NANOFLUIDS

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Emanuel Negrão (UFPA)

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MOTIVATION

NANOFLUIDS

- Innovative class of heat transfer fluids created by dispersing nanoparticles (10–50 nm) in traditional heat transfer fluids (**Choi, S. U. S.** Enhancing thermal conductivity of fluids with nanoparticles. Developments and Applications of Non-Newtonian Flows, FED-Vol. 231/MD-Vol. 66, 99–105 , 1995).
- Nanofluids appear to have the potential to significantly **increase heat transfer rates** in a variety of areas such as industrial cooling applications, nuclear reactors, transportation industry (automobiles, trucks, and airplanes), micro-electromechanical systems (MEMS), electronics and instrumentation, and **biomedical applications** (nano-drug delivery, cancer therapeutics, cryopreservation).
- Possible improved thermal conductivity translates into higher energy efficiency, better performance and lower operating costs.

MOTIVATION

- **Main motivation: Improve energy-intensive oil and gas processes.**

Two projects sponsored by Petrobras: Thermophysical properties and single-phase forced convection

(i) **2006 – 2007:** Manufacture a nanofluid (INMETRO – Prof. Achete), ambient conditions and laminar flows

(ii) **2011 – 2012:** Commercial nanofluids, high temperatures - high pressures and transition/turbulent flows

ALSO….

- **Improve absorption in NIR and RF: Hyperthermia for cancer treatment**
- **Inverse problems within the Bayesian framework:** thermophysical properties, state estimation problems and control
- **Increase thermal conductivity of heat spreaders:** Nanocomposites – Profa. Carolina Cotta

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NANOFLUIDS



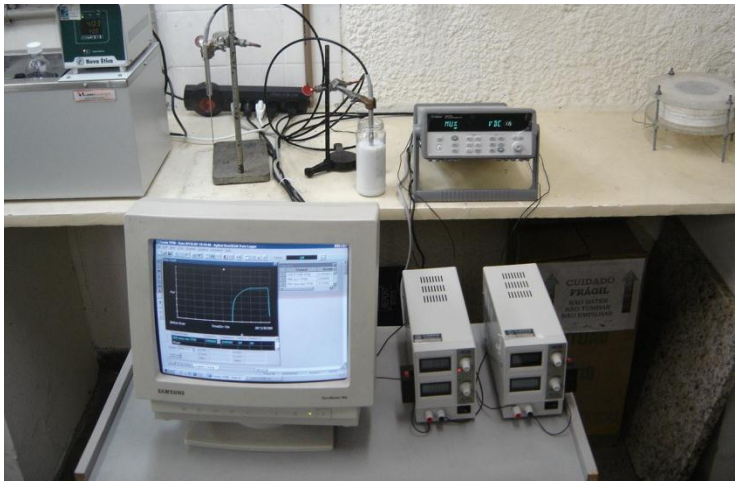
Nanoparticle	SiO_2
Mean diameter	30 nm
Density of nanoparticles	2.2 g/cm^3
pH	6-7
Concentration	25 % wt

