ESTIMATION OF SOIL AND GROUT THERMAL PROPERTIES THROUGH GEOTHERMAL RESPONSE TEST

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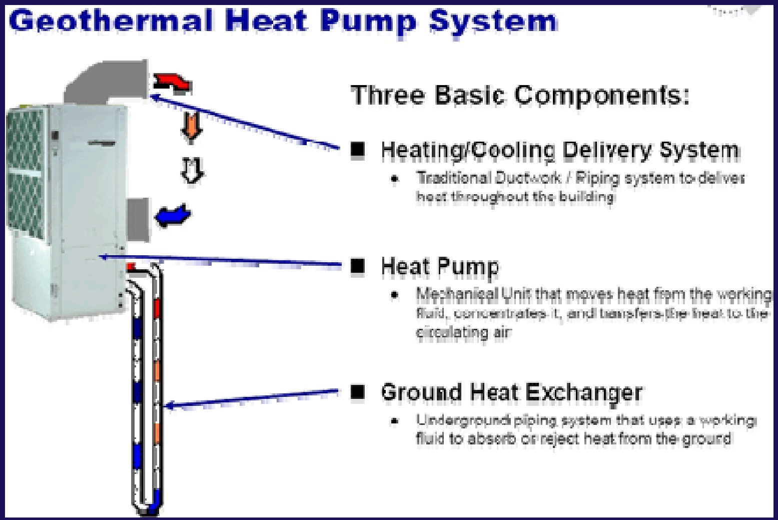
INTRODUCTION



- On account of environmental and energetic emergency, the usage of high efficiency energy systems, like ground coupled heat pumps (GCHP), has been advanced.

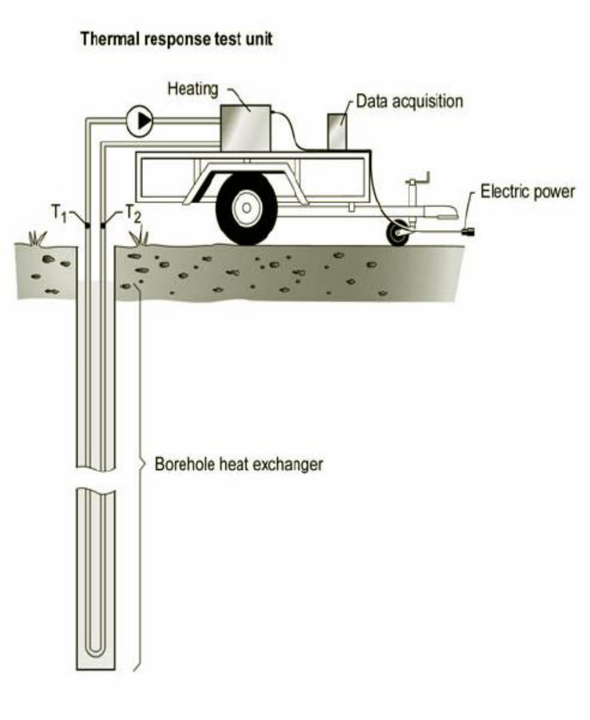
- As a matter of fact the soil represents one of the most attractive heat sources thanks to its temperature that is year round roughly constant

INTRODUCTION

➢ The proper design of the GCHP, particularly of the ground heat exchanger (GHE), requires the knowledge of the soil thermal properties.

➢Overestimating borehole resistance produces an oversized design that results in immediate significant expenses that cannot be repayed, even in long time.

GEOTHERMAL RESPONSE TEST



- For estimating ground proprieties and for evaluating the performance of existing GHE, the Thermal Response Test (TRT) method is often adopted.

- It consists in providing constant heat power to a carrier fluid (usually water), which is circulated through the GHE.

- The elaboration of TRT data allows to set out the two most important properties for the GHE design :

- soil thermal conductivity (λ_{eq})

- borehole thermal resistance (Rb_{eq}).

GEOTHERMAL RESPONSE TEST

Many are the methods used to elaborate TRT data:

- **LINE SOURCE METHOD**

based on an approximated analytical solution for a constant-heat-output line source in an infinite medium.

