

Heat flux parameter estimation by the Levenberg-Marquardt Method: application to the Gas Tungsten Arc Welding.

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A bit of geography



Outlines

- ◆ What is the GTAW process?
- ◆ Context of the work / objective
- ◆ Physics involved during GTA Welding
- ◆ GTAW heat transfer and hydrodynamic model & simulation
- ◆ Inverse Boundary Heat Transfer Problem
 - Definition
 - Levenberg-Marquardt method
 - Sensitivity analysis
 - Numerical cases
- ◆ Conclusions (and future works)

GTAW process

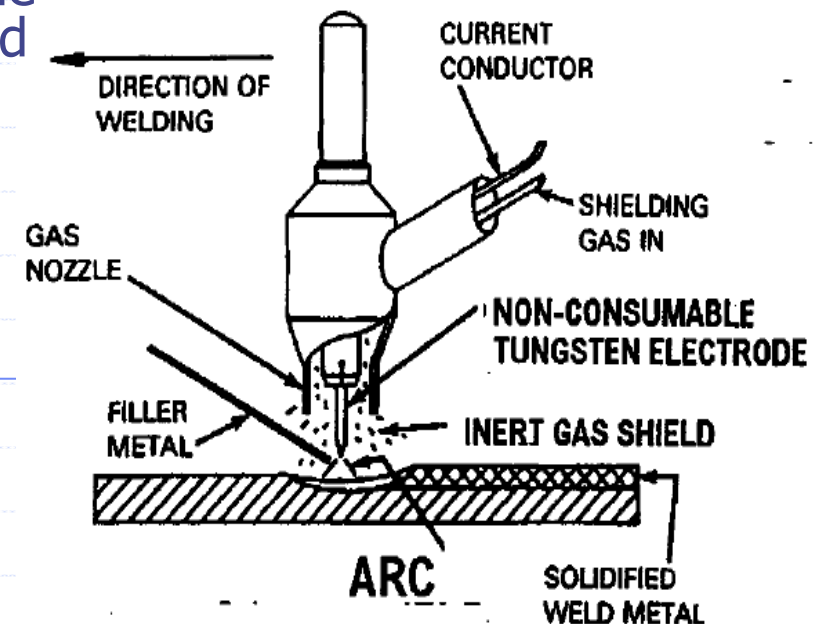
In GTAW process consist of an electrical arc maintained between a Tungsten electrode and the work piece.

The heat generated by the electrical arc melts the work piece.

Inert gas help initiating and stabilizing the electrical arc as well as it shields the weld zone from atmospheric oxydation.

Welding environment is severe:

- ◆ plasma rays in the UV range
- ◆ plasma $\sim 10000-20000\text{ }^{\circ}\text{C}$
- ◆ for welding steel $T > T_{\text{fusion}} \sim 1500^{\circ}\text{C}$
- ◆ high welding intensity ($\gg 3\text{A}$)



Context / objective

Main concerns of welding industry:

- ◆ Improving joint quality (mechanical properties ...), reducing post-welding treatments (due to geometrical deformations)
- ◆ real time detection of defect during the welding operation

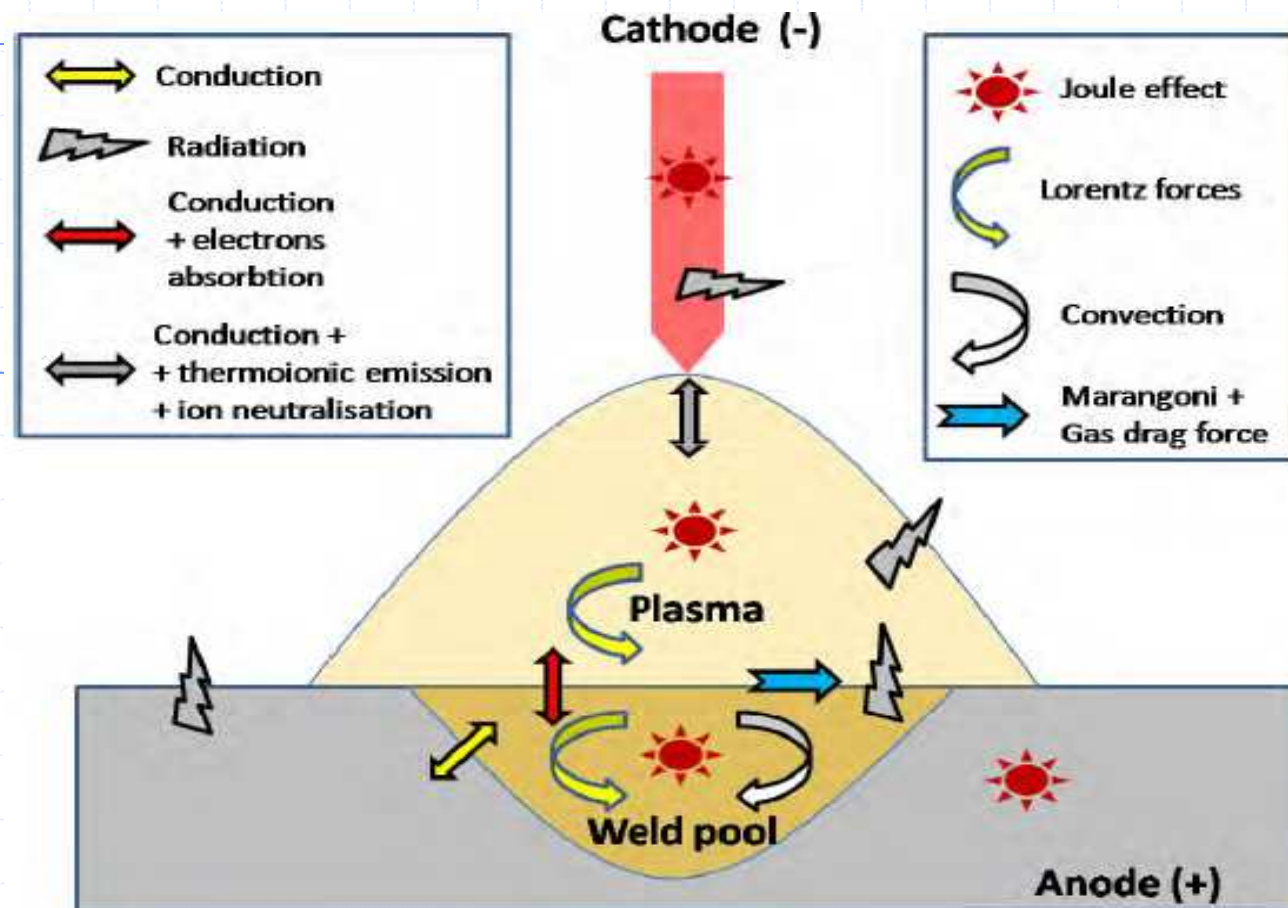
Due to the severe welding operating conditions, welding operation settings are made experimentally according to some standards.

One solution is the simulation of the welding operation in order to predict the effects of its process parameters on the final welded parts (microstructure, penetration depth ...).

We aim to link the weld pool geometry (or shape) to the welding process parameters. This weld pool geometry plays a key role in the final welded parts.

Then we established a GTAW model but some model's parameters are missing ...

