Finite element analysis of heat transfer in double U-tube Borehole Heat Exchangers

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An introduction on Ground-Coupled Heat Pump (GCHP) systems

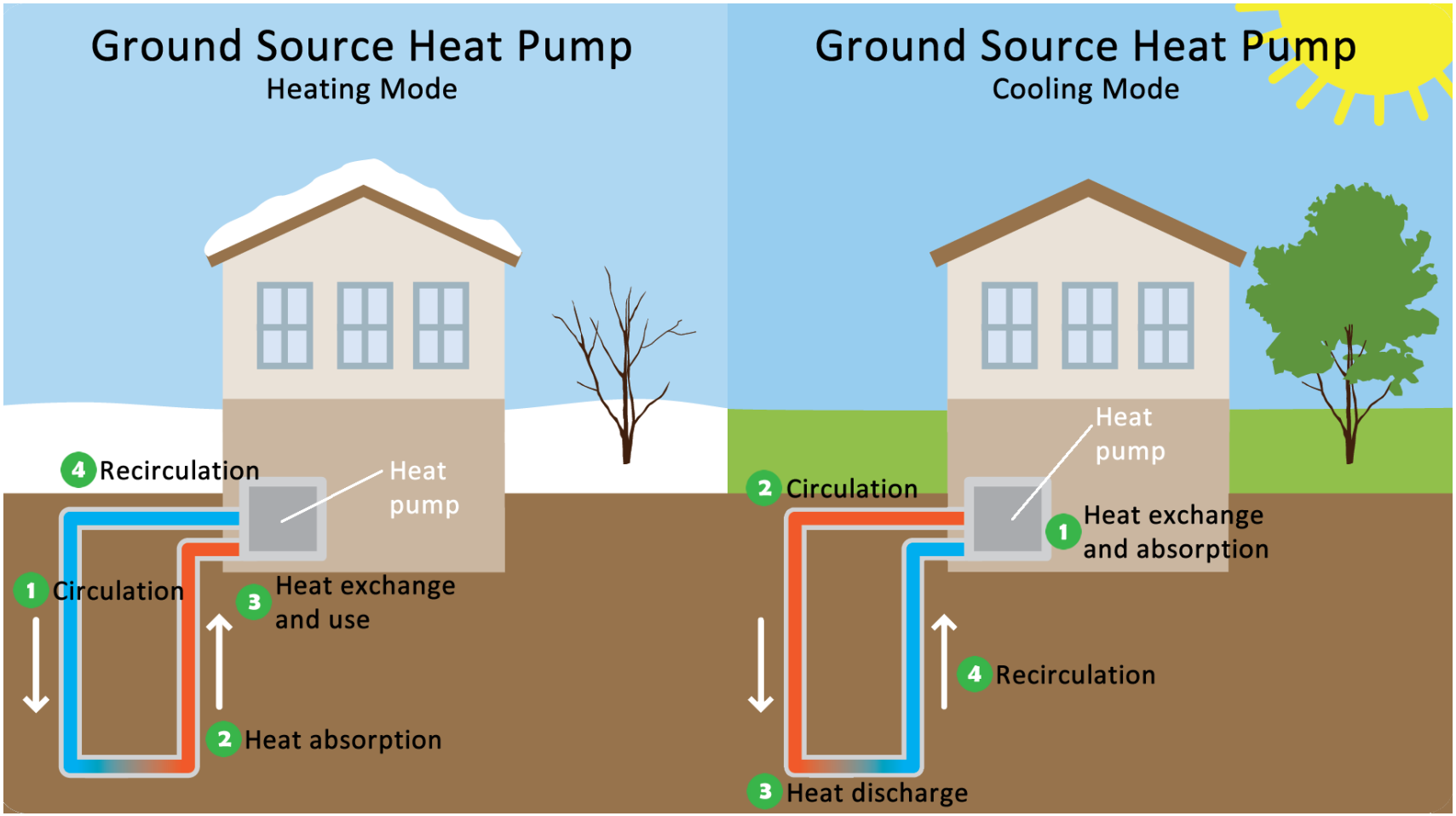
- Adoption of renewable energy , particularly geothermal energy, is an optimal way to shift from a fossil-based development towards a sustainable development.

- Ground-Source Heat Pump (GSHP) systems are an efficient and economic technology for building heating, cooling and production of domestic hot water (DHW).

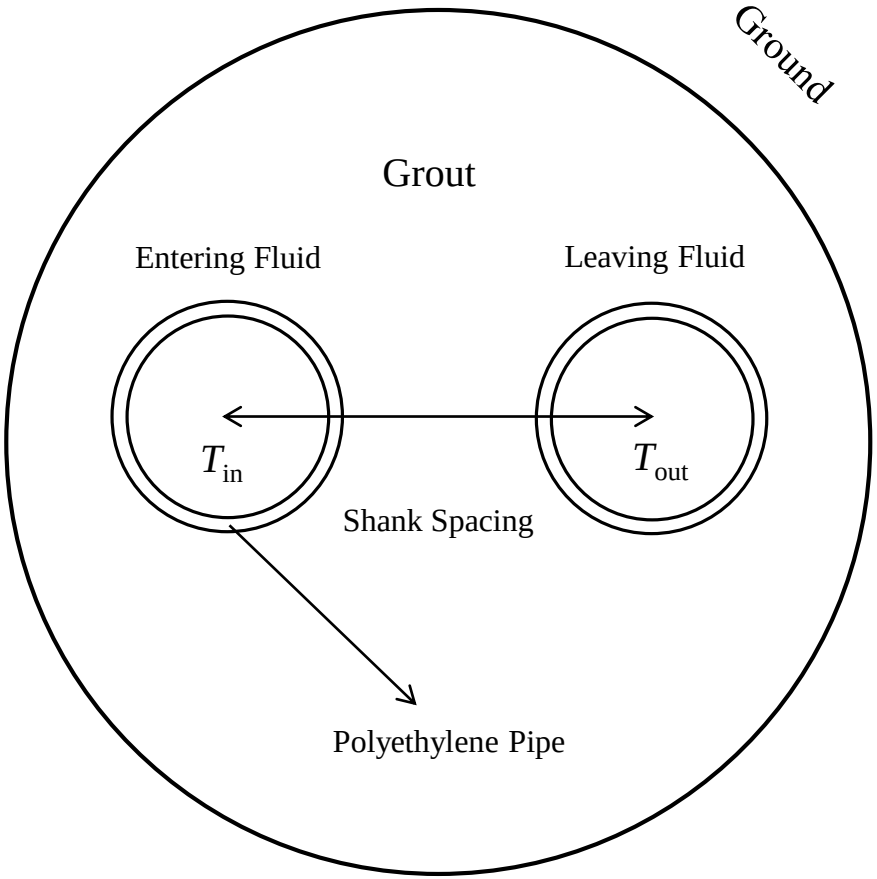
- Ground-Coupled Heat Pumps (GCHPs) appear as the most promising kind of GSHPs for the future development, due to their applicability in any location