Very simple but small perturbation in the power input produce big error. Moreover, these approaches require quasi steady-state data for good results and, consequently, they need, at least, 80 hours to be carried out

- **PARAMETER ESTIMATION BASED METHOD**

Various input, especially the ground thermal cunductivity, are adjusted systematically on a numerical model of the the borehole and surrounding ground.

Although these techniques are more complex than the standard TRT method, they allow getting results already in a transient thermal regime, reducing the time requested by the test to 50 hours; moreover, they allow simultaneously restoring both the soil and the grout thermal diffusivity.

GOAL OF THIS PAPER

- A flexible parameter estimation technique based on a 3D numerical model of the geothermal system is applied to simulated TRT data, in order to validate a procedure aimed to restore the proper value of both the soil and the grout thermal properties.

- 4 proprieties are restored:

  - grout thermal conductivity (λ_g)
  - grout heat capacity per unit volume (C_g)
  - soil thermal conductivity (λ_s)
  - soil heat capacity per unit volume (C_s)

PARAMETER ESTIMATION PROCEDURE

A procedure, suitable to estimate unknown parameters through the comparison between experimental results and the corresponding theoretical model, is based on least squares minimization:

$$S(\mathbf{P})=[\mathbf{Y}-\mathbf{T}(\mathbf{P})]^T[\mathbf{Y}-\mathbf{T}(\mathbf{P})]$$

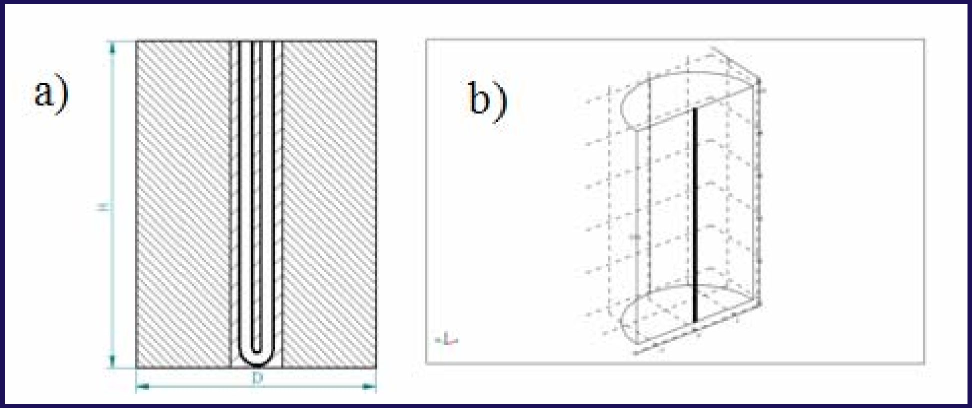
Steps: $\mathbf{P}^{k+1}=\mathbf{P}^{k}+\Delta\mathbf{P}^{k}$

Based on the Gauss Linearization Method:

$$\min_{\Delta \mathbf{P}^k} S(\mathbf{P}^{k+1})=\min_{\Delta \mathbf{P}^k} [\mathbf{Y}-\mathbf{T}(\mathbf{P}^k+\mathbf{J}^k\Delta\mathbf{P}^k)]^T[\mathbf{Y}-\mathbf{T}(\mathbf{P}^k+\mathbf{J}^k\Delta\mathbf{P}^k)]$$

Procedure assisted by the 3D numerical simulation of the Geothermal System implemented within the **Comsol Multiphysics®** environment

NUMERICAL MODEL



Geothermal Energy Storage System's Geometry

3D transient conduction heat transfer problem within the soil, the grout and the HDPE tubes is coupled with the 1D convective problem within the carrier fluid

- **1D convective problem within the carrier fluid:**
  Weak Form to the U-tube lateral surface

- **Power supplied to the working fluid:**
  Periodic edge condition inlet-outlet

GOVERNING EQUATIONS

$$\rho c_p \frac{\partial T}{\partial t} = div(\lambda \nabla T)$$

$T(r, z, 0) = T_0$ Initial condition

$-\lambda \left.\frac{\partial T}{\partial r}\right|_{r=r_t} = h_o\left[T_{fluid}(z,t) - T\,(r_t, z, t)\right]$ Boundary condition

Transient tri-dimensional heat transfer conduction governed by the Fourier equation is solved in the domain of the soil, the filling material and the high density polyethylene tubes.

