Data Reduction and Thermal Product Determination or Single and Two-layered Substrate Thin-film Gauge

N. BILLIARD, V. ILIOPOULOU, F. FERRARA, R. DENOS
Von Karman Institute for Fluid Dynamics
Turbomachinery & Propulsion Department

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2. Analytical solution
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5. Example of measurement
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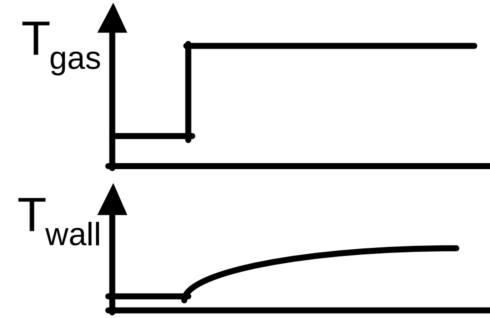
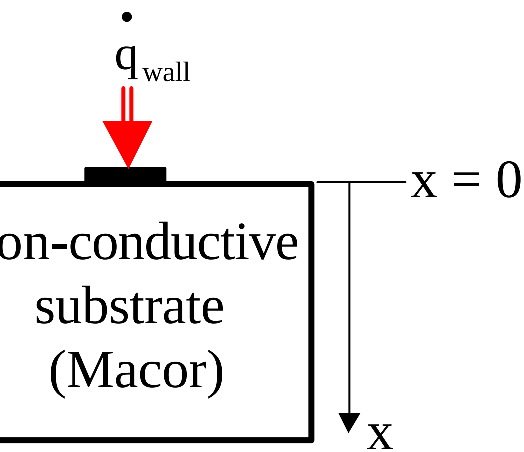
Thin film gauge operating principle

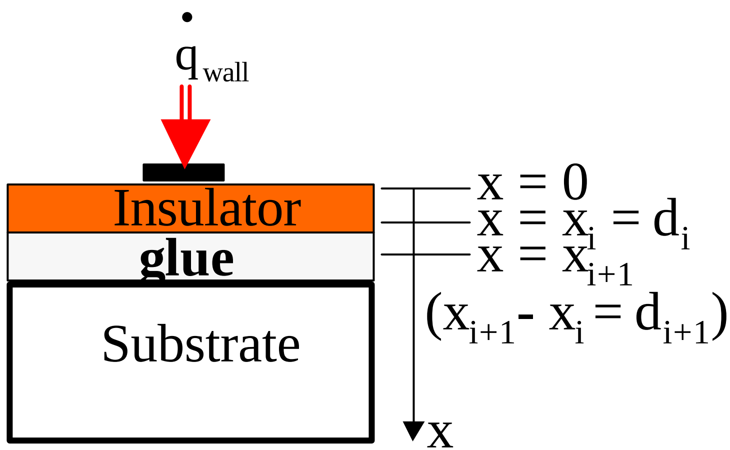


Heat transfer coefficient $h = \frac{\dot{q}_{wall}(t)}{\left(T_{gas} - T_{wall}(t)\right)}$

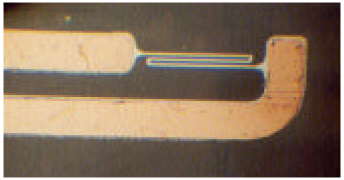
Unsteady conduction $\frac{\partial^2 T_i(x,t)}{\partial x^2} = \frac{1}{a_i}\frac{\partial T_i(x,t)}{\partial t}$ with $a_i = \frac{k_i}{?_i\ C_i}$



Single-layer



Two-layer



- 1D conduction
- Semi-infinite subs

- Heat flux at the w

$$\dot{q}_{wall}(t) = -k_1\left(\frac{\partial T_1}{\partial x}\right)_{x =}$$

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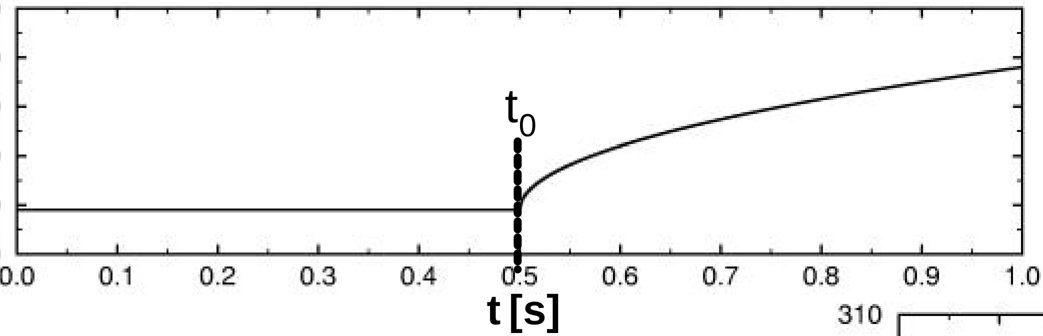
Analytical solution

