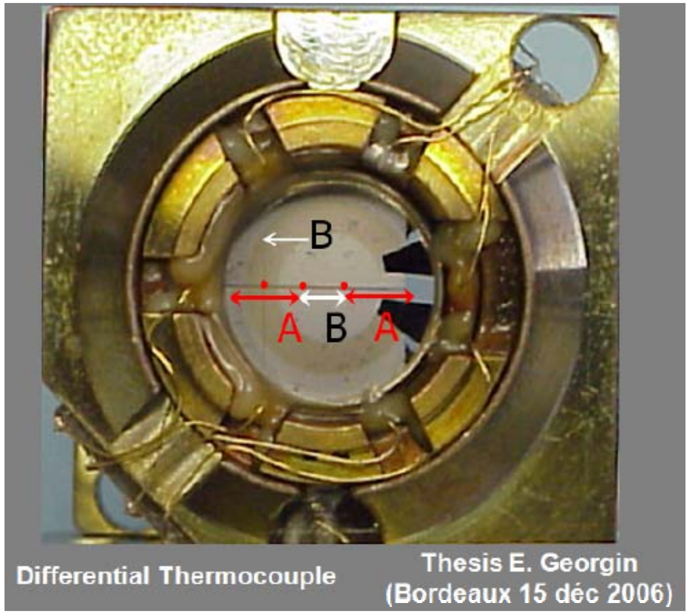




K type (7.6/12.7 µm)



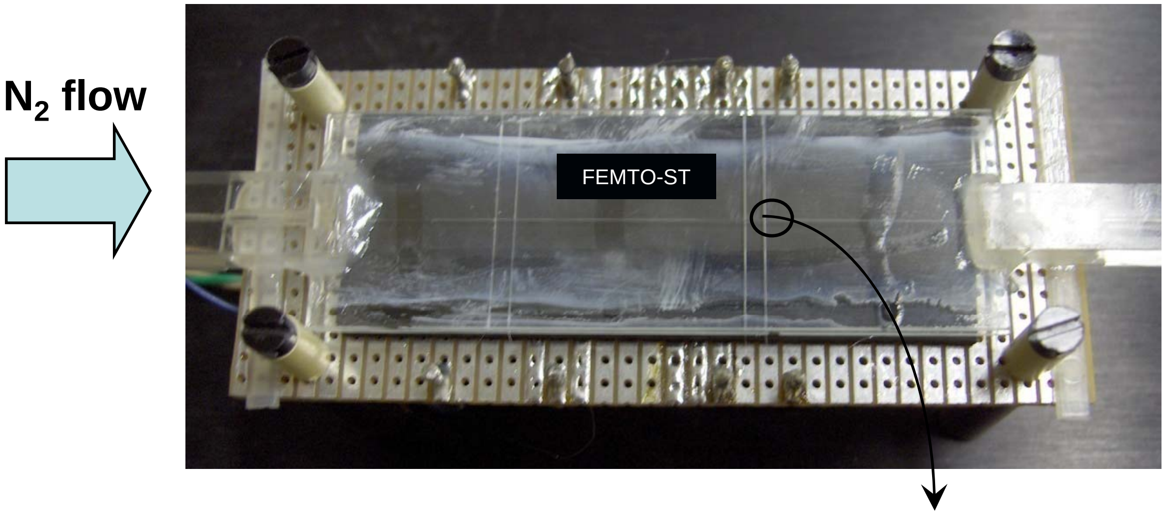
K type 25.4 µm directly welded on a solid surface (inox)



Differential Thermocouple

Thesis E. Georgin
(Bordeaux 15 déc 2006)

Temperature and flow measurements



Microfluidics gas flow

K type 25.4 µm

Channel :

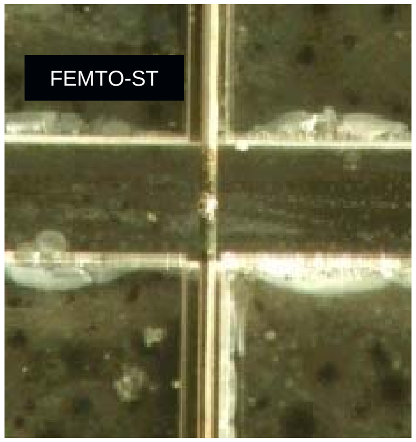
Materials :

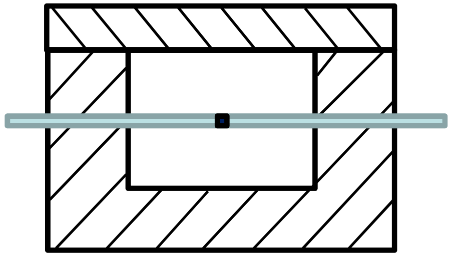
- **PMMA (transparent thermoplastic)**
- **Glass**

Length = 50 mm

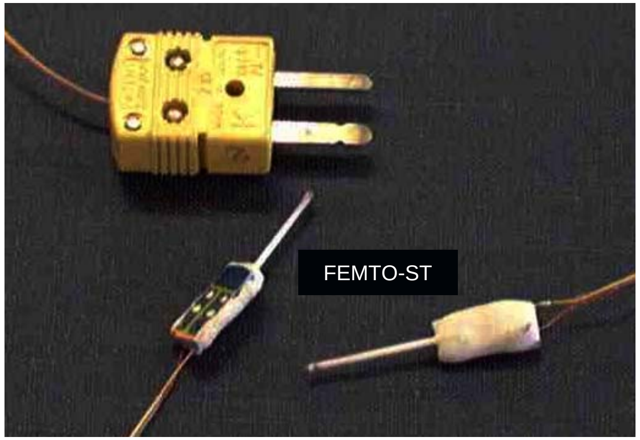
section = 150 µm X 200 µm

(hydraulic diameter = 170 µm)

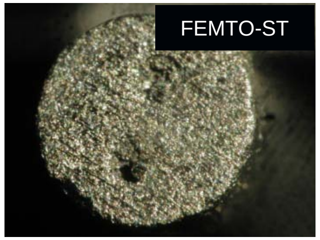




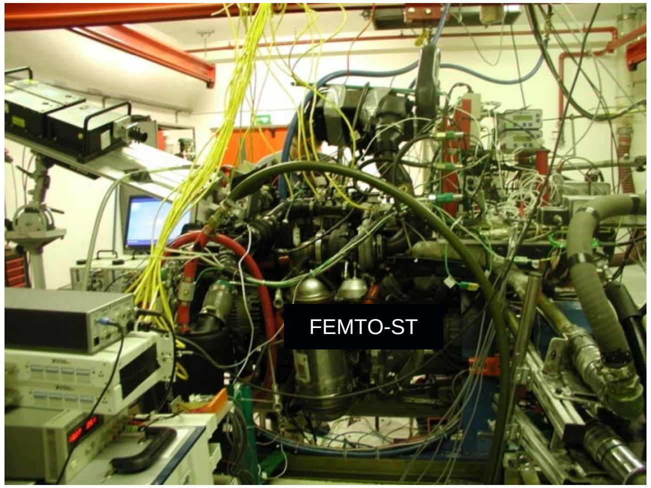
Surface temperature measurements in heat engines



Thin film junction on wires thermocouple

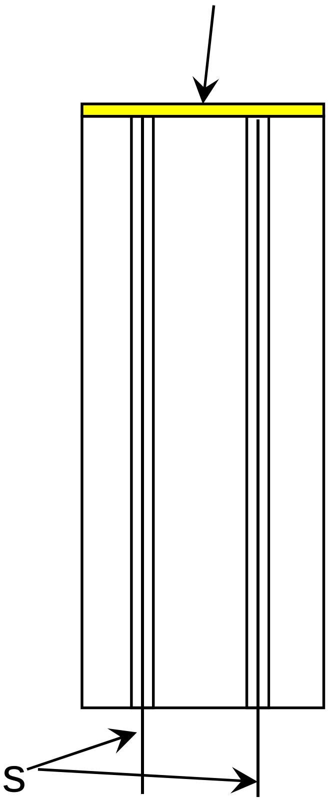


Tungsten thin film



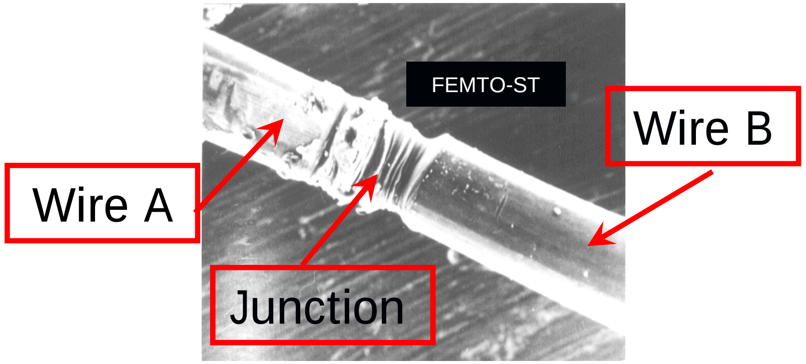
K type wires : diam = 12,7 µm

Thin film (hot junction) = gold, tungsten, …

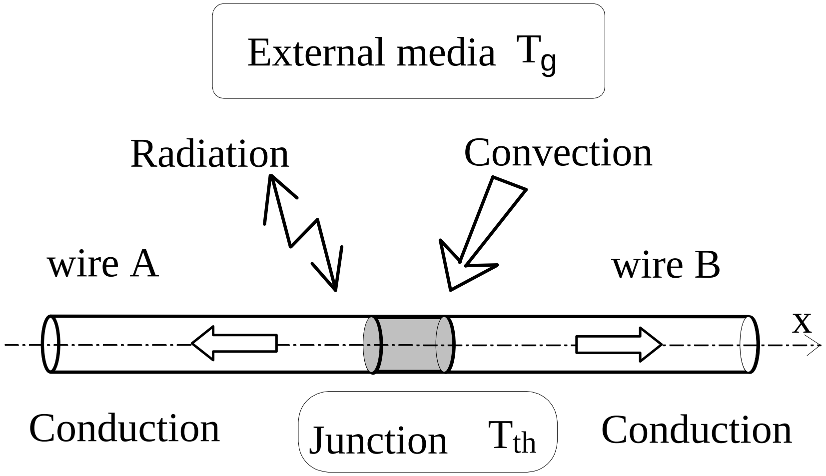

Gold thin film

wires

2 Theoretical model for transient measurements



Thermocouple type K
Diametre = 50 µm



Heat balance :

- convection in the boundary layer around the thermocouple
- conduction along the wires
- radiation between the wires and the external medium
- contribution of another source of energy (a laser source in our work)

HEAT BALANCE

$$\overbrace{\rho_{th} c_{th} \frac{\pi d^2}{4} \frac{\partial T_{th}}{\partial t}}^{\textbf{Heat accumulated}} = \overbrace{Nu\, \lambda_g \pi \left(T_g - T_{th}\right)}^{\textbf{Convection}} + \overbrace{\lambda_{th} \frac{\pi\, d^2}{4} \frac{\partial^2 T_{th}}{\partial x^2}}^{\textbf{Conduction}}$$

$$\underbrace{-\sigma\, \varepsilon(T_{th}) \left(T_{th}^4 - T_w^4\right) \pi\, d}_{\textbf{Radiative heat transfer}} + \underbrace{\sqrt{\frac{2}{\pi}} \frac{\left(1-\bar{R}\right)}{a} P_L\, erf\left[\frac{d}{a\sqrt{2}}\right] \exp\left[-2\,\frac{x^2}{a^2}\right]}_{\textbf{External heat flux (laser beam)}}$$

Gas temperature measurement $T_g(t)$?

