Capteur fluxmétrique dynamique pour la caractérisation de coefficients d'échange dans le bâtiment

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Objective and why using an active sensor ?

- **Objective:** to follow continuously external climatic factors outside buildings (heat transfer coefficient, outside equivalent temperature….)

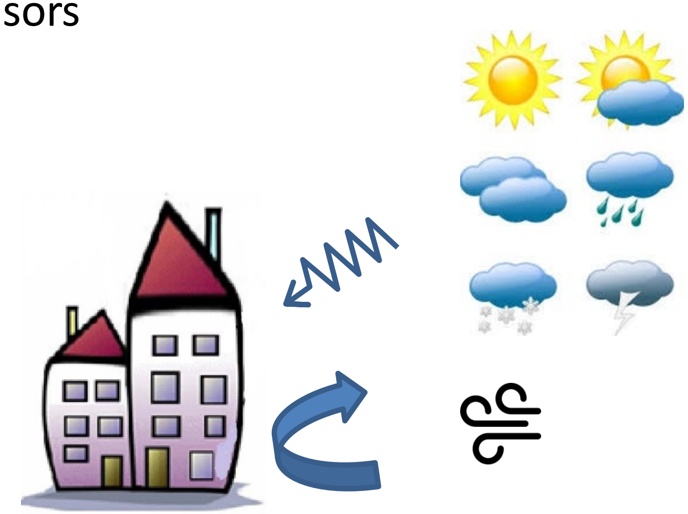
- **Interests:**

→ to improve thermal management of buildings
→ to provide data to IA predictive models for energy saving
→ still necessary to provide pertinent and unbiased sensors

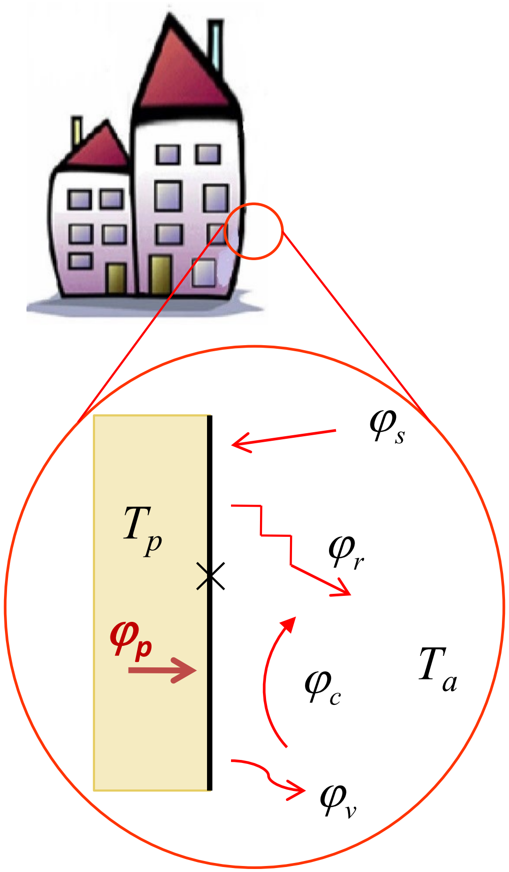
- But **how** to proceed ?

One way is to analyze all the thermal phenomena:

- convection,
- radiation
- evaporation ….



❑ Analysis of all thermal phenomena



✓Heat flux from solar radiation : φ_s (α_s : wall absorption coefficient)

✓Heat flux from infrared radiation : $\varphi_r = h_r(T_p - T_r)$

✓ Convective heat flux : $\varphi_c = h_c(T_p - T_a)$

✓ Heat flux from evaporation $\varphi_v = h_v(T_p - T_a) + \sigma_v$

(h_v and σ_v are proport. to the latent heat of evaporation)

By adding heat fluxes ($\varphi_p = \varphi_c + \varphi_r + \varphi_v - \alpha_s\varphi_s$), the wall heat flux is:

$$\varphi_p = h_c(T_p - T_a) + h_r(T_p - T_r) + h_v(T_p - T_a) + \sigma_v - \alpha_s\varphi_s \quad \text{(Eq. 1)}$$

➡ The full characterization of all the parameters of Eq.(1) is rather complex since it would require several types of measurement