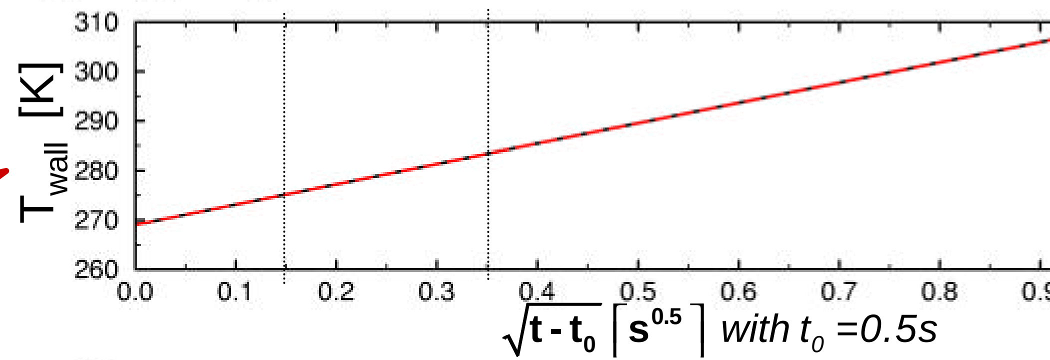
2.1 Single-layer thin-film gauge

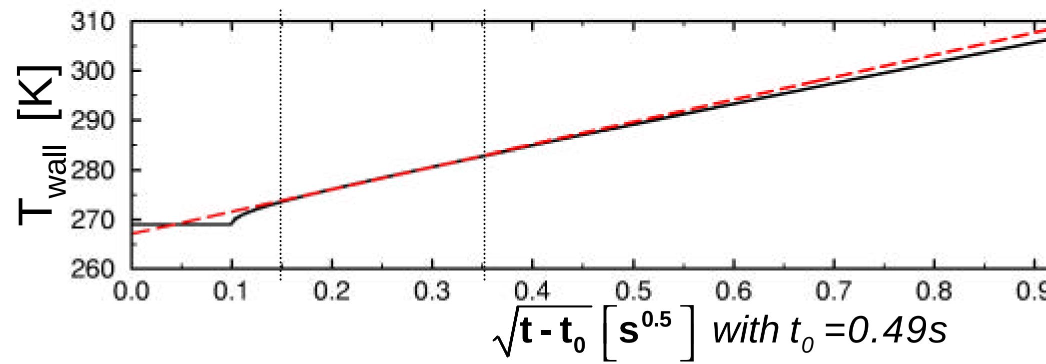


• Linear law in $\sqrt{t}$

$$T_{wall}(t) - T_0 = \frac{2}{\sqrt{p}} \frac{\dot{q}_{wall}}{\sqrt{? C k}} \sqrt{t}$$