GTAW- A highly coupled multiphysics problem



- Scientific Fields:**
- Electromagnetism - Arc Processes
 - Fluid dynamics - Weld pool Formation
 - Thermodynamics - Phase transformation
 - Heat transfer - Heat Input, Cooling

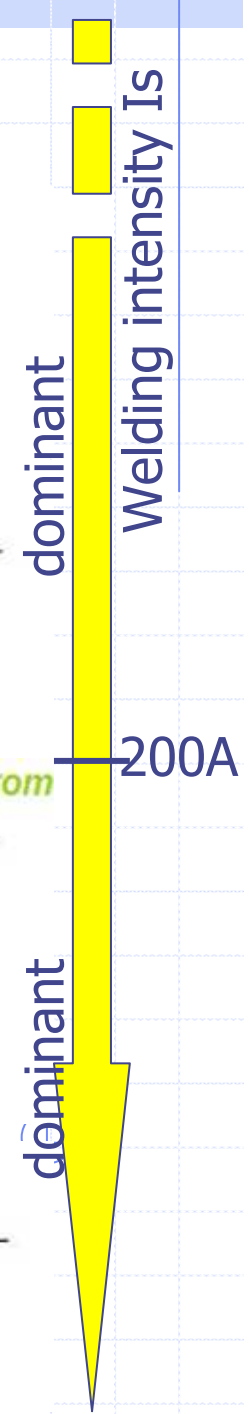
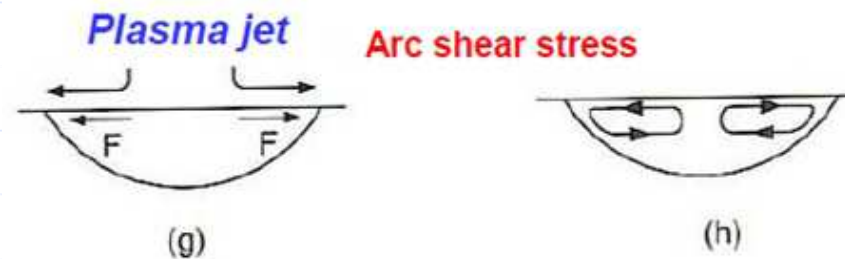
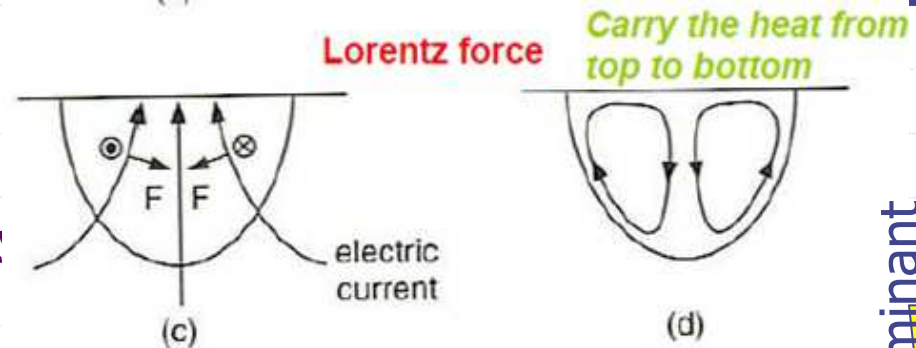
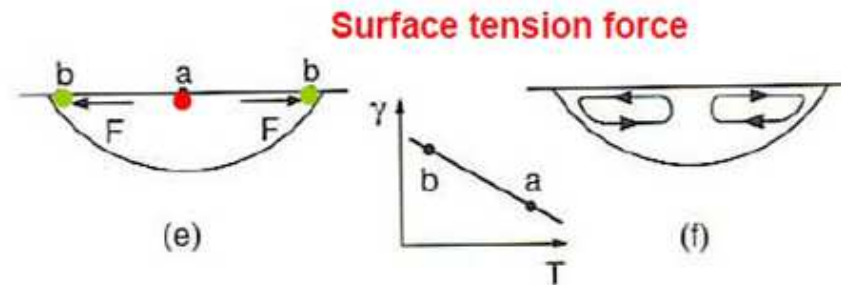
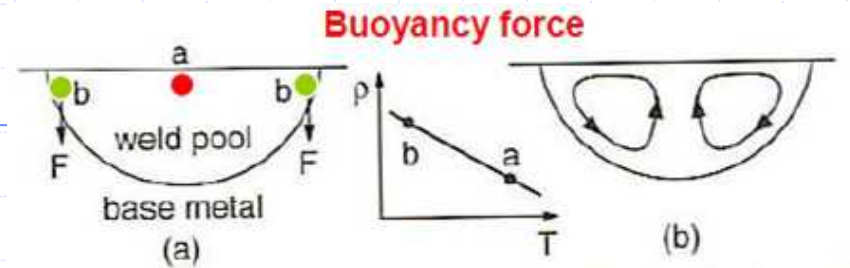
Driving Forces for Weld Pool Convection

liquid metal sinks along pool boundary and rises along pool axis.

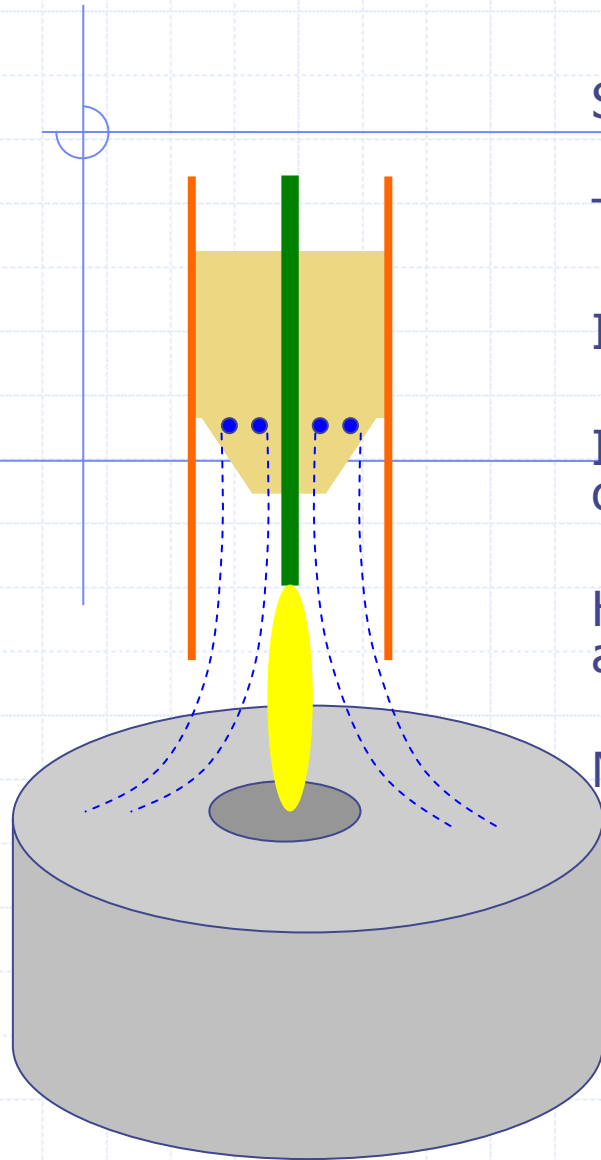
For lower surface tension, liquid metal flows from center to the edge along the pool surface.

liquid metal flows downward along pool axis and rises along pool boundary.

