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Surface Thermometry in the Industry: A Calibration Method



1

Index

- Introduction: Context and Motivation
- Theoretical Justification
- Development / Description
- Results Analysis
- Conclusions

Introduction

Industry Demand


1. Automotive Industry:  
 Painting and Drying Process :  $130^{\circ}\text{C} < T < 180^{\circ}\text{C}$ .  
 Tol  $\sim \pm 5^{\circ}\text{C}$
2. Aeronautical:  
 Painting and Drying Process :  $60^{\circ}\text{C} < T < 80^{\circ}\text{C}$ .  
 Tol  $\sim \pm 10^{\circ}\text{C}$  (enclosure)



Introduction

Variety of Sensors

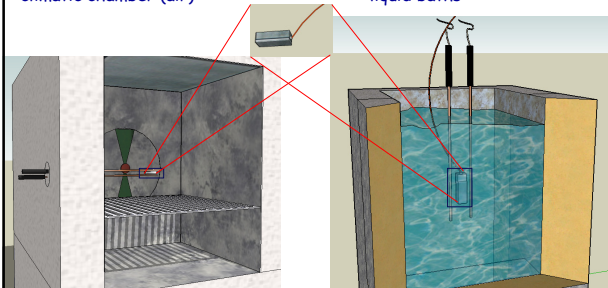
Variety of Surface Temperature sensors in the market



Introduction

"Traditional" possibilities

Comparative Calibration in climatic chamber (air)      Comparison Calibration in liquid baths




Introduction

Suitability

Are these methods completely suitable for our purposes?

- Privileged Heat Transfer Directions?
- Thermal Contact Effects?
- Natural Convection vs Forced Convection?
- Material Effects?
- Logistic Difficulties within traditional methods (Liquids)



## Introduction

### Method's Description

Measurement Process' Simulation: Material piece conditioning by forced convection in Furnace (chamber) and measurement on surface.

Material Piece + Surface  
Reference Sensors  
Thermal Diffuser  
Calibrating Sensors

## Introduction

### Pictures

Global viewpoint of the system with surface sensors

## Theoretical Basis

### Base Hypothesis and Mathematical relations

As in Isothermal enclosures, the key concept lies in the thermal equilibrium

Sensores con carcasa  
Sensores pasivos  
Bloque de Aluminio

Fundamental Heat Flows.  
 $\Omega =$  Considered System.  
 $\partial\Omega =$  System's Boundary

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c_p} \nabla^2 T \quad \text{in } \Omega$$

$$-\lambda_{mat} \nabla T = h \cdot (T - T_{\infty}) \cdot \vec{n} \quad \text{in } \partial\Omega$$

Perturbations ( $T - T_{\infty}$ ) against the boundary equilibrium propagates towards the inside:

$$|\delta T|_{mat} = \frac{h}{\lambda_{mat}} |\delta T|_{air} \cdot \Delta L_{mat}$$

## Theoretical Basis

### Previous Calculations

The value of the convective heat exchange "h" is defined by the geometry of the system and the flow conditions

Pohlhausen's relation:

$$h \cdot L / \lambda_{air} = Nu = 0,664 \cdot Re^{1/2} \cdot Pr^{1/3}$$

$Re < 2 \cdot 10^5$  and  $0,6 < Pr < 1,0$

## Theoretical Basis

### Calculations I

From the data tables of materials, we can do the calculations within the range -50 to 150 °C, applying the perturbation technique described before.

Perturbations ( $\delta T \sim T - T_{\infty}$ ) to apply

Nominal T (°C)	Max. Instability (°C)	Max. Inhomogeneity (°C)
-50	0,10	0,84
1	0,03	0,52
20	0,06	0,26
70	0,10	1,0
100	0,10	1,9
150	0,26	3,0

Material Properties & flow

$\rho$  (Al) (kg/m<sup>3</sup>) 2700  
 $c_p$  (Al) (J/kg·K) 900  
 $\lambda$  (Al) (W/m·K) 210  
 $v$  air (m/s) 5,5  
 $Pr$  air (-50 a 150°C) 0,735 to 0,701  
 $Re$  air(-50 a 150°C) 59500 to 19200  
 $Nu$  air(-50 a 150 °C) 146,1 to 81,8

$$|\delta T|_{mat} = \frac{h}{\lambda_{mat}} |\delta T|_{air} \cdot \Delta L_{mat}$$

Chamber characterization results in the whole volume.

## Theoretical Basis

### Calculations II

For the most pessimistic case  $\delta T_{max} = 3^\circ C$ :

$$|\delta T|_{mat} = \frac{h}{\lambda_{mat}} |\delta T|_{air} \cdot \Delta L_{mat}$$

$h \approx 30 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$      $h/\lambda \approx 0,14 \text{ m}^{-1}$      $h \cdot \delta T_{max} / \lambda \approx 0,32 \text{ K} \cdot \text{m}^{-1}$   
 $\Delta L \sim 10 \text{ cm of material}$      $\Rightarrow$      $\delta T_{mat} \approx 0,032 \text{ K}$

**Oversaw:** Thermal Perturbations in the air decay when they soak in a material with high density and high thermal conductivity because the transference is done in terms of **Energy** rather than directly in **Temperature**. This makes the system able to get differences in that order of magnitude inside the material.