THERMOPHYSICAL PROPERTIES

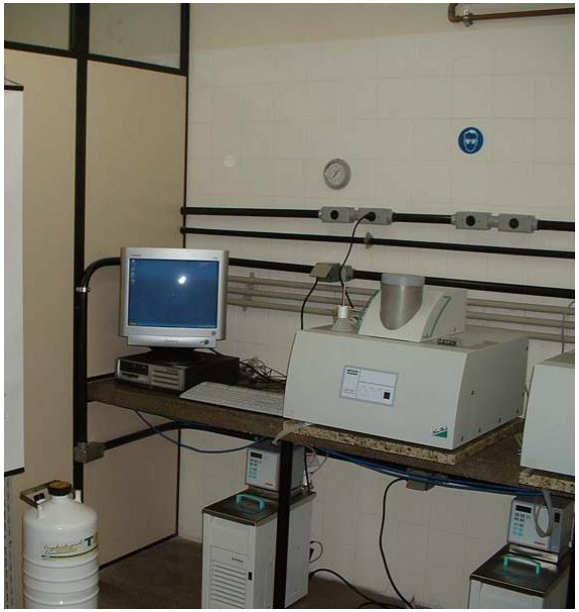
THERMAL CONDUCTIVITY

Line Heat source probe: Hukseflux TP-02 and TP-08





Flash method: Netzsch LFA 447

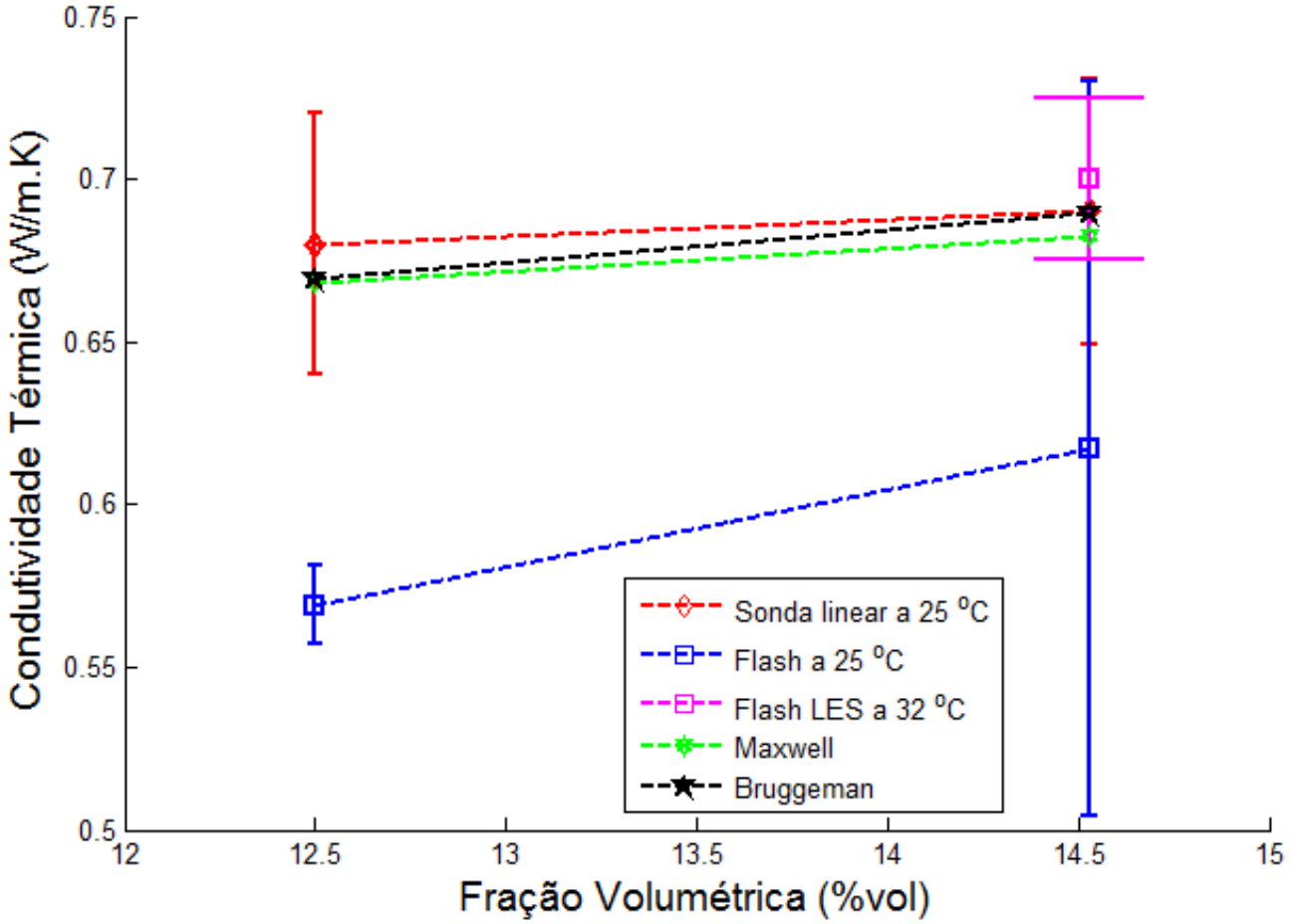




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THERMOPHYSICAL PROPERTIES

THERMAL CONDUCTIVITY: Nanofluid SiO_2/H_2O



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THERMOPHYSICAL PROPERTIES

VISCOSITY: Rheometer Brookfield LVDV-IIIU

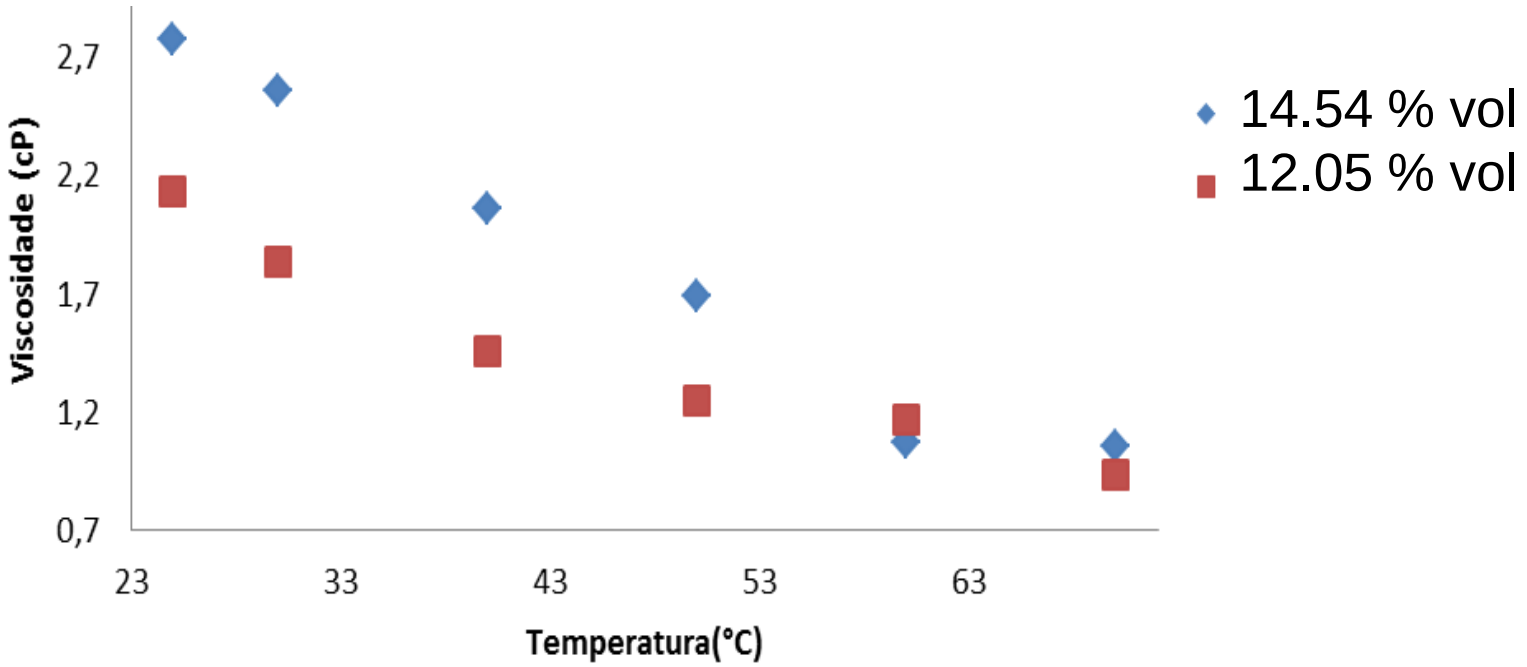






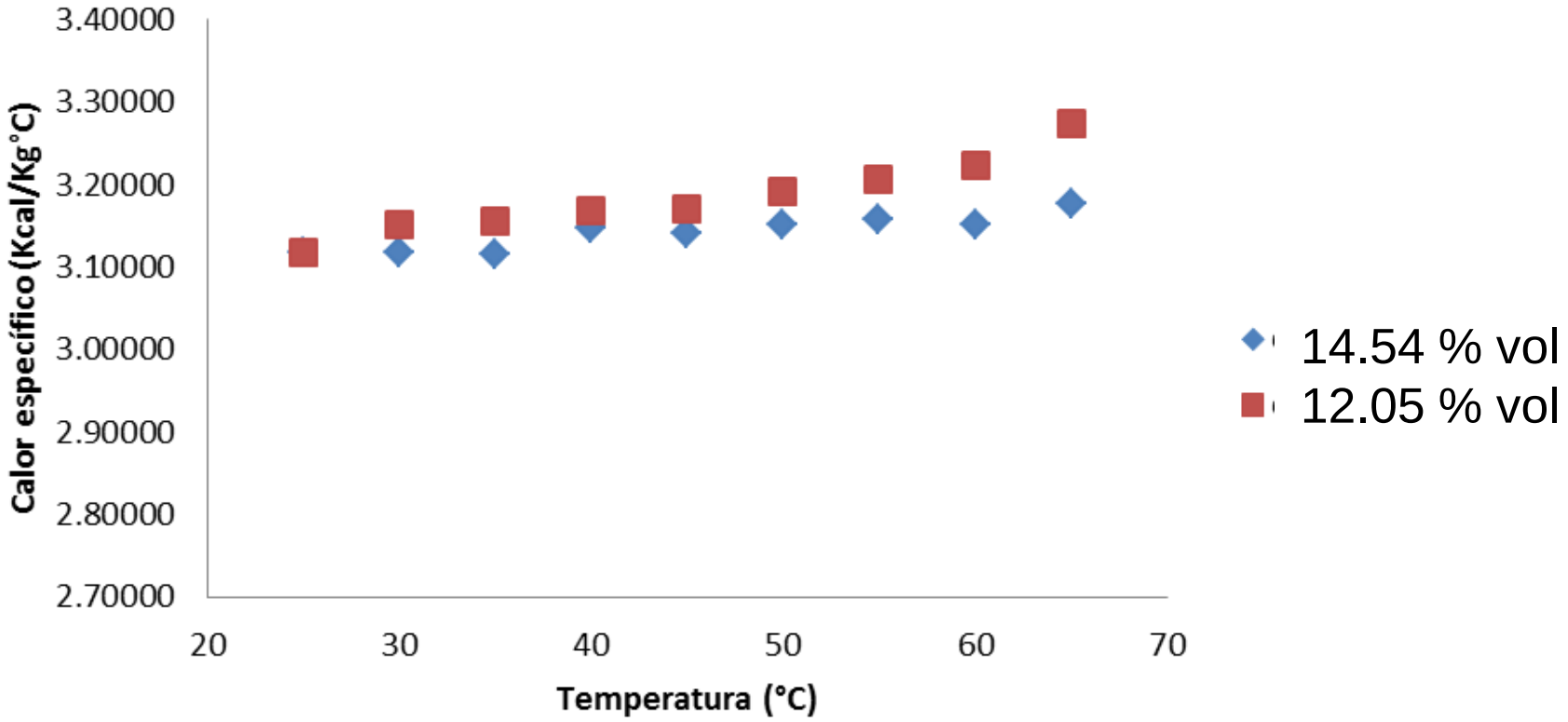
THERMOPHYSICAL PROPERTIES

VISCOSITY: Nanofluid SiO_2/H_2O



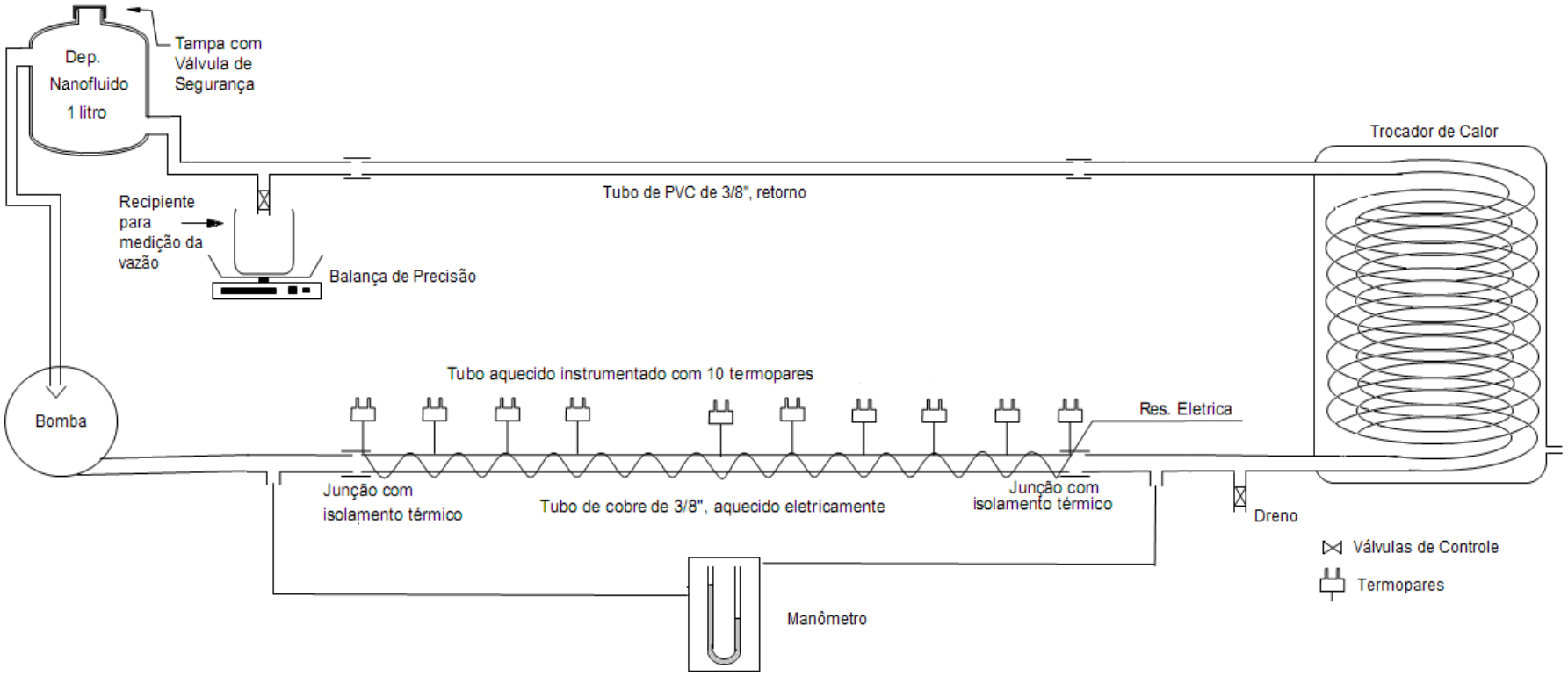
THERMOPHYSICAL PROPERTIES

SPECIFIC HEAT: Netzsch DSC 204 F1 Phoenix



SINGLE PHASE FORCED CONVECTION:

Laminar



SINGLE PHASE FORCED CONVECTION:

Laminar

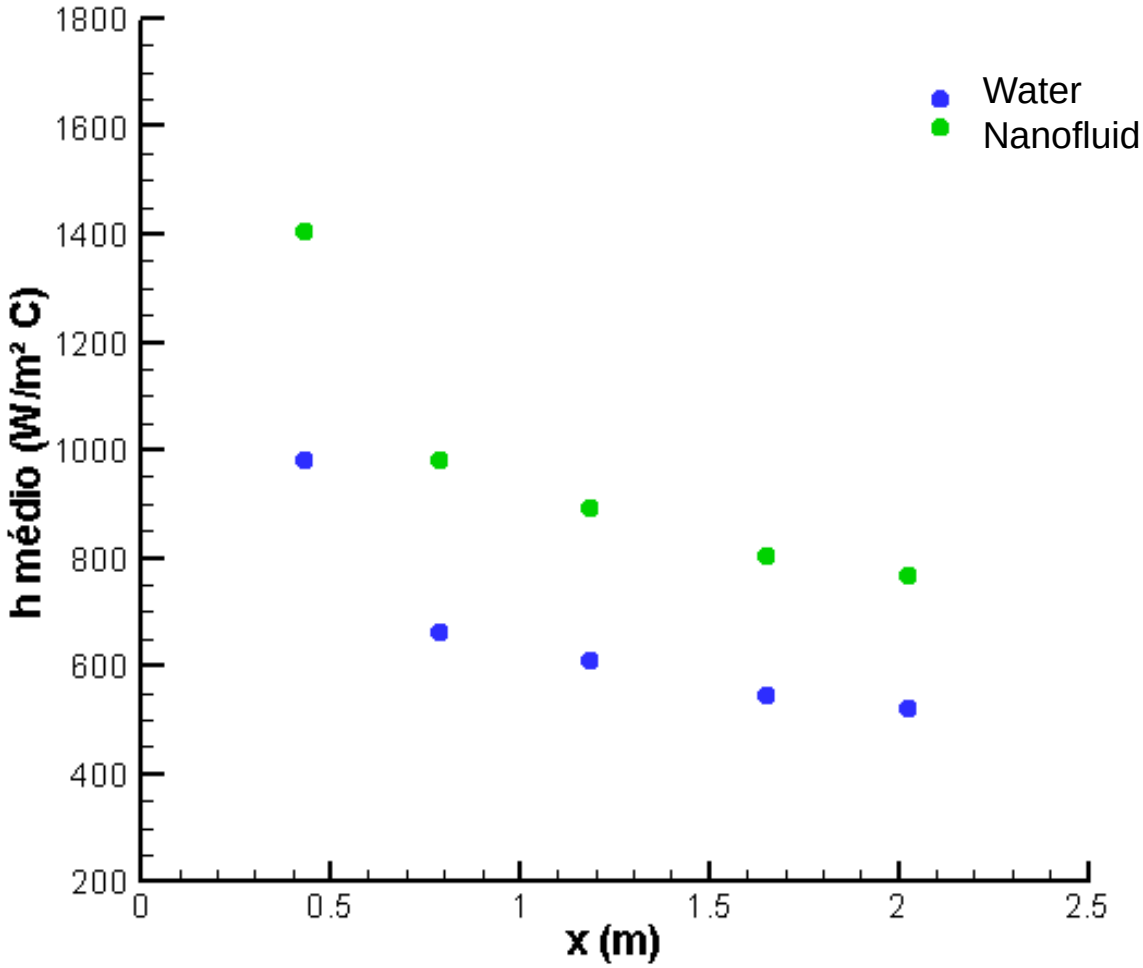




SINGLE PHASE FORCED CONVECTION:

Laminar

At least 30% increase in the mean heat transfer coefficient with respect to water!



SINGLE PHASE FORCED CONVECTION:

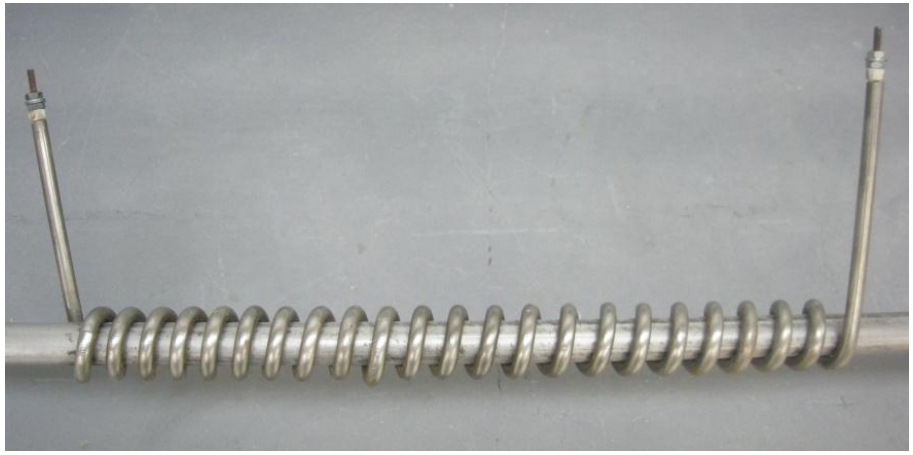
Transition and Turbulent

DESIGN CHARACTERISTICS

- Heat transfer fluid produced by Petrobras
- Inlet temperature = 150 ºC
- Temperature increase in the test section = 20 ºC
- Electric power = 27 kW
- Stainless steel 1/2”, Schedule 40
- Oil flow rate = 2020 kg/h
- Reynolds number = 16000

SINGLE PHASE FORCED CONVECTION:

Transition and Turbulent







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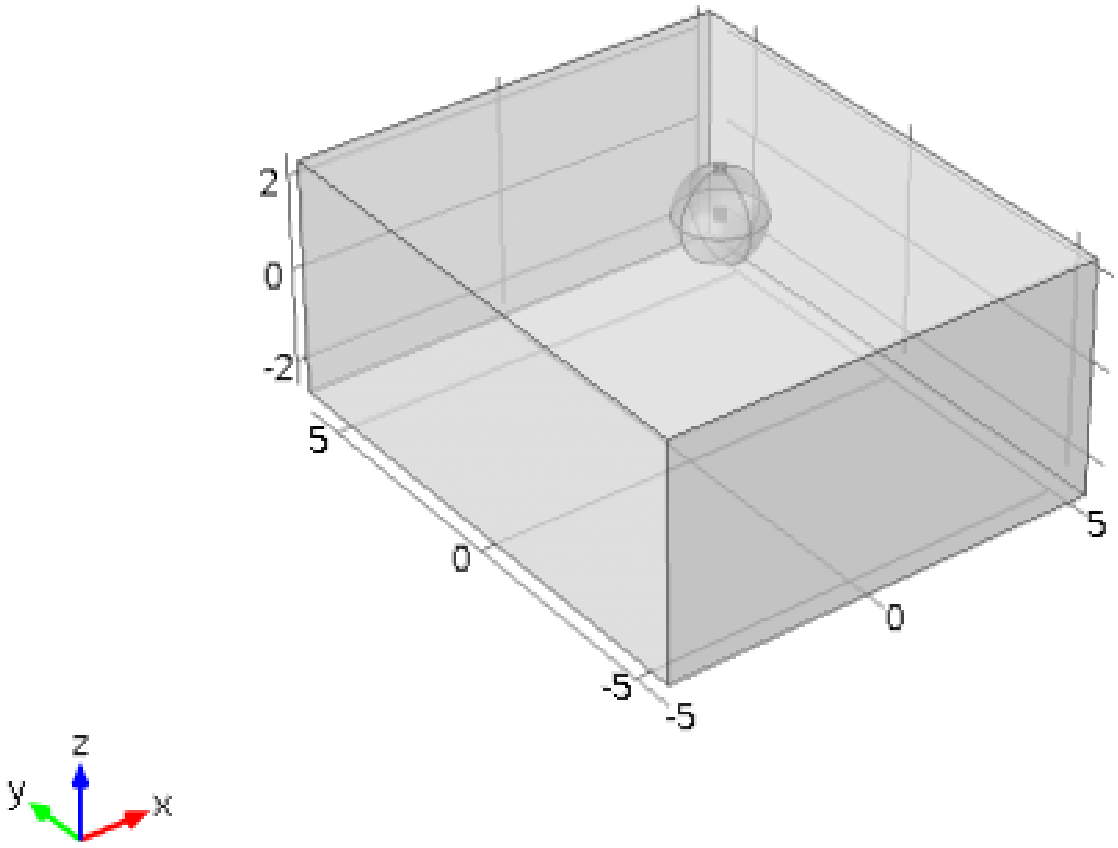
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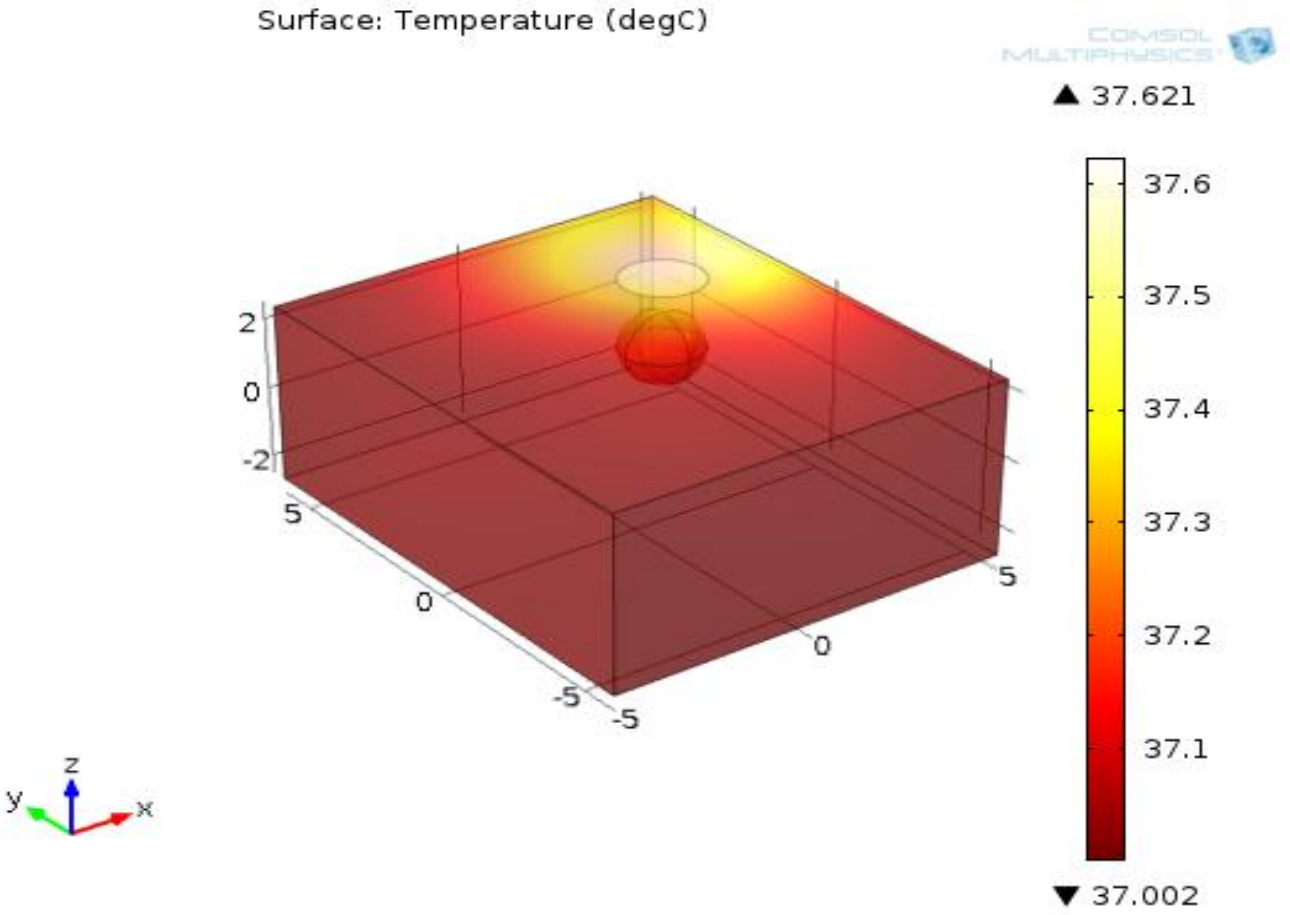
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NUMERICAL SIMULATIONS



NUMERICAL SIMULATIONS

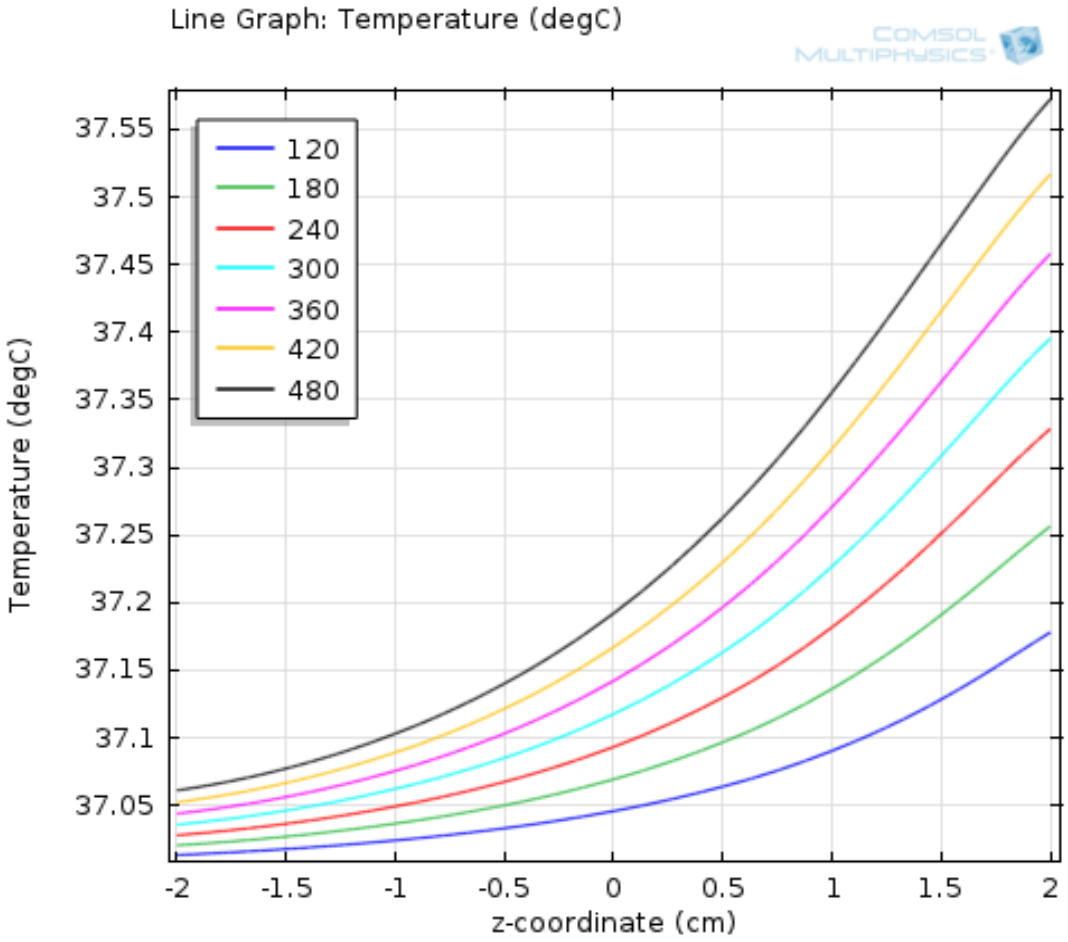
Without nanoparticles



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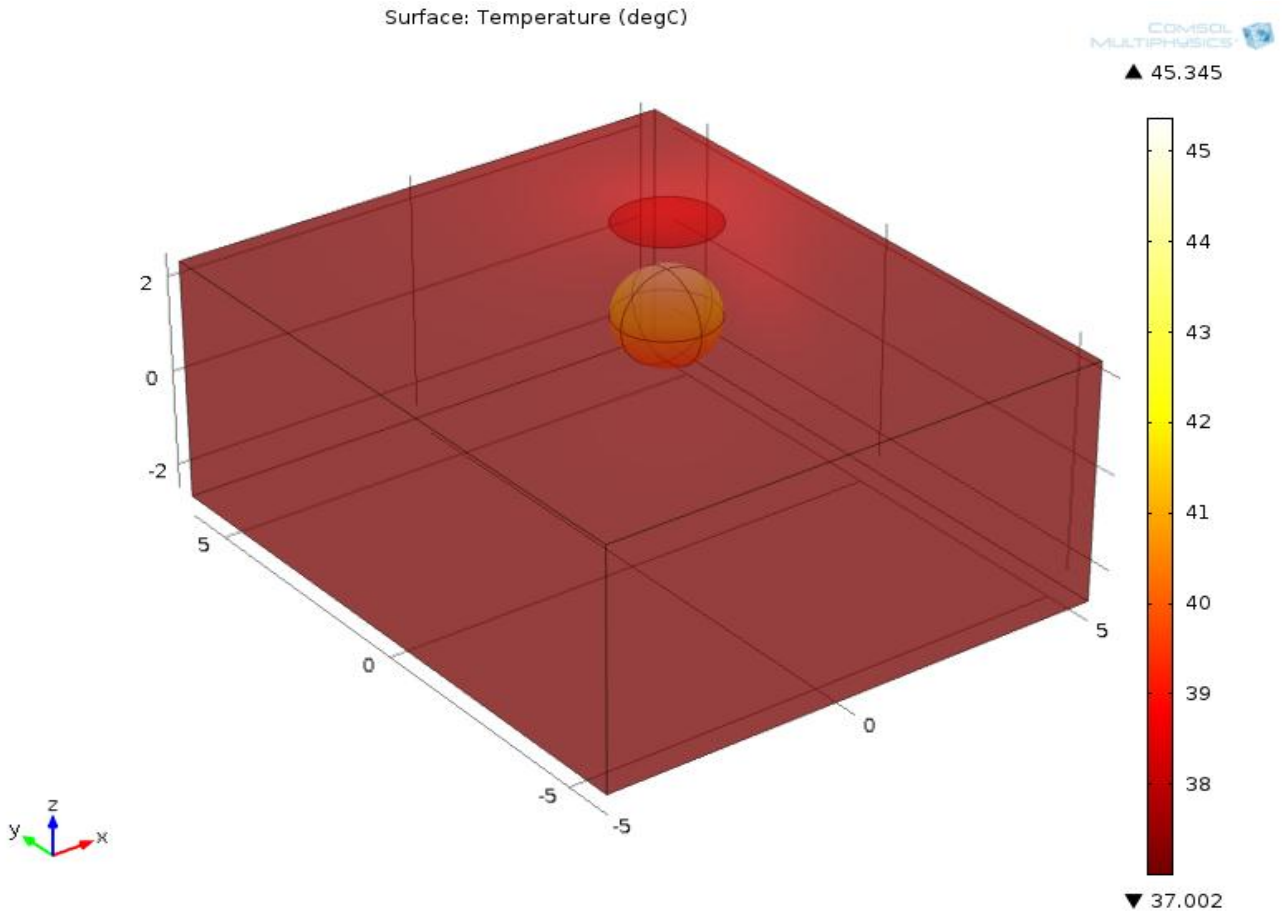
NUMERICAL SIMULATIONS

Without nanoparticles



NUMERICAL SIMULATIONS

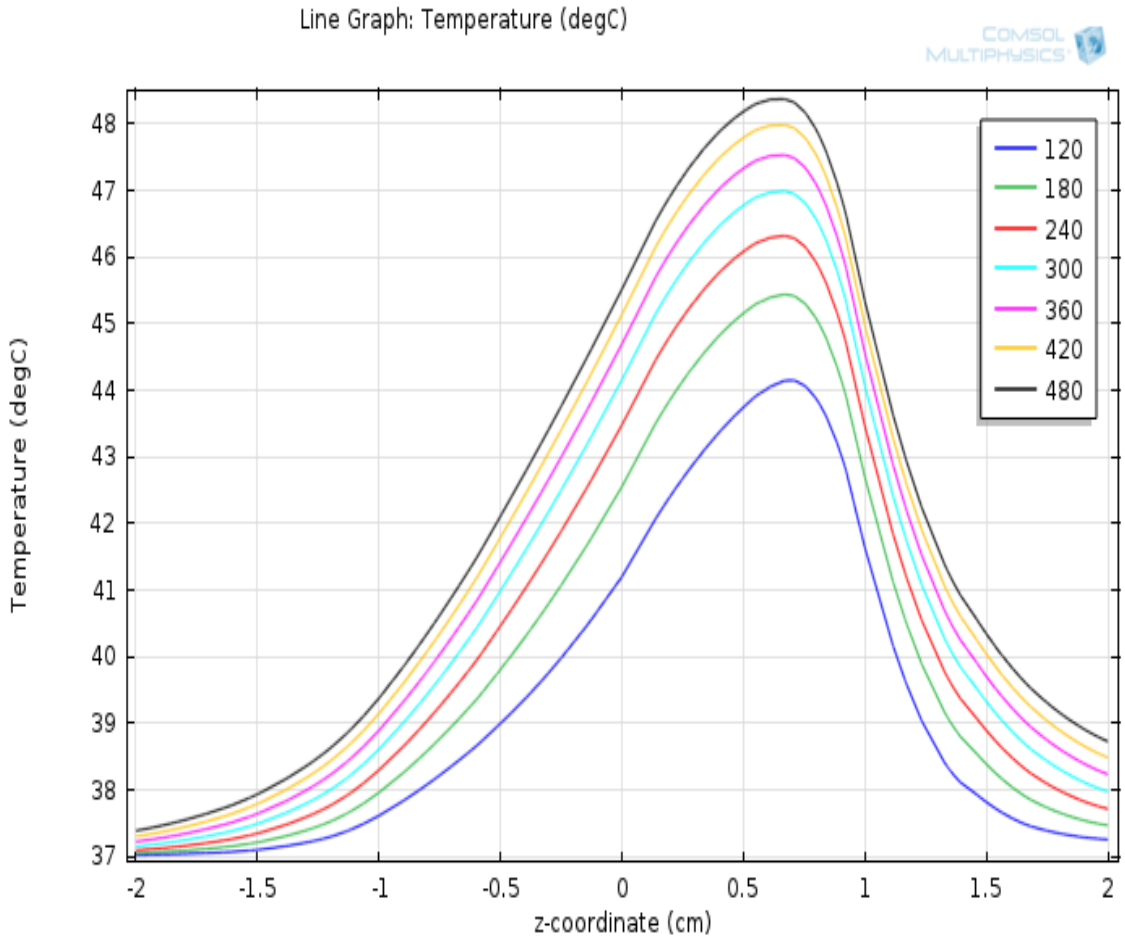
With nanoparticles



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NUMERICAL SIMULATIONS

With nanoparticles



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PHANTOMS LOADED WITH NANOPARTICLES