Metal flows from center to the edge of the pool



GTAW stated model: heat transfer and fluid flow



Static study => axisymmetric geometry

Two domains: Ω^1 fluid & Ω^2 solid

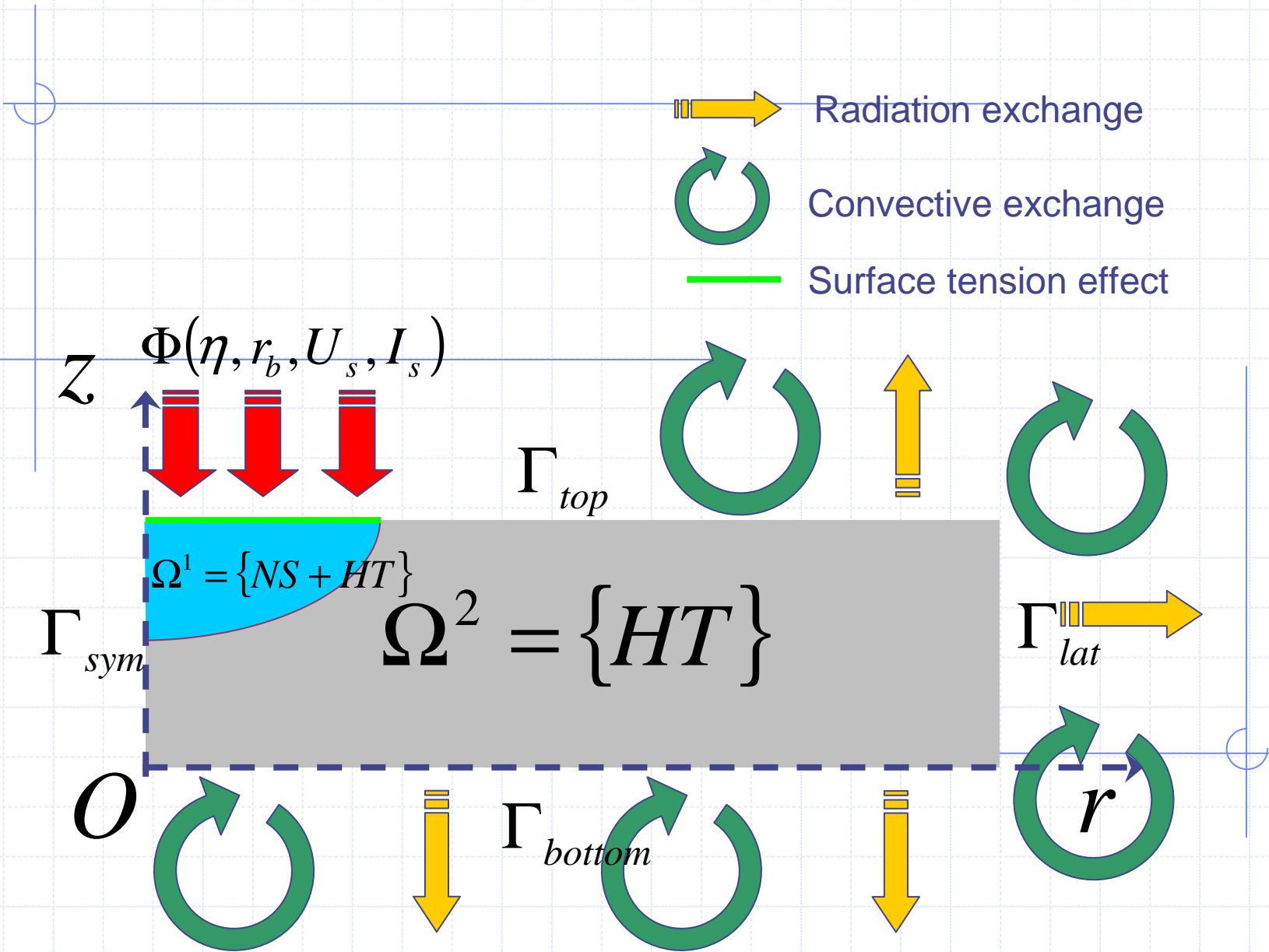
Incompressible fluid

$I_s < 200A$ => Lorentz force, arc pressure force are not considered

Heat flux is supposed to have a gaussian distribution and it is applied on top surface

Material: Carbon steel S235

Fluid flow / Navier Stokes equations



GTAW stated model: heat transfer and fluid flow

This model needs to solve the following PDE system:

- ◆ the heat transfer (HT) equation in both domains + boundary conditions
- ◆ the Naviers-Stokes (NS) equations only in the domain where the weld pool occurs + boundary conditions

In the HT problem, the heat flux generated by the electrical arc is modelled as follows:

$$\Phi(U_s, I_s, r_b, \eta) = \eta \frac{1}{2} \frac{U_s(t) \cdot I_s(t)}{\pi r_b^2} e^{-\frac{1}{2} \left(\frac{r}{r_b} \right)^2}$$

In the NS equations, two terms are added:

- ◆ one takes into account that the solid is not converted into a fluid instantaneously
- ◆ the other one is the buoyancy force

On the top surface of the weldpool (NS boundary condition) the marangoni effect (liquid surface tension) is considered as follows:

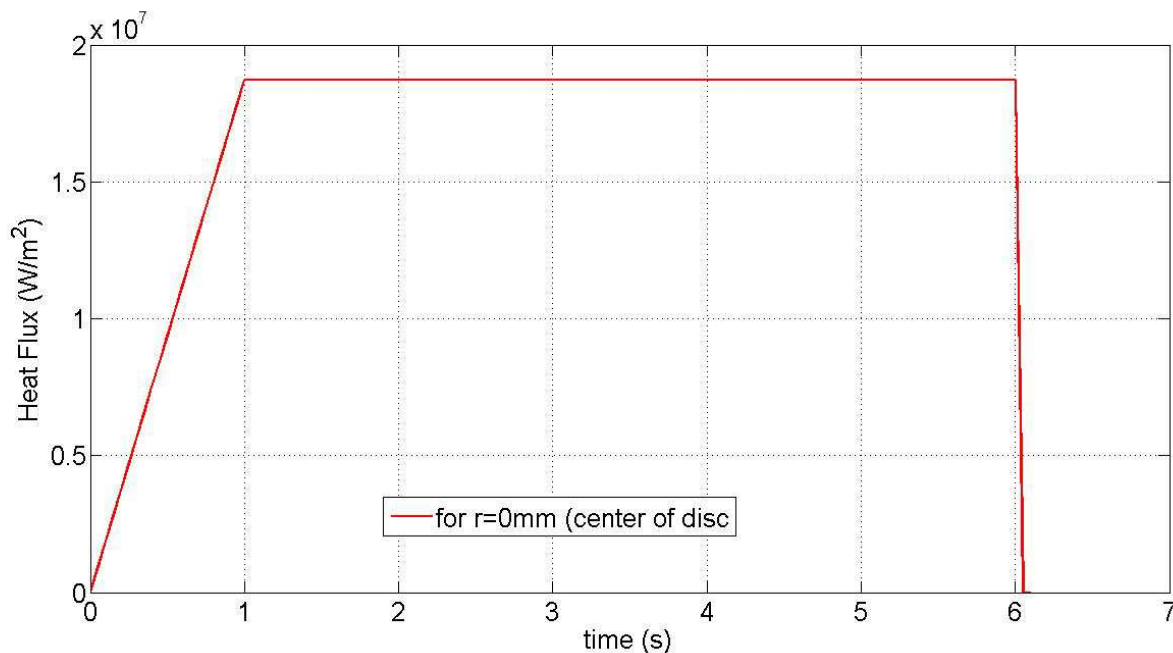
$$\mu \frac{\partial u}{\partial z} = \frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial r}$$