- The most diffuse GCHP systems utilize the vertical ground heat exchangers, also called Borehole Heat Exchangers (BHEs), which are composed of pipes in high density polyethylene, inserted in a drilled hole and then sealed with grouting materials.

An introduction on Ground-Coupled Heat Pump (GCHP) systems



An introduction on Ground-Coupled Heat Pump (GCHP) systems



Schematic of a single U-tube BHE cross section

PROBLEM STATEMENT

- For the design of a GCHP system, the BHE thermal resistance per unit length R_b must be determined either by a Thermal Response Test (TRT) or by numerical or analytical methods. However, different definitions of BHE thermal resistance can be applied, that yield different results. In particular the thermal resistance determined by a TRT can be sharply higher that the thermal resistance of a BHE cross section.

- The mean fluid temperature is usually approximated by $T_{ave} = (T_{in} + T_{out})/2$. Some authors have pointed out that, on account of the internal thermal short-circuiting, a relevant difference between T_m and T_{ave} can occur and can yield an overestimation of the BHE thermal resistance determined through a TRT. Therefore, a correct estimation of T_m from measured values of T_{in} and T_{out} could be useful in the evaluation of TRTs.

- In dynamic simulation of GCHPs, the knowledge of the difference between T_m and T_{ave} would allow a more accurate evaluation of T_{out}, the relevant parameter to determine the heat pump COP. A correct estimation of T_m could be useful for dynamic simulations of GCHPs.

AIM OF THE STUDY

The scope of this work is :

1. **To analyze the effects of the temperature distribution on the BHE thermal resistance and to compare the outcomes of different definitions**
2. **Proposing correlations to determine the mean fluid temperature of a double U-tube BHE.**

Numerical Model

Ground modeled as a cylinder coaxial with BHE and external diameter 20 m, length 110m. Adiabatic external boundary.
Initial temperature equal to undisturbed ground temperature:

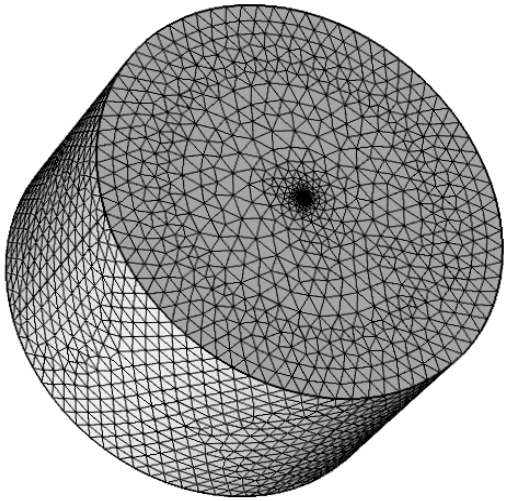
$T(z) = T(10)+[T(0)-T(10)]* e^{(-z)}$, for $0 \leq z \leq 10$ m;
$T(z) = 14 + 0.03\, z$, for $z > 10$ m

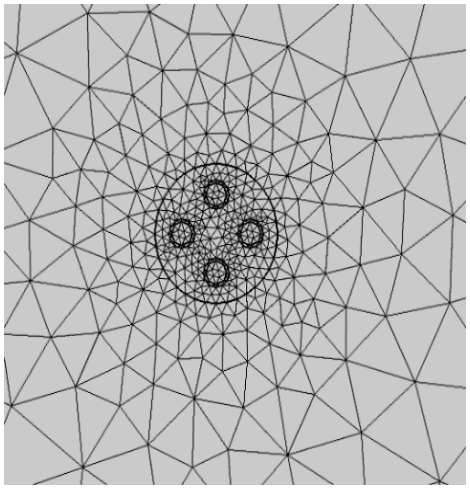
BHE length 100 m. Diameter 0.152 m, tubes with external diameter 0.032 m and internal diameter 0.026 m, distance between the axes of opposite tubes 0.085 m.

Simulations performed through COMSOL Multiphysics, by employing the 3D finite element method. Time dependent problem solved for 100 hours.

Simulations were performed with different unstructured meshes with tetrahedral elements.