Error induced by t_0



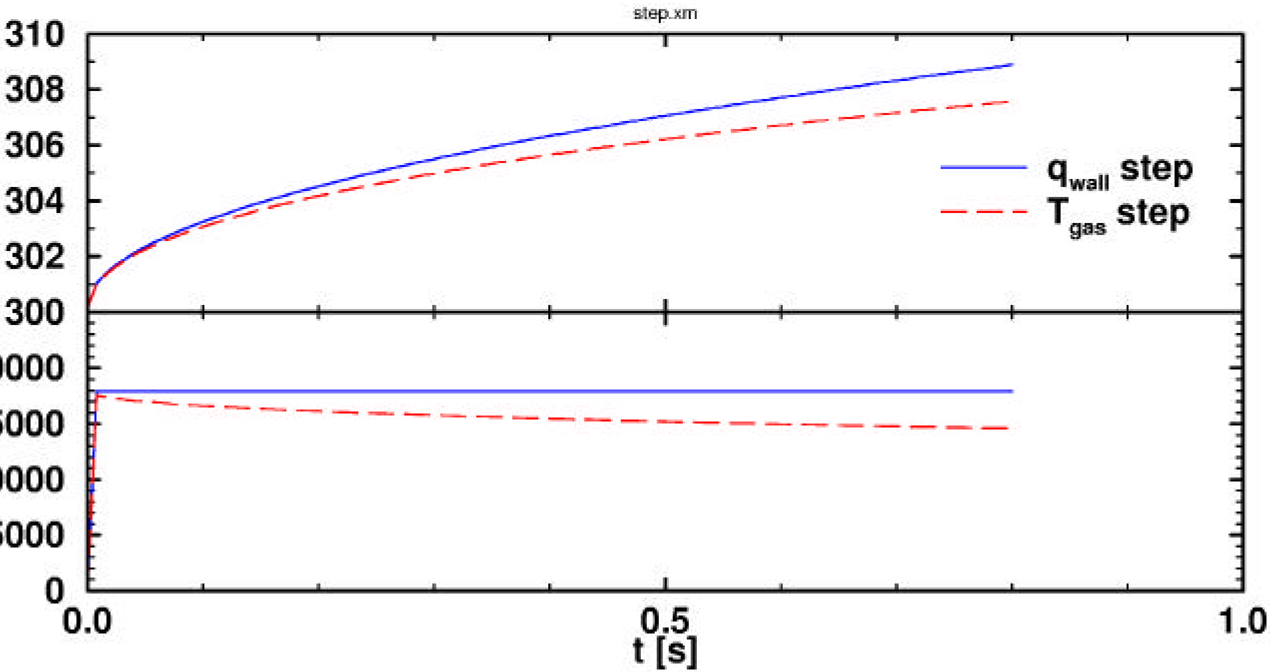


01s of error in t_0

›10% error on heat flux

$(\dot{q}_{wall} = 75250 \text{ W/m}^2)$

1 Single-layer thin-film gauge



as step

lution

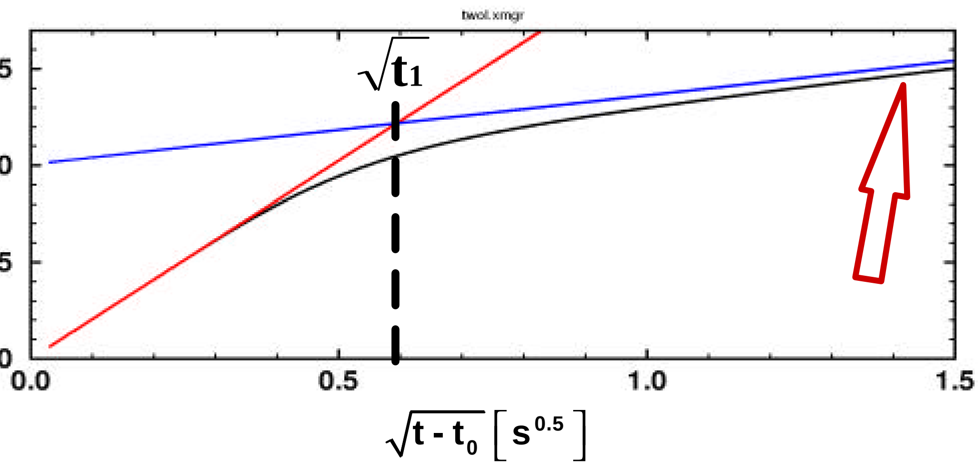
$$\frac{T_{wall}(t) - T_{wall}(t=0)}{T_{gas} - T_{wall}(t=0)} = 1 - e^{(ß^2)}\,\mathrm{erfc}(ß)$$

Depends only

$$ß = \frac{h\sqrt{t}}{\sqrt{?\,C\,k}}$$

Two-layer thin-film gauge

$$T_{wall}(t) = \frac{2\ \dot{q}_{wall}}{\sqrt{p}\ \sqrt{?_2\ C_2\ k_2}}\ \sqrt{t} + \dot{q}_{wall}\ \frac{d_1}{k_1}\left[1 - \frac{?_1\ C_1\ k_1}{?_2\ C_2\ k_2}\right]$$



- slopes ⇒ thermal propertie
- "switch point" ⇒ thickness

△ Error induced by finite temperature evolution

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Numerical solution

Unsteady conduction equation solved thanks to finite difference Crank-Nicholson scheme :

$$\frac{\partial T(x,t)}{\partial t} = a \frac{\partial^2 T(x,t)}{\partial x^2}$$

$$\frac{T_j^{m+1} - T_j^m}{?\,t} = a\left[\frac{?\left(T_{j-1}^{m+1} - 2\,T_j^{m+1} + T_{j+1}^{m+1}\right)}{?\,x^{2}} + \frac{(1-?)\left(T_{j-1}^{m} - 2\,T_j^{m} + T_{j+1}^{m}\right)}{?\,x^{2}}\right]$$

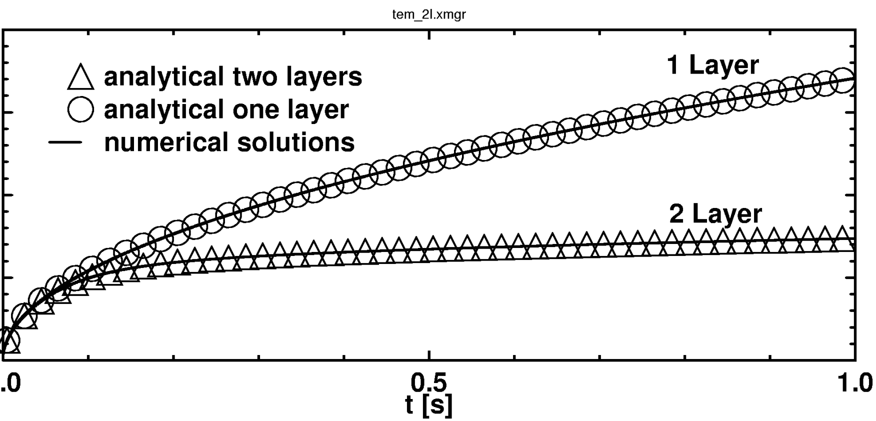
If **?>0.5**, the scheme is unconditionally stable

⇒ space step and time step are independent.

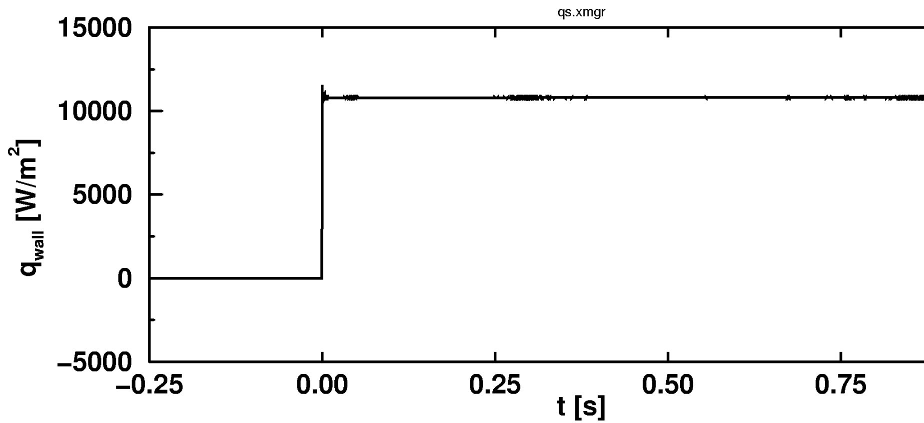
Numerical solution

Validation

surface temperature $T_{wall}(t)$



surface heat flux $q_{wall}(t)$



♣ Very flexible, no constraint

ACCURATE $\dot{q}_{wall}$

Û

ACCURATE $\sqrt{?_1\ C_1\ k_1}$ **,** d_1 **and** $\sqrt{?_2\ C_2\ k_2}$ **(needed)**