Heat transfer-fluid flow model simulation

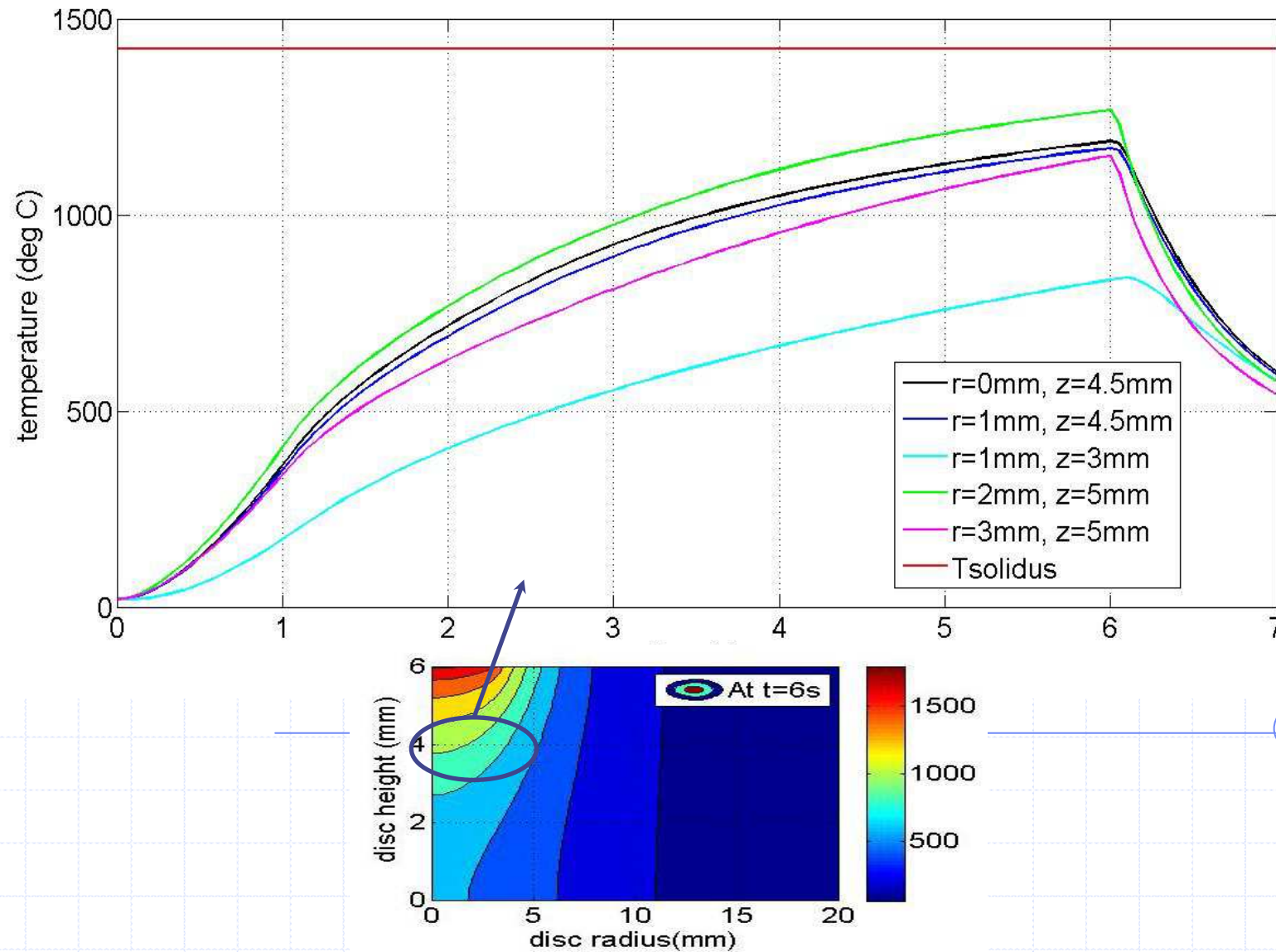
Other assumptions:

Material density, specific heat, dynamic viscosity are assumed to be temperature constant (and its value is high when the metal is solid and takes a normal value when it is fluid).

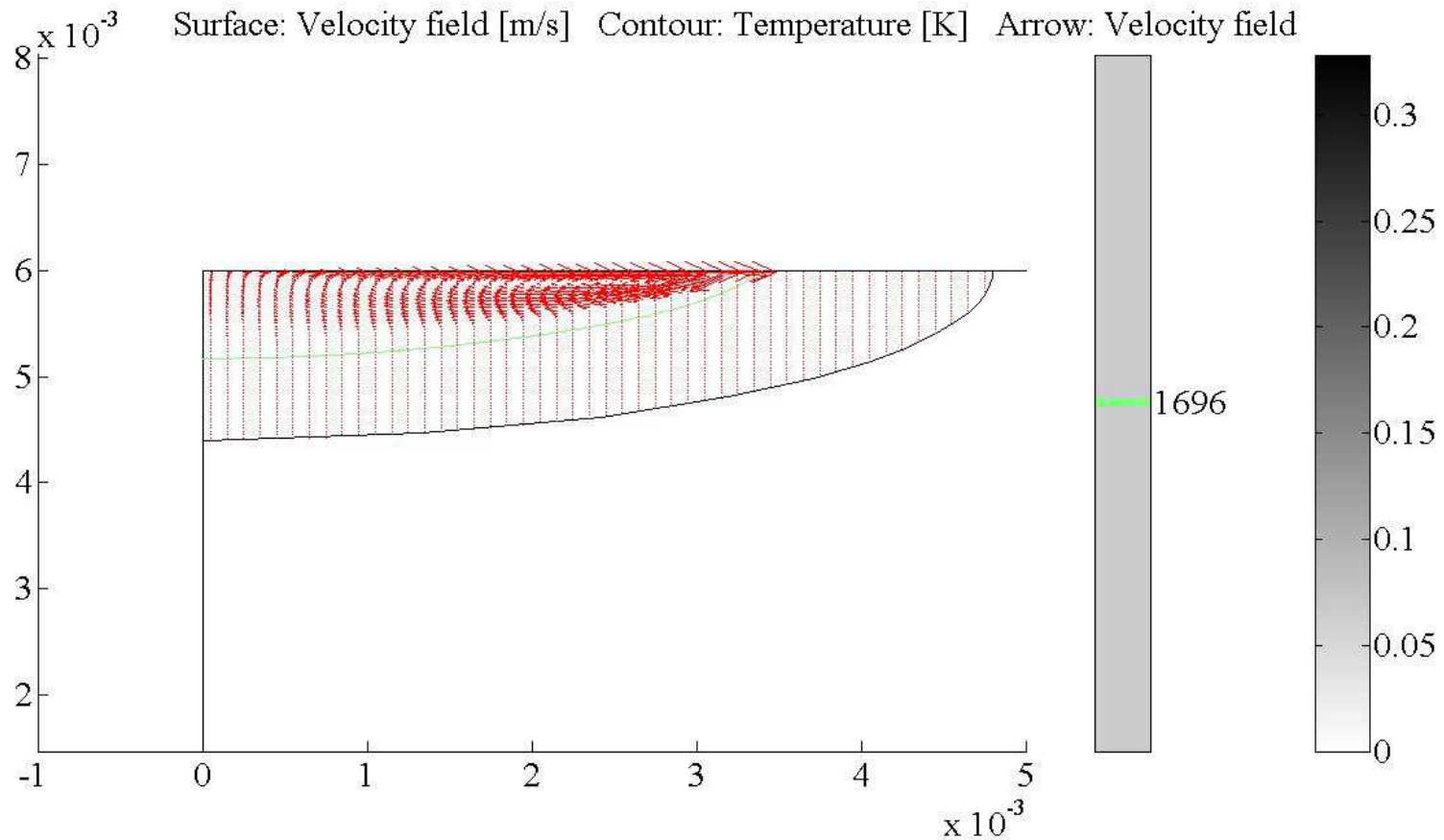
Surface tension temperature coefficient: $\frac{\partial \gamma}{\partial T} = -3.10^{-4} \text{ N.m}^{-1} . \text{K}^{-1}$