Numerical Model

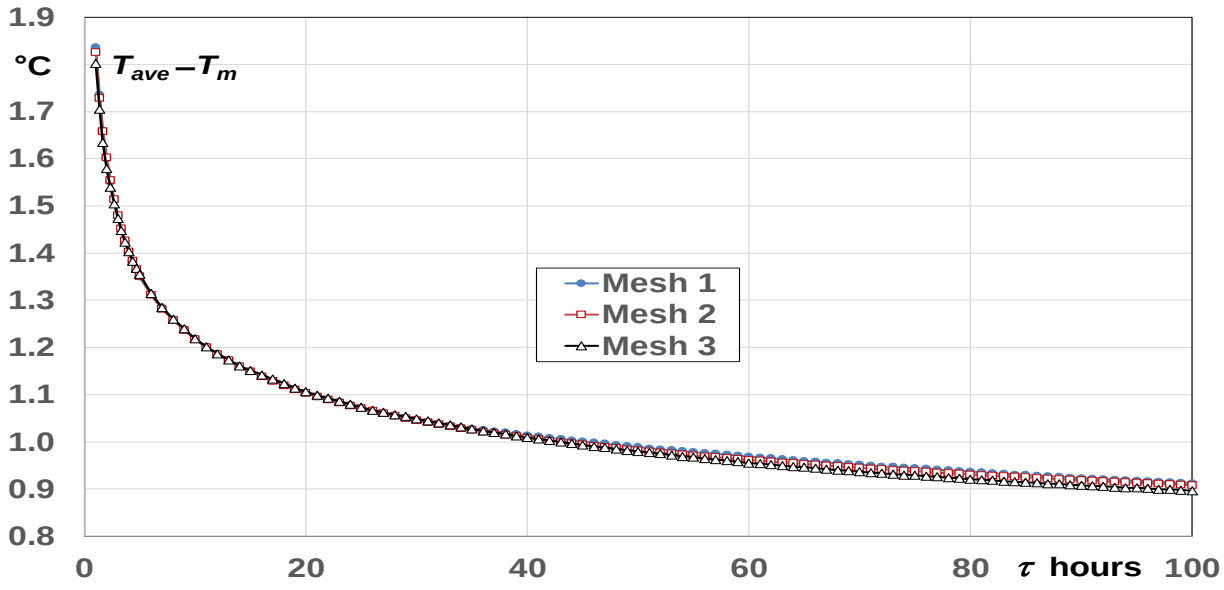




Selected mesh (left) and particular thereof on the surface $z = 0$ (right)

Numerical Model

Mesh Independence



Plots of $T_{ave} - T_m$ versus time for k_{gt} = 1.6 W/(mK), k_g = 1.8 W/(mK), flow rate 12 liters/minute

1. Thermal Resistance of a double U-tube BHE

- Three definitions of thermal resistance of a BHE exist:

1. The first, that we denote by $R_{b,2D}$, refers to a BHE cross sections and is:

$$R_{b,2D} = \frac{T_f - T_s}{q_l}$$

2. The second is effective thermal resistance which is defined by:

$$R_{b,eff} = \frac{T_{f,ave} - T_{s,m}}{q_{l,m}}$$

1. Thermal Resistance of The double U-tube BHE

3. The third that we call it 3D thermal resistance is obtained by:

$$R_{b,3\mathrm{D}} = \frac{T_{f,m} - T_{s,m}}{q_{l,m}}$$

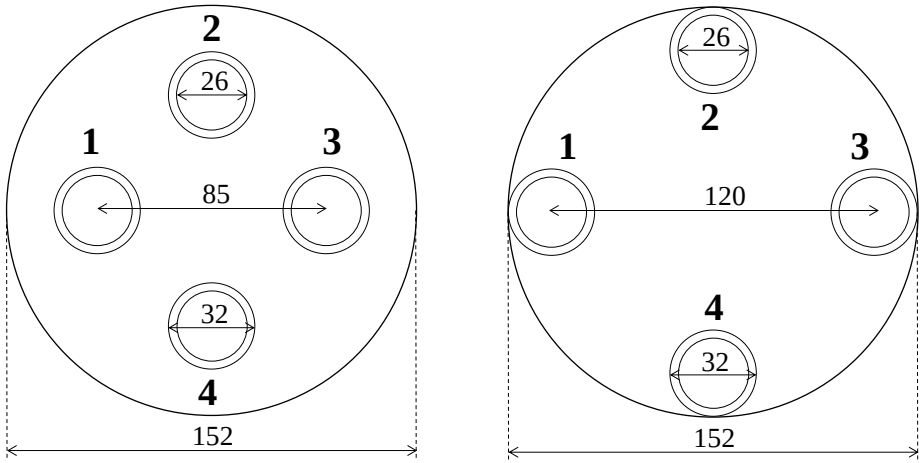
- $T_{f,m}$ is defined as:

$$T_{f,m} = \frac{1}{2L}\left(\int_0^L T_{f,d}(z)\,\mathrm{d}z + \int_0^L T_{f,u}(z)\,\mathrm{d}z\right)$$

- The aim is:

1. To analyze the effects of the temperature distribution on thermal resistance of Double U-tube BHEs
2. To compare the results of different definitions and to analyze the accuracy of approximate analytical expressions by means of 3D finite element simulation.

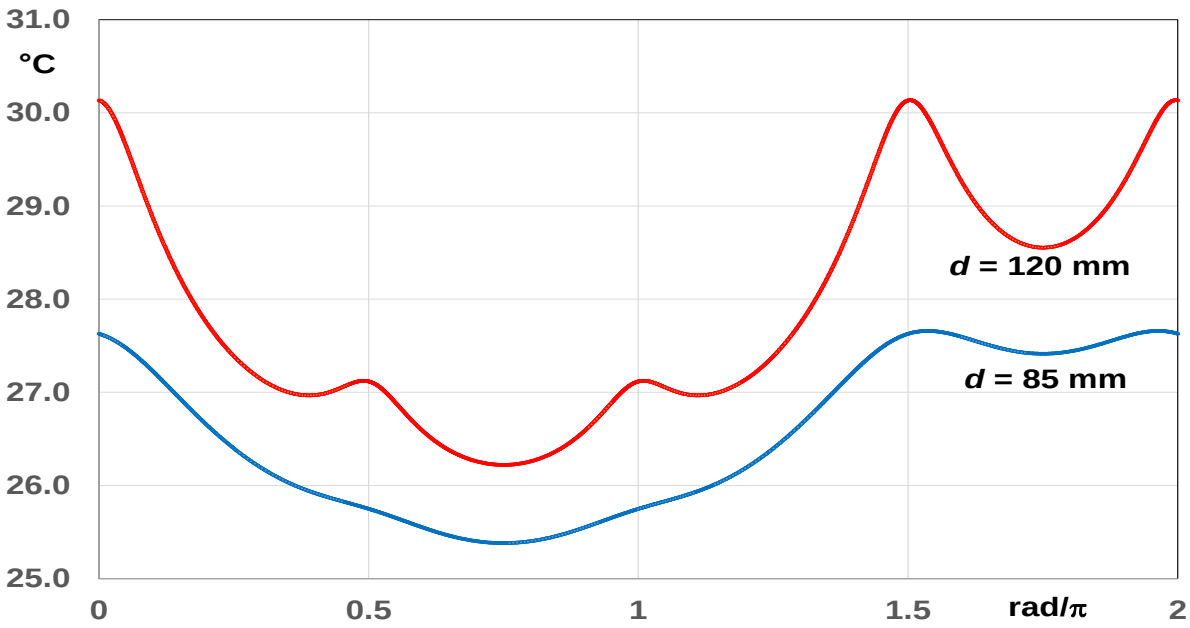
1. Thermal Resistance of The double U-tube BHE