By assuming that the convection problem in both the tubes of the heat exchanger is one-dimensional

$$A\ \rho_f c_{pf}\left(\frac{\partial T_i}{\partial t} + u\ \frac{\partial T_i}{\partial z}\right) = h_o\left[T\ (r_t, z, t) - T_i(z,t)\right]$$

$T_i(z, 0) = T_0$ Initial condition

Energy equation for the right-tube downward fluid flow

$$A\ \rho_f c_{pf}\left(\frac{\partial T_f}{\partial t} - u\ \frac{\partial T_f}{\partial z}\right) = h_o\left[T\ (r_t, z, t) - T_f(z,t)\right]$$

$T_f(z, 0) = T_0$ Initial condition

Energy equation for the left-tube upward fluid flow

GOVERNING EQUATIONS

The U-connection at the bottom of the pipe between the downward and upward fluid is here modelled by imposing for z=H that the mean temperature of the upward fluid equals the mean temperature of the downward fluid:

$$T_i(H,t) = T_f(H,t)$$

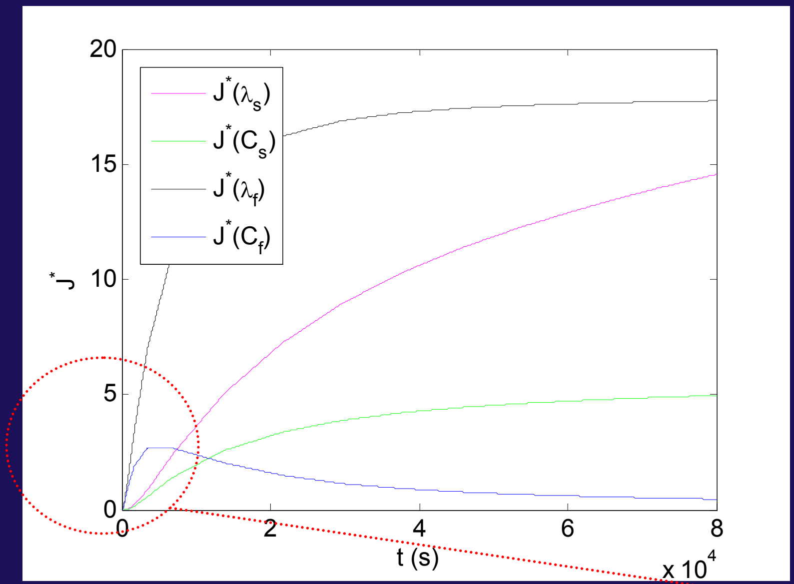
The condition of power supplied to the working fluid is implemented by the periodic edge condition:

$$T_i(0,t) = T_f(0,t) + \Delta T$$

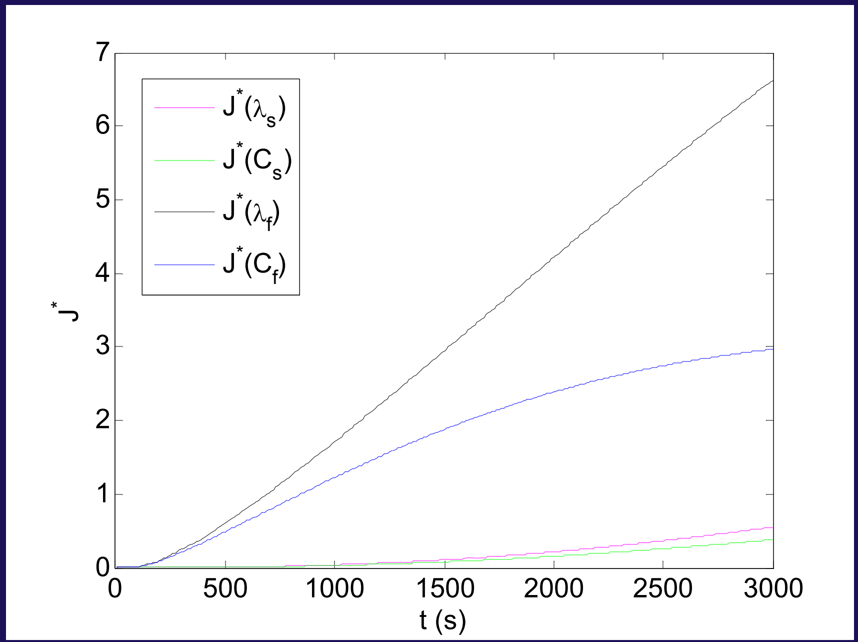
with ΔT constant over the whole temporal domain.