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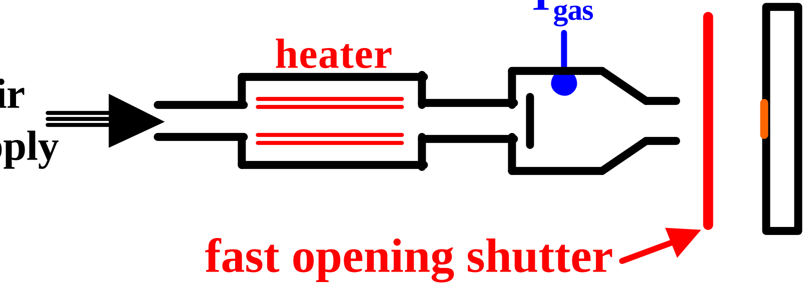
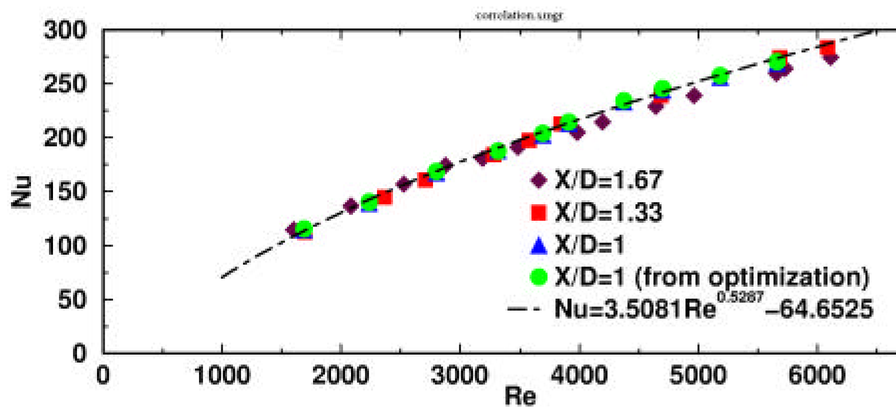
Thermal properties determination