The sensor measures

I need to determine

$$T_g(t)=T_{th}(t)+\tau_{cv}\left[\begin{array}{l}\dfrac{\partial T_{th}}{\partial t}-\dfrac{\lambda_{th}}{\rho_{th}c_{th}}\dfrac{\partial^2 T_{th}}{\partial x^2}+\dfrac{4\,\sigma\,\varepsilon(T_{th})}{\rho_{th}c_{th}d}\left(T_{th}^4-T_w^4\right)\\ -\dfrac{4}{\rho_{th}c_{th}d^2}\sqrt{\dfrac{2}{\pi}}\dfrac{\left(1-\bar{R}\right)}{a}P_L\;erf\left[\dfrac{d}{a\sqrt{2}}\right]exp\left[-2\dfrac{x^2}{a^2}\right]\end{array}\right]$$

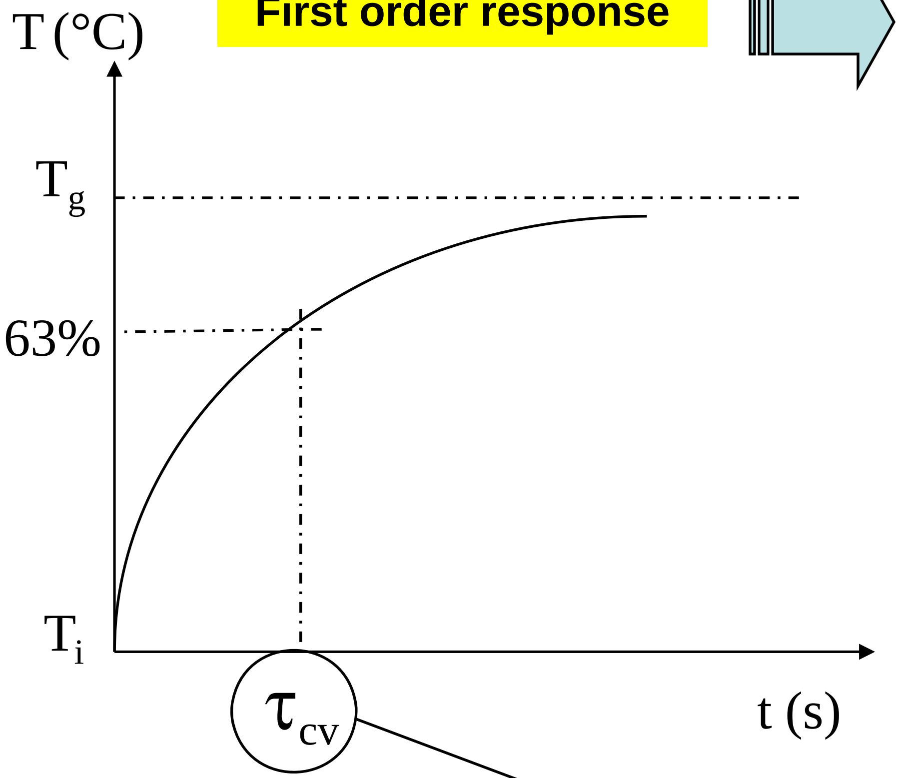
Convection time constant $\blacklozenge_{cv}$:

$$\tau_{cv}=\frac{\rho_{th}\;c_{th}\;d^2}{4\;Nu\;\lambda_g}=\frac{\rho_{th}\;c_{th}\;d}{4\;h}$$

Influenced by :
- diameter *d*
- convection coeffition *h*

Step unit response (see Tutorial T4)

First order response



Heat balance with convection only !!

$$\rho_{th} c_{th} \frac{\pi d^2}{4} \frac{\partial T_{th}}{\partial t} = Nu\, \lambda_g \pi \left(T_g - T_{th} \right)$$

$$T_g = T_{th} + \tau_{cv} \frac{\partial T_{th}}{\partial t}$$

$$\frac{T_g - T_{th}}{T_g - T_i} = exp\left[-\frac{t}{\tau_{cv}} \right]$$

Time constant (s)

$$\tau_{cv} = \frac{\rho_{th}\, c_{th}\, d^2}{4\, Nu\, \lambda_g} = \frac{\rho_{th}\, c_{th}\, d}{4\, h}$$

Cut-off frequency (Hz)
(Bandwidth)

$$f_c = \frac{1}{2\, \pi\, \tau_{cv}}$$

Global time constant ♦$_g$?

ASTM (1993)

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

♦$_i$ = time constant of each heat transfer mode

Lanzetta et al. (2001) : thermoelectric anemometry (velocity measurement)

$$\frac{1}{\tau_g} = \frac{1}{\tau_{cv}} + \frac{1}{\tau_{rad}} - \frac{1}{\tau_{Jeff}}$$

♦$_{cv}$ = « convection » time constant

♦$_{rad}$ = « radiation » time constant

♦$_{Jeff}$ = « Joule effect » time constant

Global “time constant” is not a constant !! =

function of the heat transfer modes : convection, radiation, conduction, etc…

It is a *characteristic time*

3 Dynamic characterization

Reality is more complex → **response = ~~first~~ order**

What is the real time constant τ ?

Response : it depends on the application !!

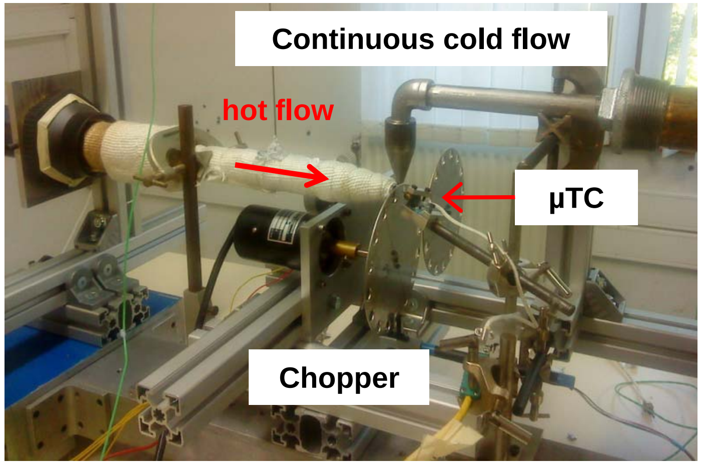
How to determine τ ?

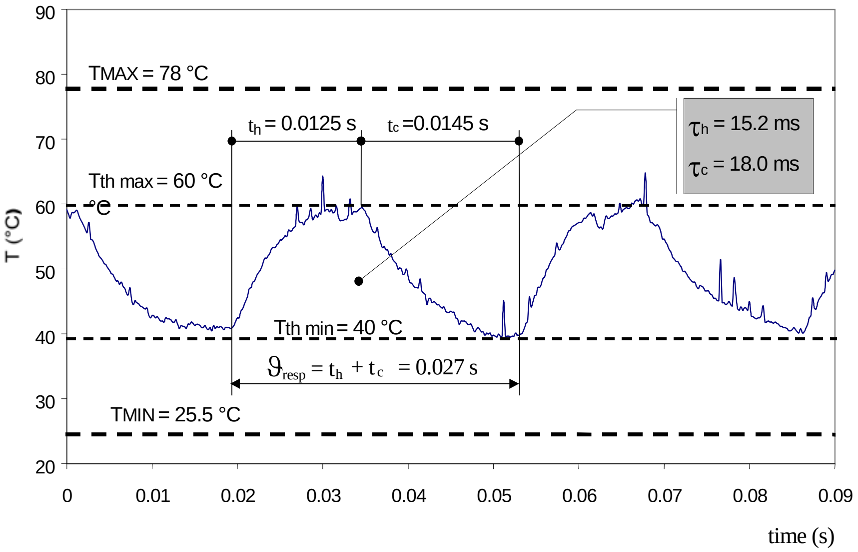
One response : experimental way

Experimental characterization of the dynamic response →

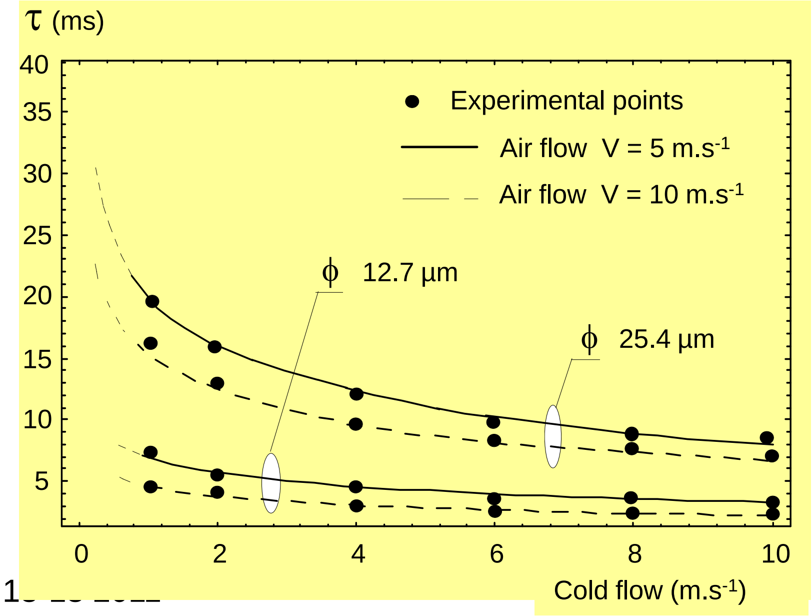
- ➊ **Convective characterization**
- ➋ **Radiative characterization**
- ➌ **Shock tube characterization**

❶ Convective calibration





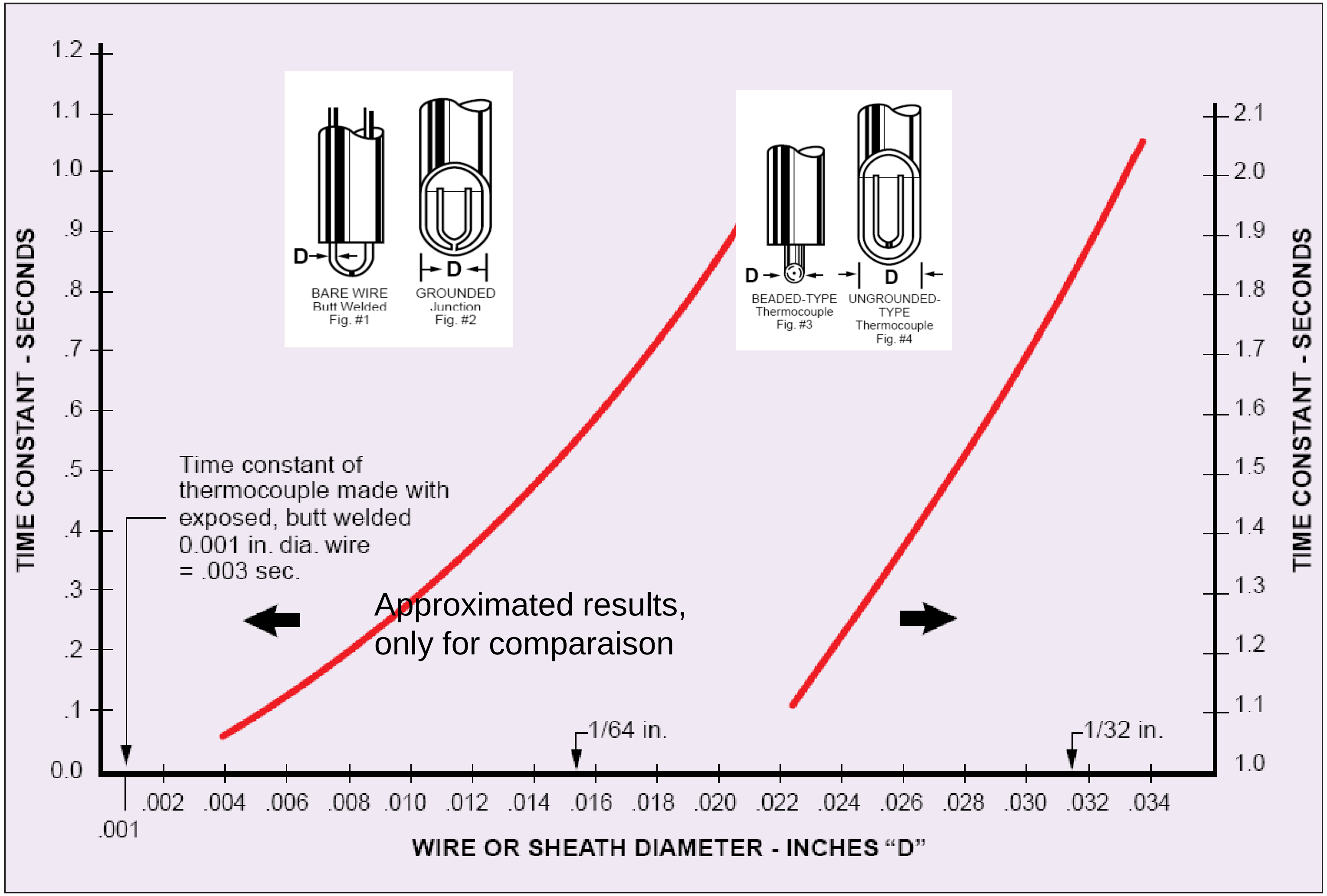
	Junction diameter d (µm)	Air velocity : 13 m.s^{-1} τ_{cv} (ms)	 Δf (Hz)	Air velocity : 23 m.s^{-1} τ_{cv} (ms)	 Δf (Hz)
S	0.5	–	–	–	–
	1.27	–	–	–	–
	5	2.9	55	2.2	72
K	12.7	15.2	10.5	8.5	18.7
	25	20	8	17	9.4
	250	32	5	25	6.4