Heat transfer-fluid flow model simulation

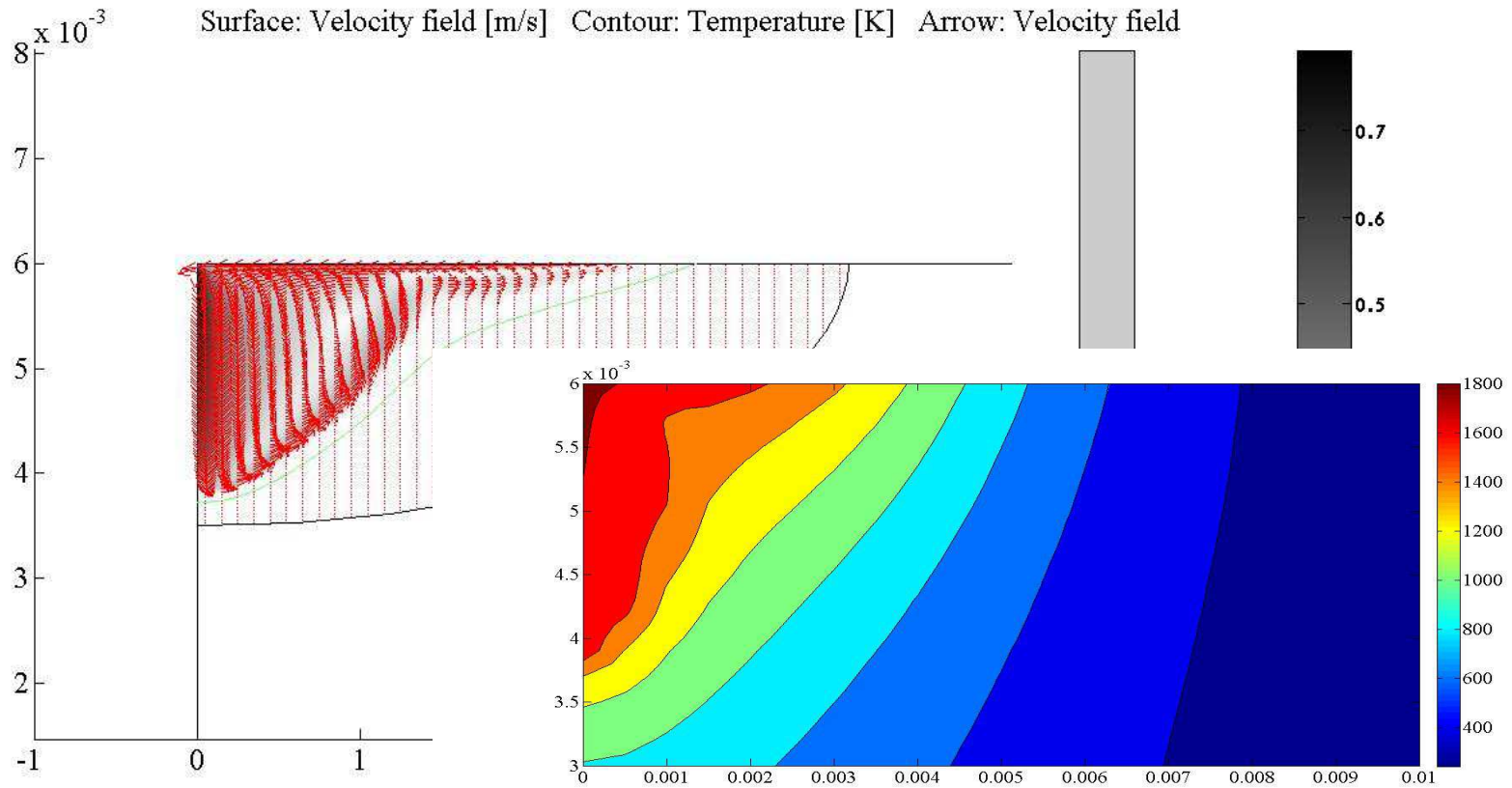


Heat transfer-fluid flow model simulation



$$\frac{\partial \gamma}{\partial T} = -3.10^{-4} \text{ N.m}^{-1} . \text{K}^{-1}$$

Heat transfer-fluid flow model simulation



=> affect the temperature distribution

$$\frac{\partial \gamma}{\partial T} = +3.10^{-4} \text{ N.m}^{-1} . \text{K}^{-1}$$

Inverse Boundary Heat Transfer Problem (IBHTP) formulation

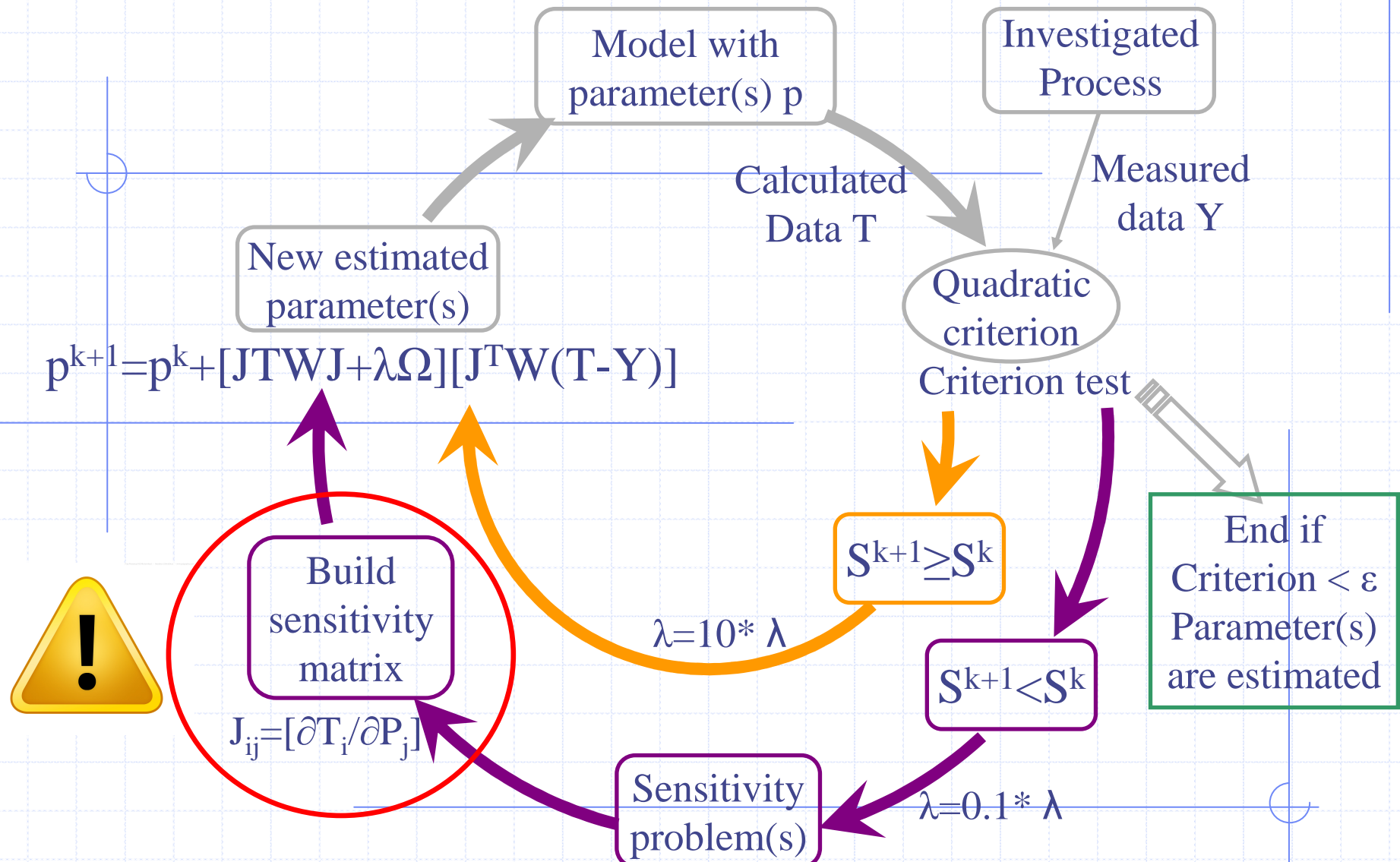
Problematic: GTAW efficiency η and Gaussian radius R_b are not well known.

Strategy: estimate these 2 parameters by an IBHTP.

IBHTP formulation:
$$S(T, \bar{z}) = \frac{1}{2} \int_{\Omega} \int_I (T_c(\vec{x}, t; \bar{z}) - \hat{T}_m(t))^2 \delta(\vec{x} - \vec{x}_i) dt d\Omega$$

=> Find the vector $\bar{z} = (\eta, R_b)$ which minimizes the cost function: $S(T, \bar{z})$

Chosen method: Levenberg-Marquardt (2 parameters only)



- LMA tends to steepest descend method
- LMA tends to Newton-Gauss method

Levenberg-Marquardt algorithm

Inverse Boundary Heat Transfer Problem (IBHTP)

Levenberg-Marquardt method

Sensitivity coefficients on the estimated parameters must be significant and linearly independent => must be checked!