4.1 Heat flux source characterization using a reference gaug

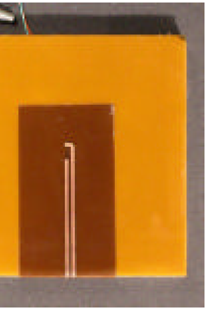


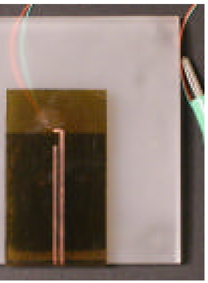


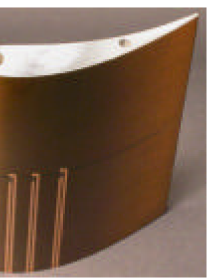
- Various P_{gas} and T_{gas}

Þ correlation **$Nu = 3.5081\ Re^{0.5287} - 64.6525$**

2 Calibration using analytical solution

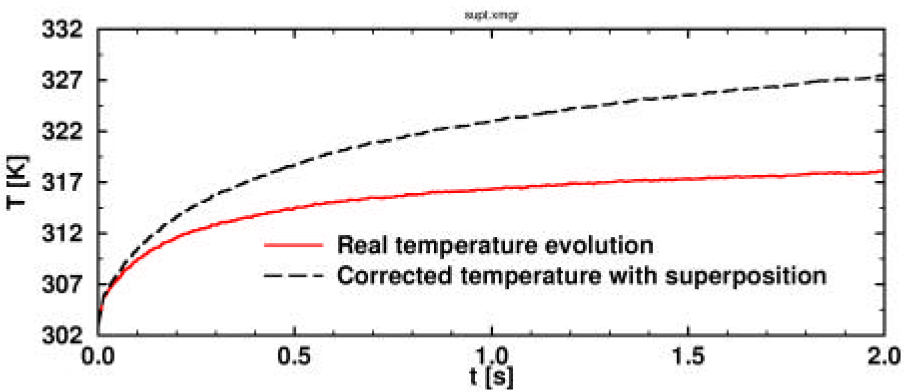


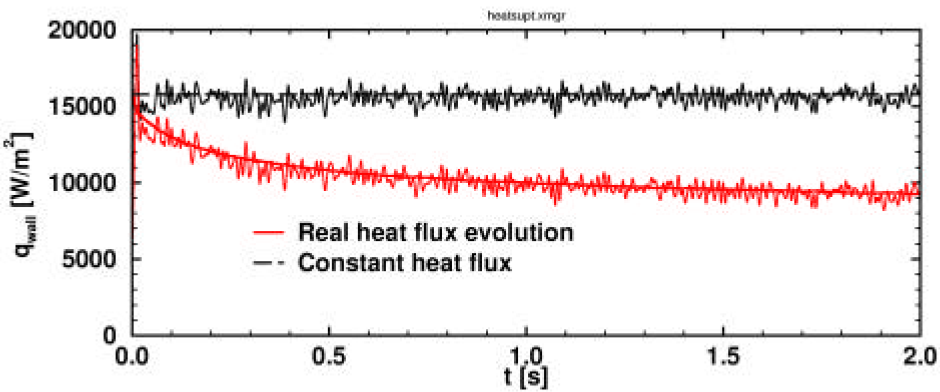




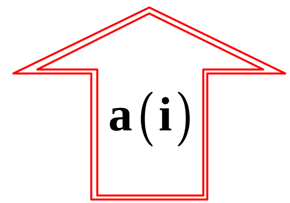
△ Analytical solution valid for constant heat flux

Conditioning temperature evolution with superposition technique





$$T_{wall\,2}(n) = \sum_{i=0}^{n} \left(a(i)\, T_{wall\,1}(n - \ldots \right.$$



$$\dot{q}_{wall\,2}(n) = \sum_{i=0}^{n} \left(a(i)\, \dot{q}_{wall\,1}(n - i \ldots \right.$$

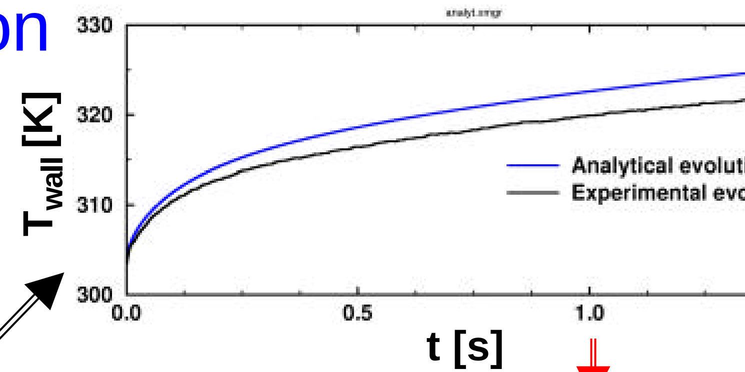
2 Calibration using analytical solution

$\dot{q}_{wall}$ **from** **Nu = 3.5081 Re$^{0.5287}$ – 64.6525**

Two-layer analytical solution

$$T_{wall}(t) = \frac{2\,\dot{q}_{wall}}{\sqrt{p}\,\sqrt{?_2\,C_2\,k_2}}\sqrt{t} + \dot{q}_{wall}\,\frac{d_1}{k_1}\left[1 - \frac{?_1\,C_1\,k_1}{?_2\,C_2\,k_2}\right]$$