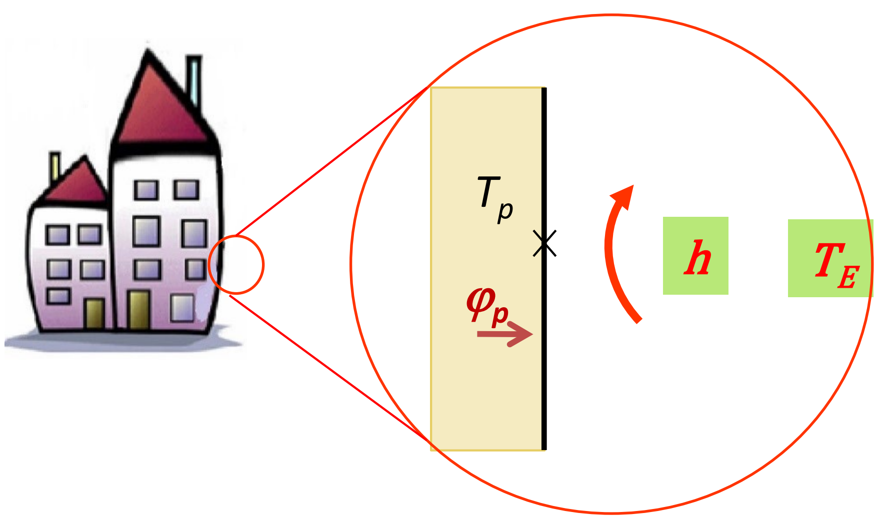
An efficient alternative: a global model

From Eq.(1): $\varphi_p = h_c(T_p - T_a) + h_r(T_p - T_r) + h_v(T_p - T_a) + \sigma_v - \alpha_s\varphi_s$

one can write:

$$\varphi_p = h\,(T_p - T_E) \qquad \begin{cases} h = h_r + h_c + h_v \\ T_E = \dfrac{(h_c + h_v)T_a + h_r T_r + \alpha_s\varphi_s - \sigma_v}{h} \end{cases}$$

T_E : equivalent surrounding temperature



But how to find h and T_E ?

- Not possible with standard passive heat flux sensor which provides $\varphi_p(t)$ and $T_p(t)$
- But, this is possible if the sensor is heated

Working principle of the dynamic heat flux sensor

$\varphi_p = h\,(T_p - T_E)$ h ?and T_E ?

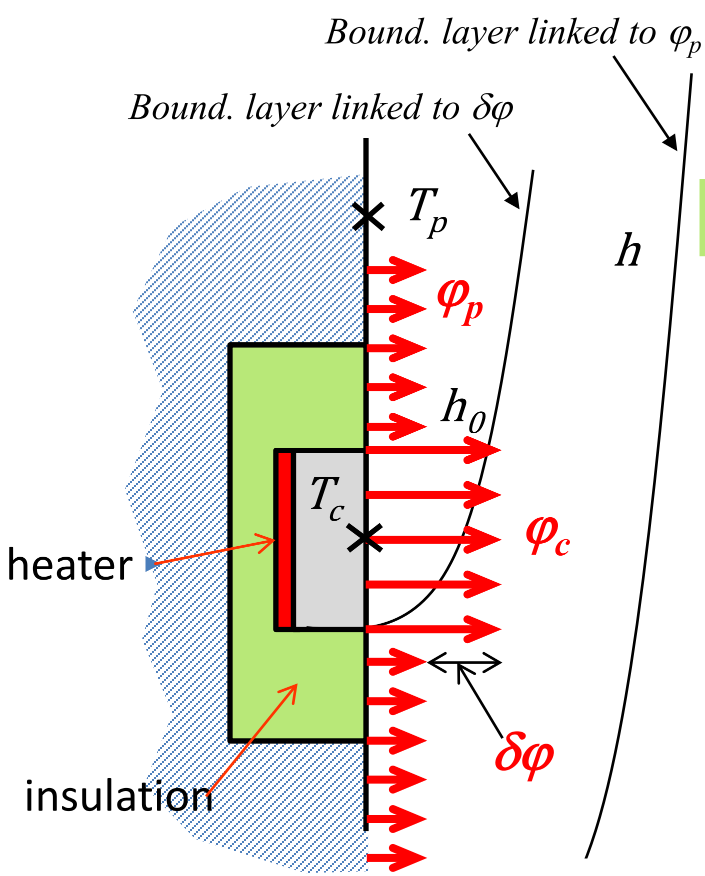
h_0

- Without insulation

$\varphi_c = \varphi_p + \delta\varphi$

$\delta\varphi = h_0\,(T_c - T_p)$

$\varphi_c = h\,(T_p - T_E) + h_0\,(T_c - T_p) + C\,dT_c/dt$



- With insulation

through sensor $\varphi_p \approx 0$ $\varphi_c \approx \delta\varphi$

If $\delta\varphi = 0$ (no sensor heating)

$0 \approx h\,(T_p - T_E) + h_0\,(T_{c0} - T_p) + C\,dT_{c0}/dt$

as $C\,dT_{c0}/dt \approx 0$:

$\boxed{\varphi_c = h\,(T_p - T_E) \approx h_0\,(T_p - T_{c0})}$

$\boxed{(h,\,T_E) \rightarrow (h_0,\,T_{c0})}$ Brunjail 1982

If $\delta\varphi = 0$; $T_E \approx T_{c0}$ sensor at T_{c0}

If $\delta\varphi \neq 0$

h_0 measurement ?