Example from Omega ©

Time constant convective characterization

Air flow = 1.8 m.s^{-1}
at room temperature and atmospheric pressure



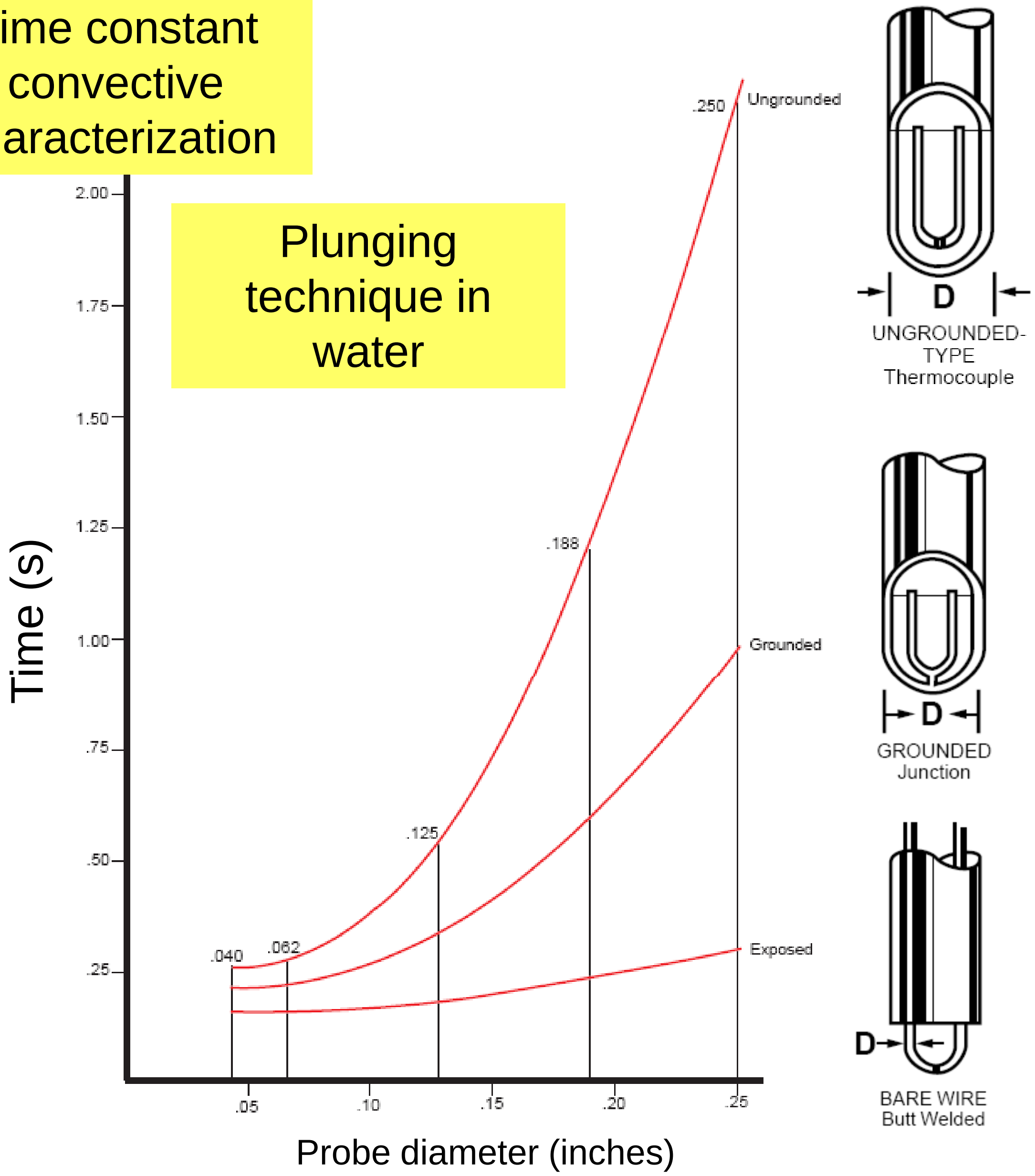
Time constant of thermocouple made with exposed, butt welded 0.001 in. dia. wire = .003 sec.

Approximated results, only for comparaison

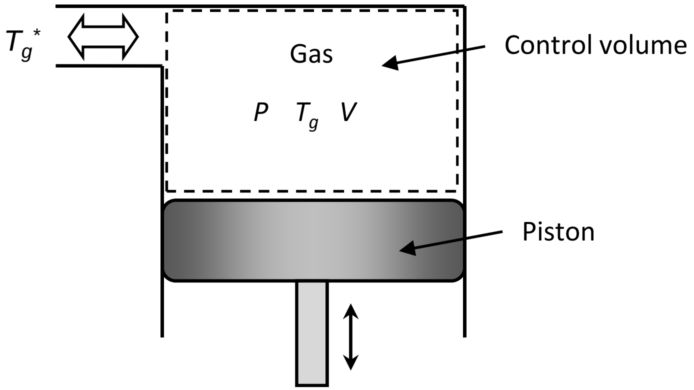
Example from Omega ©

Time constant convective characterization

Plunging technique in water



Measurements in a heat engine cylinder : heat density $q''(t)$ = ??

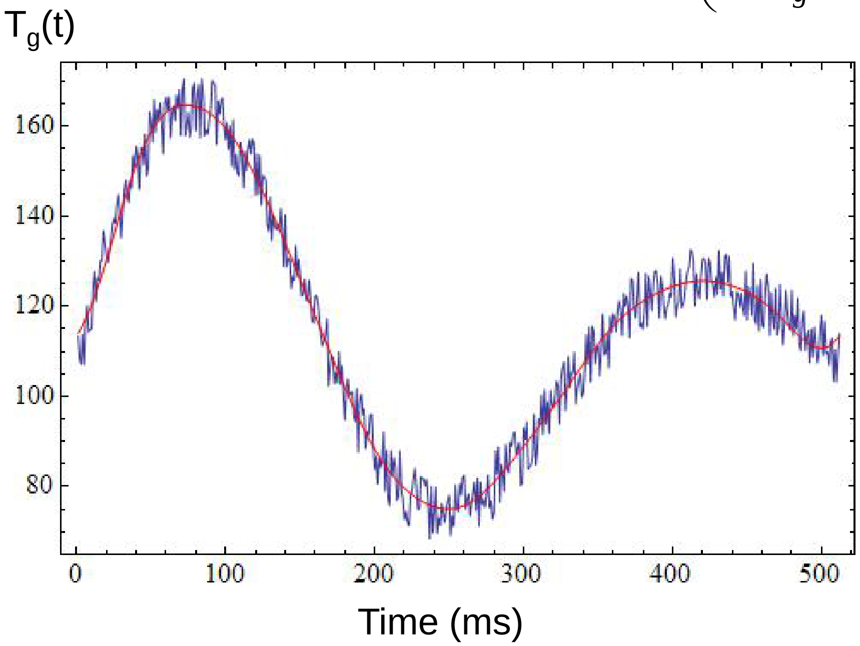


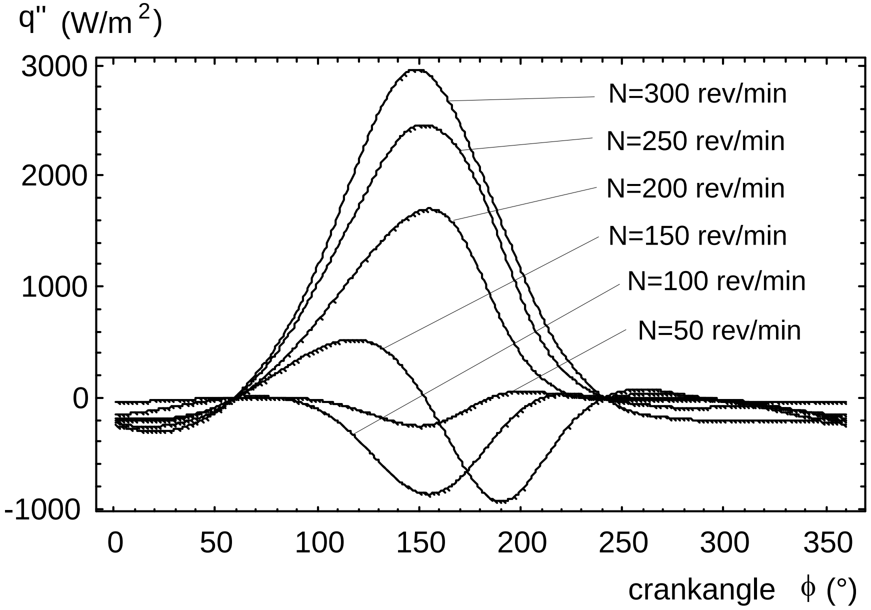
Measurements : $P(t)$, $T_g(t)$, $T_g^*(t)$ and $V(t)$

Determination of smoothed values for

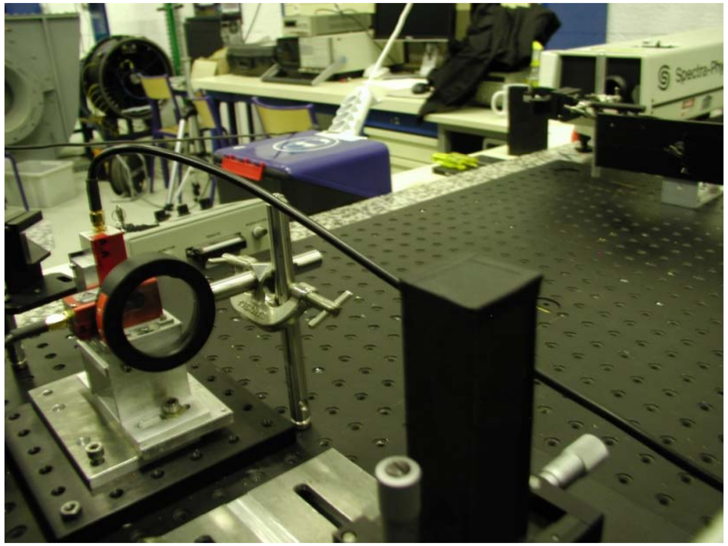
$$dP(t)/dt \qquad dV(t)/dt \qquad dT_g(t)/dt$$

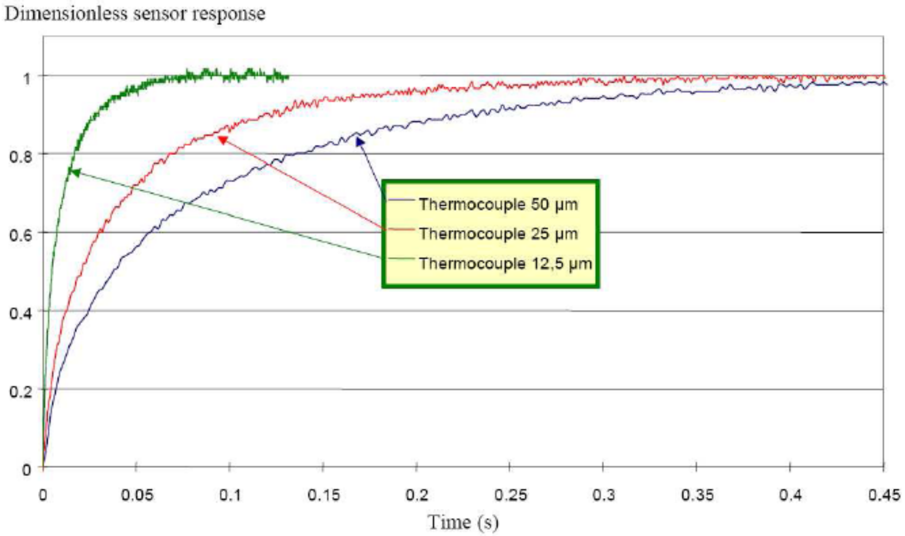
$$\Rightarrow \quad q''(t) = \frac{\gamma}{\gamma-1}\left(\frac{T_g^* - T_g}{T_g}\right)PdV + \left(\frac{\gamma T_g^* - T_g}{(\gamma-1)T_g}\right)VdP - \frac{\gamma}{\gamma-1}\left(\frac{T_g^*}{T_g}\right)PV\,\frac{dT_g}{T_g}$$