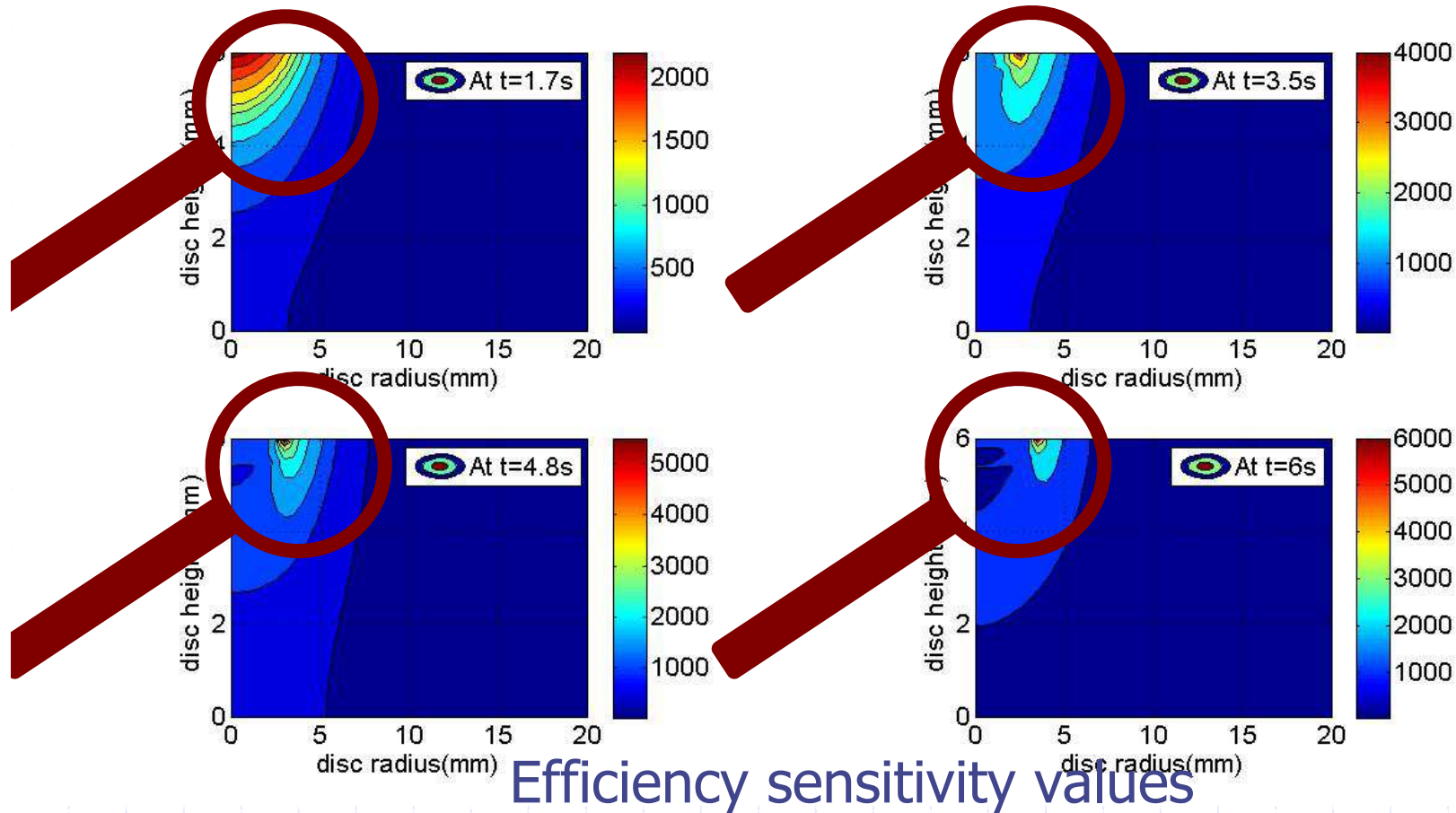
For each parameter to estimate, sensitivity coefficients will be computed by a forward difference finite scheme:

$$\frac{\partial T(\bar{z})}{\partial \bar{z}} = \frac{T_c(\bar{z} + \varepsilon \bar{z}) - T_c(\bar{z})}{\varepsilon \bar{z}} \quad \text{with } \varepsilon = 0.05$$

What are we looking for here?

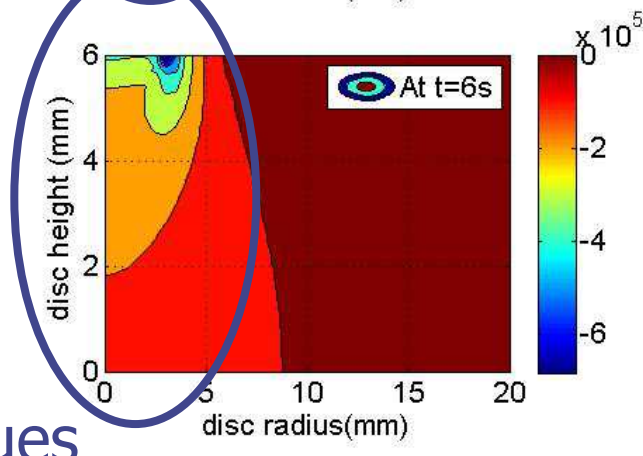
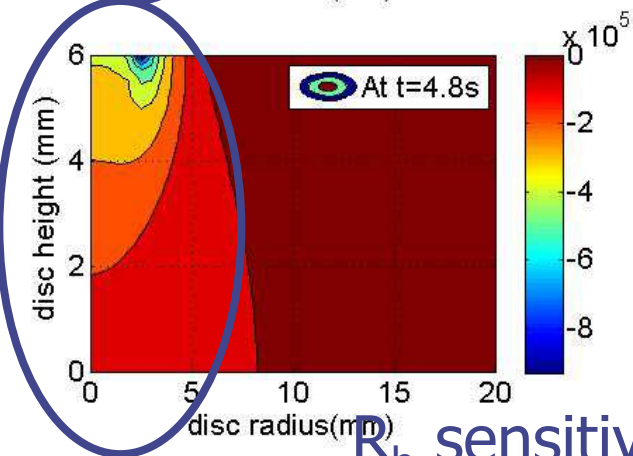
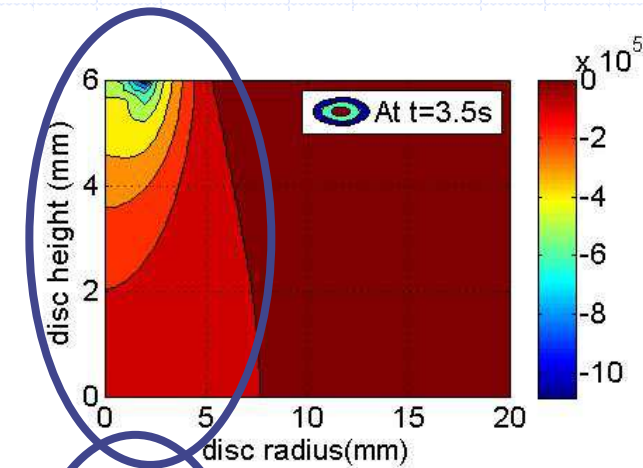
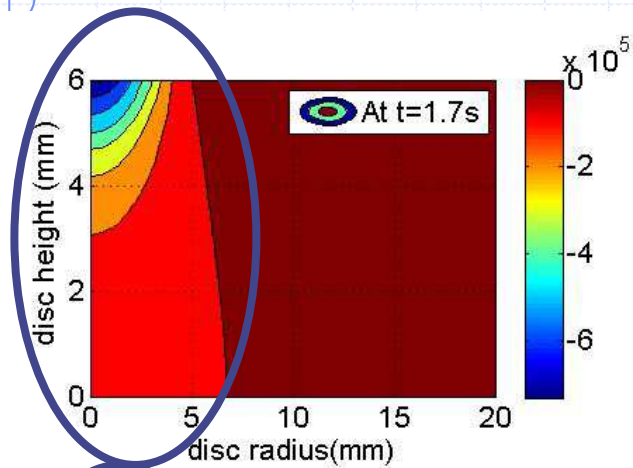
- ◆ are sensitivity coefficients significant?
- ◆ are the parameters to estimate linearly independent ?
- ◆ where and when do we have to measure the temperature?
- ◆ Can we solve this IBHTP ?