- Capacitive model (lumped system)

$$\theta = T_c(t) - T_{c0}(t)$$

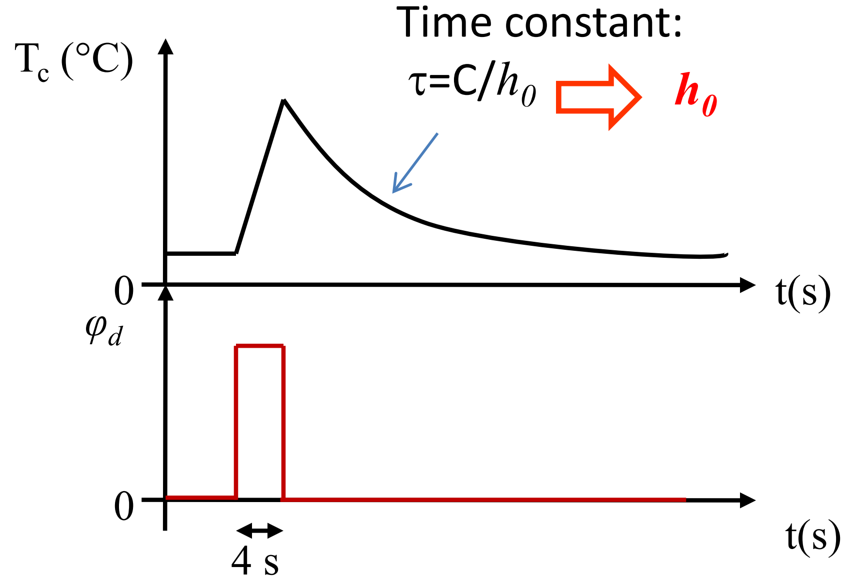
$$\delta\varphi = h\theta + C\frac{d\theta}{dt}$$

$$\theta = \frac{\varphi_0}{h_0}\left(1 - exp\left[-\frac{h_0}{C}t\right]\right)$$

$1/\tau$

Time constant:

$\tau = C/h_0 \Rightarrow h_0$



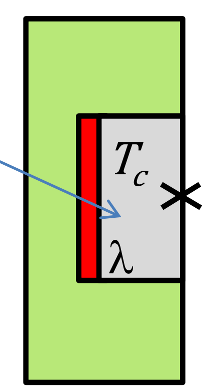
0.1 <Biot<0.3

- Conductive model : Instead of a lumped system, one can take into account heat transfer through the sensor (i.e. its substrate)

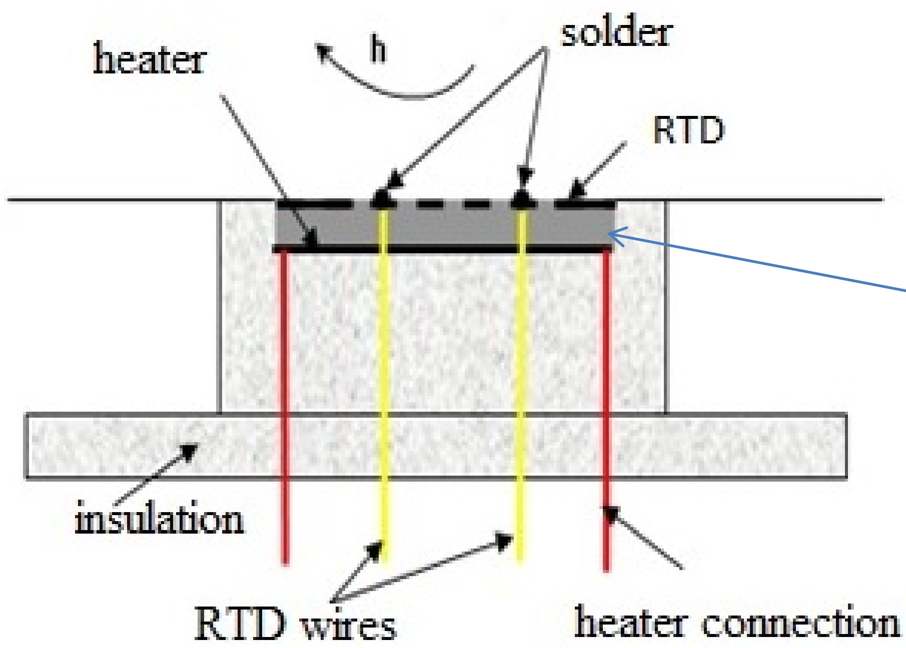
(λ : epoxy susbtrate thermal conductivity)

$$T_c(t) - T_{c0}(t) = \sum_{k=1}^{\infty} A_k\, cos(u_k) e^{-\frac{a u_k^2 t}{L^2}}\left(e^{-\frac{a u_k^2 t_0}{L^2}} - 1\right)$$