Cross section of the BHE considered, with shank spacing 85 mm (left) and 120 mm (right)

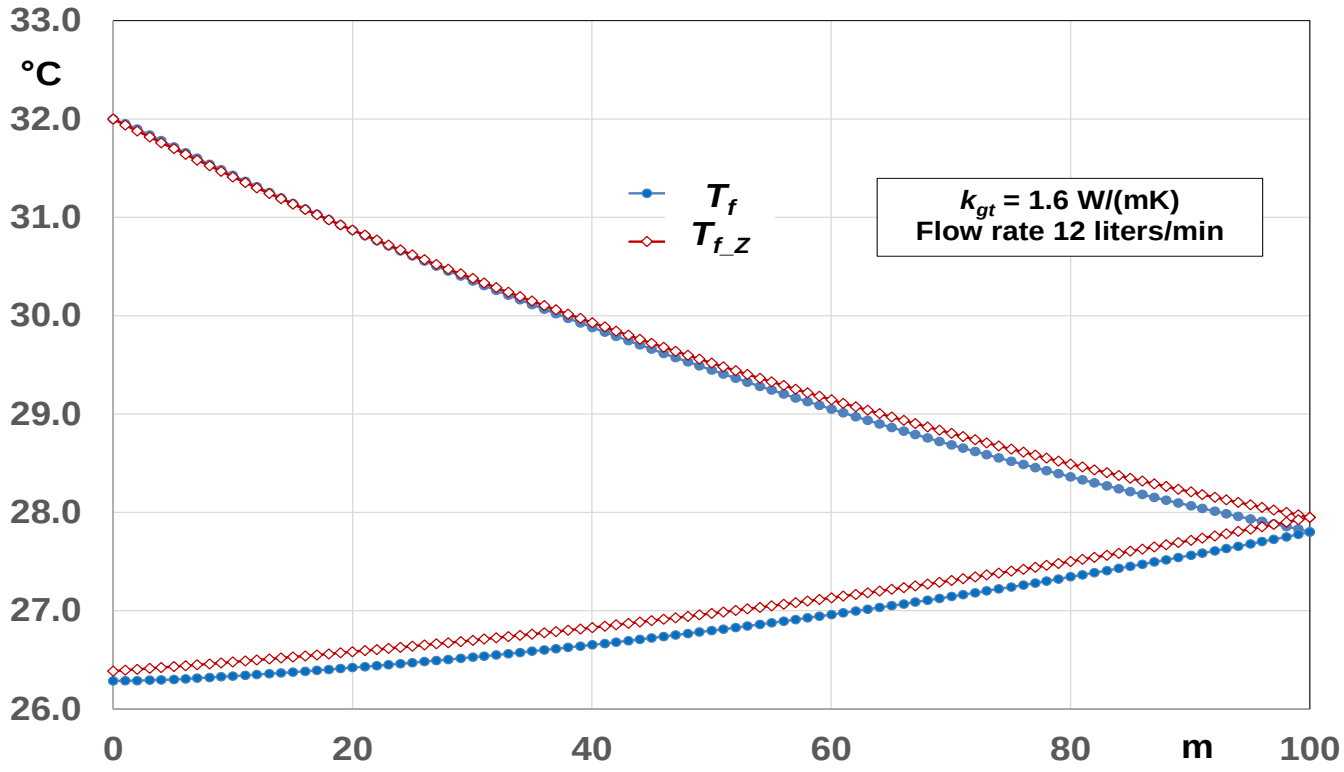
- Different thermal conductivity for the ground and grout, various volume flow rates and two different shank spacing were considered.