Inverse Boundary Heat Transfer Problem (IBHTP) sensitivity analysis



Most sensitive part of the domain
=> temperature measurement must be there

Inverse Boundary Heat Transfer Problem (IBHTP) sensitivity analysis

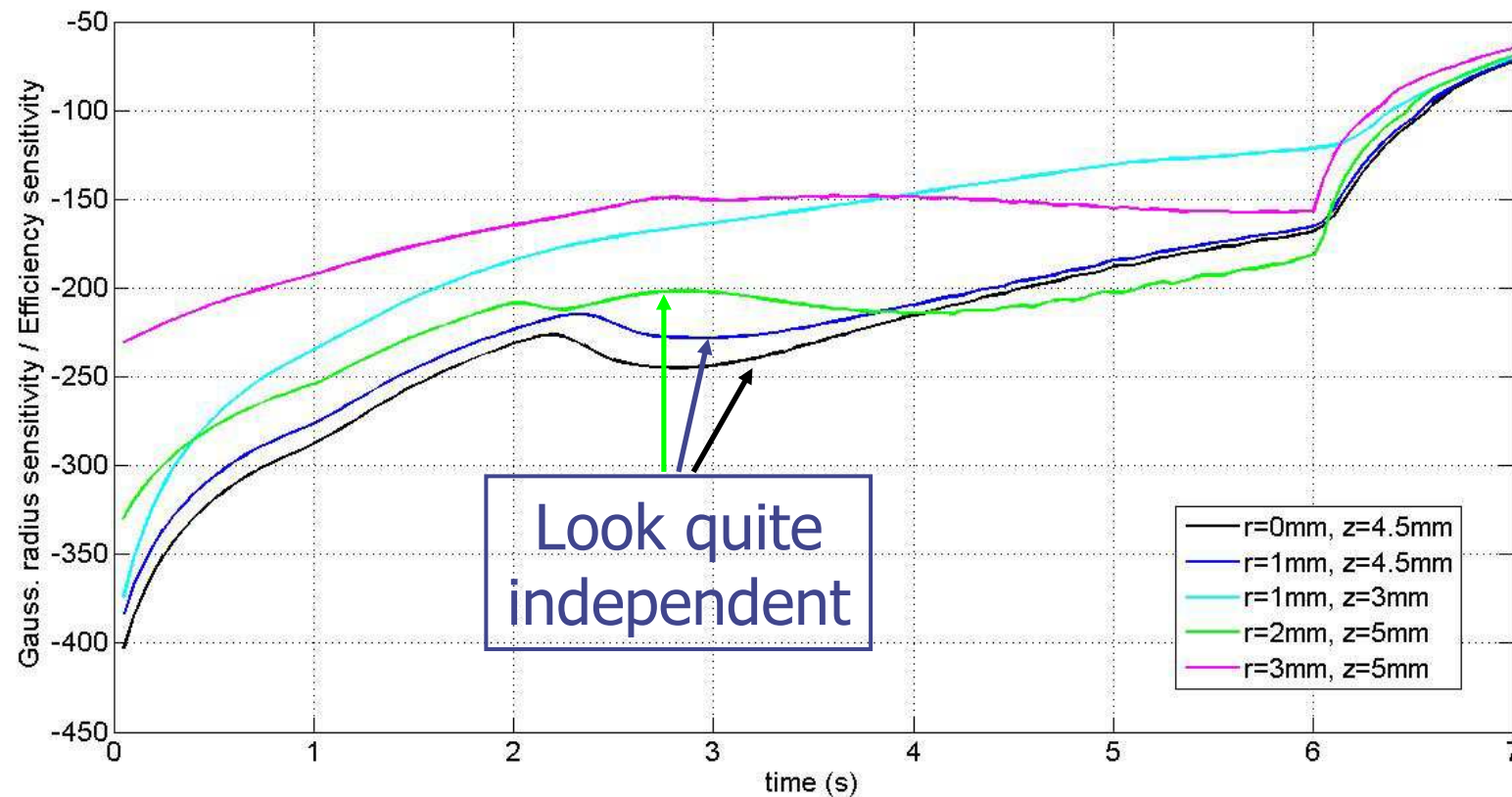


R_b sensitivity values

Pretty tough to check their independence:
=> normalised sensitivity (\Leftrightarrow degrees)

$$X(\bar{z}) = \bar{z} \cdot J(\bar{z})$$

Inverse Boundary Heat Transfer Problem (IBHTP) sensitivity analysis



Parameters to estimated look linearly independent IF
Temperature measurement are close to sollicitated boundary

How is this method set up in Matlab®

Load measured temperatures (input data)

Test loop 1: $S(p^k) < S_{\text{stop}}$ (if true, go to 2)

[1] Solve **forward_problem.m** (comsol file converted in matlab file)

Export calculated temperatures from Comsol structure to Matlab

Compute criterion $S(p^k)$

Test loop 2: $S(p^k) < S(p^{k-1})$ or first iteration

$\lambda = 0.1 * \lambda$ (if not first iteration)

Solve the **sensitivity_problems.m** (comsol files converted in matlab files)