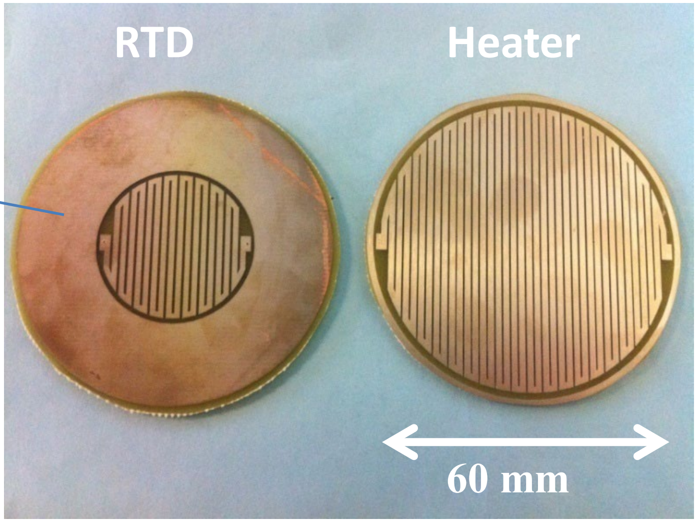
$$u_k \tan(u_k) = \frac{h_0 L}{\lambda} \Rightarrow h_0$$

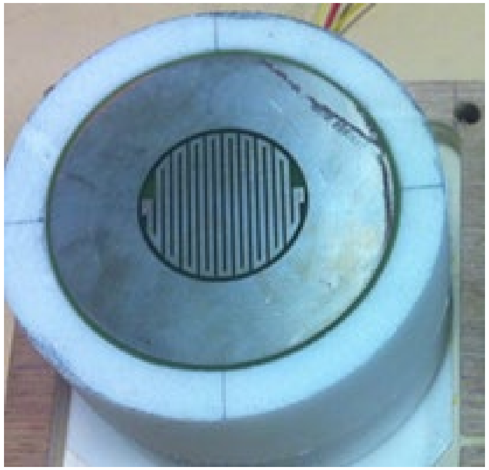


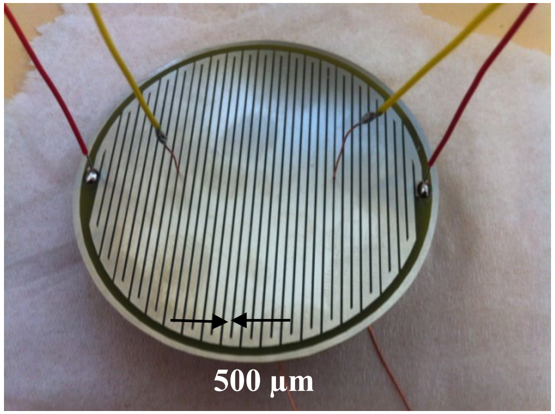
Realisation of the active heat flux sensor



Substrate FR4 (epoxy+ glass fiber)