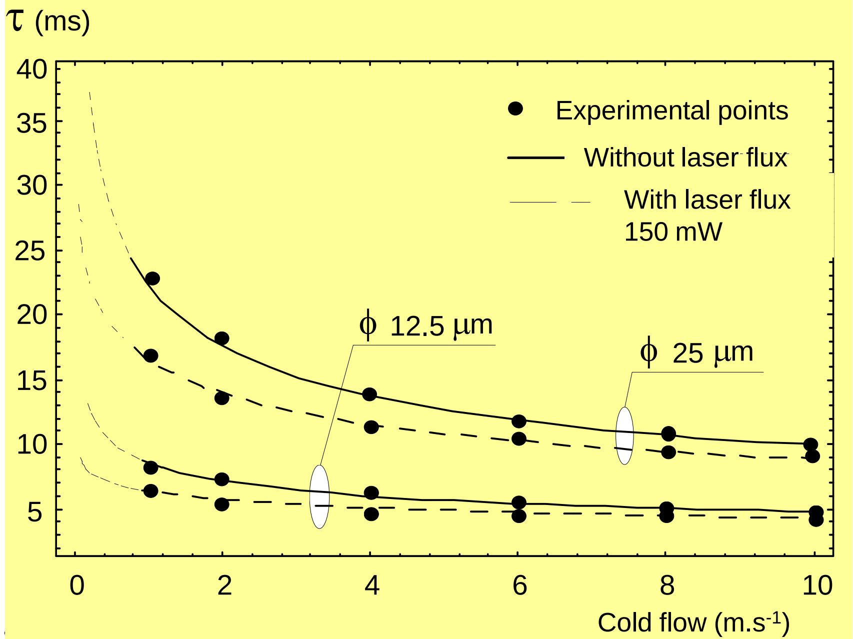


❷ Radiative calibration

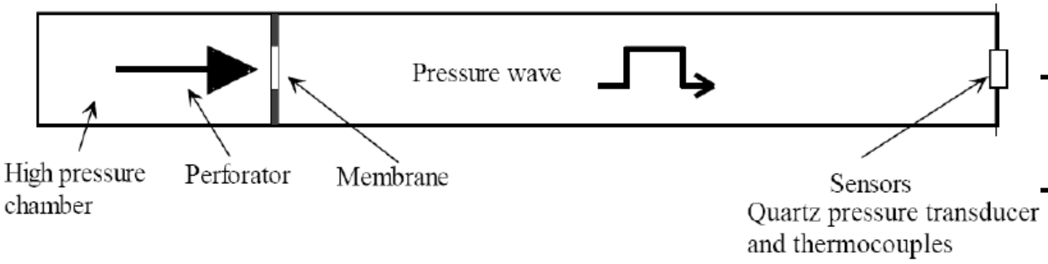




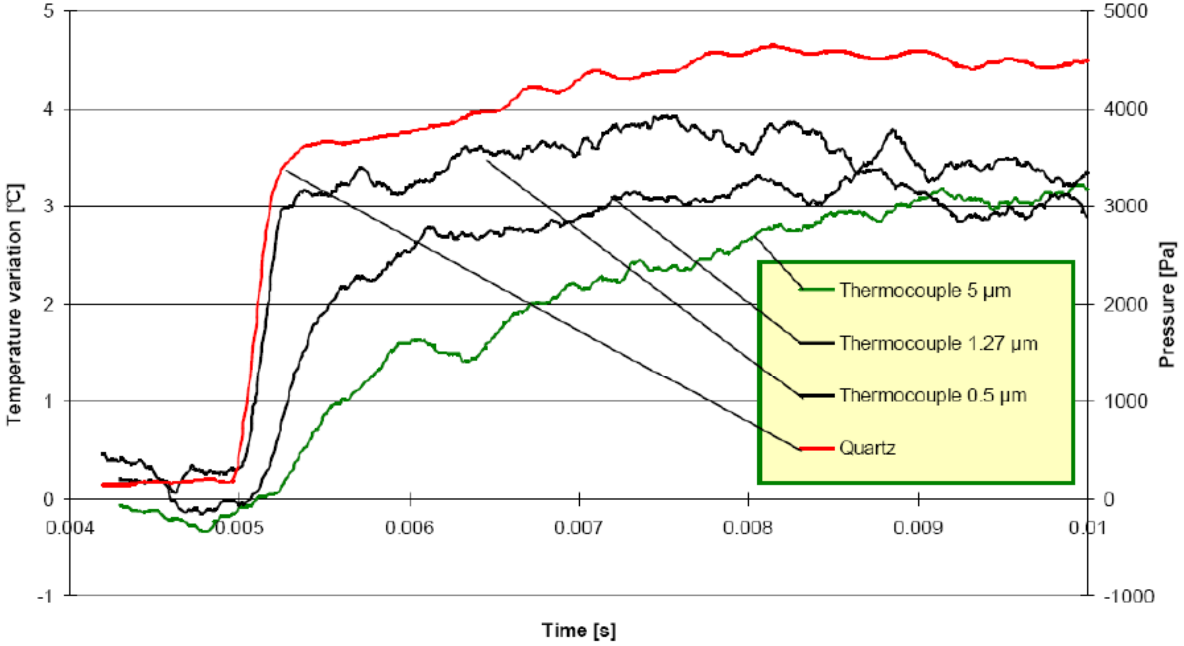
	Junction diameter d (µm)	Radiative time constant τ_{rad} (ms)	Bandwidth Δf (Hz)
S	0.5	0.07	2274
	1.27	0.18	884
	5	1.3	123
K	12.7	8.5	19
	25	34	5
	50	64.5	2.5



❸ Shock tube calibration



	Junction diameter d (µm)	Pseudo-convective time constant τ_{pc} (ms)	Bandwidth Δf (Hz)
S	0.5	0.21	758
	1.27	0.45	354
	5	1.50	106
K	12.7	–	–
	25	–	–
	50	–	–



– And more ?

Thermoelectric anemometry

« Active » thermocouple

- Heating by Joule effect
- Cooling by the fluid (relaxation)

Simultaneous measurements temperature/flow (velocity)

Simultaneous measurements temperature/pressure

3 methods

- Relaxation frequency
- Flying time
- Phase

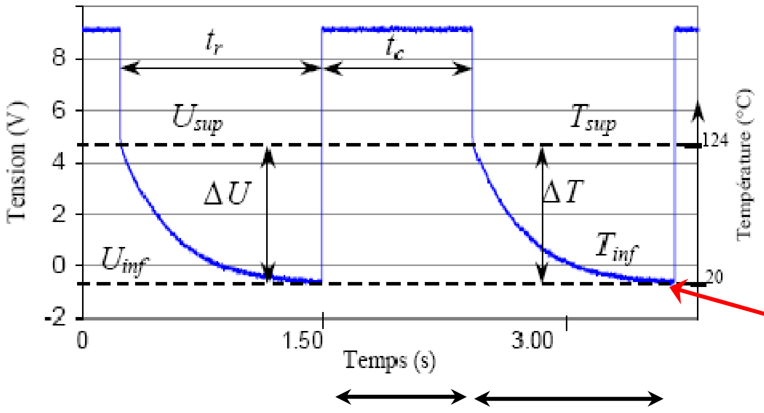
1 method

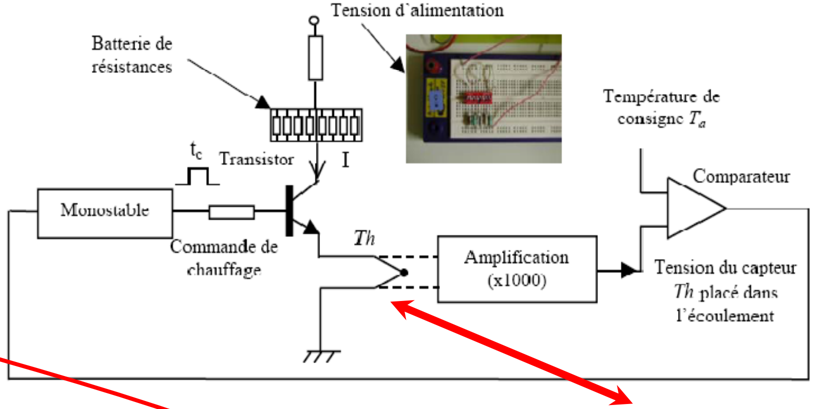
- Relaxation frequency

❶ Relaxation frequency method

Simultaneous measurements temperature/flow (velocity)

Simultaneous measurements temperature/pressure



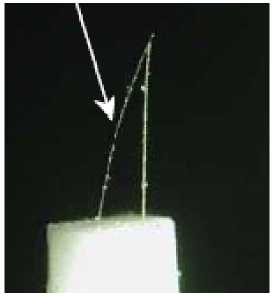


Heating t_c Relaxation t_r

Fixed duration : Tension, Resistance

Variable duration : f(state of the fluide) = flow V or pressure P

Thermocouple Th_1
Type K, d = 25.4 µm



Oscillation function of the velocity or the pressure

$$f = \frac{1}{t_c + t_r}$$

Temperature measurement at the end of the relaxation

Simultaneous measurements temperature/flow (velocity)

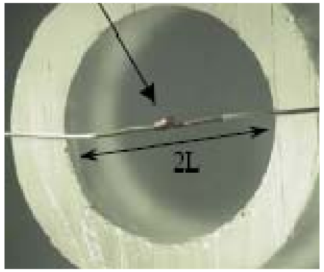
Oscillation frequency

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

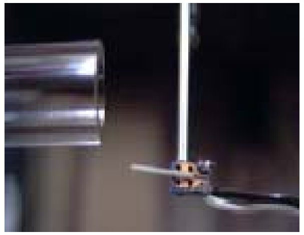
$$\frac{1}{\tau_g^*} = \frac{1}{\tau_{cv}} + \frac{1}{\tau_{rad}}$$

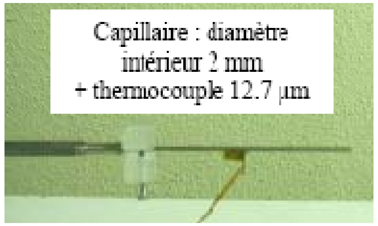
Velocity V

Thermocouple K : 127 µm

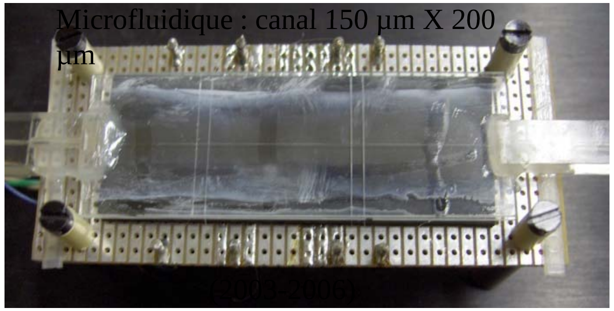


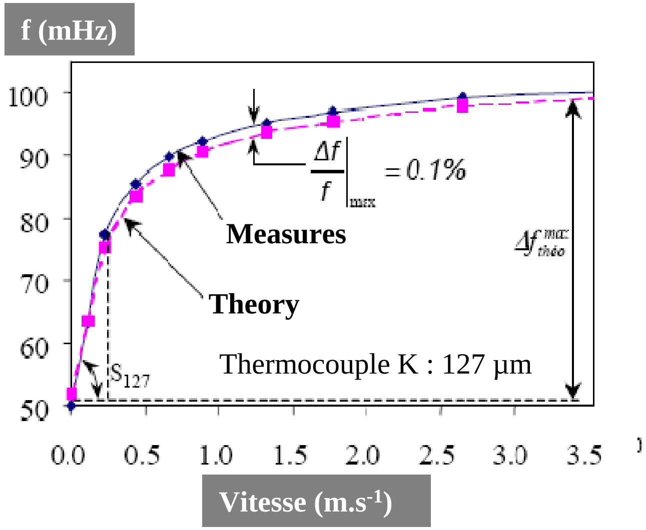
Thermocouple K : 25.4 µm

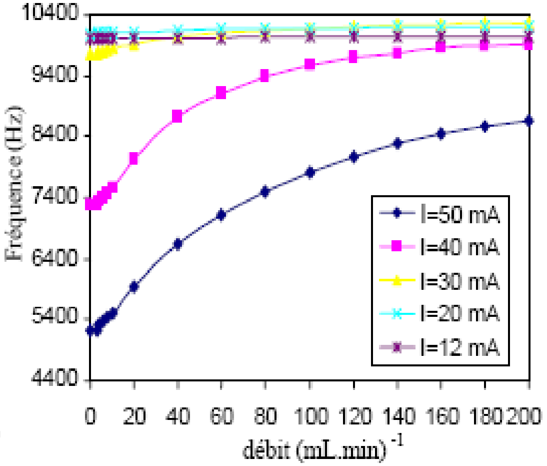



Capillaire : diamètre intérieur 2 mm + thermocouple 12.7 µm

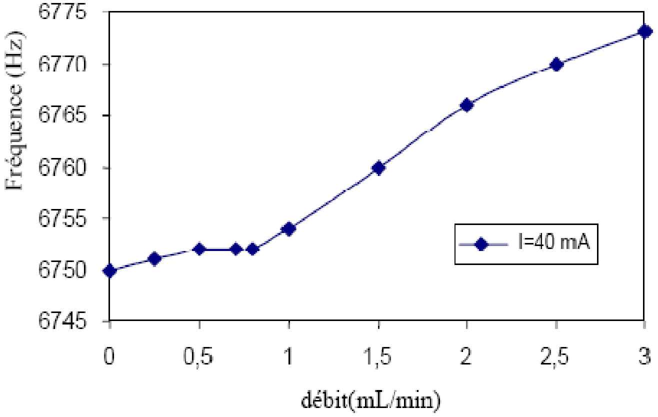
Étalon = débitmètre massique


Microfluidique : canal 150 µm X 200 µm



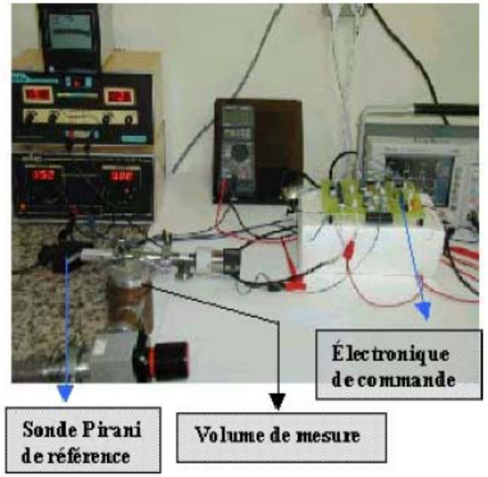


Thermocouple K : 12.7 µm

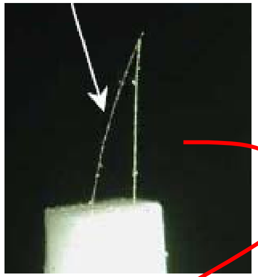


Thermocouple K : 12.7 µm

Simultaneous measurements temperature/pressure



Thermocouple Th_1
Type K, d = 25.4 µm



Volume expérimental (cylindre de 90 cm^3)