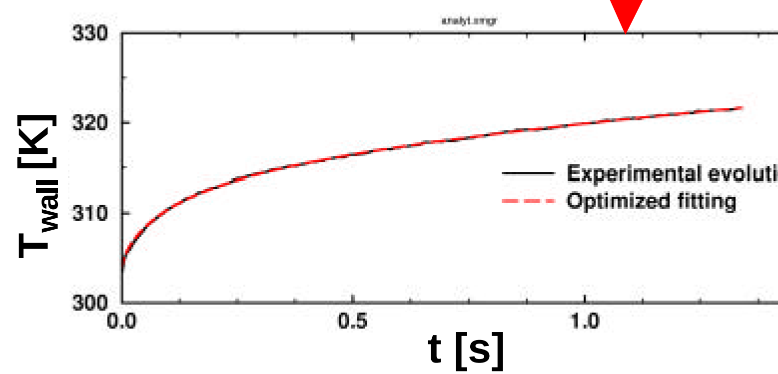
First guess
$\sqrt{?_i\ C_i\ k_i}$, d_i



$$\sum\left(T_{reconstruted} - T_{experiment}\right)$$

Optimization routine

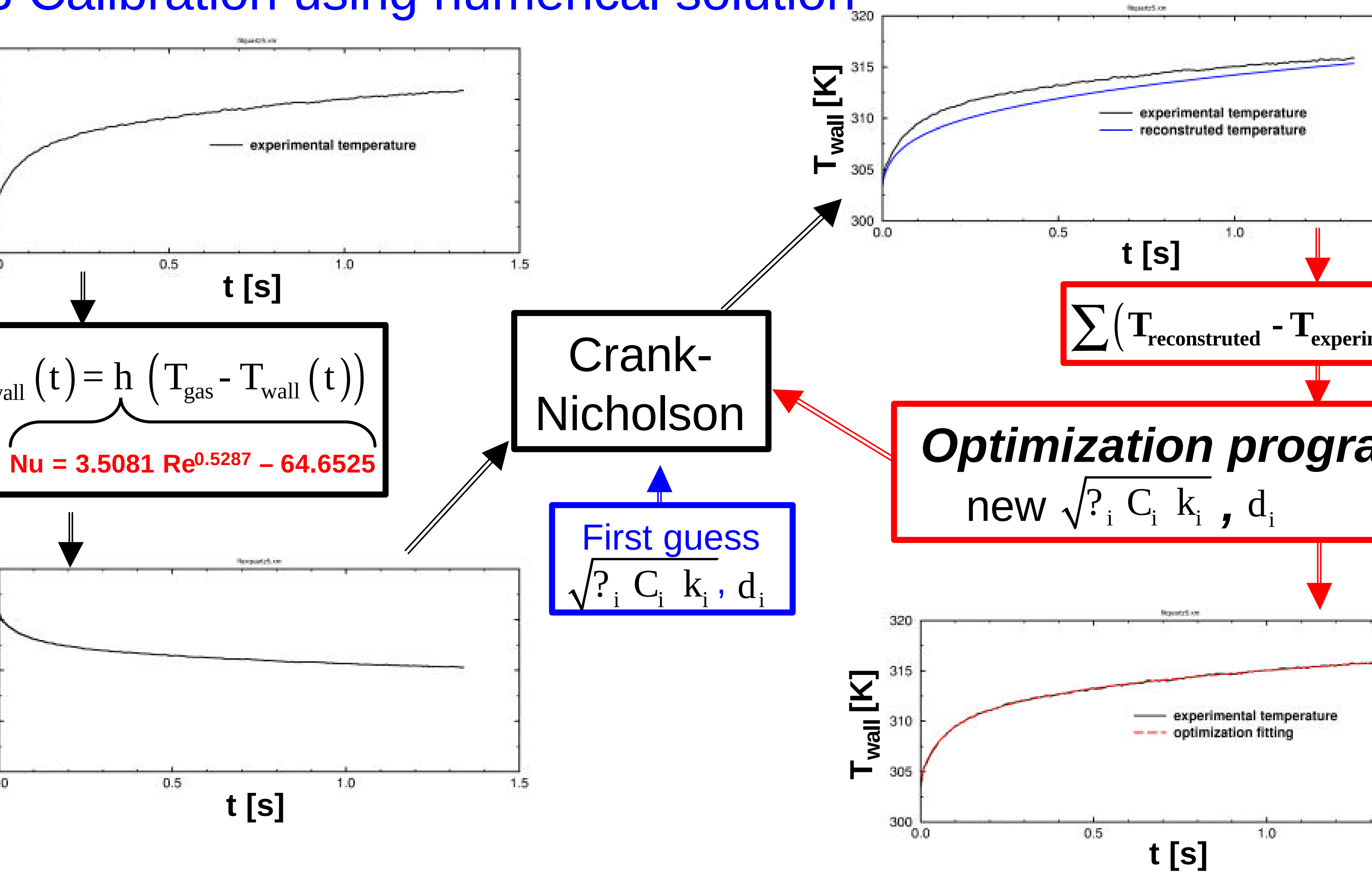
new $\sqrt{?_i\ C_i\ k_i}$ **,** d_i



2 Calibration using analytical solution

	$\sqrt{? C k}$ Upilex [J/m^{2}Ks$^{0.5}$]	Upilex Thickness [µm]	$\sqrt{? C k}$ 2nd layer [J/m^{2}Ks$^{0.5}$]
on Macor (8 tests)	747	310	2255
Dispersion (20:1)	2.1%	15.1%	6.1%
Standard value	692	250 (350)	1780
on quartz (9 tests)	787	168	1763
Dispersion (20:1)	3.7%	5.2%	5.1%
Standard value	692	125 (150)	1521
on steel (5 tests)	732	177	10570
Dispersion (20:1)	13.4%	10.2%	20.6%
Standard value	692	125 (150)	8088

3 Calibration using numerical solution



3 Calibration using numerical solution

	$\sqrt{? C k}$ Upilex [J/m^{2}Ks$^{0.5}$]	Upilex Thickness [µm]	$\sqrt{? C k}$ 2nd layer [J/m^{2}Ks$^{0.5}$]
on Macor (8 tests)	731	305	2117
Dispersion (20:1)	2.3%	3.9%	5.9%
Standard value	692	250 (350)	1780
on quartz (9 tests)	752	167	1726
Dispersion (20:1)	3.9%	3.9%	4.9%
Standard value	692	125 (150)	1521
on steel (5 tests)	699	175	8147
Dispersion (20:1)	8.8%	8.7%	9%
Standard value	692	125 (150)	8088