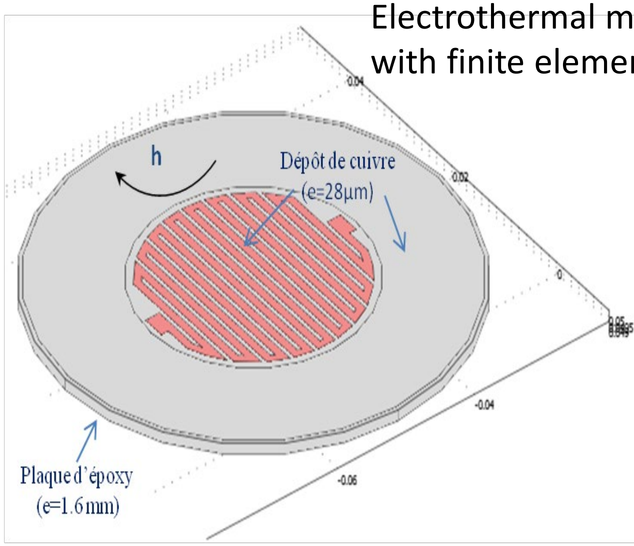


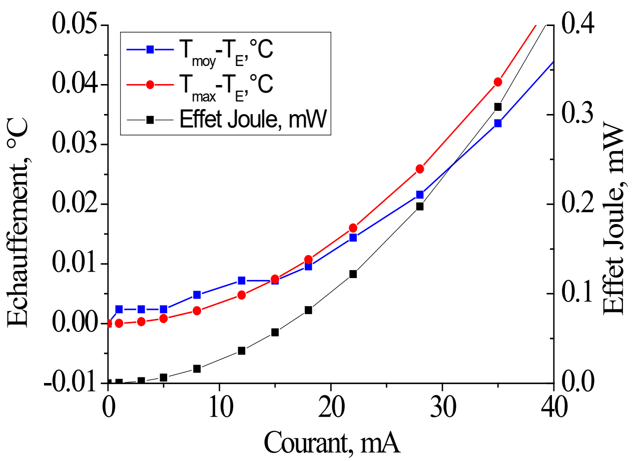


Realisation of the active heat flux sensor

- **RTD self heating (ΔT_{sf}) ?**

Electrothermal model with finite elements

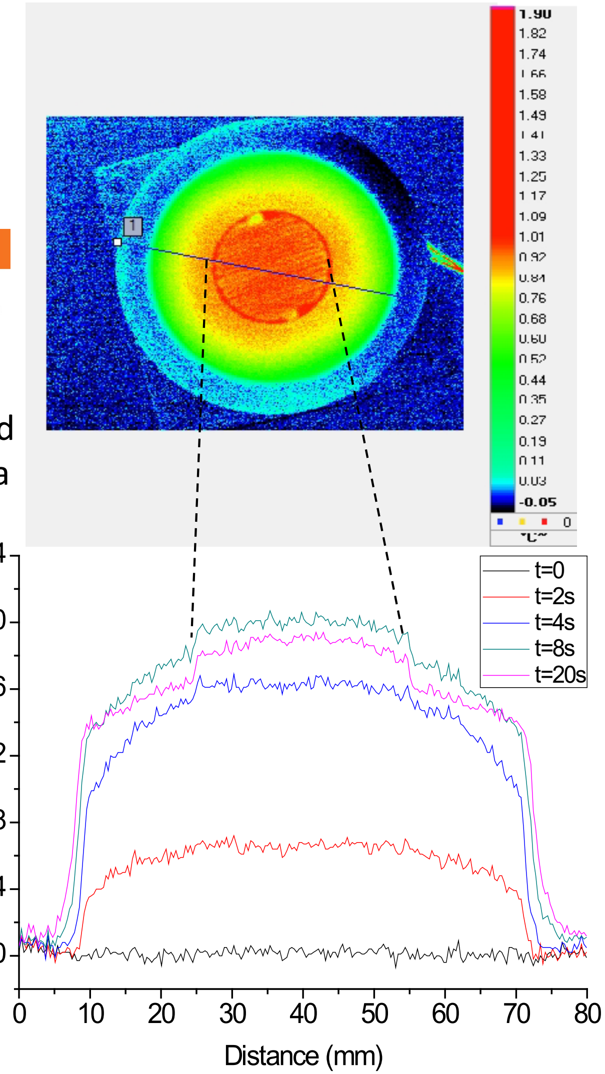




i = 30 mA → $\Delta T_{sf} \approx$ 0. 03 °C, $\Delta\phi \approx$ 0.2 mW

- **Sensor temperature uniformity (ΔT_u)**