From left to right are the PVC-P Phantom, PVC-P loaded with SiO_2 nanoparticles, PVC-P mixed with thermal paste, PVC-P loaded with TiO_2 nanoparticles

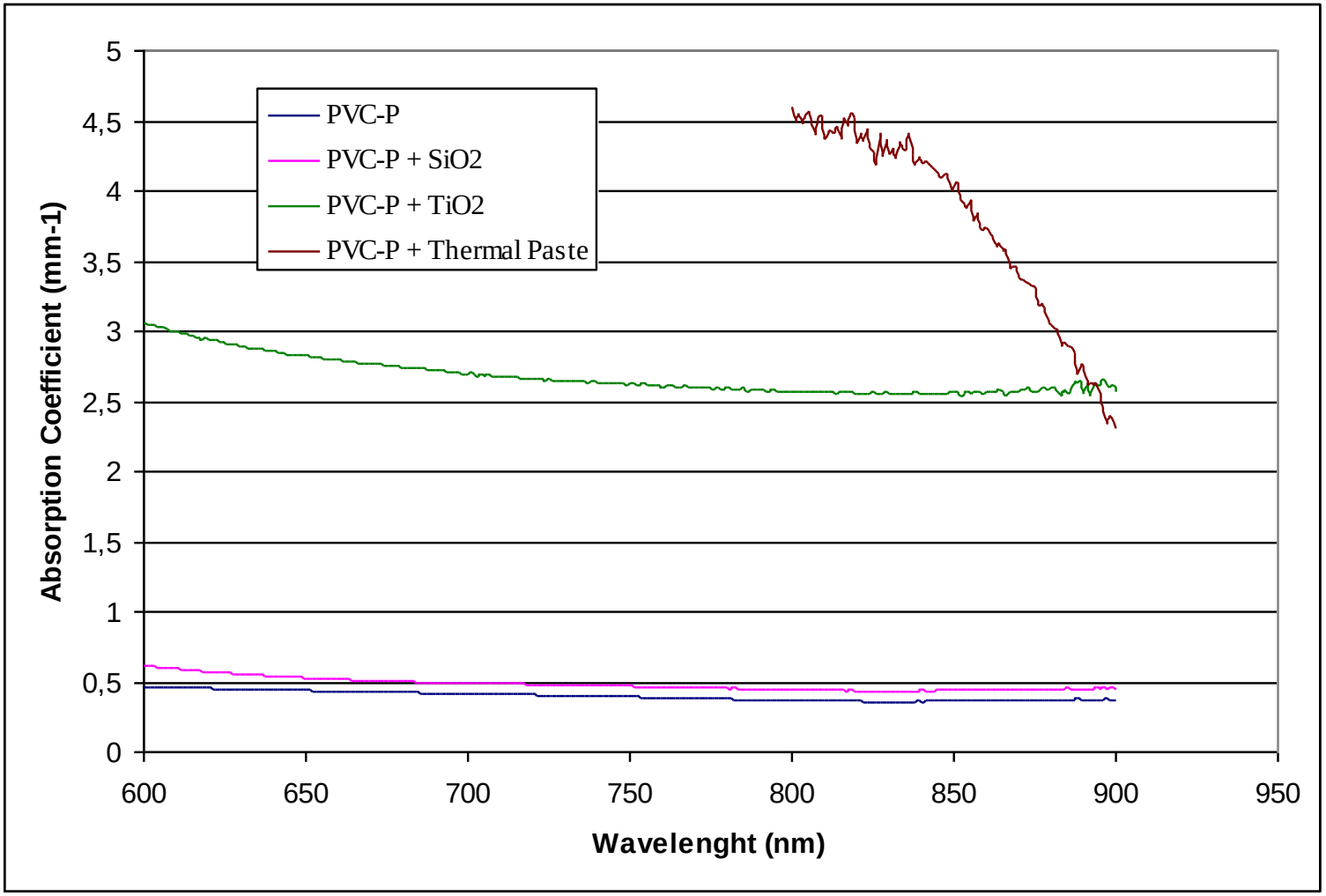
PHANTOMS LOADED WITH NANOPARTICLES

Phantom	Thickness (mm)	Concentration (%w)
PVC-P	2.70	-
PVC-P with SiO_2 nanoparticles	3.2	3.05
PVC-P with TiO_2 nanoparticles	2.55	0.69
PVC-P with thermal paste	2.80	10.56

Phantoms	Density (Kg/m^3)	Thermal diffusivity (10^{-8}) (m^2/s)	Thermal conductivity ($W/m\ ^oC$)	Specific Heat ($J/g\ ^oC$)
PVC-P	995.1±0.1	8.70±0.32	0.150±0.004	1.7900± 0.0094
PVC-P + SiO_2	989.3±0.1	8.76±0.24	0.150± 0.002	1.7200± 0.0097
PVC-P + TiO_2	1080.8±0.1	8.80±0.33	0.173±0.001	1.7700± 0.0097
PVC-P + Thermal Paste	1094.2±0.1	12.00±0.51	0.24±0.01	1.7500± 0.0049

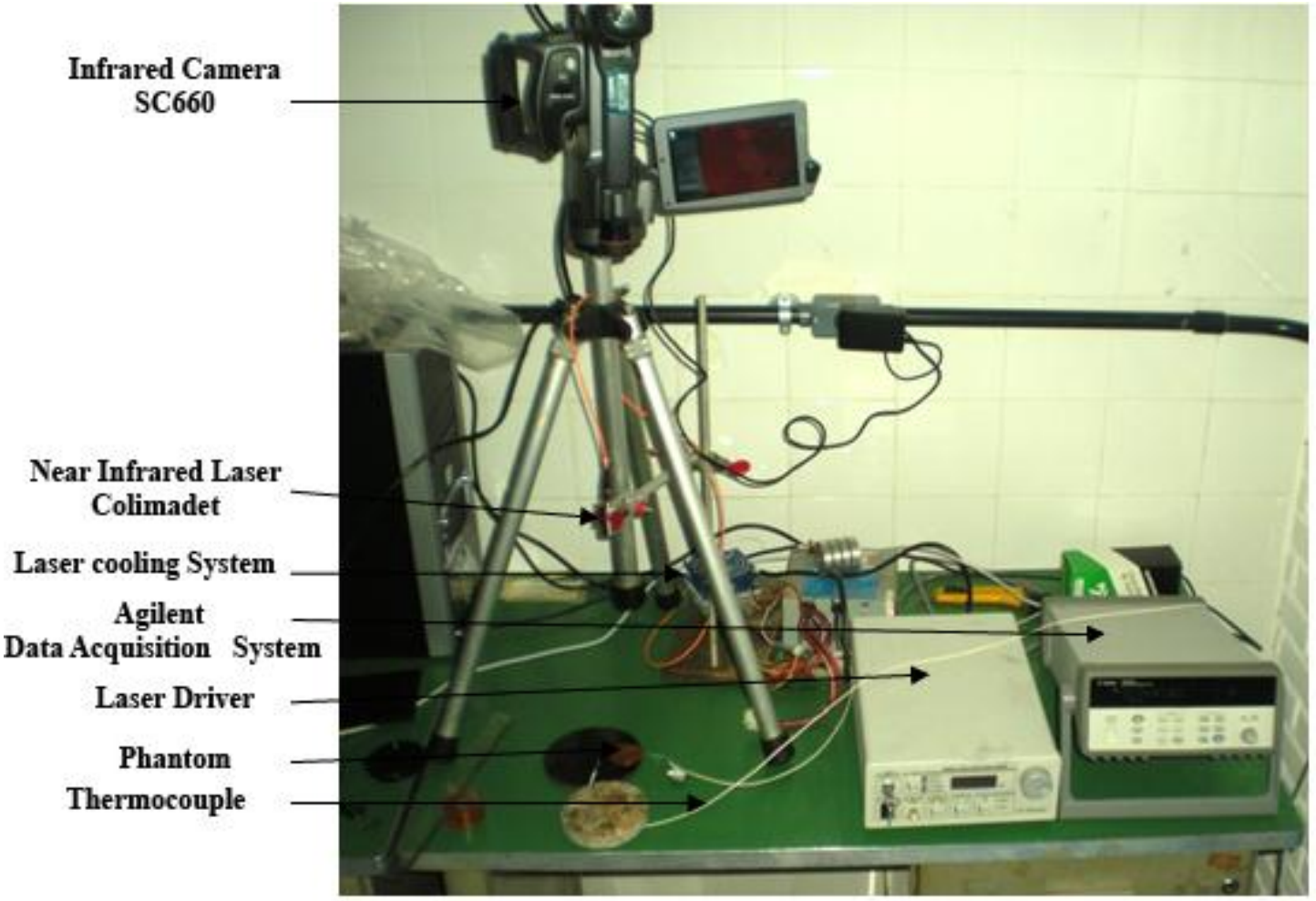
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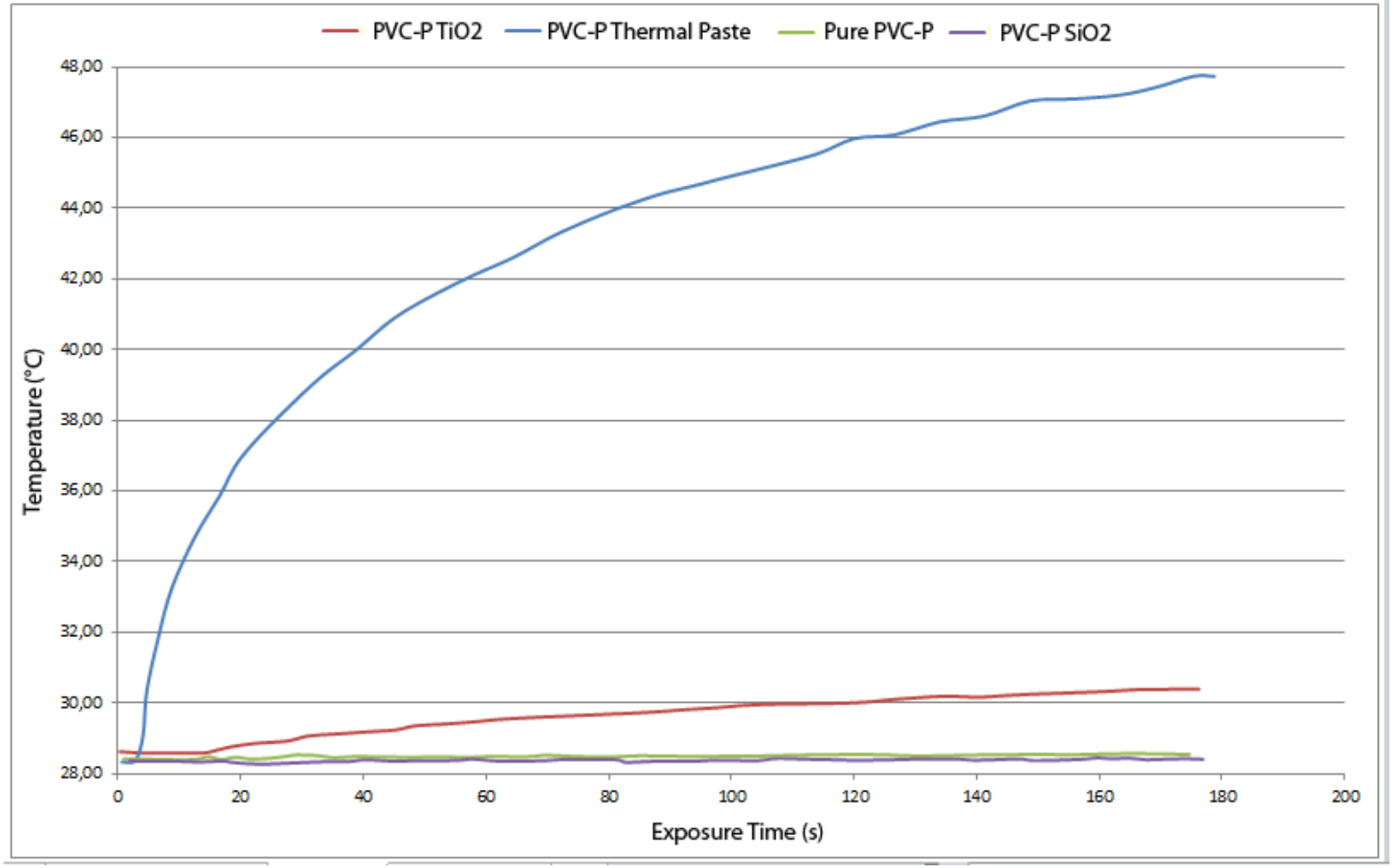
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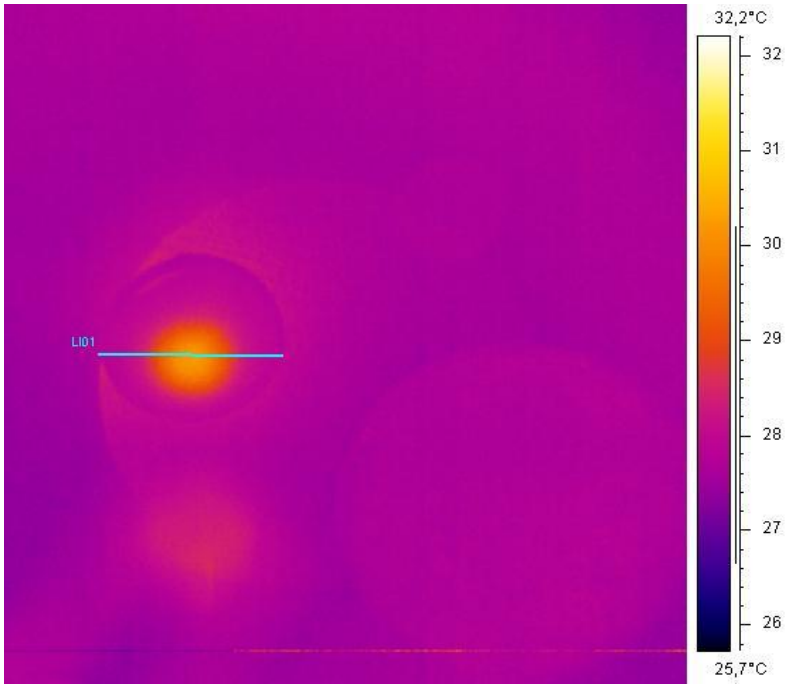
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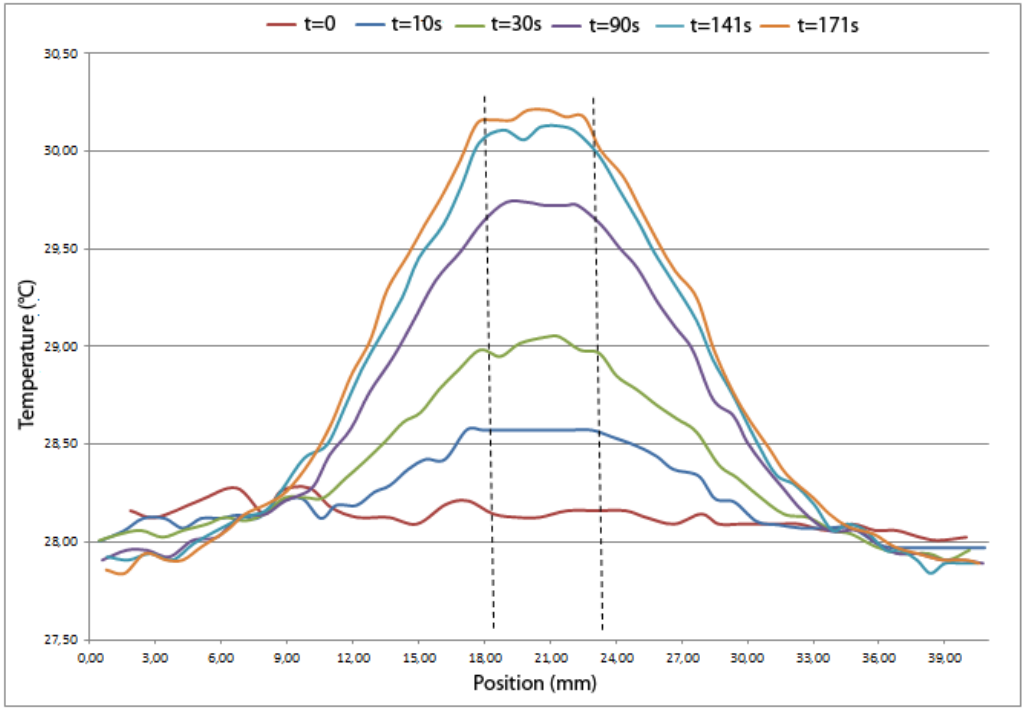
PHANTOMS LOADED WITH NANOPARTICLES