Heating

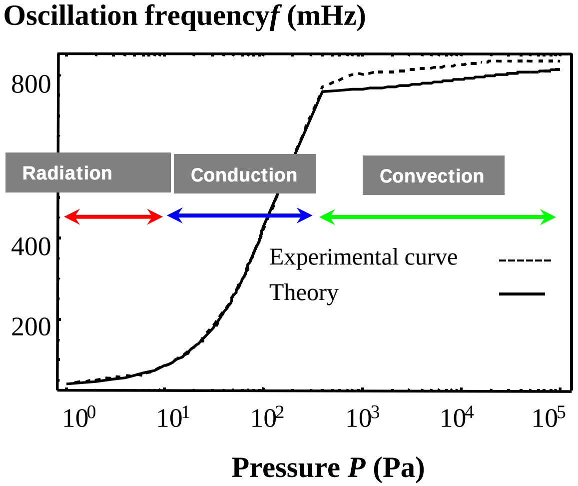
$$\frac{dT}{dt}+\left(T-T_f\right)\left(K\left(P\right)\left(T-T_f\right)^m+\frac{1}{\tau_{rad}}-\frac{1}{\tau_{él}}\right)-AI^2=0$$

$$K\left(P\right)=\frac{4\lambda_f C}{\rho c_p d^2}\left(\frac{g c_{pf} d^3}{T_f^2 \lambda_f \nu_f} \boxed{P}\right)^m \qquad \frac{1}{\tau_{cv}}=K\left(P\right)\left(T-T_f\right)^m$$

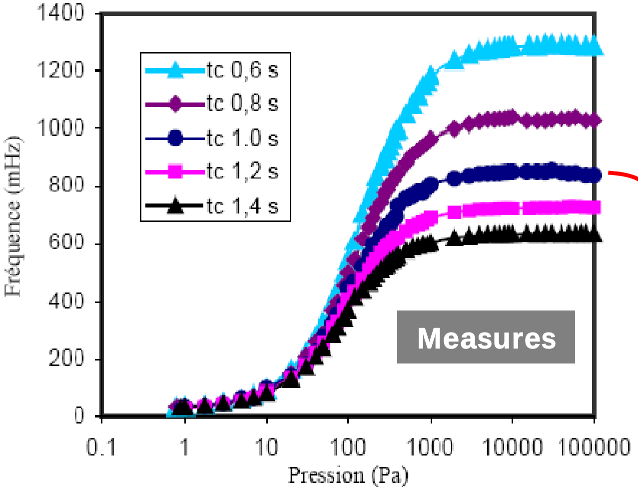
Pressure

Cooling

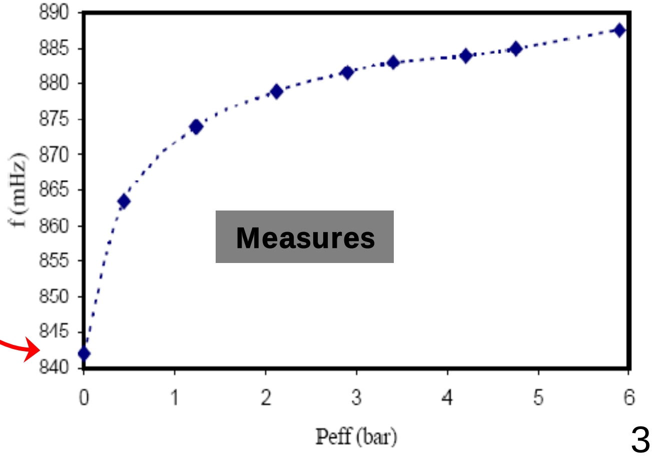
$$\frac{dT}{dt}+\left(T-T_f\right)\left(K\left(P\right)\left(T-T_f\right)^m+\frac{1}{\tau_{rad}}\right)=0$$



Low pressure (0.8 Pa – 10⁵ Pa)

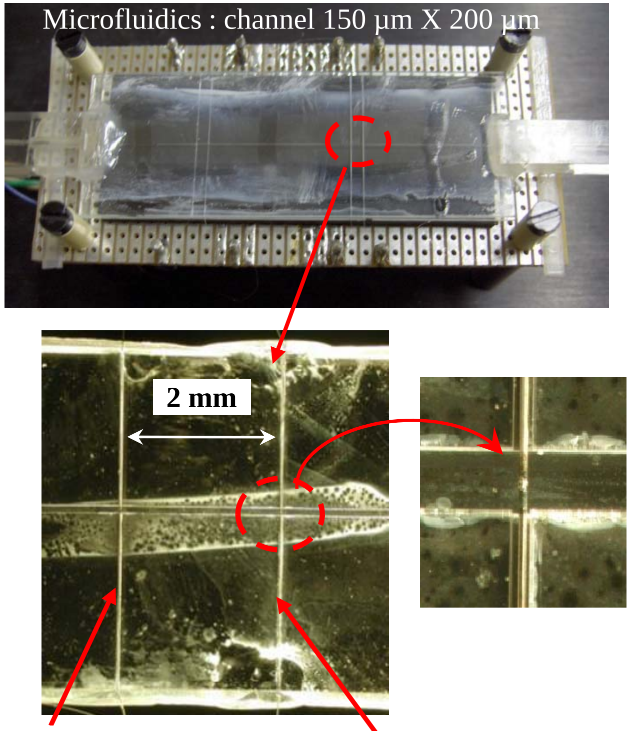


High pressure (10⁵ Pa – 5.10⁵ Pa)



❷ Flying time method

Simultaneous measurements temperature/flow (velocity)



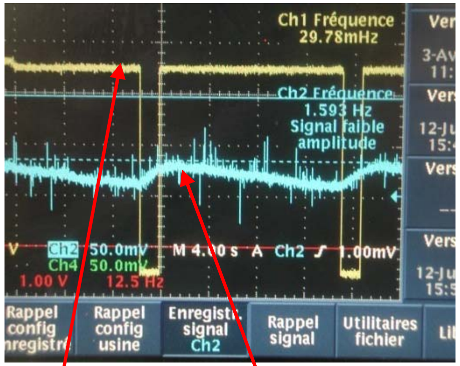
Emission :
Chromel wire
25.4 µm heated by
Joule effect with
step unit response

Reception :
K thermocouple
25.4 µm

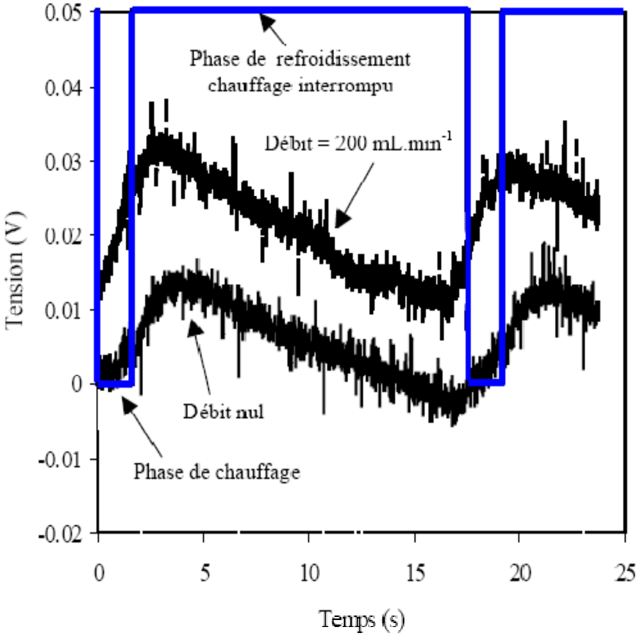
Principe

$$\text{Velocity} = \frac{\text{Distance Emission-Reception}}{\text{Duration of the transport phenomena (heat flux in fluid)}}$$

V_{mes} ≈ 3 mm.s-¹



Emission Reception

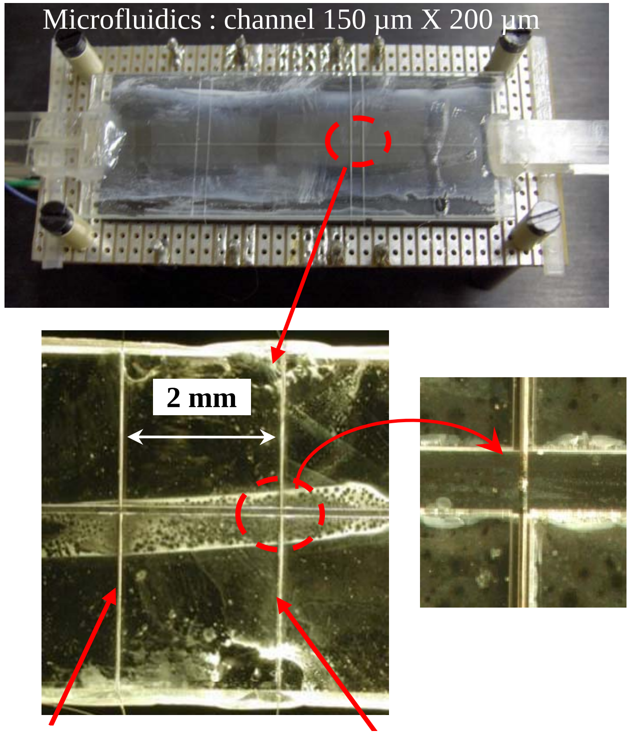


Prospective work…

❸ Phase method

Simultaneous measurements temperature/flow (velocity)

Microfluidics : channel 150 µm X 200 µm



Emission :
Chromel wire
25.4 µm heated by
Joule effect with
sinusoidal signal

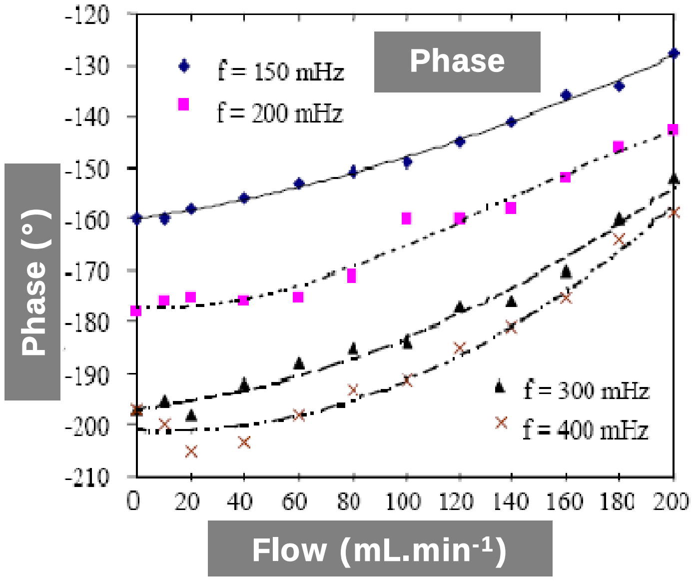
Reception :
K thermocouple
25.4 µm

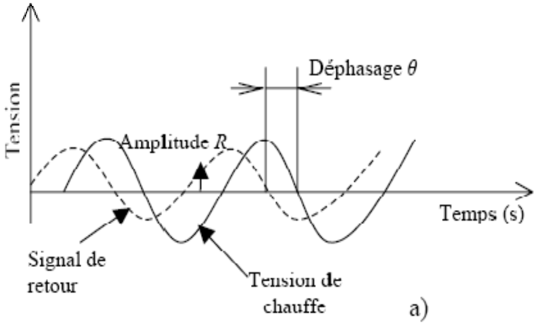
Method

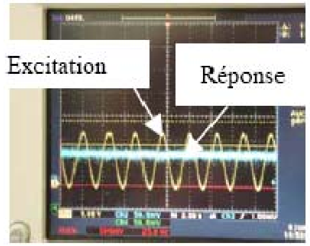
Emission = periodic heating

Reception = measure of a temperature phase lag

Velocity information is present in the phase !!







Conclusion

Micronic and sub-micronic thermocouples

- S type : ϕ 0.5, 1.27 and 5.3 μm
- K type : ϕ 7.6, 12.7, 25.4 and 53 μm

Spatial resolution and dynamic response

<u>Problem</u> : robustness ↘ with ↘ dimensions

<u>Applications</u> :

- **fluctuations measurements**
- **photothermal microscopy**
- **acoustic**
- **thermal phenomena**

} **Micro thermocouples**

Lecture 5-A

Part 2 : B. Garnier

Measurements with contact : temperature and heat flux

Metti^{5} Roscoff June 13-18 2011

- Whatever the selected temperature measurement method, one have ***parasitic effects***

- Two type of errors

  - ✓ thermometric phenomenon
  - ✓interaction between sensor, medium and environment which involves a local disturbance of the temperature field.