1. Thermal Resistance of The double U-tube BHE



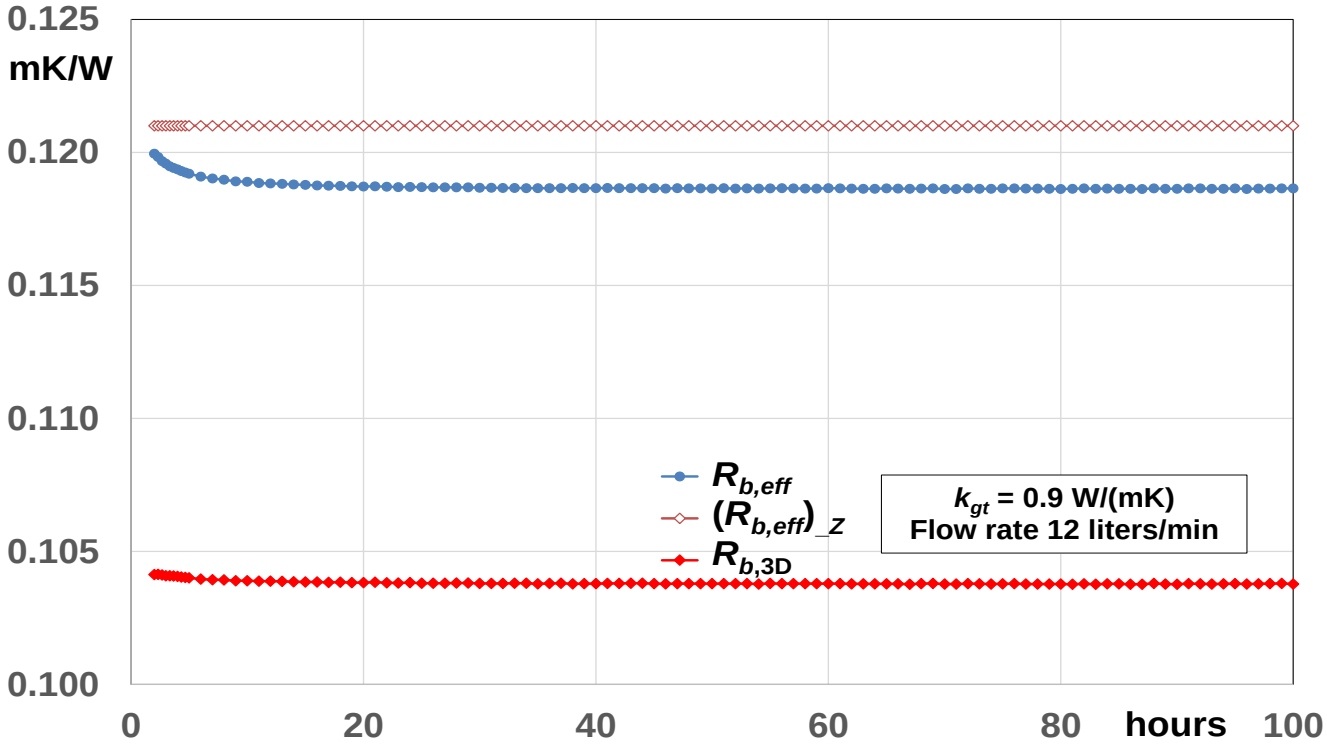
Temperature distribution on the BHE surface versus the angular distance from the upper point of BHE, with d = 85 mm and d = 120 mm, for k_{gt} = 0.9 W/(mK) and k_g = 1.4 W/(mK)

1. Thermal Resistance of The double U-tube BHE



T_f versus the vertical coordinate z, compared with that yielded by the method of Zeng et al., T_{f_Z}, for k_{gt} = 1.6 W/(mK) and volume flor rate 12 liters per minute

1. Thermal Resistance of The double U-tube BHE



Plots of $R_{b,eff}$ and of $R_{b,3D}$ versus time, compared with the steady state value $(R_{b,eff})_{_Z}$ yielded by the method of Zeng et al., for k_{gt} = 0.9 W/(mK) and volume flor rate 12 liters per minute.

1. Thermal Resistance of The double U-tube BHE

Percent difference between $(R_{b,eff})_{Z}$ and $R_{b,eff}$, $R_{b,eff}$ and $R_{b,3D}$, $R_{b,3D}$ and $R_{b,2D}$

k_{gt} W/(mK)	$\dot{V}$ dm^3/min	$\frac{(R_{b,eff})_{Z} - R_{b,eff}}{R_{b,eff}} \times 100$	$\frac{R_{b,eff} - R_{b,3D}}{R_{b,3D}} \times 100$	$\frac{R_{b,3D} - R_{b,2D}}{R_{b,2D}} \times 100$
0.9	12	2.02	14.26	0.58
0.9	24	3.57	3.71	0.49
1.6	12	– 2.02	28.50	0.16
1.6	24	0.04	7.47	0.10

- ✓ The results showed that if the real mean fluid temperature is considered, the 3D thermal resistance coincides with the thermal resistance of BHE cross section, provided that the latter is invariant along BHE.

- ✓ Percent difference between the 3D and effective thermal resistances in some cases can exceed 28%. Higher difference would occur for the longer BHE, with same grout conductivity and volume flow rate. On the other hand, the difference between the 2D and 3D thermal resistances is nearly vanishing, so they can be considered as coincident.

1. Thermal Resistance of The double U-tube BHE

- ✓ The thermal resistance of a BHE cross section is not influenced by the bulk temperature difference between pairs of the tubes. It is influenced by the thermal conductivity of the ground when the shank spacing is high.

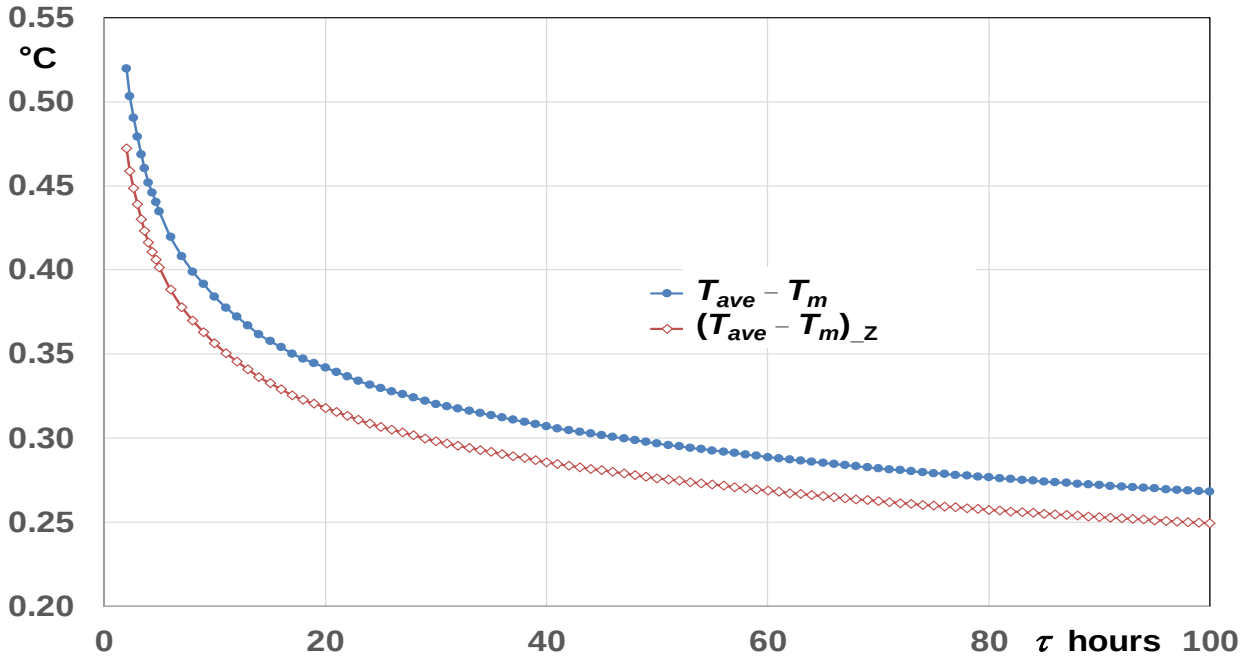
2. Correlations to determine mean fluid temperature of double U-tube BHE