PHANTOMS LOADED WITH NANOPARTICLES

Phantom containing TiO_2





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INVERSE PROBLEMS

Inverse heat transfer problems deal with the estimation of unknown quantities appearing in the mathematical formulation of physical processes in thermal sciences, by using measurements of temperature, heat flux, radiation intensities, etc.

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INTRODUCTION

Inverse Problems are *Ill-Posed*.

A solution for a *well-posed* problem (Hadamard) must satisfy the conditions of:

- existence
- uniqueness
- stability with respect to the input data

SOLUTION OF INVERSE PROBLEMS
General Considerations

Consider the mathematical formulation of a heat transfer problem, which, for instance, can be linear or non-linear, one or multi-dimensional, involve one single or coupled heat transfer modes, etc.

We denote the **vector of parameters** appearing in such formulation as:

$$\mathbf{P}^T = [P_1, P_2, \ldots, P_N]$$

where ***N* is the number of parameters**

• These parameters can possibly be thermal conductivity components, heat transfer coefficients, heat sources, boundary heat fluxes, etc.
• They can represent constant values of such quantities, or the parameters of the representation of a function in terms of known basis functions.

SOLUTION OF INVERSE PROBLEMS
General Considerations

Consider also that transient measurements are available within the medium, or at its surface, where the heat transfer processes are being mathematically formulated.

The vector containing the **measurements** is written as:

$$\mathbf{Y}^T = \left(\vec{Y}_1 \ , \ \vec{Y}_2 \ , \ldots , \vec{Y}_I \right)$$

$$\vec{Y}_i = \left(Y_{i1} \ , \ Y_{i2} \ , \ldots , Y_{iM} \right)$$

M = # of sensors
I = # of transient measurements per sensor

$D = MI$ = # of measurements

• The measured data are not limited to temperatures, but could also include heat fluxes, radiation intensities, etc.

SOLUTION OF INVERSE PROBLEMS
Bayesian framework

BAYES' FORMULA

$$\pi_{posterior}(\mathbf{P}) = \pi(\mathbf{P}|\mathbf{Y}) = \frac{\pi_{prior}(\mathbf{P})\pi(\mathbf{Y}|\mathbf{P})}{\pi(\mathbf{Y})}$$

Where: $\pi_{posterior}(\mathbf{P})$ = posterior probability density (conditional probability of the parameters **P** given the measurements **Y**)

$\pi_{prior}(\mathbf{P})$ = prior density (information about the parameters prior to the measurements)

$\pi(\mathbf{Y}|\mathbf{P})$ = likelihood function (expresses the likelihood of different measurement outcomes **Y** with **P** given)

$\pi(\mathbf{Y})$ = probability density of the measurements (normalizing constant)

$$posterior \propto prior \times likelihood$$

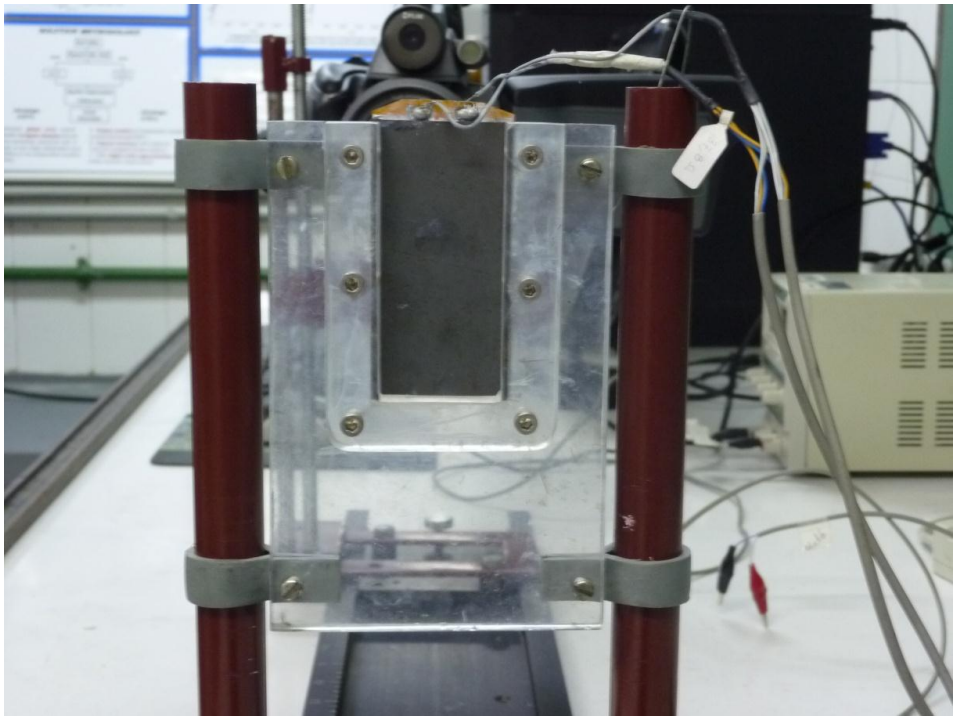
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SOLUTION OF INVERSE PROBLEMS
Bayesian framework

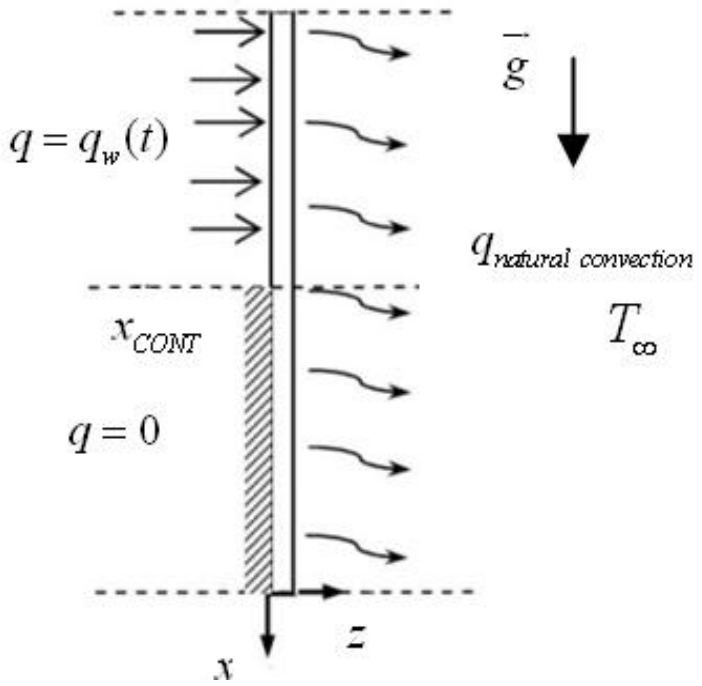
- In many cases, the Posterior Probability Distribution does not allow an analytical treatment.
- Draw samples from the set **Ω** of all possible **P**'s, each sample with probability $\pi(\mathbf{P}|\mathbf{Y})$.
- Get a set $\Theta = \{\mathbf{P}_1, \mathbf{P}_2, \ldots, \mathbf{P}_M\}$ of samples distributed like the posterior distribution.
- Inference on $\pi(\mathbf{P}|\mathbf{Y})$ becomes inference on $\Theta = \{\mathbf{P}_1, \mathbf{P}_2, \ldots, \mathbf{P}_M\}$, for example the mean of the samples in Θ give us an estimation of the average values of $\pi(\mathbf{P}|\mathbf{Y})$.
- We generally need the constant that normalizes the probability distribution:
  MARKOV CHAIN MONTE-CARLO METHODS
  (Metropolis-Hastings Algorithm)
- Very time consuming.