$\delta T_{mat} \approx 0,032 \text{ K}$  ✓

### Development

**Strategy: Measurements and Validation**

Calibrate 5 sensors PRT100 (class A UNE 60751) + multimeter (6½+multiplexer) by two methods and compare results

### Development

**Measurements**

- Calibrations were done by comparison, in the nominal temperatures: -50, -20, 0, 20, 50, 100, 150 °C, by both methods: Immersive in Liquid bath & "Surface".
- At each temperature, 10 lectures were done during 10 minutes, once the system was stabilized.
- The result of the calibration is a table containing correction (or error) values of the thermometer at each temperature.
- The Reproducibility was evaluated by immersive method at 0°C and in surface method at 20°C.
- In the surface method, it was measured the external gradient against the air temperature.

### Development

**Uncertainty: Budget**

Calibration uncertainty is calculated for each nominal temperature value. Budget:

### Development

**Uncertainty: "ad hoc" Components**

Self heating of the sensors.

Thermal Gradient ( $\nabla T$ ), measured at 5 cm from the sensors

Nominal T <sup>a</sup> (°C)	-50	-20	0	20	50	100	150
$\Delta T$ (°C)	-0.13	-0.07	0.06	-0.06	0.03	0.31	0.74

Pondering of the gradient as a function of distance:  $\Delta T/d = 1/5$

### Development

**Uncertainty: Gradient**

○ This component has a big weight. We must ask about it's probability distribution

### Development

**Uncertainty: MMC for Surface**

Given these strange behaviour, the combined uncertainty must be evaluated following: **GUM & GUM.S1 (MMC)**.

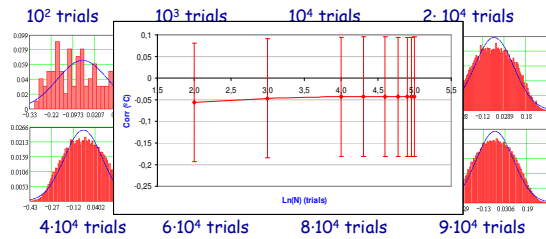
Gradient distributed Uniformly      Gradient distributed in U-shape (Arcsin)

\* N = 10<sup>5</sup> Trials

## Development

### Uncertainty: MMC Convergence

Series' convergence, from  $10^2$  to  $10^5$  "trials":



Gradient as U- distribution (Arcsin)

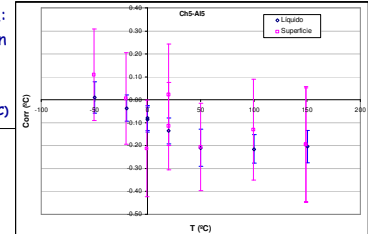
## Results

### Compatibility of measurements

Compare the results obtained by both calibration methods: Immersion in Liquids vs Contact on Surface.

Predictions  $\delta T \sim 0,03^\circ\text{C}$  have been confirmed in meas.: Max. Temp. Differences in material:

$T^a$ ( $^\circ\text{C}$ )	Mat. Uniformity ( $^\circ\text{C}$ )	Mat. Stability ( $^\circ\text{C}$ )
-50	0,077	0,005
-20	0,005	0,025
20	0,020	0,007
50	0,044	0,007
150	0,019	0,007



## Results

### Table of Results

Normalized Errors (Compatibility indexes) of 5 sensors in 8 measured points by both methods.

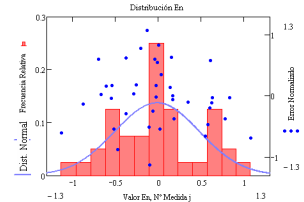
$$E_n = \frac{C_1 - C_2}{\sqrt{U_1^2 + U_2^2}}$$

$T^a$ ( $^\circ\text{C}$ )	Sensor					$\mu$
	Ch1	Ch2	Ch3	Ch4	Ch5	
-50	-0,60	-0,87	-1,12	0,35	-0,47	0,011
-20	-0,13	-0,28	-0,25	0,15	-0,20	
0	0,60	0,62	0,61	0,64	0,58	
20	0,02	0,03	-0,01	-0,06	-0,11	
50	0,16	0,19	0,17	0,01	-0,02	
100	-0,03	0,78	0,55	-0,37	-0,37	
150	0,17	1,08	0,84	-0,10	-0,02	
20	-0,54	-0,51	-0,54	-0,66	-0,69	0,494

## Resultados

### Graphs

Distribution (Histogram) of Normalized Errors. There must be observed the low statistical significance of this experience (40 measurements)



## Conclusions

### Conclusions I

- Comparison 3 methods: Air vs Surface vs Liq. Immersion
- Usual Uncertainties in comparison calibration:

Temperature ( $^\circ\text{C}$ )	U Liquid ( $^\circ\text{C}$ )	U Material ( $^\circ\text{C}$ )	U Air ( $^\circ\text{C}$ )
-50	0,050	0,18	0,70
-20	0,030	0,17	0,40
0	0,010	0,17	0,30
20	0,030	0,11	0,15
50	0,030	0,17	0,40
100	0,030	0,20	0,70
150	0,050	0,24	1,30

## Conclusions

### Conclusions II

- Compatible methods in general lines.
- Proposed method avoids some "logistic difficulties".
- The method represents (in the theory) the utilization process.

- Applicability is limited to minimal thermal gradients processes.
- Validation (Immersion comparison) is applicable with sensors whose inner contact effects have not much significance and it is dependent on the value of the measured gradient.
- The  $U_{VT}$  gradient U-component can be very heavy at extreme Temps.. It's distribution must be carefully treated (GUM.S1)
- There must be studied other sensors typologies, materials, etc. and go deeper in uncertainty budgets.