Illustration- Tutorial 4-

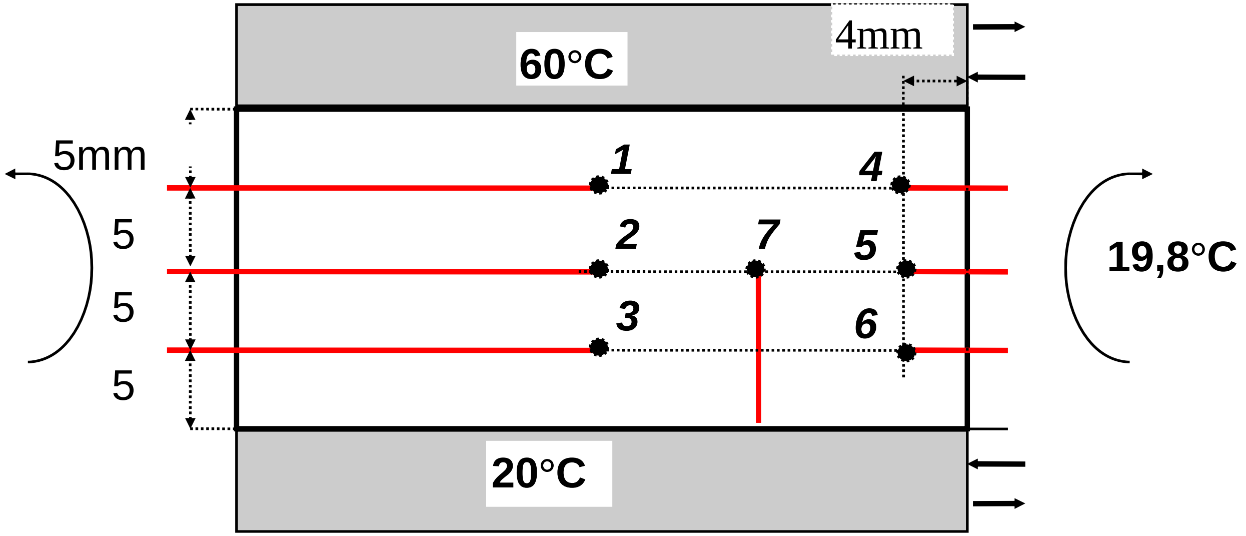


Fig.1 : instrumented ***PMMA sample*** *with 0.2mm dia. type K thermocouple*

Table 3 : steady state temperature measurements

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		

$T_7 - T_2 = 5.7°C$!

Overview

2.4. Error introduced by the disturbance of the local temperature using direct contact temperature measurement

2.4.1. Introduction

2.4.2 Error analysis and model

2.4.2.1 Surface temperature measurement

2.4.2.2 Temperature measurement within a volume

2.4.2.3 Error model

2.4.3. Practical consequence and examples, semi intrinsic thermocouples

2.4.3.1. Practical consequences

2.4.3.2. Application for a thermocouple with and without a contact disc

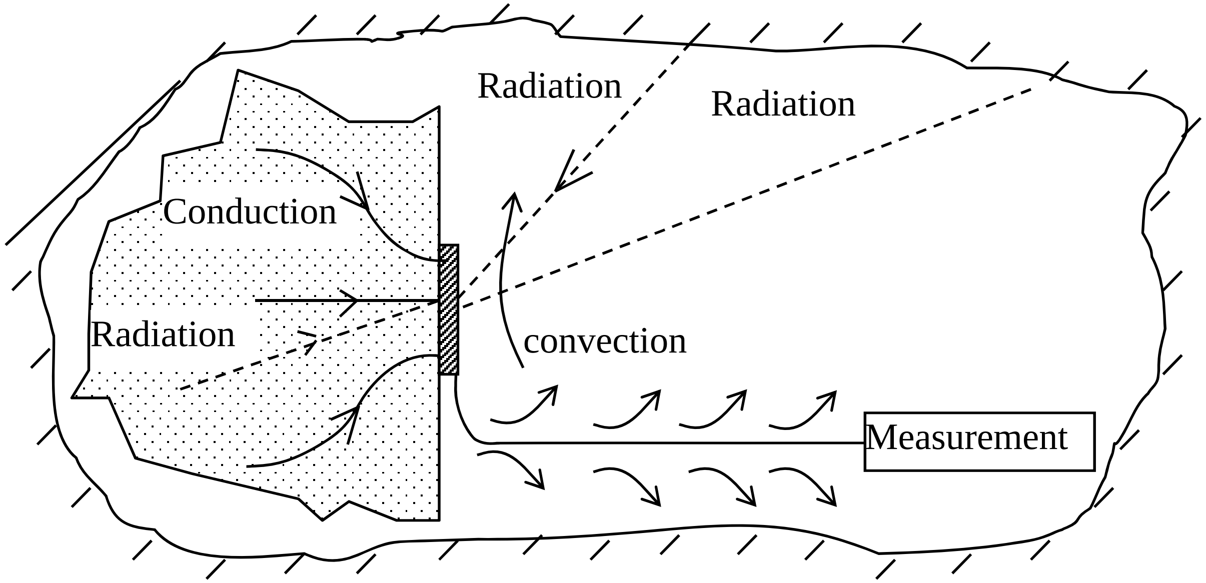
2.4.3.3. Temperature measurement with semi intrinsic thermocouple

2.5. Heat flux measurement: direct methods

2.4.2 Error analysis and model

2.4.2.1 Surface temperature measurement

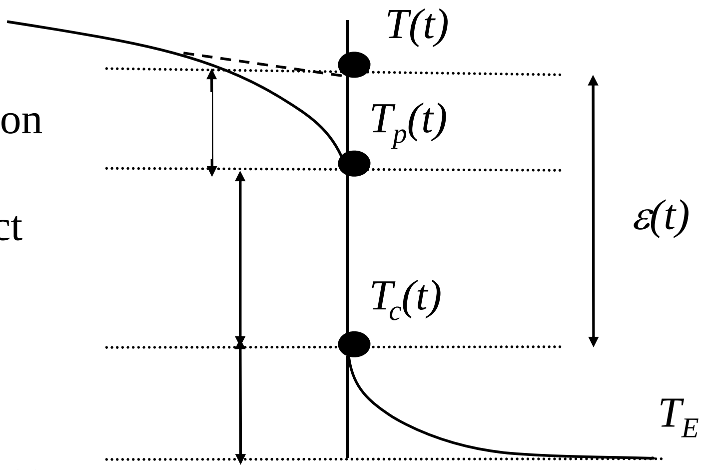
Bardon 1999, Cassagne 1980 & 1986



For an opaque medium:

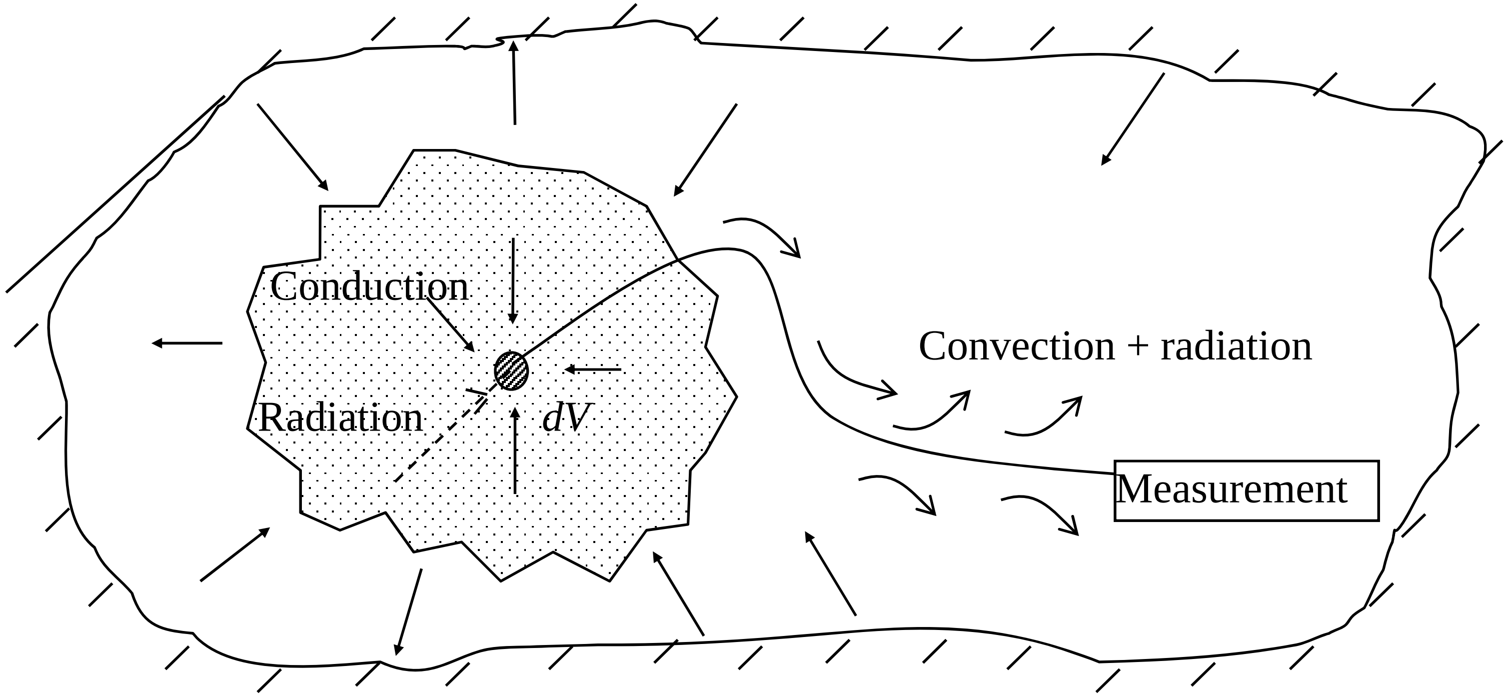
3 effects

- Macroconstriction
- Thermal contact resistance
- Fin



→Measurement error : $\boldsymbol{\varepsilon(t) = T(t) - T_c(t)}$

2.4.2.2 Temperature measurement within a volume



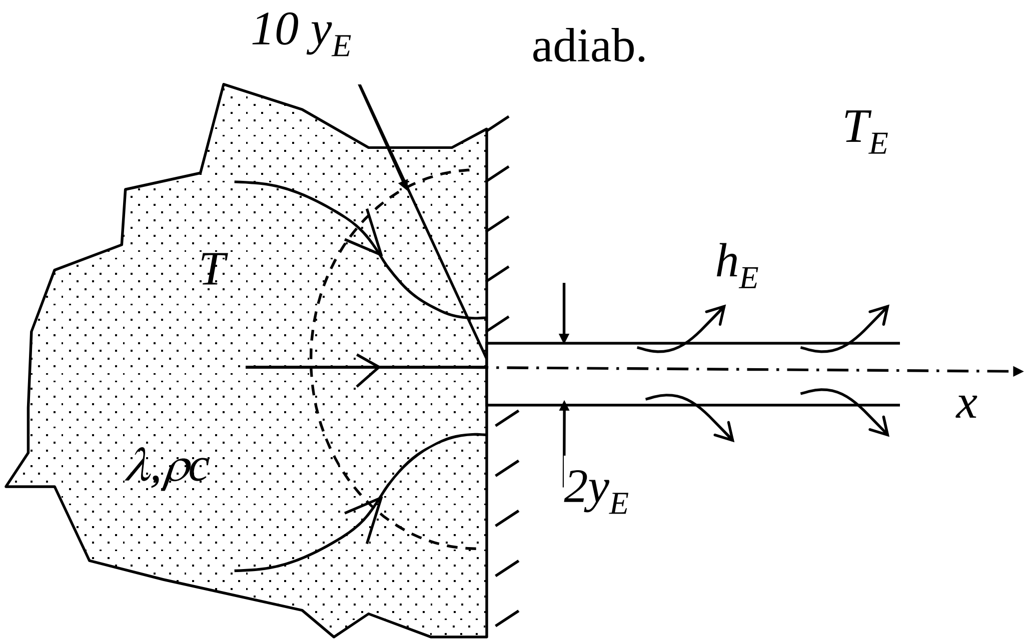
Same 3 effects:

- Macroconstriction
- Thermal contact resistance
- Fin

→Measurement error : $\varepsilon(t) = T(t) - T_c\,(t)$

2.4.2.3 Error model

- *Steady state surface temperature measurement of an opaque medium*



$$h_E = h_c + h_r$$

$$T_E = \frac{h_c\,T_f + h_r\,T_o + F}{h_E}$$

λ : thermal conductivity

a) Macroconstriction effect : $T - T_p = r_M\,\phi$ with $r_M = \dfrac{1}{4 y_E \lambda}$

for a disc of radius y_E

→ 96% of the *T - T_p* temperature drop is within an hemisphere of center 0 and radius *10 y_E*