Export each calculated sensitivities from Comsol structure to Matlab

Build up the sensitivity matrix $J(p^k)$

Compute the new set of parameters $p = [R_b, \text{Eff}]$

Else

$\lambda = 10 * \lambda$

Compute the new set of parameters, ...,,

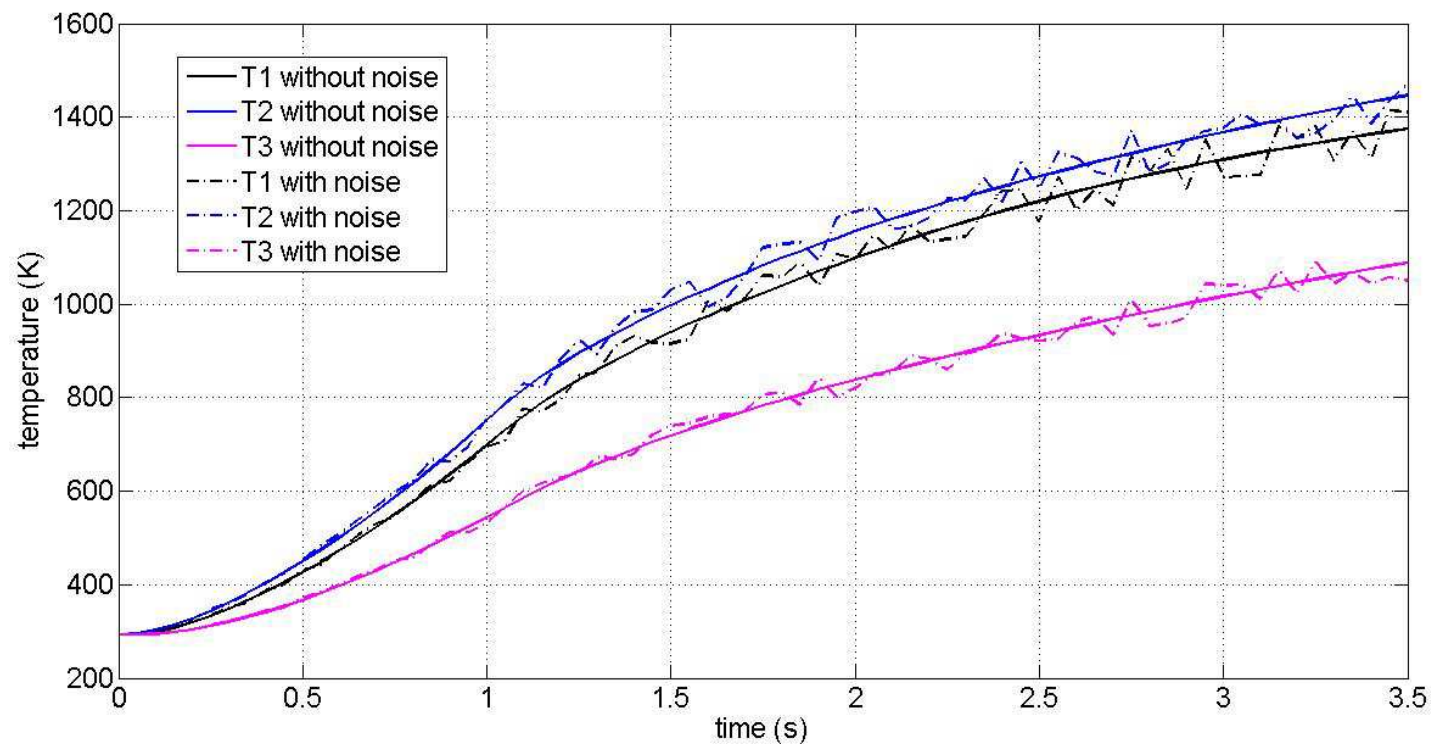
End test 2

[2] End test 1

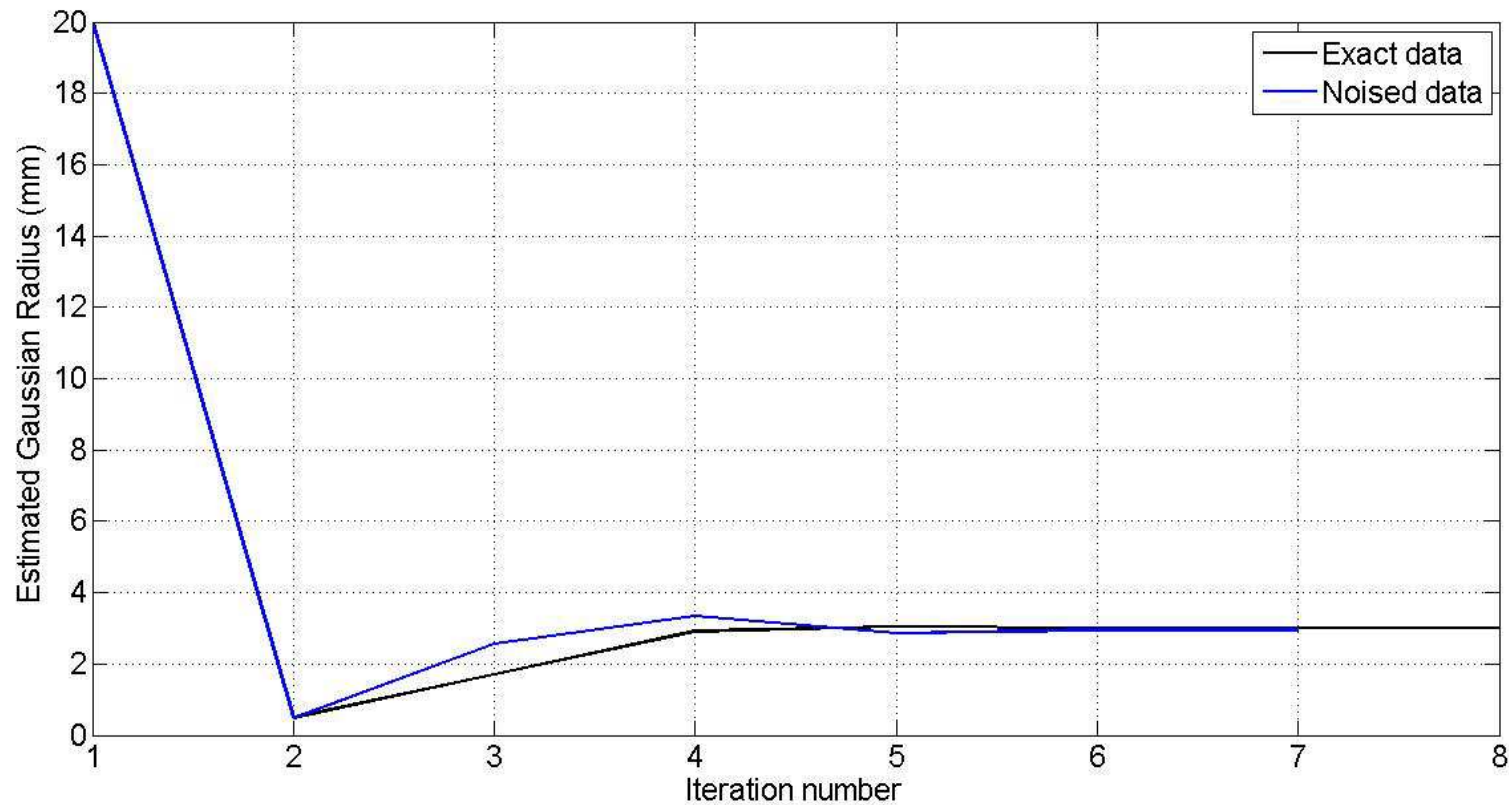
Inverse Boundary Heat Transfer Problem (IBHTP) numerical cases

Two numerical cases:

- ◆ 1st IBHTP is solved with exact input temperatures (without any noise)
- ◆ 2nd IBHTP is solved with noised input temperatures ($\sigma \pm 5\%$ of current T_p)



Inverse Boundary Heat Transfer Problem (IBHTP) numerical cases



Inverse Boundary Heat Transfer Problem (IBHTP) numerical cases

The sensitivity matrix can be used to compute the Hessian matrix.

By assuming that the inverse of the Hessian matrix is related to the Covariance matrix, we can evaluate the accuracy on the estimated parameters since:

$$\sigma_{(p_i)}^2 = Cov(\bar{p})_{ii}$$

	Exact values	Case 1	Case 2 (noised)	Accuracy (%)	σ
Gauss. Radius	3 mm	3 mm	2.955 mm	0.2	± 0.8 mm
Efficiency	0.7	0.7	0.69	1.4	± 0.0008

Conclusions & future works

Preliminary study

A GTAW heat transfer fluid-flow model was simulated.

An inverse problem was stated in order to estimate two parameters describing the heat flux. The Levenberg-Marquardt Algorithm was used.

According to the sensitivity analysis, temperature data must be measured close to where is applied the heat flux.

With relevant input temperature data and GTAW model, the two parameters can be estimated accurately.

However this GTAW modelling is pretty « simplified »:

- Some model's parameters = temperature constant
- ElectroMagnetism is not considered (Lorentz force)
- Free surface + arc plasma pressure are not considered

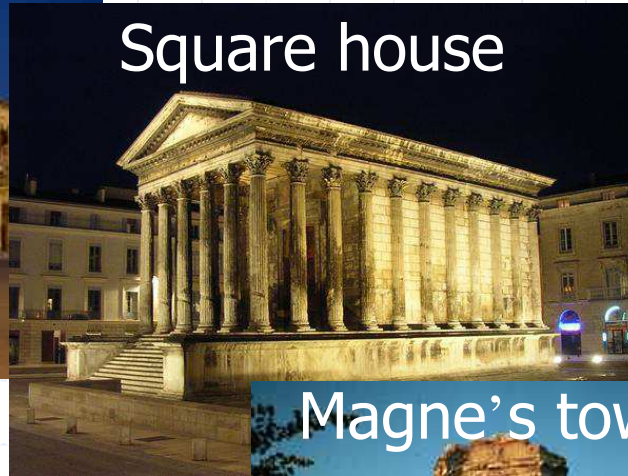
=> next stage.

Nîmes and around ...

Nîmes's roman arena



Square house



Magne's tower



Thank you / Merci

Thanks to the
INVW05
organising
committee for let
me present
this topic.



« Pont du gard »