SOLUTION OF INVERSE PROBLEMS
Bayesian framework

Example: Characterization of Heterogeneous Media



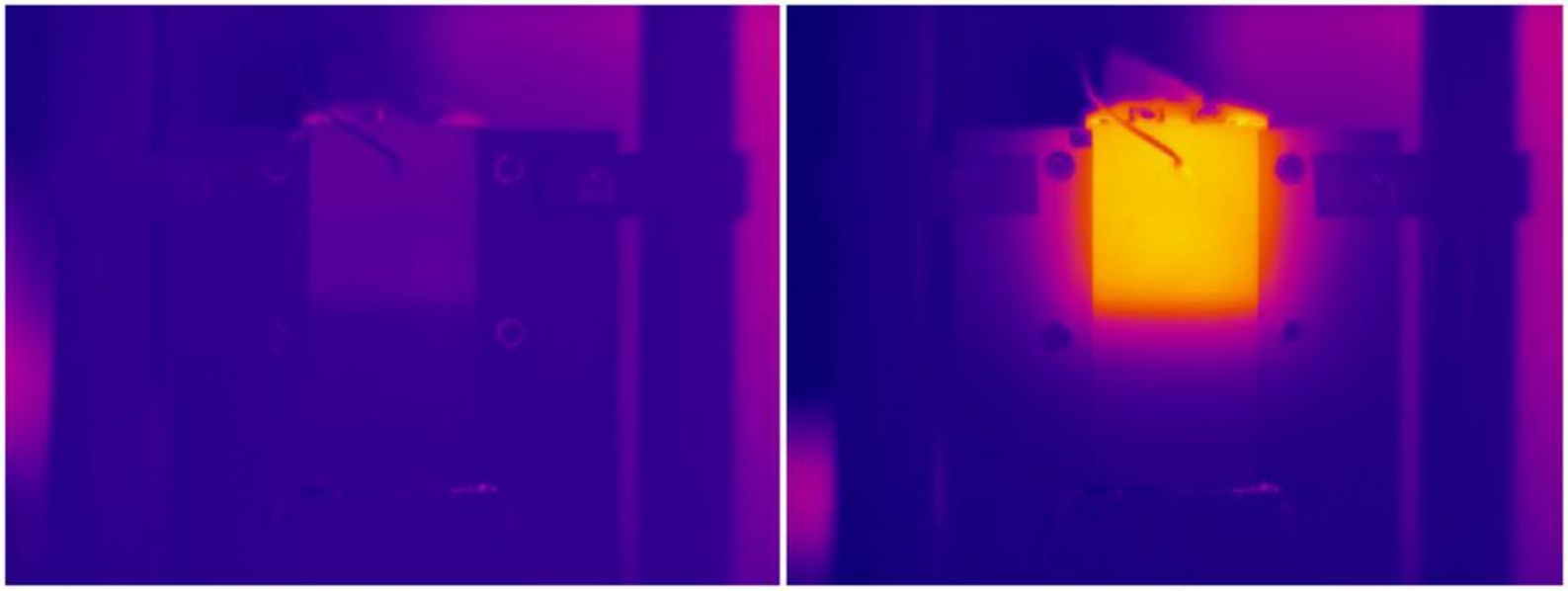
Thin plate: Lumped model in *z*



Diego C. Knupp, Carolina P. Naveira Cotta, João Vitor C. Ayres, Renato M. Cotta and Helcio R. B. Orlande, J., Identification of Thermophysical Properties of Nanocomposites via Integral Transforms, Bayesian Inference and Infrared Thermography, *Inverse Problems in Science and Engineering*, 2012, in press

SOLUTION OF INVERSE PROBLEMS
Bayesian framework

Example: Characterization of Heterogeneous Media



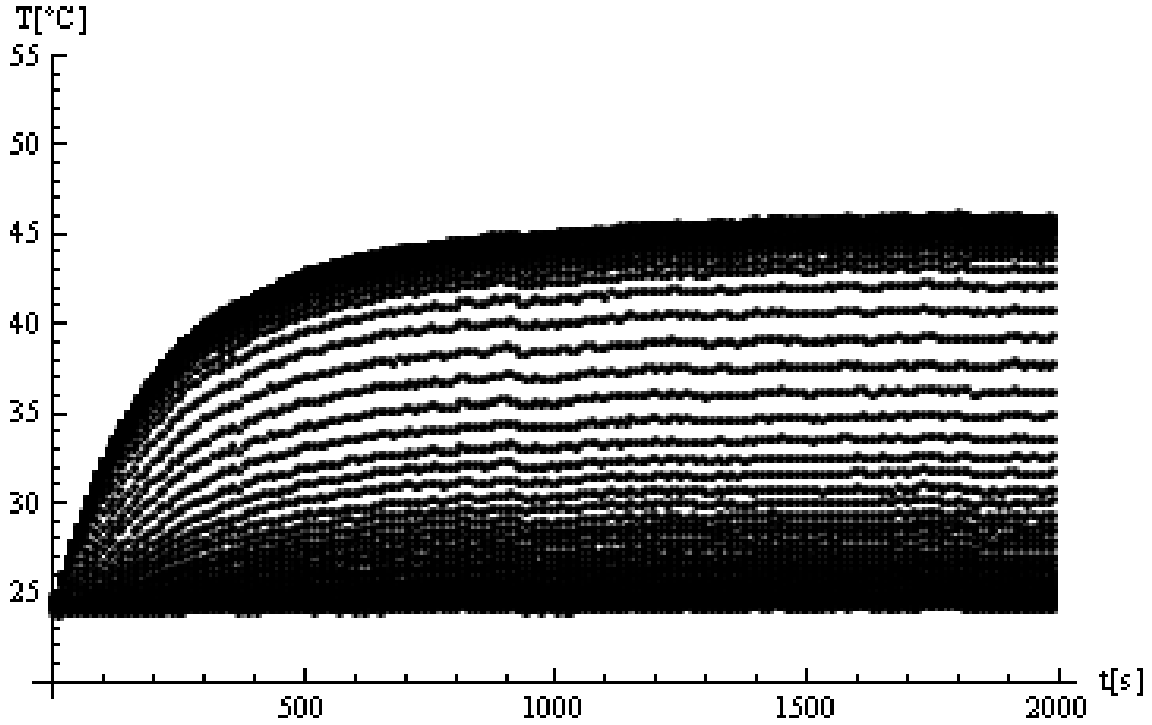
(a) (b)

Figure 7 – (a) Infrared camera image acquired at the moment the DC source is switched on. (b) Infrared camera image acquired after some elapsed time during heating period.

Naveira-Cotta, C., Orlande, H., Cotta, R., Nunes, J., Integral Transforms, Bayesian Inference, And Infrared Thermography In The Simultaneous Identification Of Variable Thermal Conductivity And Diffusivity In Heterogeneous Media, IHTC14, August 8-13, Washington, DC, USA, paper IHTC14-22511, 2010

SOLUTION OF INVERSE PROBLEMS
Bayesian framework

Example: Characterization of Heterogeneous Media



The number of pixels in the vertical direction for the configuration that has been tested provides the total number of **328 spatial measurements** along the 8 cm of the plate.

SOLUTION OF INVERSE PROBLEMS
Bayesian framework

Example: Characterization of Heterogeneous Media
Data Compression

Another advancement of the present study was the solution of the inverse problem in the transformed field, from the **integral transformation of the experimental temperature data, thus compressing the experimental measurements in the space variables into a few transformed fields**. Once the experimental temperature readings have been obtained, one proceeds to the integral transformation of the temperature field at each time through the integral transform pair below:

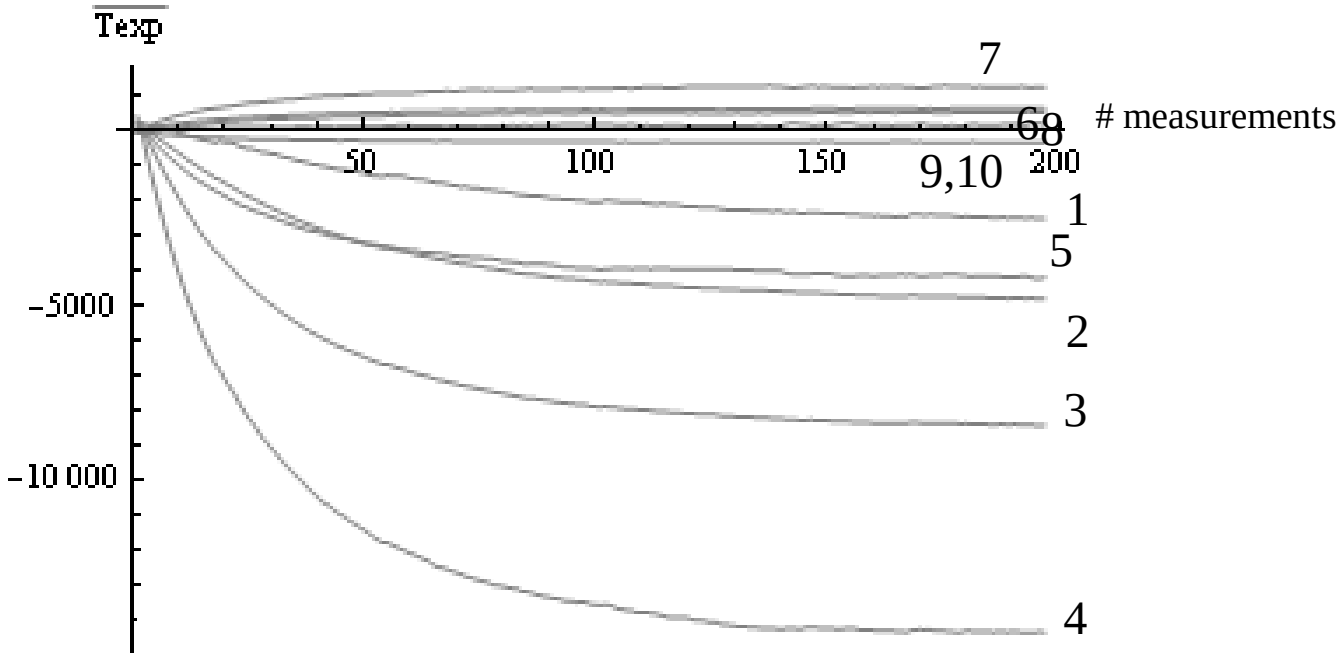
Transform
$$\overline{T}_{\exp,i}(t) = \int_0^{Lx} w(x)\tilde{\psi}_i(x)[T_{\exp}(x,t) - T_\infty]dx$$

Inverse
$$T_{\exp}(x,t) = T_\infty + \sum_{i=0}^{Ni} \tilde{\psi}_i(x)\overline{T}_{\exp,i}(t)$$

Naveira-Cotta, C., Cotta, R., Orlande, H., Inverse Analysis with Integral Transformed Temperature Fields: Identification of Thermophysical Properties in Heterogeneous Media, *Int. J. Heat Mass Transfer*, 2011, (to appear).

SOLUTION OF INVERSE PROBLEMS
Bayesian framework

Example: Characterization of Heterogeneous Media
Data Compression

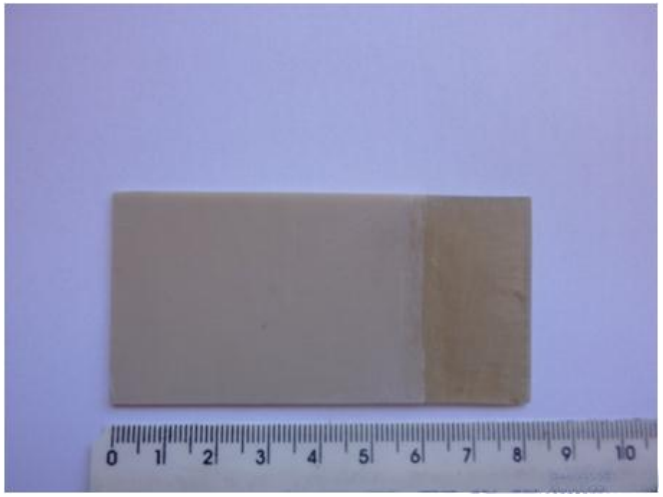


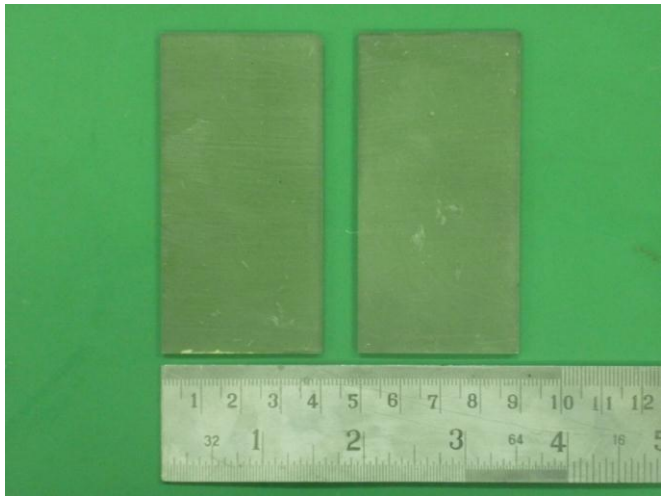
These are in fact the quantities that are employed in the inverse problem analysis. Therefore, a significant **data reduction of more than 95%** is achieved, as one chooses to solve the inverse problem in the transformed temperature domain.