Aim of the study

- To propose correlations to determine the mean fluid temperature of double U-tube BHE;

Providing tables of a dimensionless coefficient that allows an immediate evaluation of T_m in any working condition.
Moreover, the applicability of the correlations was checked under any working condition (Summer/Winter/TRT), Transient and quasi-stationary period. The effects of different BHE diameters and ground thermal conductivity were taken into account.

2. Correlations to determine mean fluid temperature of double U-tube BHE



Time evolution of $T_{ave} - T_m$ obtained numerically and through the analytical model by Zeng et al. for k_{gt} = 1.6 W/(mK), k_g = 1.8 W/(mK), flow rate 24 liters/minute

2. Correlations to determine mean fluid temperature of double U-tube BHE

The difference between T_{ave} and T_m is expressed through the positive dimensionless parameter:

$$\varphi = \frac{\dot{V}}{\dot{V}_0} \frac{T_{ave} - T_m}{T_{in} - T_{out}}$$

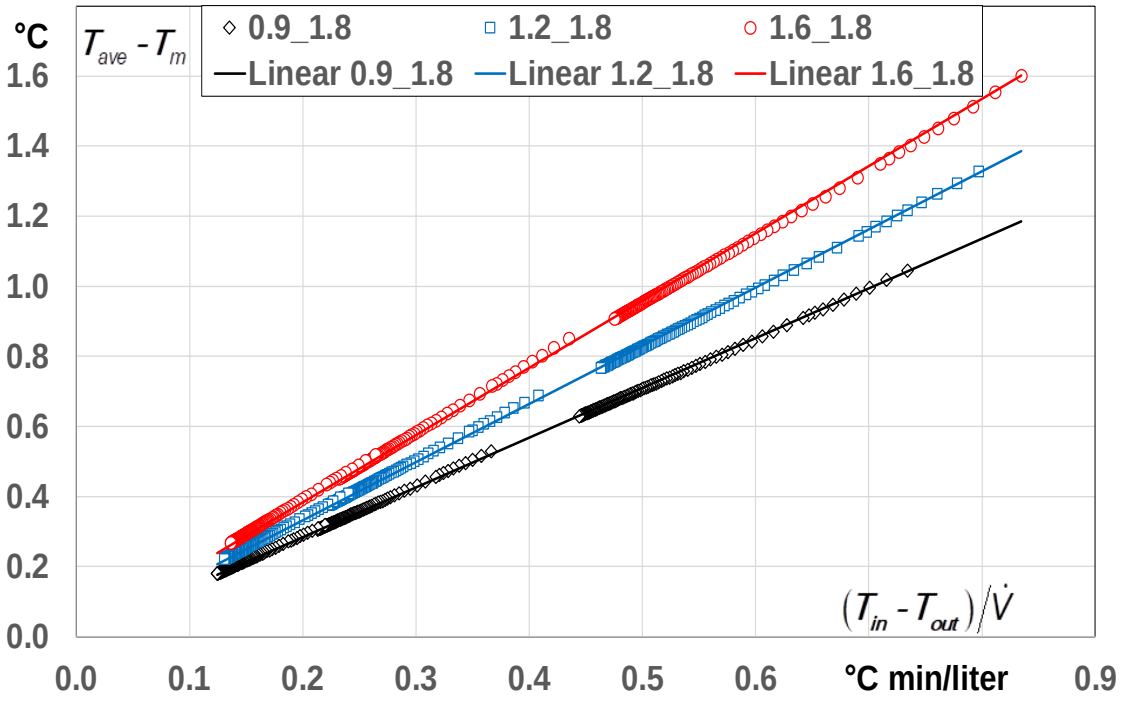
Results for quasi stationary regime:

$$T_{ave} - T_m = 1.420 \frac{T_{in} - T_{out}}{\dot{V}}$$, for k_{gt} = 0.9 W/(mK)

$$T_{ave} - T_m = 1.662 \frac{T_{in} - T_{out}}{\dot{V}}$$, for k_{gt} = 1.2 W/(mK)

$$T_{ave} - T_m = 1.918 \frac{T_{in} - T_{out}}{\dot{V}}$$, for k_{gt} = 1.6 W/(mK)

2. Correlations to determine mean fluid temperature of double U-tube BHE



Linear interpolations of $T_{ave} - T_m$ as a function of $(T_{ave} - T_m)/V$, for kgt = 0.9, 1.2, 1.6 W/(mK)