SENSITIVITY ANALYSIS

Sensitivity analysis versus time for 22 hours



Sensitivity analysis versus time for 3000 seconds



DIMENSIONLESS PARAMETER SENSITIVITY:

$J^*(j) = J_j * P_j$

TWO-STEPS PARAMETER ESTIMATION PROCEDURE

The sensitivity analysis suggests to split the estimation procedure into two steps:

STEP 1: $t < 3000$ s

Estimation of grout thermal conductivity (λ_g) and heat capacity per unit volume (C_g)

λ_g C_g → INPUT STEP 2

STEP 2: 1 h $< t <$ 22 h

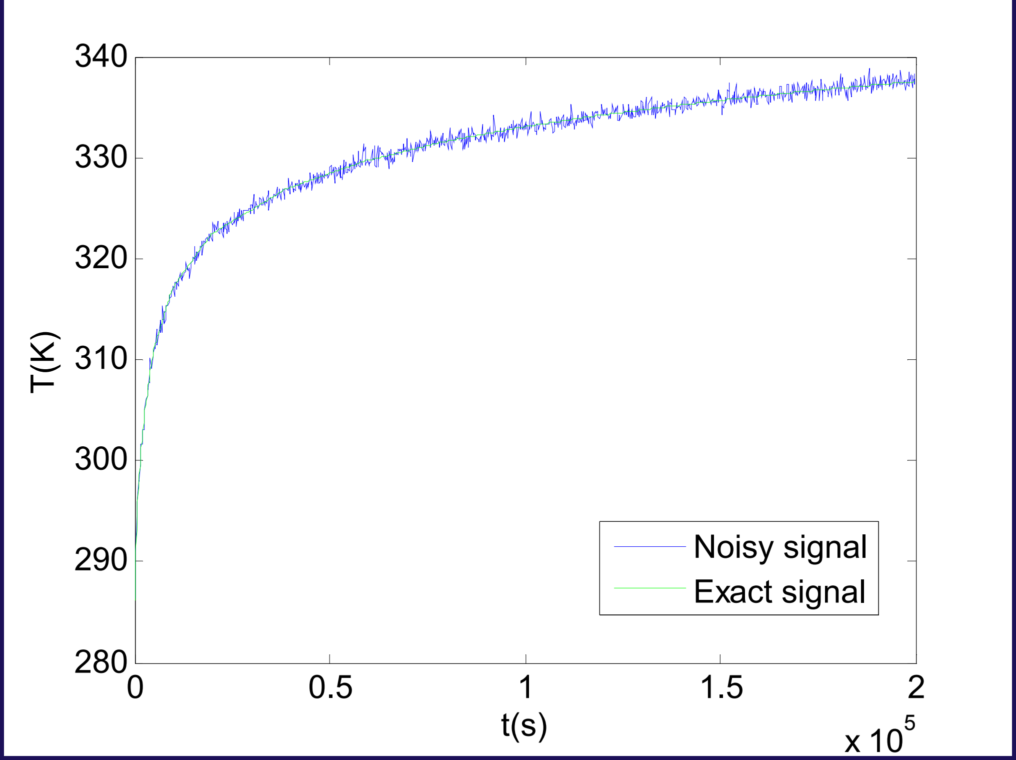
Estimation of soil thermal conductivity (λ_s) and heat capacity per unit volume (C_s)

SIMULATED EXPERIMENTAL DATA

The signal representative of the experimental outlet fluid temperature distribution has been simulated

Exact numerical signal
+
Random Gaussian noise N(0; 0.5^2)