SOLUTION OF INVERSE PROBLEMS
Bayesian framework

Example: Identification of Thermophysical Properties of Nanocomposites

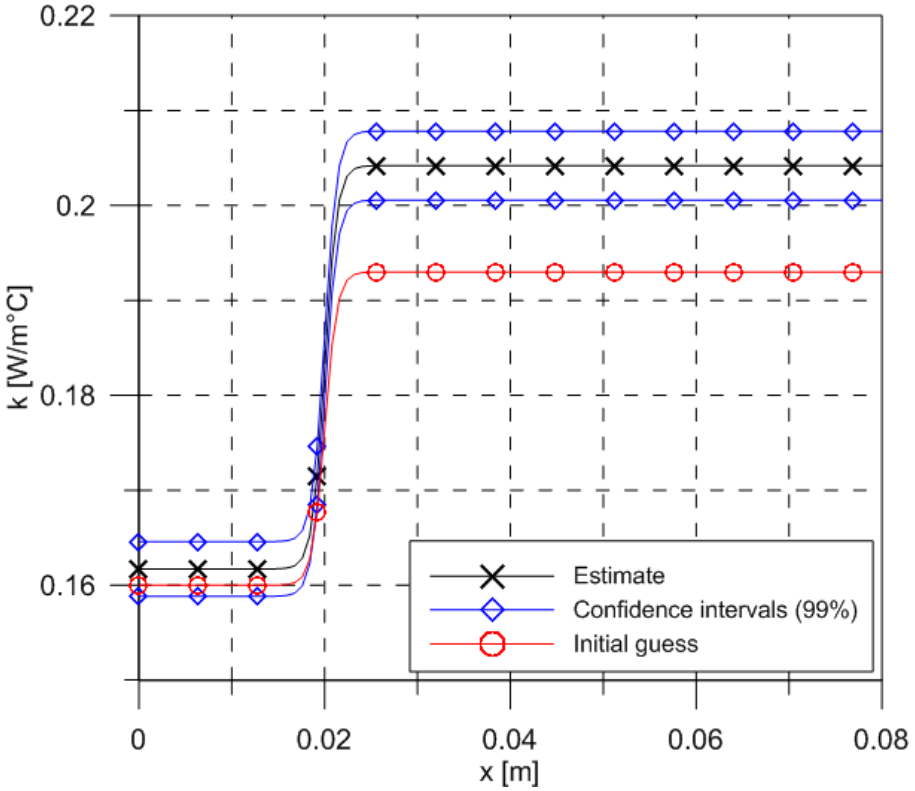
Polyester resin as matrix and alumina nanoparticles as filler, in such a way that ¾ of the plate's length has 28.5% of alumina nanoparticles in mass and the other ¼ of the plate's length is composed only of polyester resin, with no addition of filler.

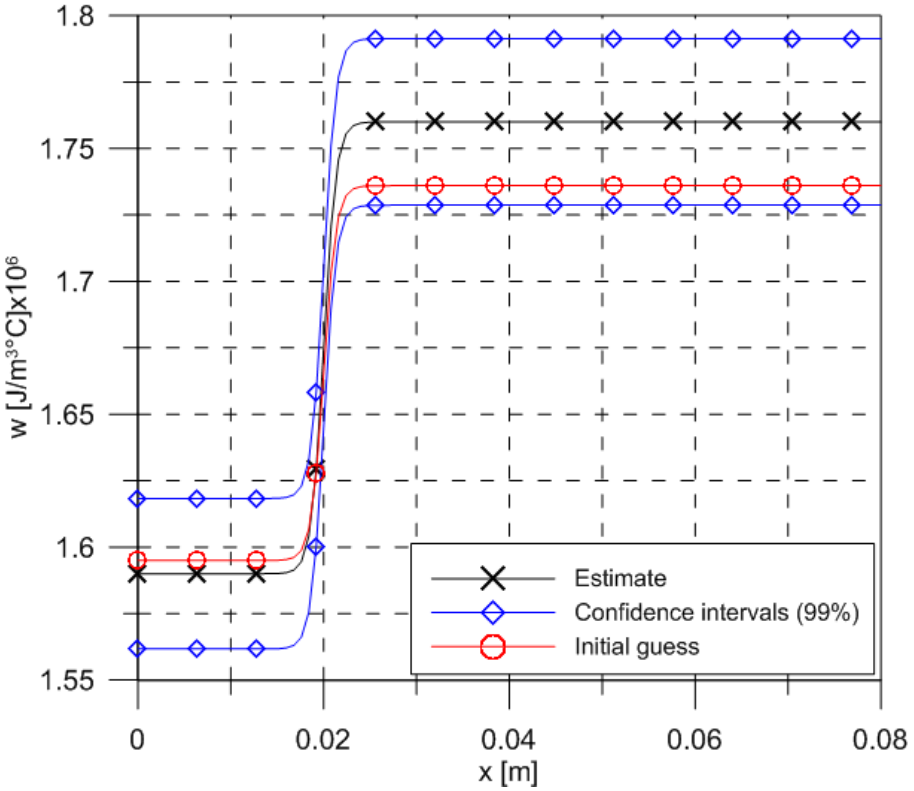




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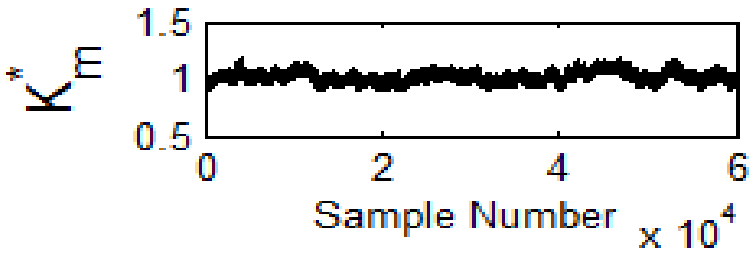
SOLUTION OF INVERSE PROBLEMS
Bayesian framework

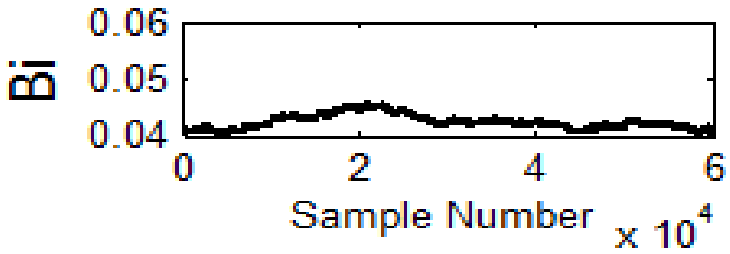


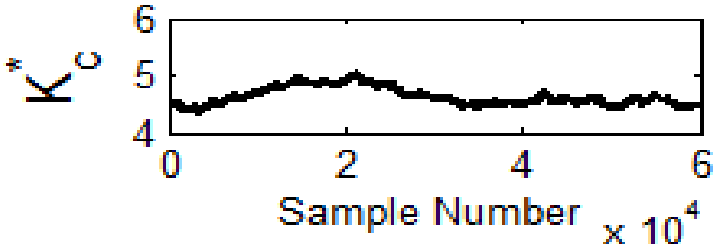


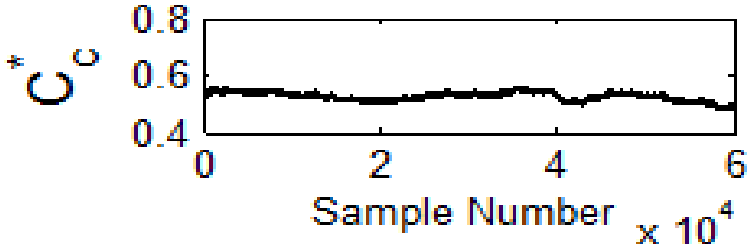
Diego C. Knupp, Carolina P. Naveira Cotta, João Vitor C. Ayres, Renato M. Cotta and Helcio R. B. Orlande, J., Identification of Thermophysical Properties of Nanocomposites via Integral Transforms, Bayesian Inference and Infrared Thermography, *Inverse Problems in Science and Engineering*, 2012, in press

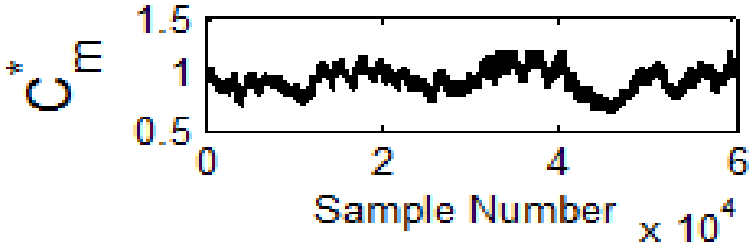
LINE HEAT SOURCE: Simultaneous identification of thermal conductivity and volumetric heat capacity