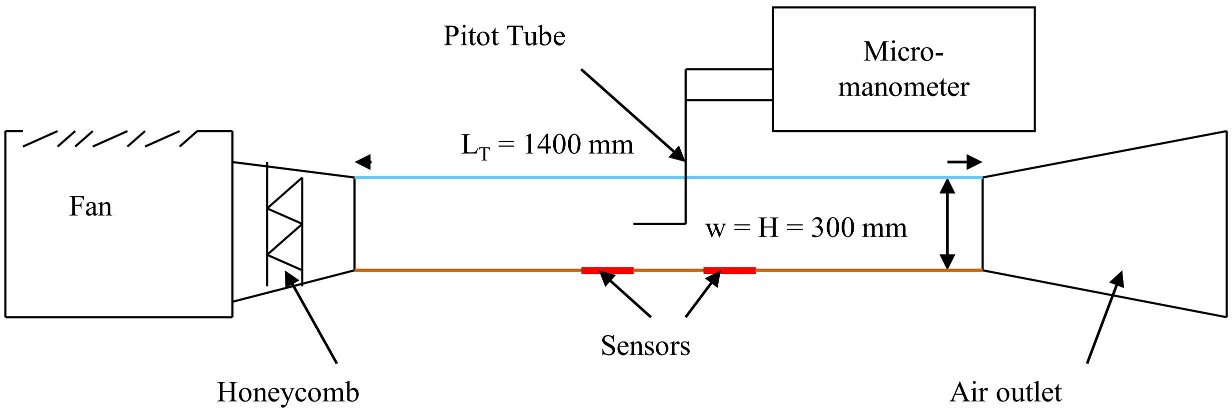
InSb Infrared Camera

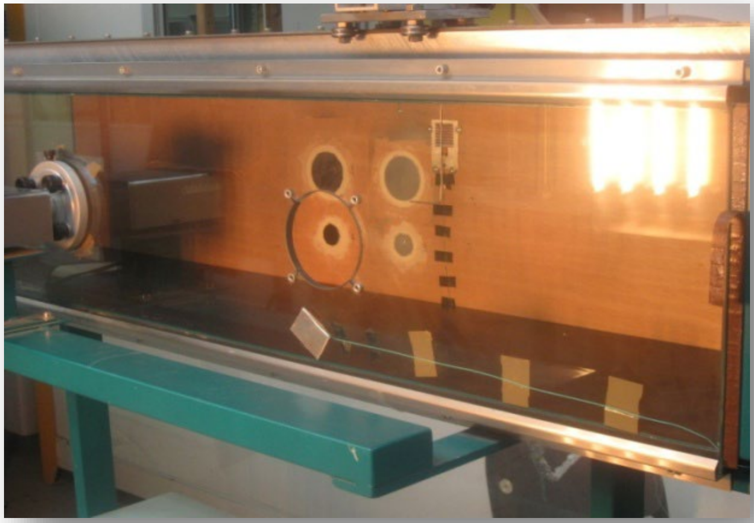


→ ΔT_u < 0. 2°C for ΔT=2 °C

Wind Tunnel setup and h_0 results

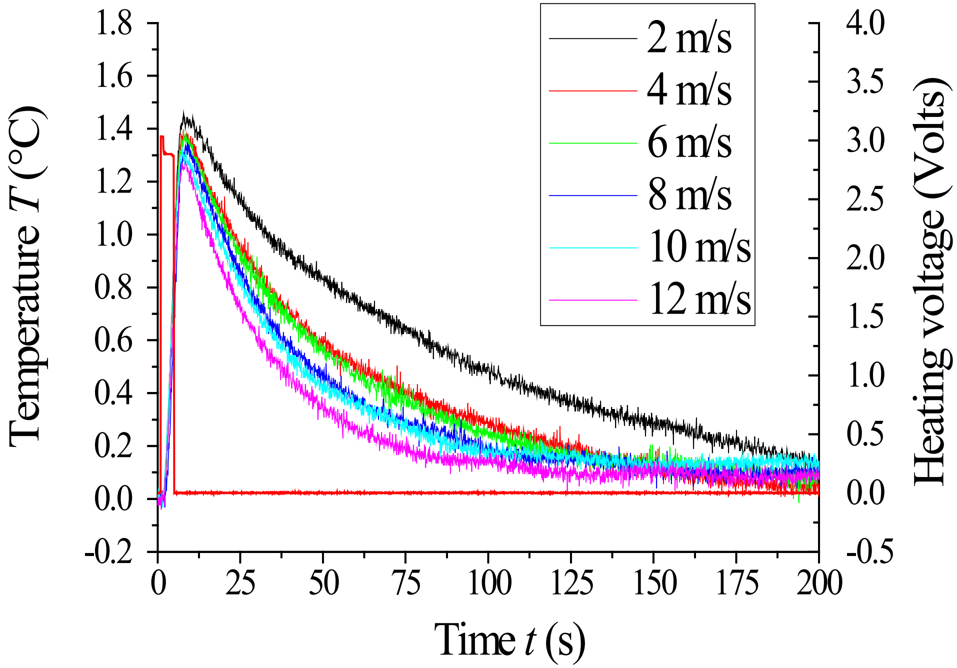
Air velocity from 0 to 12 m/s





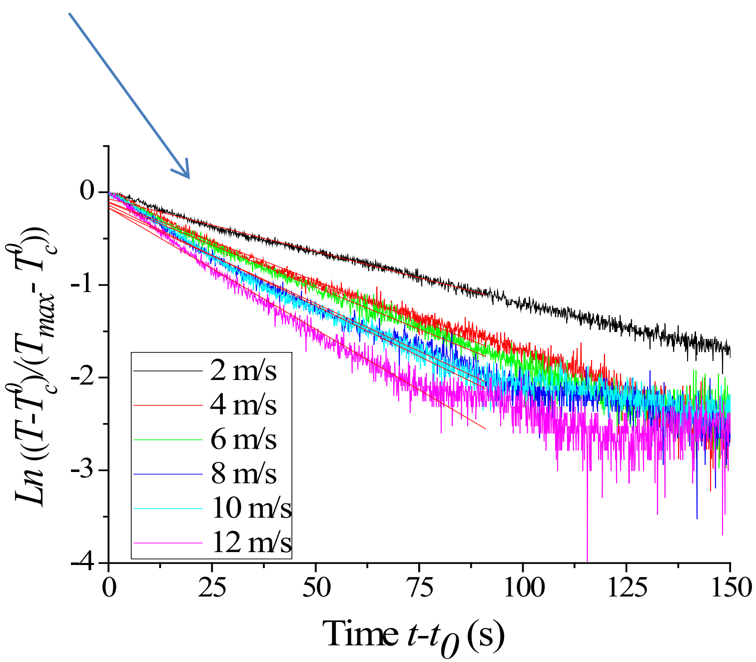
❑ Temperature vs. time

Laminar flow (Re < 5 10^{5})