Error model

b) *The contact resistance effect*

$$T_p - T_c = r_c\,\phi$$

$r_c = R_c / S$ $\quad$ R_c (m^2 K W^{-1})

c) *The fin effect:*

$$T_c - T_E = r_E\,\phi$$

thermocouple assumed as a rod of radius y_E

$$r_E = 1/(\pi\, y_E \sqrt{2 h_E \lambda_E y_E}\,)$$

Measurement error $\varepsilon = T - T_c$?

$$T - T_p = r_M\,\phi$$

$$T_p - T_c = r_c\,\phi$$

$$T_c - T_E = r_E\,\phi$$

$$T - T_c = (r_M + r_c)\,\phi$$

$$\phi = \frac{T - T_E}{r_M + r_c + r_E}$$

$\varepsilon = T - T_c = K\,(T - T_E)$ with $K = \dfrac{1}{1 + \dfrac{r_E}{r_c + r_M}}$

$\varepsilon = T - T_c = K\,(T - T_E)$ with $K = \dfrac{1}{1 + \dfrac{r_E}{r_c + r_M}}$

Discussion:

ε small if:

- $T - T_E$ small
- K small $\quad r_E >> r_c + r_M \qquad r_M = \dfrac{1}{4 y_E \lambda}$

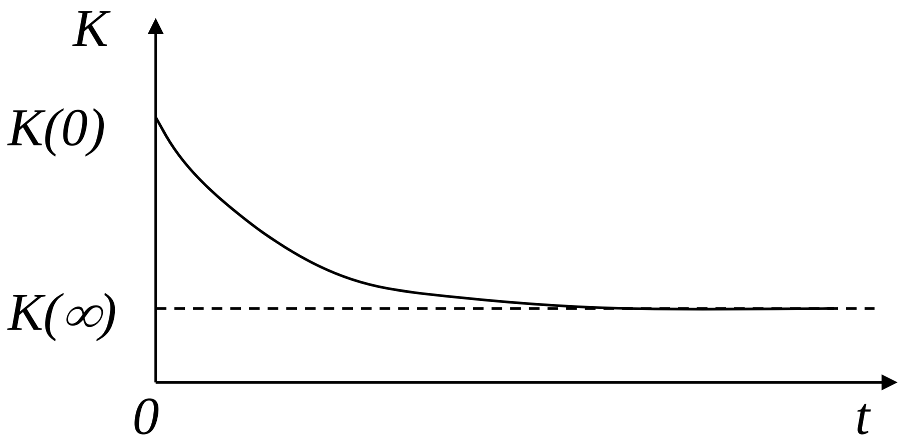
✓ high thermal conductivity medium $\quad r_M << \boldsymbol{r_c}$

✓ low thermal conductivity medium $\quad \boldsymbol{r_M} >> r_c$

and

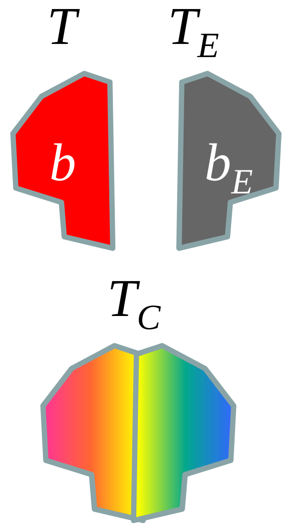
Transient surface temperature measurement

$$\varepsilon(t) = K(t)\,[T(t) - T_E\,]$$



K(0) ?

- If $r_c \neq 0$, $K(0)=1$, the error is about 100% at $t=0$
- If $r_c = 0$ (perfect contact), the initial error is smaller:



t<0

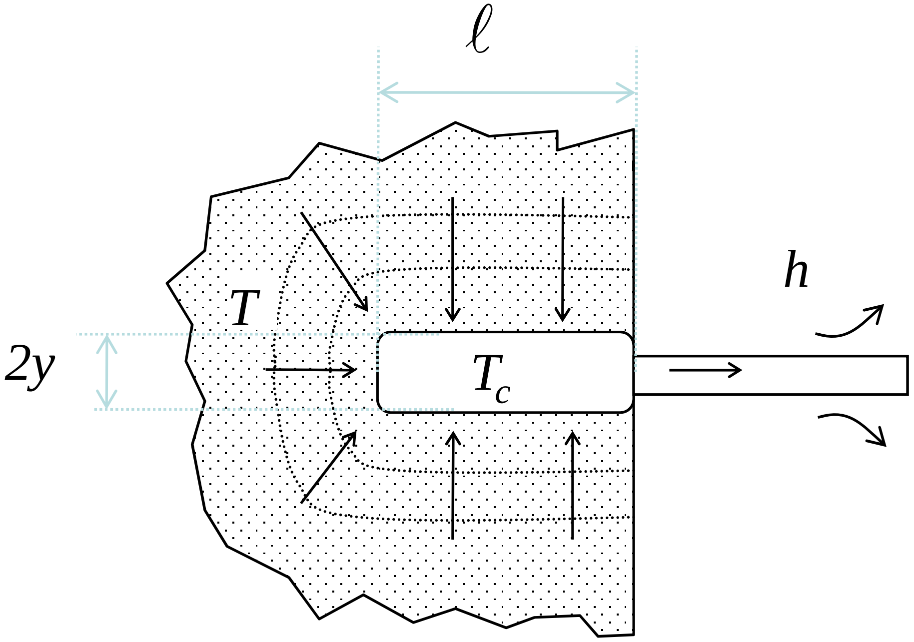
t ≥ 0

$$\frac{T - T_C}{T_C - T_E} = \frac{b_E}{b} \longrightarrow \varepsilon(0) = T - T_C = \frac{b_E}{b}[(T_C - T) + (T - T_E)]$$

$$\varepsilon(0) = T - T_C = \frac{b_E}{b + b_E}(T - T_E) \longrightarrow \boxed{K(0) = \frac{b_E}{b + b_E} < 1}$$

$b = \sqrt{\lambda \rho c}$ $\quad b_E = \sqrt{\lambda_E b_E \rho_E}$ effusivities

Temperature measurement within a volume



Temperature measurement with a cylindrical sensor inside the medium

- $r_c = R_c/S$ $\qquad S = 2\pi y \ell$

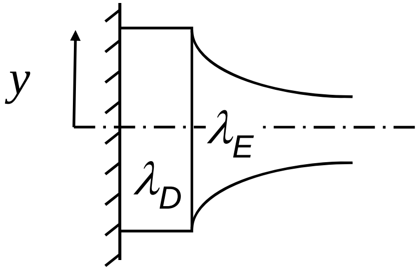
Same error model but with :

- $$r_M = \frac{1}{2\pi\lambda\ell}\,\mathrm{Log}\,\frac{2\ell}{y} \qquad \ell >> y$$

2.4.3. Practical consequence and examples, semi intrinsic thermocouples

- **Practical consequences :**

1. even for perfect contact $r_c = 0$ there is an error which depends on the ratio r_M / r_E.
2. *For high thermal conductivity* material, $r_M << r_c$ Thus, one must take care that r_c is small and remains stable. The contact pressure will have to be high and constant, surface will have to be plane without waviness, the interstitial medium with the highest possible thermal conductivity (welding, grease…). In addition, one should avoid oxide films as well as mechanical shocks and vibrations which can modify considerably r_c and consequently the measurement error.
3. For *low thermal conductivity* material , $r_M >>> r_c$. One can reduce macroconstriction effect by increasing the radius of the sensitive element without increasing the section of the connections A contact disc of high thermal conductivity material will be used.



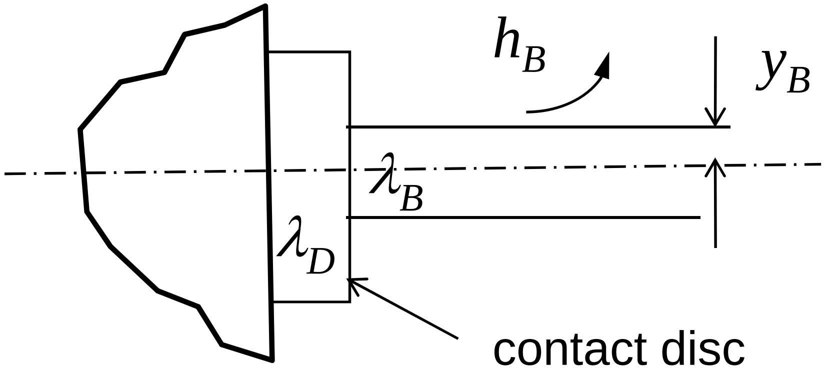
4. Whatever the type of measurement, the fin thermal resistance r_E should be as high as possible. The transversal area, the conductivity, the heat transfer coefficient have to be chosen the smallest possible. One also should have low emissivity surface, connection protected from high temperature fluids movements or radiation, T_E being modified in those situations.

5. Finally, the error is all the more small as T_E should be as close as possible to the temperature T to measure . At the price of a technological complication, one can add an external heat source on the connection so that its temperature T_E is controlled in order to stay a close as possible as T “**compensated heat flux sensors”.** However for correct measurement, the thermal resistance r_E should stay high in order to prevent the compensation heating from disturbing the temperature field in the medium.

- **Application -for steady state temperature measurement** using a thermocouple with and without a contact disc

- thermocouple →unique rod with a radius $y_B = 0.5$ mm, an infinite length, $\lambda_B = 15\ \mathrm{W.m^{-1}.K^{-1}}$ and $h_B = 5\ W.m^{-2}K^{-1}$.

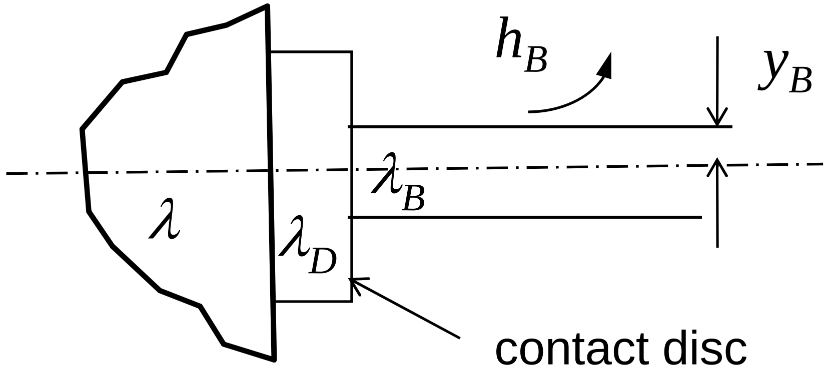
- r_E ?
  - ✓ $r_E = r_B$ without contact disc, $r_B = \dfrac{1}{\pi y_B \sqrt{2 h_B y_B \lambda_B}}$
  - ✓ $r_E \approx r_B + \dfrac{1}{4 y_B \lambda_D}$ with contact disc



femto-st with contact disc
sciences & technologies

Tab 1. Effect of the thermal conductivities of the medium and of the disc on r_M, r_c, r_E and K

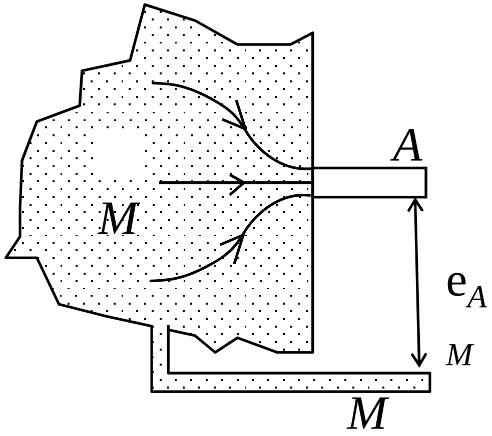
	Low thermal conductivity $\lambda=10^{-1}$ W.m^{-1}.K^{-1}		High thermal conductivity $\lambda=100$ W.m^{-1}.K^{-1}	
	without disc	with disc	without disc	with disc
r_M (K.W^{-1})	**5000**	250	**5**	0.25
R_c (K.W^{-1}m^2)	**10^{-3}**	10^{-3}	**10^{-4}**	10^{-4}
r_c(K.W^{-1})	**1270**	3,18	**125**	0.31
r_E (K.W^{-1})	**1700**	1733	**1700**	1733
K	**0.786**	0.127	**0.072**	0.0003

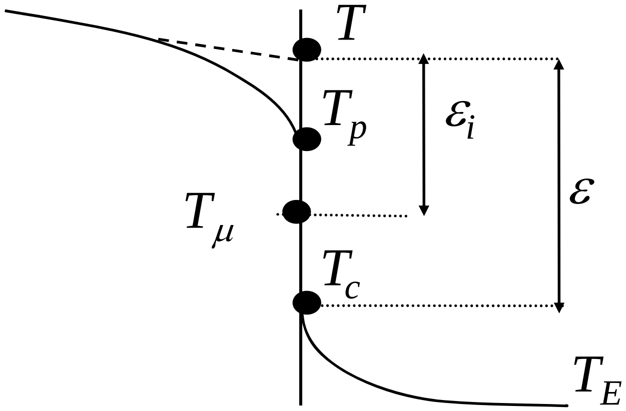


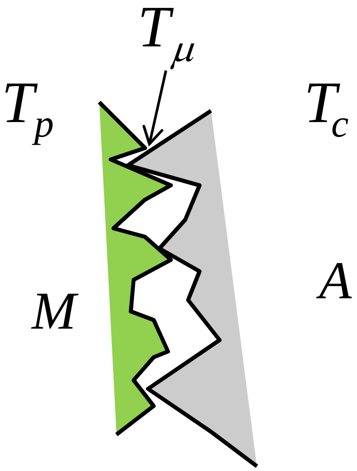
• Temperature measurement with semi intrinsic thermocouple