2. Correlations to determine mean fluid temperature of double U-tube BHE

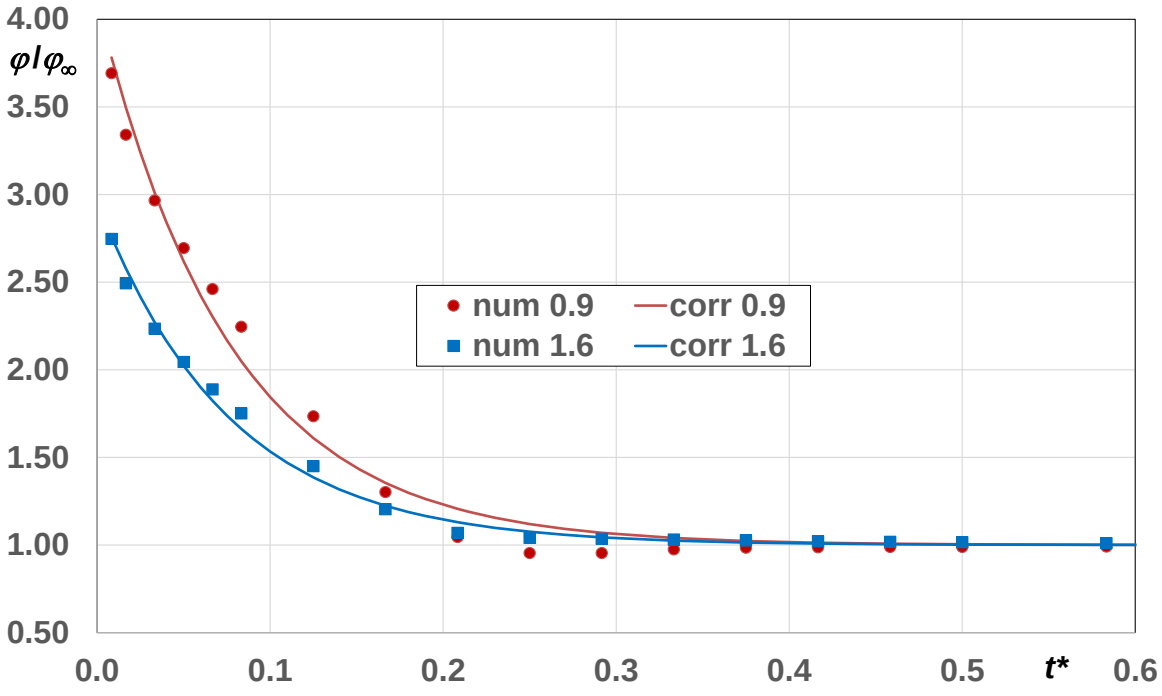
Results for first 2 hours:

$$\varphi = \varphi_\infty \left(1 + a\,\mathrm{e}^{-bt^*}\right)$$

Values of φ_∞ and coefficient a & b

k_{gt} W/(mK)	φ_∞	a	b
0.9	0.1183	$3.1 + 3.5\,(\dot{V}/\dot{V}_0 - 1)$	$13 + 11\,(\dot{V}/\dot{V}_0 - 1)$
1.2	0.1385	$2.45 + 3.1\,(\dot{V}/\dot{V}_0 - 1)$	$13 + 11\,(\dot{V}/\dot{V}_0 - 1)$
1.6	0.1598	$1.96 + 2.7\,(\dot{V}/\dot{V}_0 - 1)$	$13 + 11\,(\dot{V}/\dot{V}_0 - 1)$

2. Correlations to determine mean fluid temperature of double U-tube BHE

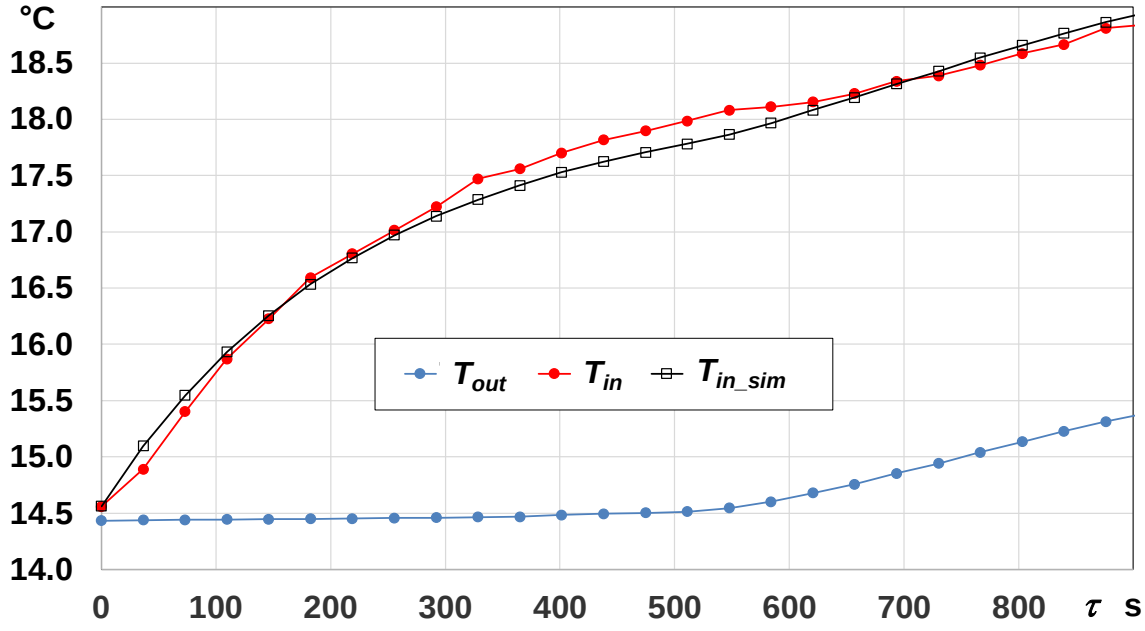


– Plots of φ/φ_∞ versus t^*, for k_{gt} = 0.9 and k_{gt} = 1.6 W/(mK), with flow rate 12 liters/minute, in the range