T vs. t after a 4 s heat pulse

Slope→Time constant: $\tau = C/h_0 \rightarrow h_0$



$Ln((T_c - T_c^0)/ (T_{max} - T_c^0))$ .vs. $(t-t_0)$

Log-linear of the exponential cooling signal

❑ Local heat transfer coefficient values (h_0) :

Table 1: Experimental values of h_0 with the new dynamic heat flux sensor

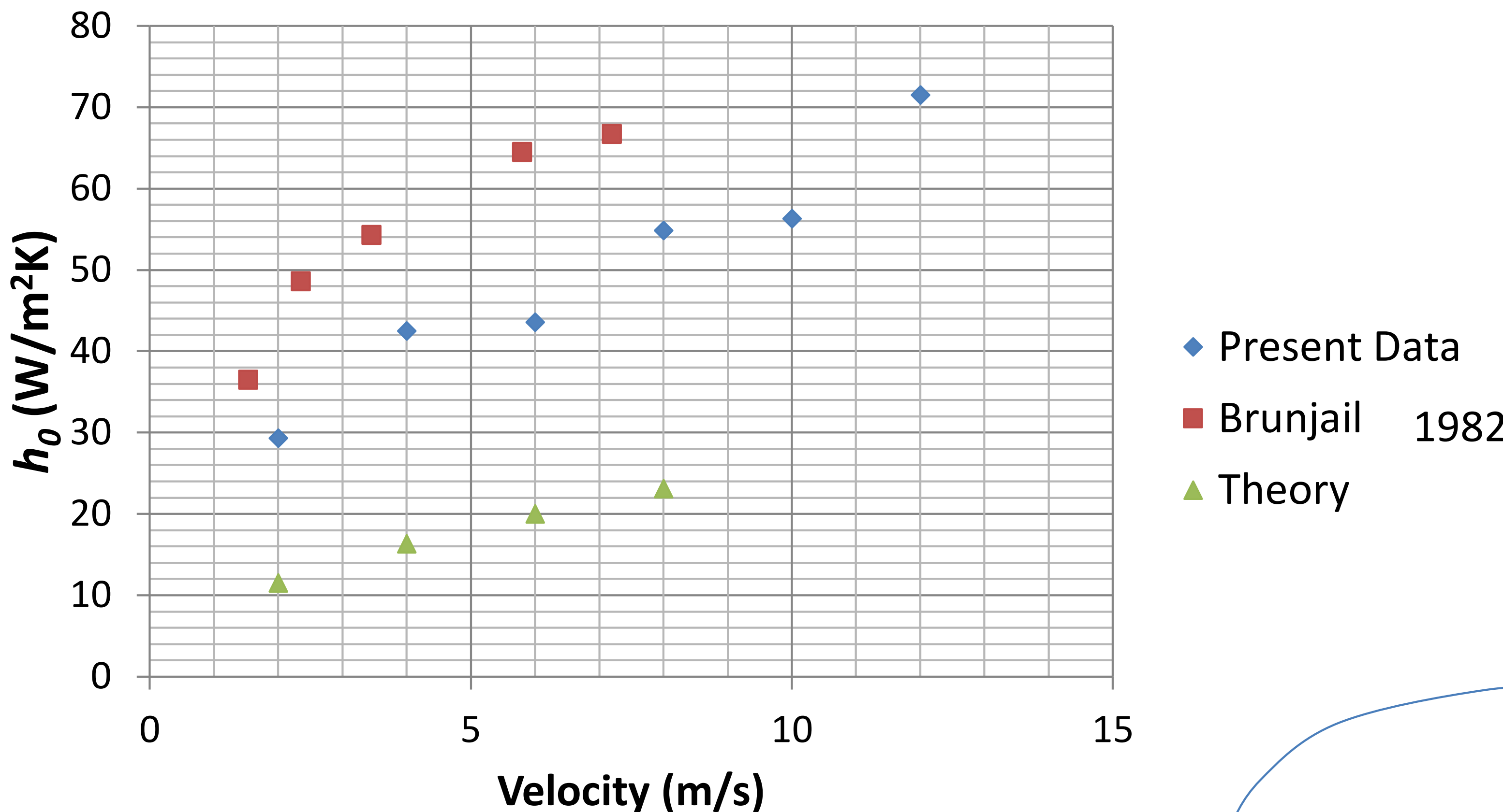
Air speed (m/s)	Time constant τ (s)	**Capacitive model** $h_0 = \frac{C}{\tau}$ (W/(m²K))	**Conductive model** $h_0 = u_1 \frac{\lambda}{L} \tan u_1$ (W/(m²K))
2	89.7	29.3 ± 1.1	30.2 ± 1.7
4	61.8	42.5 ± 1.7	44.5 ± 2.4
6	60.3	43.6 ± 1.4	45.7 ± 2.3
8	48.0	54.8 ± 1.9	58.3 ± 3.0
10	46.7	56.3 ± 2.6	60.0 ± 3.5
12	36.5	71.5 ± 2.2	78.4 ± 3.7