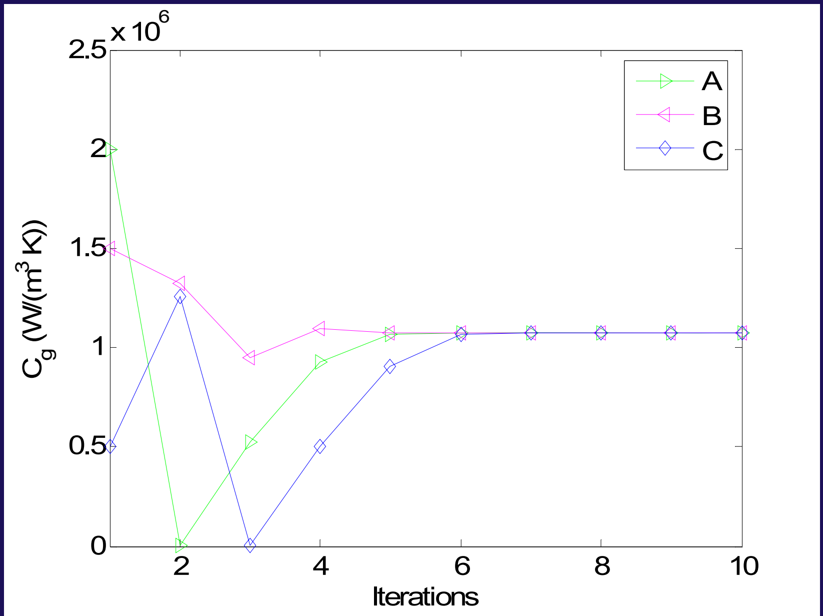
λ_g	0.9	W/(m K)
C_g	1.0	MJ/(m^3 K)
λ_s	2.0	W/(m K)
C_s	2.0	MJ/(m^3 K)