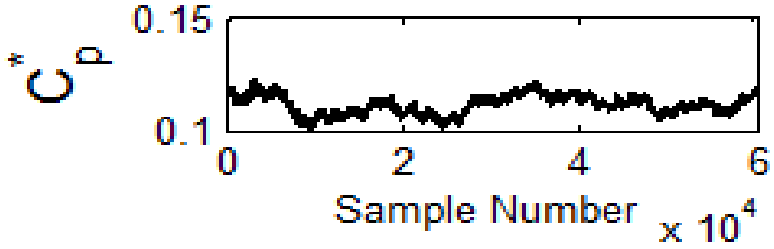


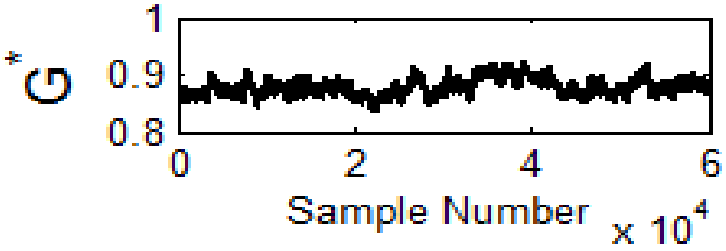




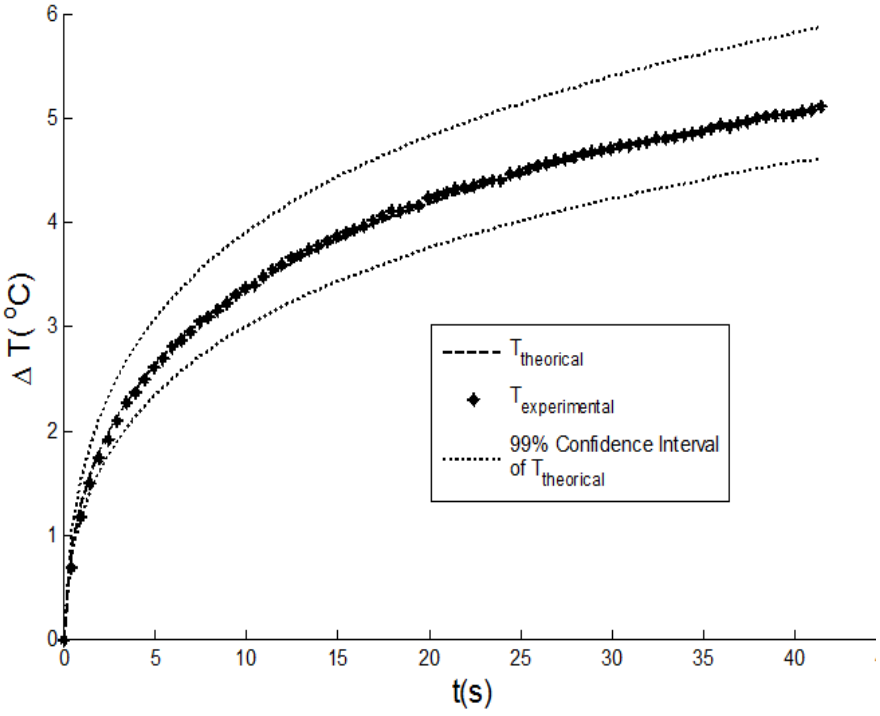


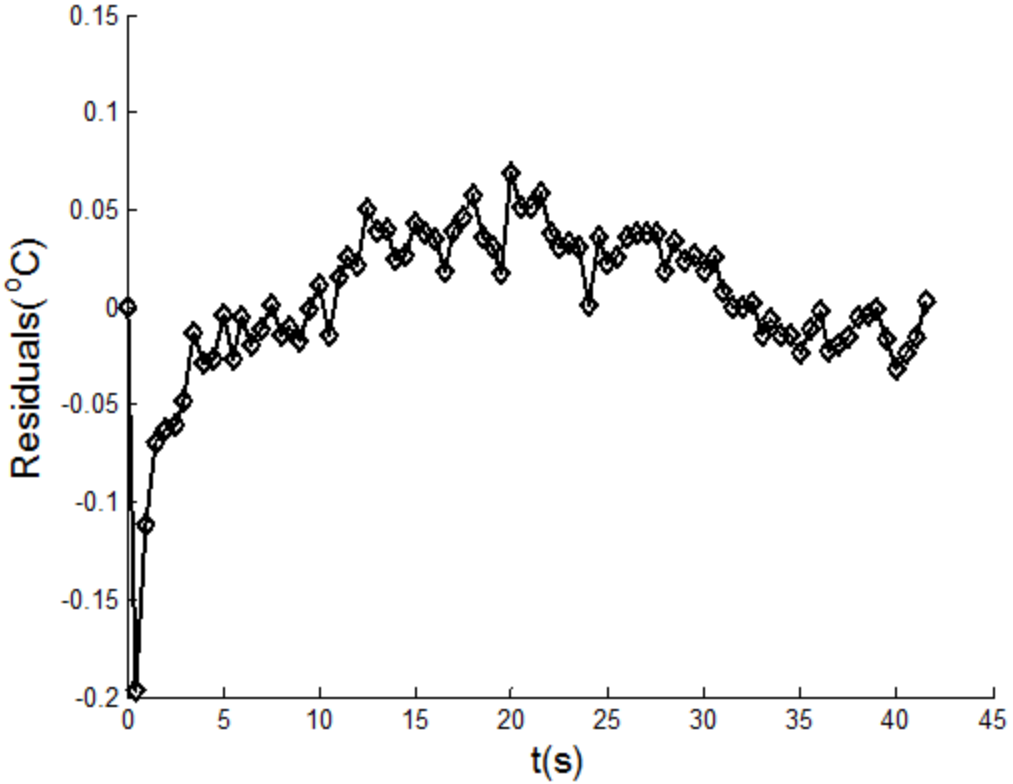






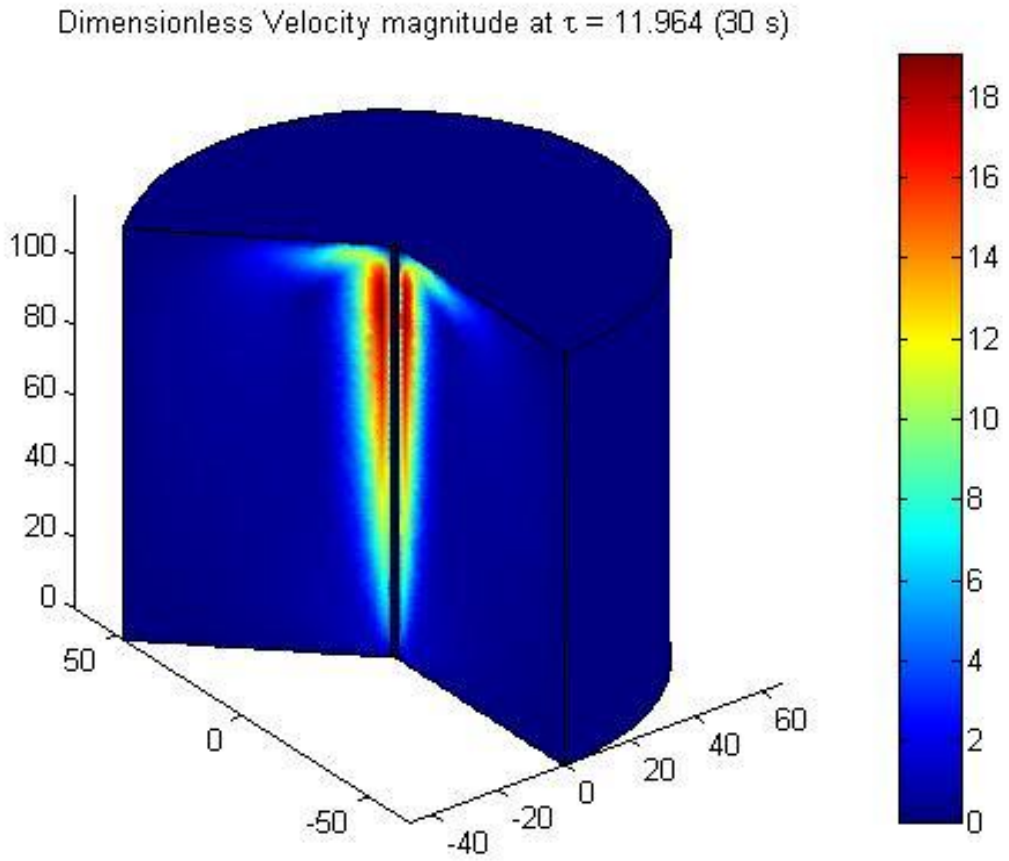
LINE HEAT SOURCE: Simultaneous identification of thermal conductivity and volumetric heat capacity





LINE HEAT SOURCE PROBE
Improvement of solutions with surrogate models

Convective effects are neglected in the models used for line heat source probe, but they can be significant, e.g., in water.



SOLUTION OF INVERSE PROBLEMS
Improvement of solutions with surrogate models

APPROXIMATION ERROR MODEL

- Kaipio, J. and Somersalo, E., *Statistical and Computational Inverse Problems*, Applied Mathematical Sciences 160, Springer-Verlag, 2004
- Nissinen, A., *Modeling Errors in Electrical Impedance Tomography*, Dissertation in Forestry and Natural Sciences, University of Eastern Finland, 2011.

In the approximation error model (AEM) approach, the statistical model of the approximation error is constructed and then represented as additional noise in the measurement model [1,19-23]. With the hypotheses that the measurement errors are additive and independent of the parameters **P**, one can write

$$\mathbf{Y} = \mathbf{T}_c(\mathbf{P}) + \mathbf{e} \qquad (16)$$

where $\mathbf{T}_c(\mathbf{P})$ is the sufficiently accurate solution of the complete model given by equations (1.a-h). The vector of measurement errors, $\mathbf{e}$ are assumed here to be Gaussian, with zero mean and known covariance matrix **W**.

SOLUTION OF INVERSE PROBLEMS
Improvement of solutions with surrogate models

APPROXIMATION ERROR MODEL

$$\mathbf{Y} = \mathbf{T}(\mathbf{P}) + [\mathbf{T}_c(\mathbf{P}) - \mathbf{T}(\mathbf{P})] + \mathbf{e} \tag{17}$$

By defining the error between the complete and the surrogate model solutions as

$$\boldsymbol{\varepsilon} = [\mathbf{T}_c(\mathbf{P}) - \mathbf{T}(\mathbf{P})] \tag{18}$$

equation (17) can be written as

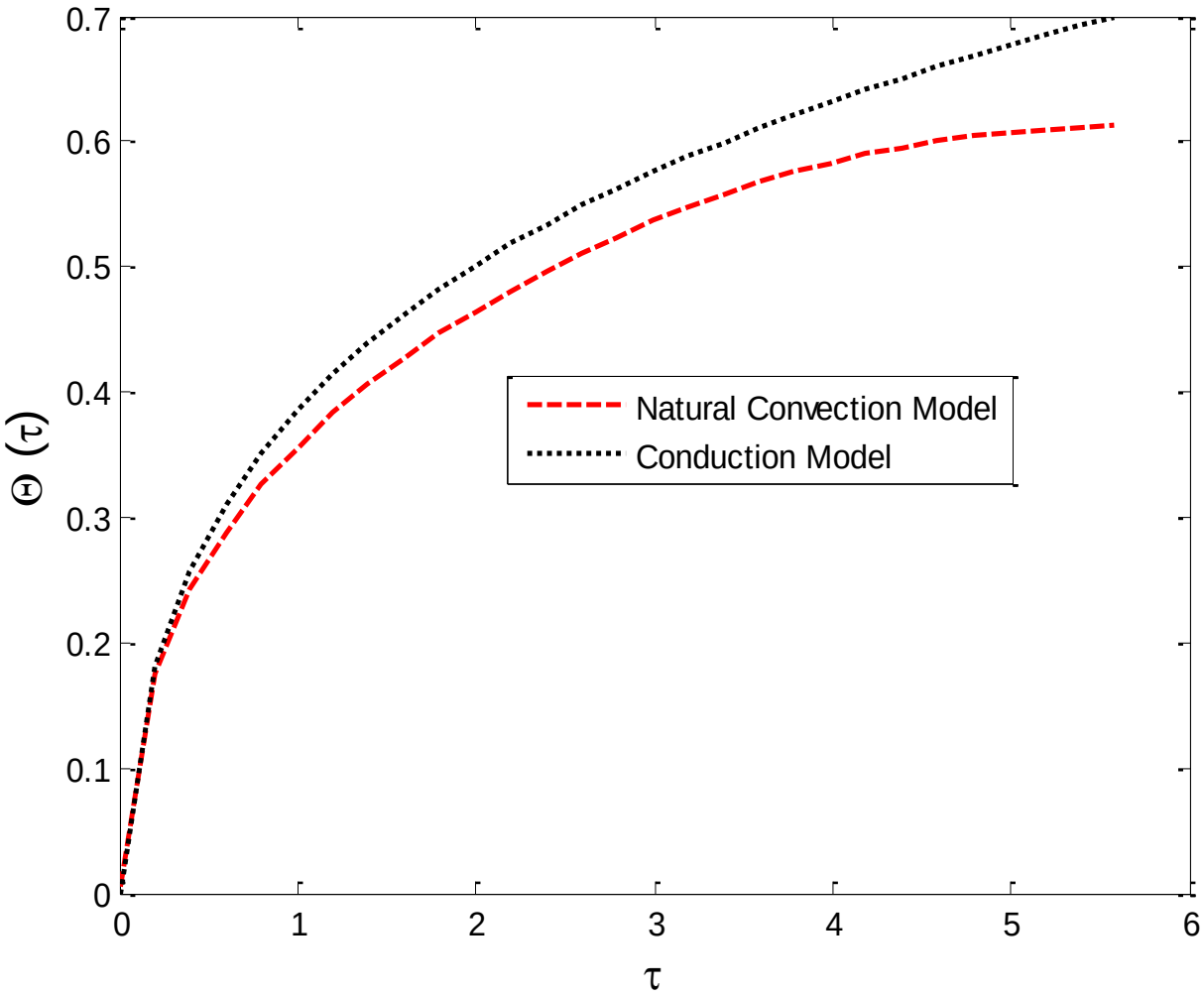
$$\mathbf{Y} = \mathbf{T}(\mathbf{P}) + \boldsymbol{\eta} \tag{19}$$

where

$$\boldsymbol{\eta} = \boldsymbol{\varepsilon} + \mathbf{e} \tag{20}$$

M. Neumayer, D. Watzenig, Helcio Orlande, Marcelo Colaço, George S. Dulikravich, Accelerated Bayesian Inference for an Inverse Heat Transfer Problem using Approximations, 2012 IEEE International Instrumentation and Measurement Technology Conference, May 13-18, 2012, Graz, Austria

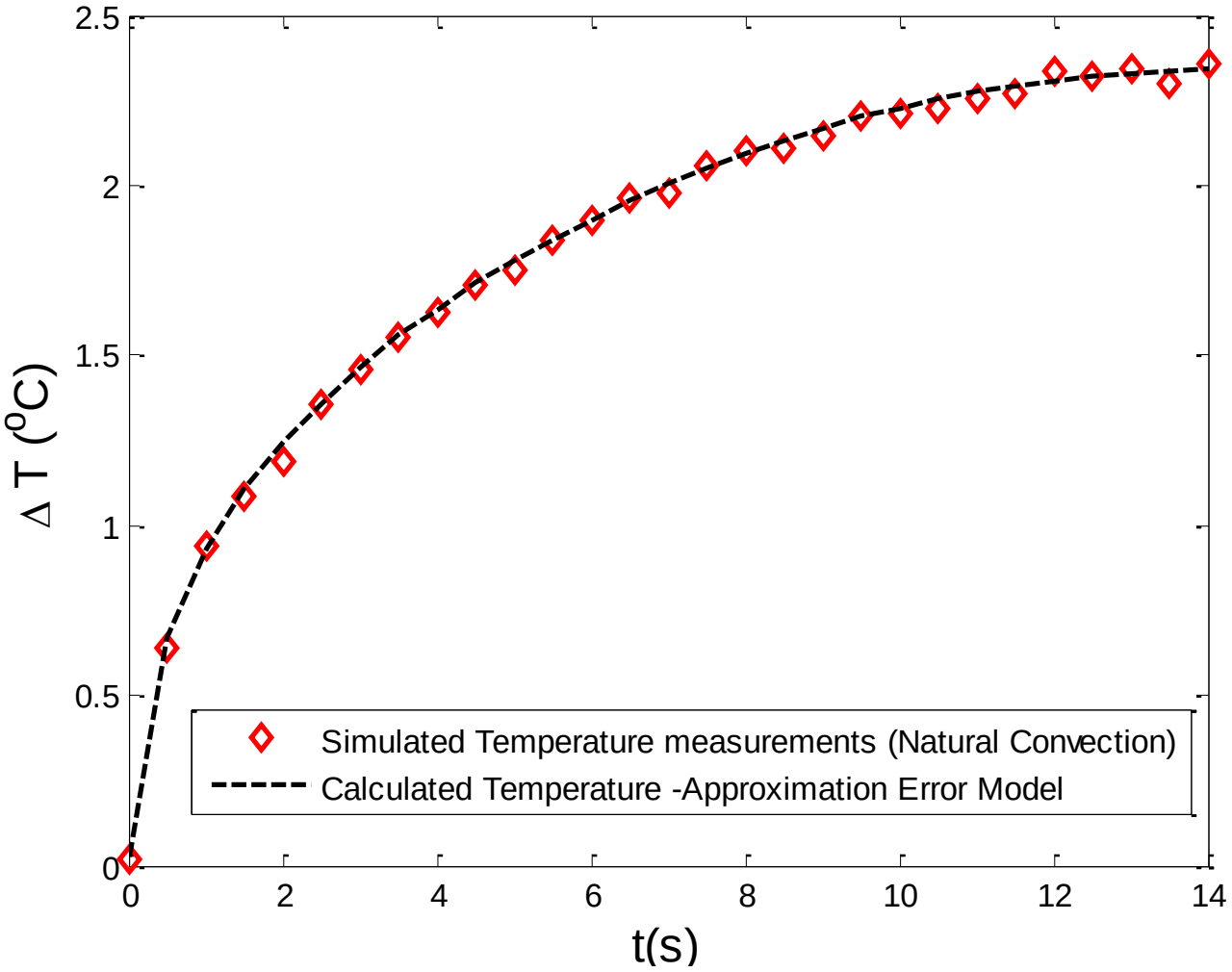
LINE HEAT SOURCE PROBE
Improvement of solutions with surrogate models



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LINE HEAT SOURCE PROBE

Improvement of solutions with surrogate models



ACKNOWLEDGEMENTS

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- **Petrobras**

DEDICATION



HELCIO ORLANDE
11/12/1938 – 10/09/2012