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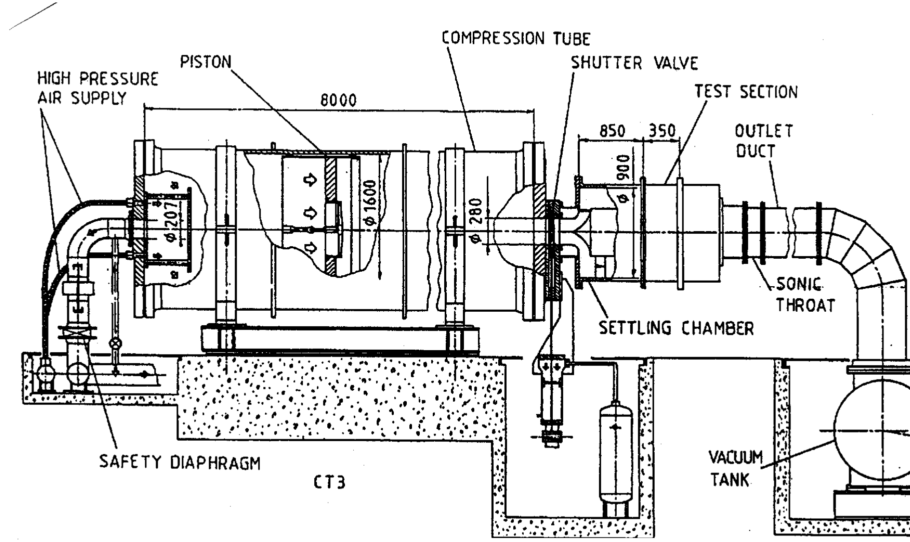
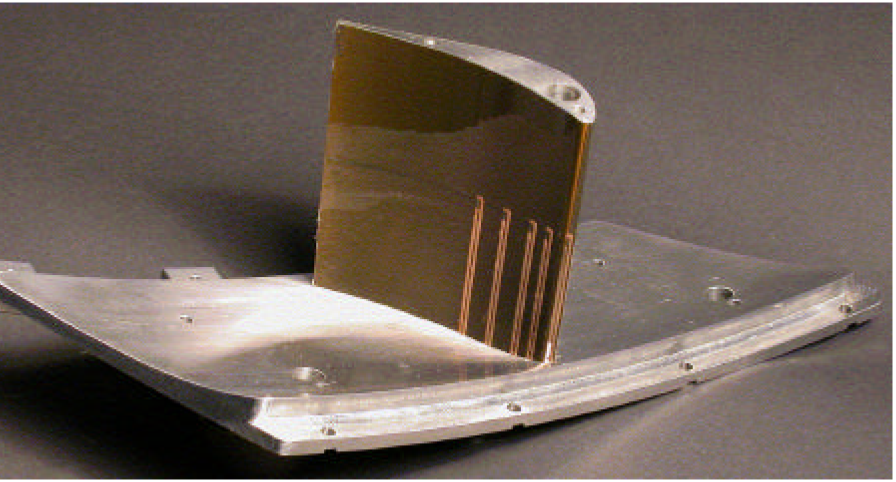
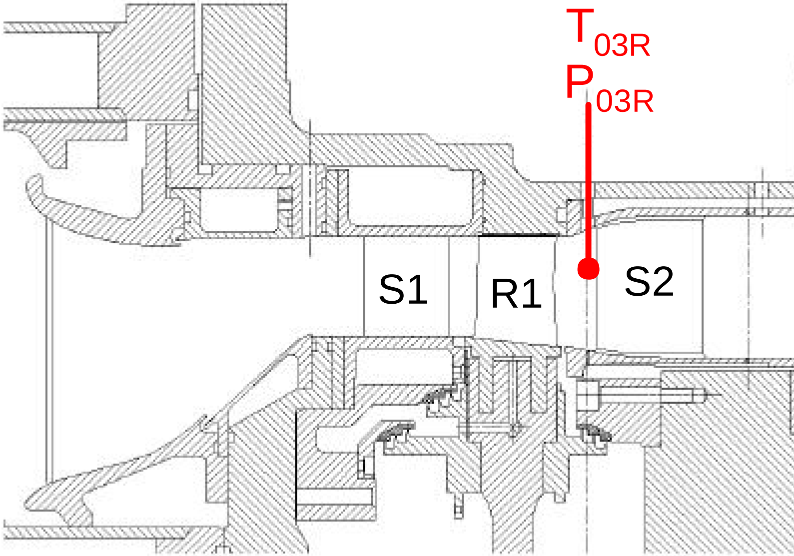
Example of measurement

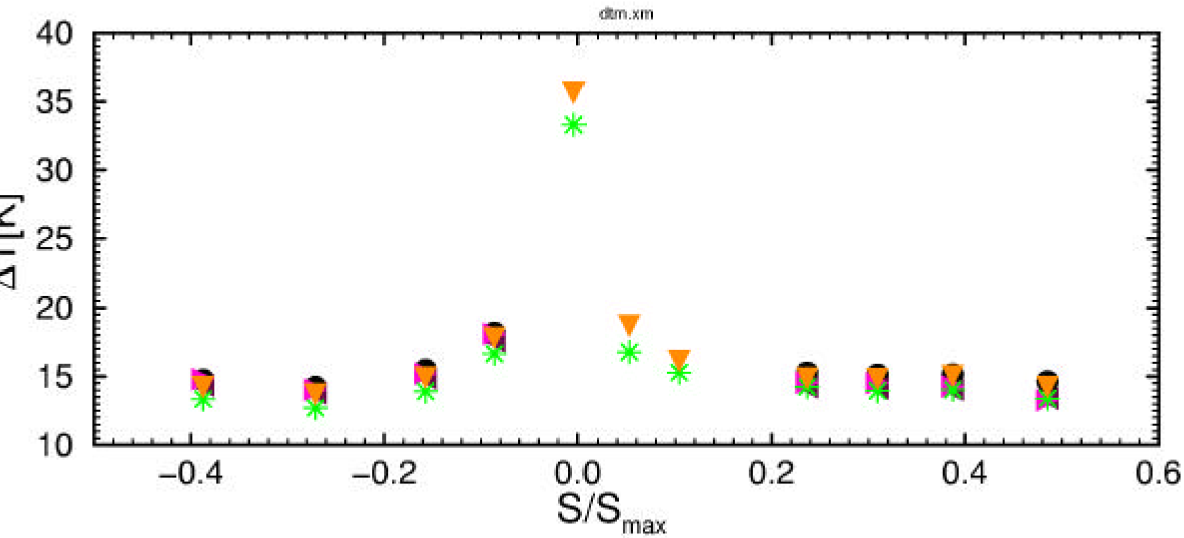
- Blowdown wind tunnel, 1.5 transonic stage
- Design rotational speed: 6500 RPM