$C = 2630$ J/(m²K).

3.3 < Discrepancy (%) < 8.8

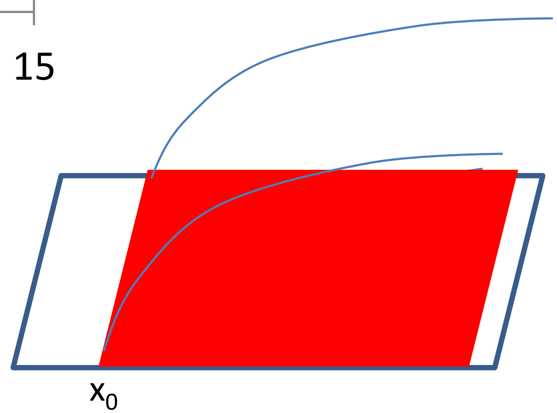
→the capacitive model (lumped system) is not so bad…

❑ Comparison of local heat transfer coefficient values (h_0) :



Theory [Kaviany 2002] :

$$Nu = \frac{h.x}{\lambda} = 0.332 Pr^{1/3}.Re^{1/2}\left[1-\left(\frac{x_0}{x}\right)^{3/4}\right]^{-1/3}$$



valid for a flat plate with a prescribed temperature and a heating starting at x_0 [Kaviany 2002].

Conclusions

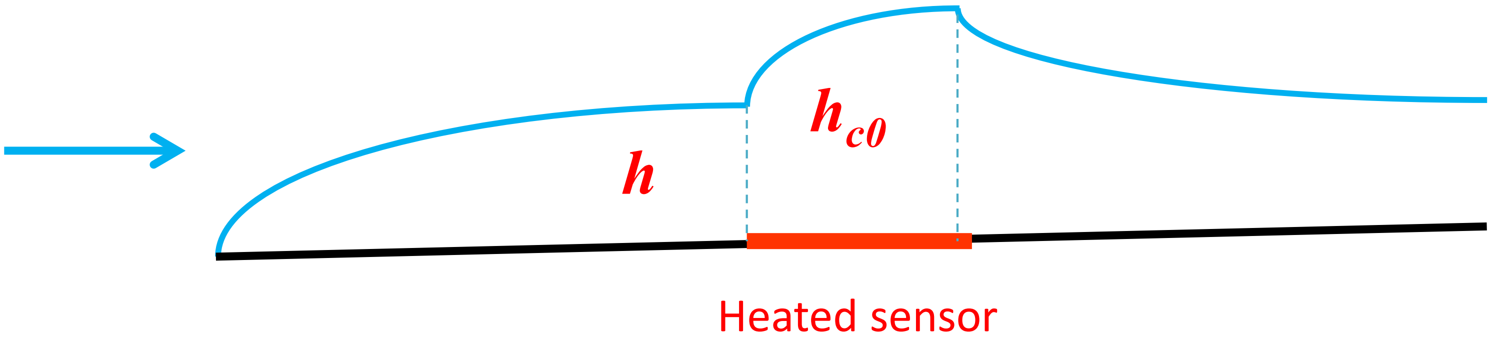
✓ New design of an active thermal sensor using thick film→ heat capacity of the sensor 20% less than previous one (Brunjail 1982)

✓ Here application for building thermal management but could be used in many others industrial situations

✓ *On going work :*

- CFD simulation to take into account the real shape of the sensor
- Calibration to get the overall heat transfer coefficient ***h*** from h_{c0} measurement →Implementation of a heated wall in the wind tunnel

- Why a calibration to get the overall heat transfer coefficient ***h*** from ***h_{c0}*** measurement ?



Acccording to Brunjail 1982: $h= a\ h_{c0}+b$

→ **Future work:** use of a wind tunnel with a heated wall