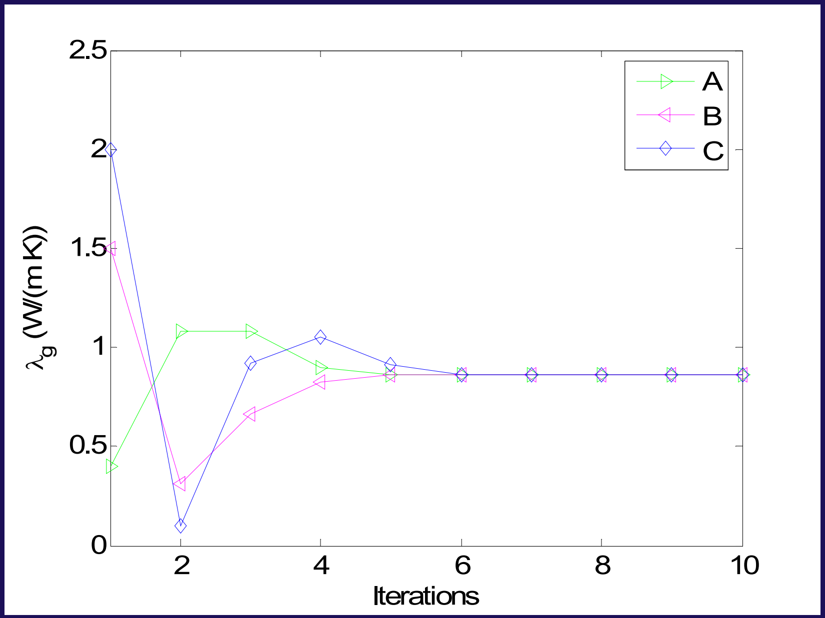
RESULTS – STEP 1

GROUT initial guess values

	λ_{g0} (W/m K)	C_{g0} (MJ/m^{3}K)
A	0.4	2.0
B	1.5	1.5
C	2.0	0.5



Iterations to GROUT heat capacity per unit volume convergence

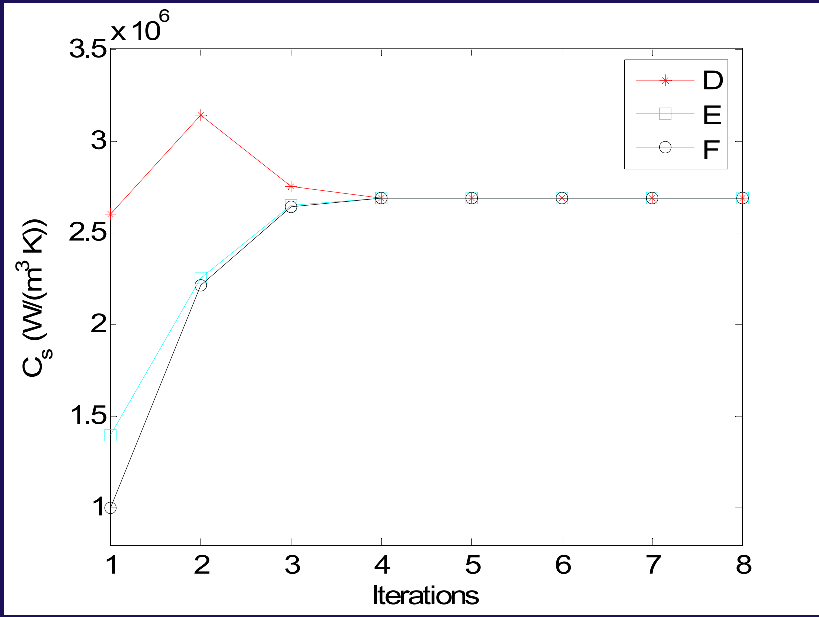


Iterations to GROUT thermal conductivity convergence

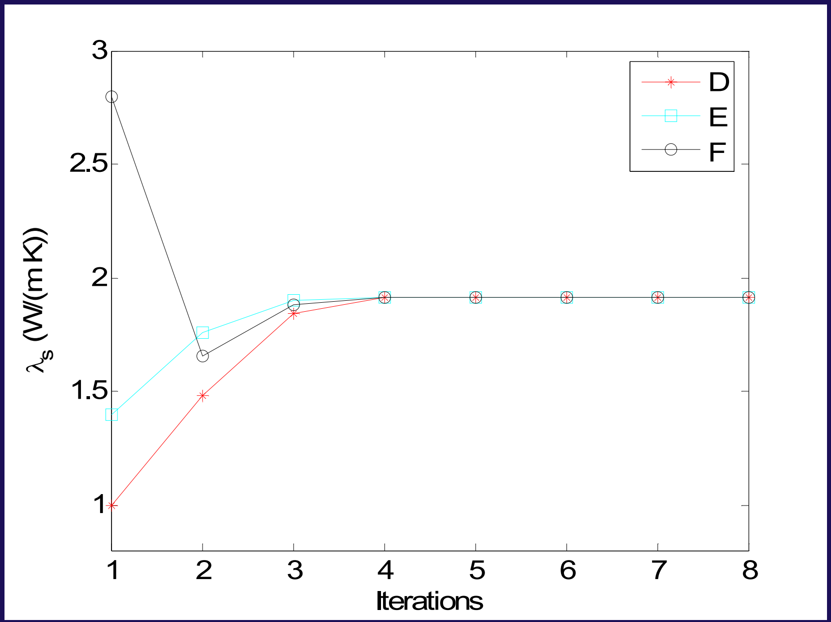
RESULTS – STEP 2

SOIL initial guess values

	λ_{s0} (W/m K)	C_{s0} (MJ/m^{3}K)
D	1.0	2.6
E	1.4	1.4
F	2.8	1.0



Iterations to SOIL heat capacity per unit volume convergence



Iterations to SOIL thermal conductivity convergence

RESULTS

	Target value	Estimated value	Error
λ_g W/(m K)	0.9	0.86	**4.4 %**
C_g MJ/(m^3 K)	1.0	1.07	**7.5 %**
λ_s W/(m K)	2.0	1.91	**4.5 %**
C_s MJ/(m^3 K)	2.0	2.68	**34 %**