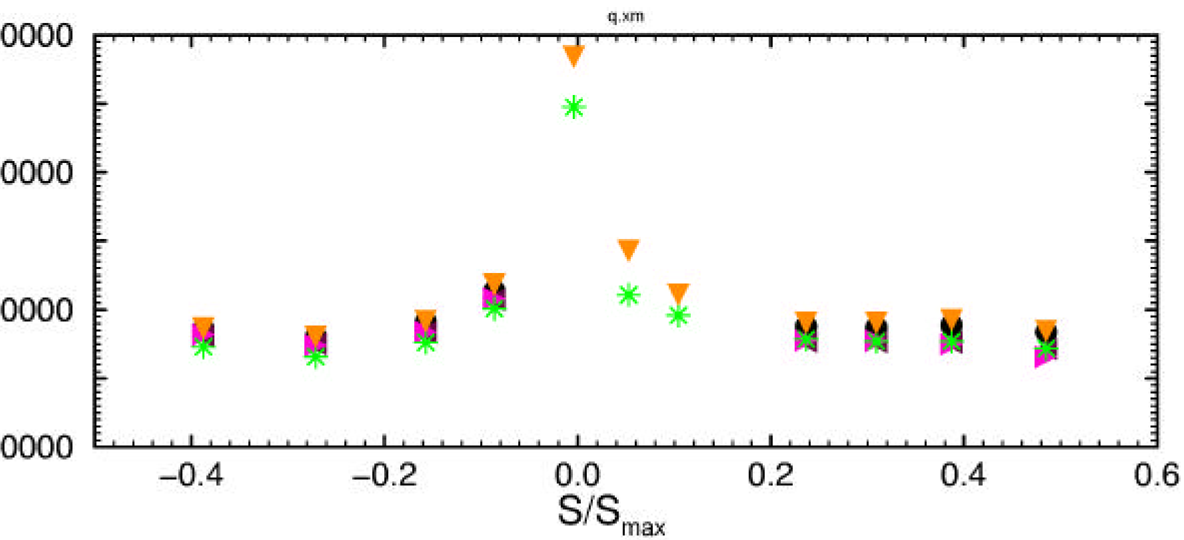






1 Time-averaged results

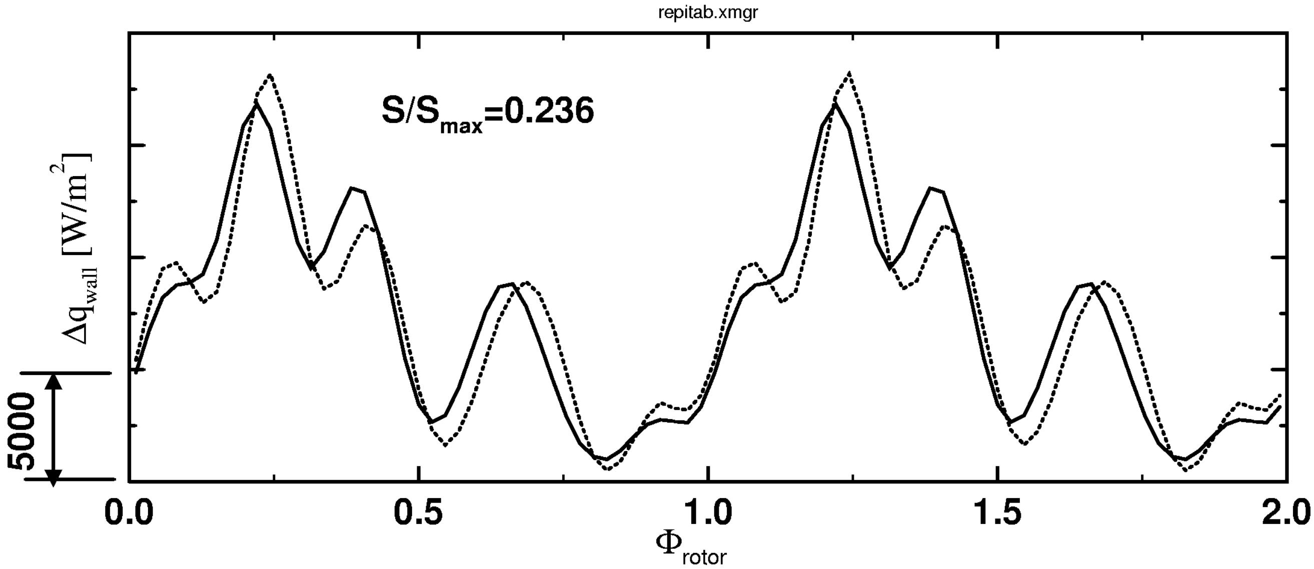




- Averaging around design rotational spee

- Computed with Cran Nicholson scheme

2 Time-resolved results



- Phase-locked average on 3 rotor revolutions

Conclusions

Flexible heat flux computation with Crank-Nicholson scheme

Calibration of two-layer gauges:
1st method fits analytical solutions instead of linearizing
2nd method uses Crank-Nicholson scheme
nd can be applied without restriction

Measurement on CT3:
uccessful use of the gauge
leat flux with Crank-Nicholson scheme

. Perspectives

Measurement on CT3:
omparison with ceramic inserts
⇒ validation of two-layer thin-film gauge