Medium M itself (presumately electrically conducting) is used as one wire of the thermocouple

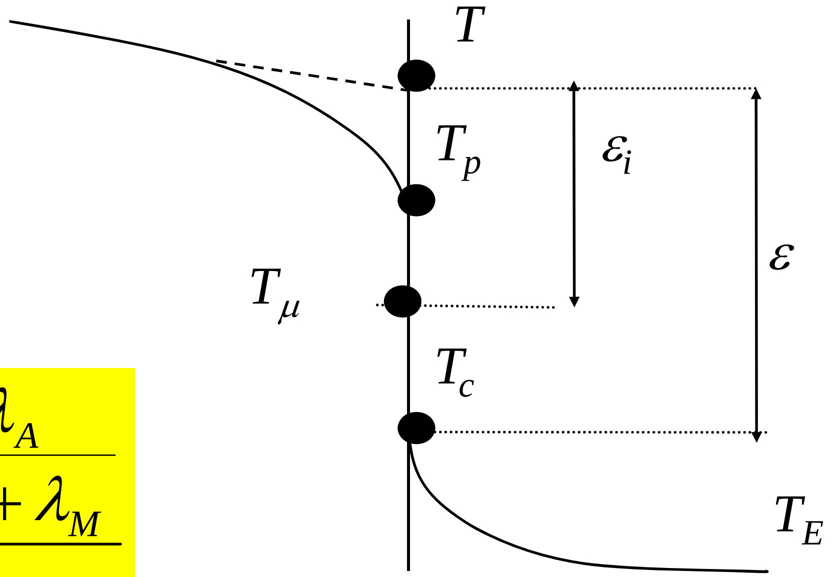
✓it has only one connection wire instead of two, thus r_E is twice larger
✓the measured temperature T_μ is intermediate between T_p and T_c







Semi intrinsic thermocouple $\varepsilon_i = T - T_\mu = K_i(T - T_E)$



$$\frac{T_p - T_\mu}{T_\mu - T_c} = \frac{\lambda_A}{\lambda_M}$$

Semi intrinsic

$$K_i = \frac{r_M + r_c \dfrac{\lambda_A}{\lambda_A + \lambda_M}}{r_M + r_c + r_E}$$

Traditional

$$K = \frac{r_M + r_c}{r_M + r_c + r_E}$$

$$\boxed{K_i < K}$$

Semi intrinsic thermocouple :

- Error is considerably lower than with a traditional thermocouple (2 to 5 times)
- In transient mode, error and thermal inertia are greatly reduced (Cassagne 1986).
- Calibration of the semi intrinsic thermocouple is almost always required.

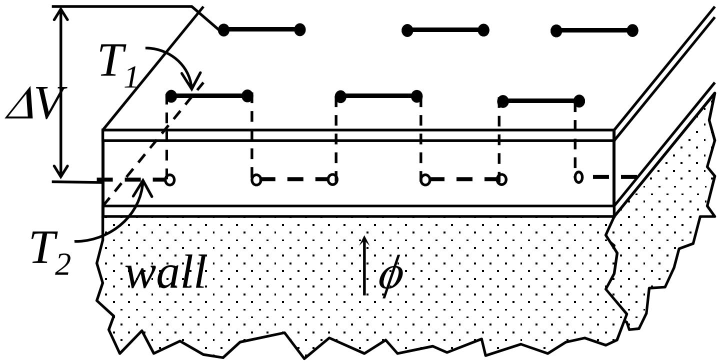
2.5. Heat flux measurement: direct and in direct methods

2.5.1. Heat flux sensor with gradient

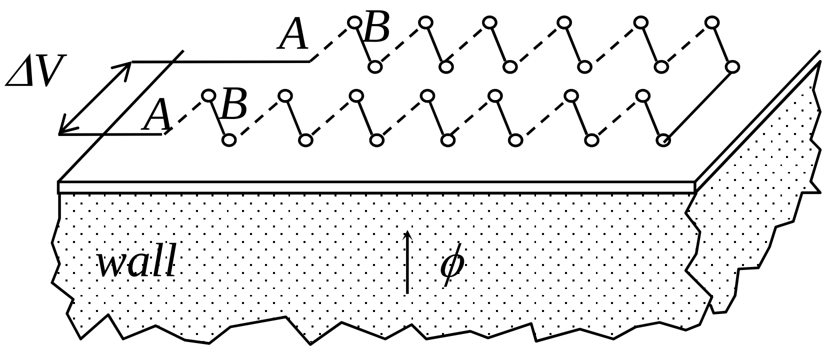
Principles :

measurement of the temperature difference within the wall itself (intrinsic method) or by covering it with an additional wall (heat flux sensor-HFS-)+ Fourier’s law

Normal



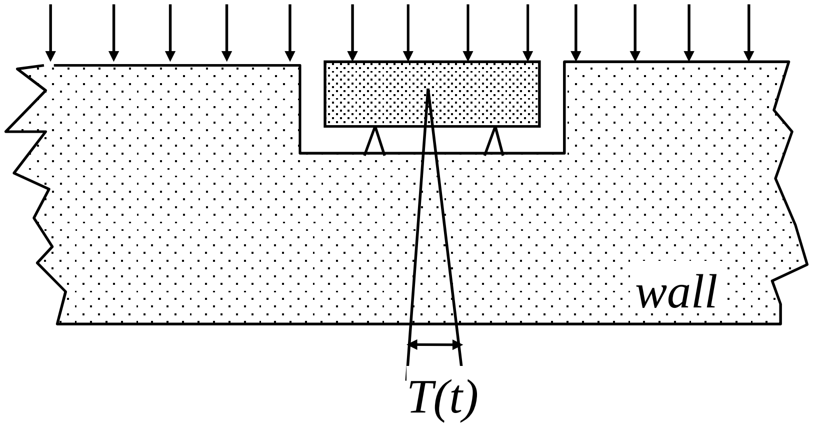
Tangential



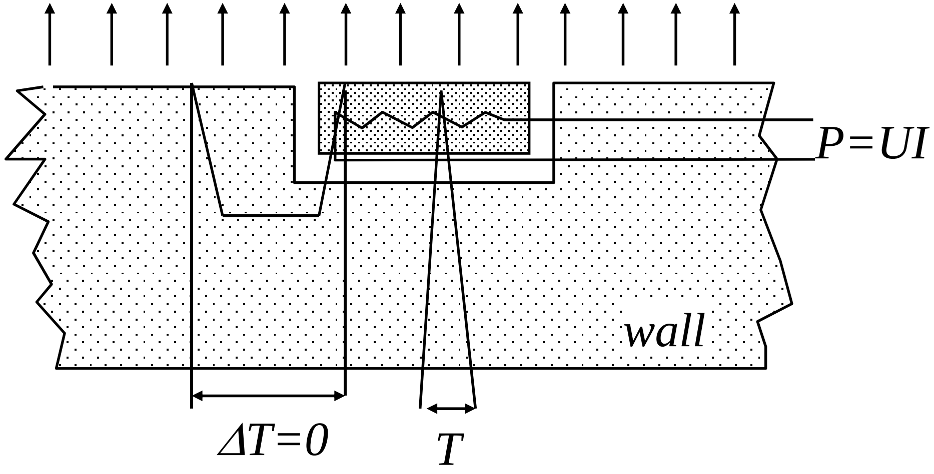
→ work whatever the heat flux direction with steady state or for slowly variable temperature.

Normal gradient : $\varepsilon \approx 8\ \%$ Khaled 20O9

2.5.2. Inertia heat flux sensor and heat flux sensor with electric dissipation (zero method)



Inertia heat flux sensor

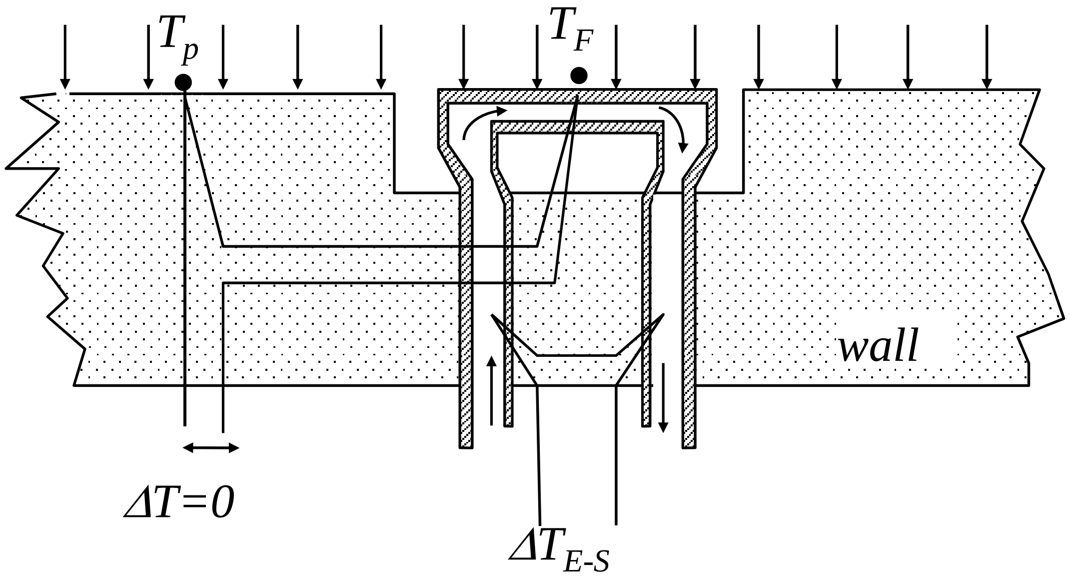


heat flux sensor with electric dissipation

works for heat flux coming from the environment

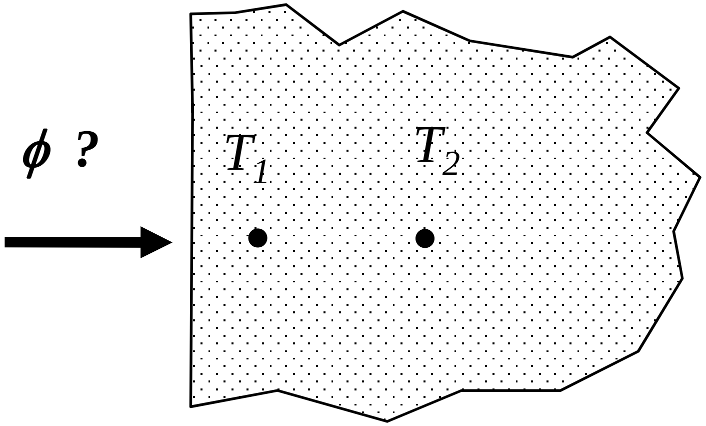
works only for heat flux leaving the wall and for steady state or slowly variable temperature.

2.5.3. Enthalpic heat flux sensor



works for heat flux coming from the environment

2.5.2. Indirect measurement (inverse method)

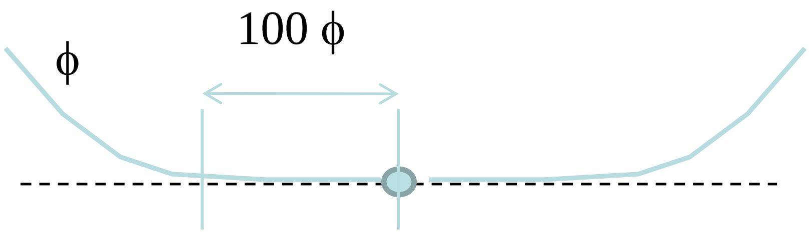


- Transient temperature measurement with embedded thermocouples
- Heat transfer model + inverse methods
- criteria for correct locations of thermocouples (→ Tutorial 4)

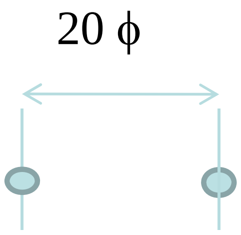
$\varepsilon \approx 2\%$ (th K 50µm) LTN

Conclusion

- ✓ Thermocouples should be mounted along isothermal lines (100 ϕ)



- ✓ Thermocouples disturbance → hemisphere of radius 10ϕ



→Thermocouples should not be too close

- ✓ Error model

$$\varepsilon = \varepsilon\,(\, r_M \,,\, r_c \;\; r_E \,,\, T\text{-}T_E \,)$$

- ✓ Semi intrinsic thermocouples → low inertia, reduced errors

Thank you for your attention….