To improve the accuracy, further reiterations of these two steps are considered

REITERATIONS IMPROVEMENT

λ_{g0} C_{g0}

λ_{s0} C_{s0}

R = 1

STEP 1: t < 3000 s

Estimation of

λ_{g1} and C_{g1}

λ_{g1} C_{g1}

STEP 2: 1 h < t <22 h

Estimation of

λ_{s1} and C_{s1}

λ_{g1} C_{g1}

λ_{s1} C_{s1}

λ_{s1} C_{s1}

R = 2

STEP 1: t < 3000 s

Estimation of

λ_{g2} and C_{g2}

λ_{g2} C_{g2}

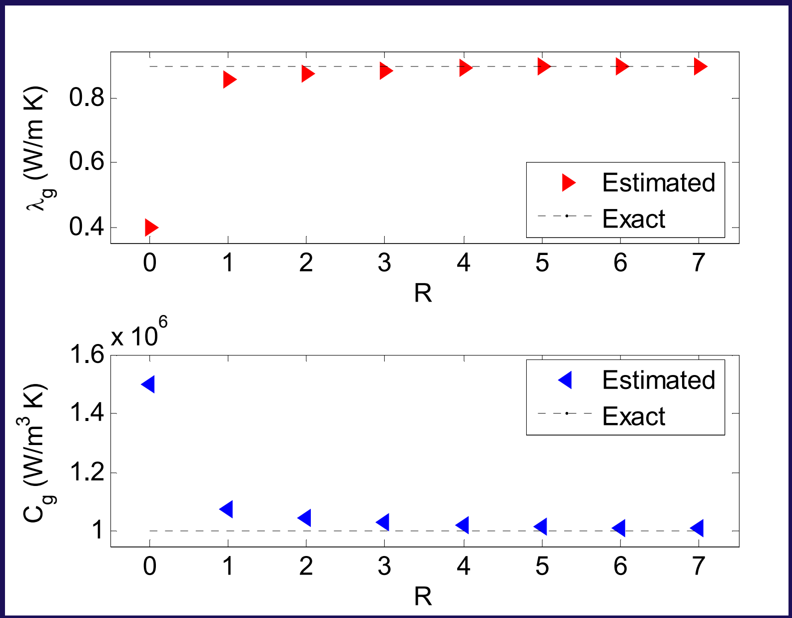
STEP 2: 1 h < t <22 h

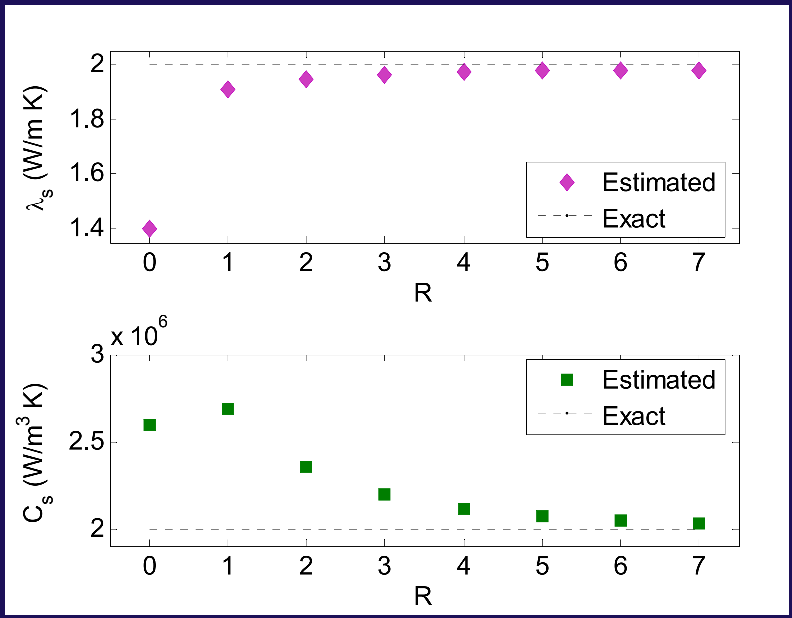
Estimation of

λ_{s2} and C_{s2}

R = …

RESULTS - REITERATIONS





Convergence of the grout and the soil thermal properties values

R = number of the <u>consecutive applications</u> of the <u>two-steps</u> iterative estimation <u>procedure</u>

CONCLUSIONS

- The iterative two-steps parameter estimation procedure estimates λ_g and λ_s with an accuracy of less than 1%, while C_g and C_s with an accuracy of less than 1.5%.
- The results allow validating the procedure applied to restore the proper value of both the soil and the grout thermal properties by considering a global time interval of 22 hours.
- The procedure requires a long computational time (with a good laptop): 1/2 hour for direct simulation of 20 m length exchanger, 5 hours for a single two-step iteration, 35 hours for the whole iterative procedure.
- The computational time required for the application to a 200 m length GHE: many weeks !

CONCLUSIONS

- This procedure has to be tested on real experimental data.
- Thank to **Professor James V. Beck** and to **Oak Ridge National Laboratory** we are testing this procedure on medium-scale laboratory GHE.
- In the real plants, there are uncertainties on borehole radius and the distance between the two pipes.