$$1/120 \le t^* \le 0.6$$

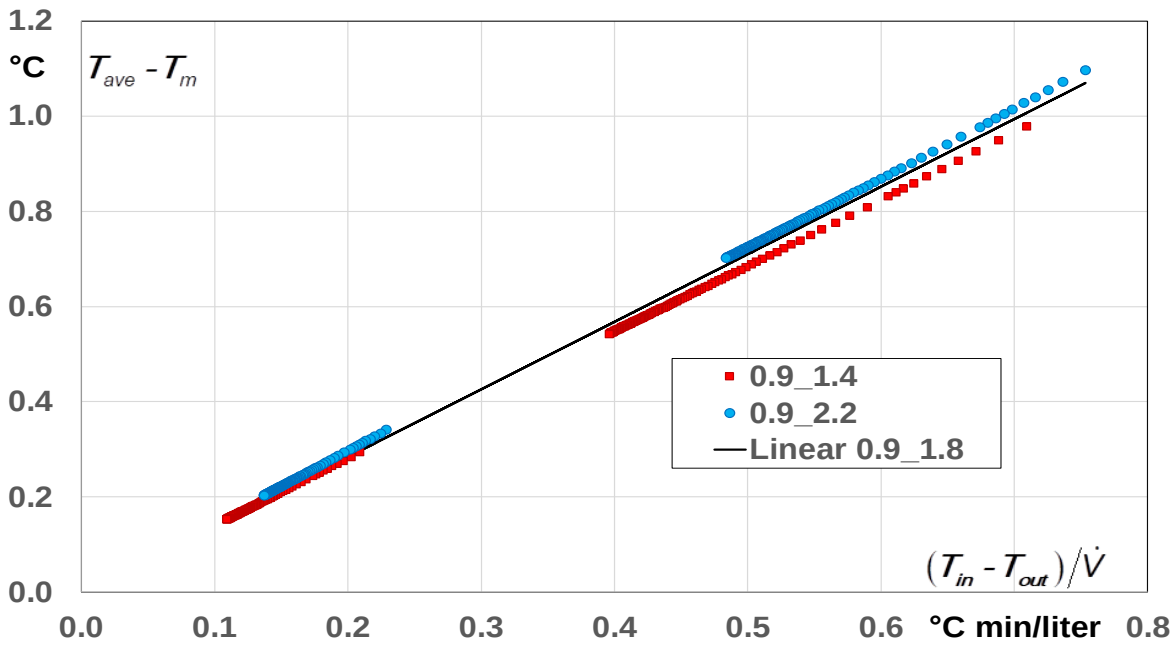
Applicability of the correlations

2. Correlations to determine mean fluid temperature of double U-tube BHE



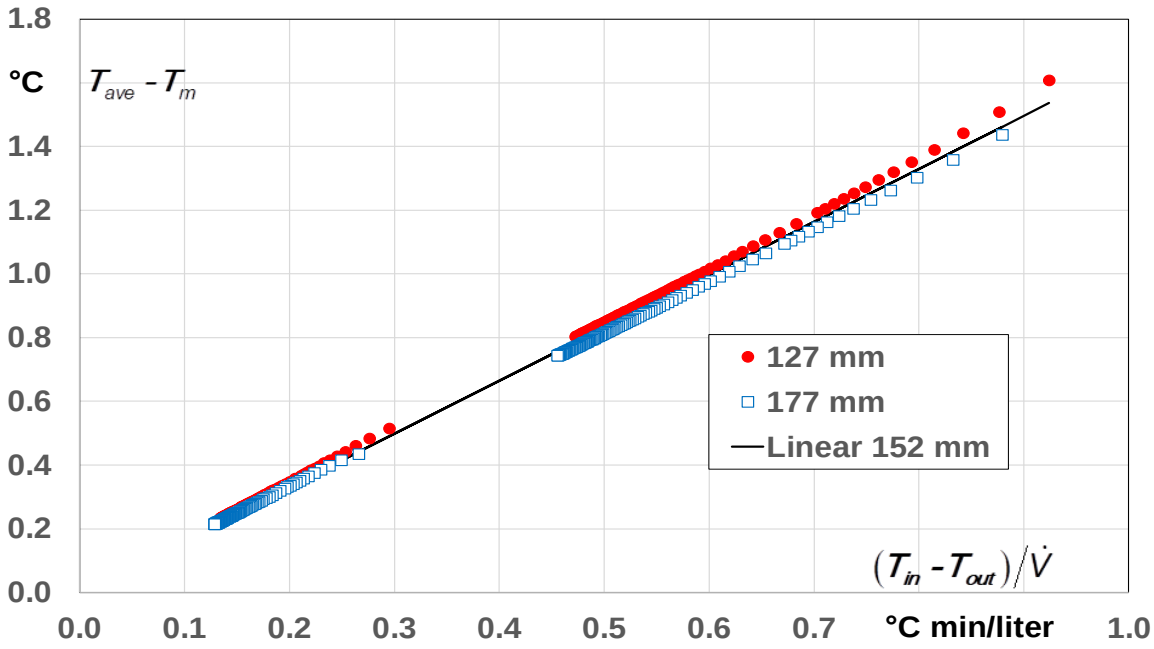
Comparison between the experimental time evolution of T_{in} and numerical results T_{in_sim}, for a TRT performed at Fiesso d'Artico (Venice)

2. Correlations to determine mean fluid temperature of double U-tube BHE



Effects of different values of k_g, namely 1.4 and 2.2 W/(mK), for k_{gt} = 0.9 W/(mK).

2. Correlations to determine mean fluid temperature of double U-tube BHE



Effects of different values of the BHE diameter, for k_{gt} = 1.2 W/(mK) and k_g = 1.8 W/(mK)

2. Correlations to determine mean fluid temperature of double U-tube BHE

- It was observed that the quasi-stationary values of φ can be considered as dependent only on the thermal conductivity of grout, and independent of the volume flow rate, of the thermal conductivity of ground, of the operative conditions and, for a fixed distance between the axes of opposite tubes, of the BHE diameter.
- The time evolution of φ during the first two hour depends also on the volume flow rate.
- The results will be extended to other values of the distance between the axes of opposite tubes and of the BHE length

CONCLUSIONS

- 3D simulations of a double U-tube BHE by means of finite element method were performed through COMSOL Multiphysics. The models takes into account the thermal short-circuiting between the descending and the ascending fluid. Different working conditions, volume flow rates, configurations, shank spacing, and variant parameters such as different values for thermal conductivities were considered.

- The results obtained have been validated by comparison with those determined by applying analytical methods.

- Different definitions for the thermal resistance of the double U-tube BHE were analyzed and the effects of the temperature distribution on thermal resistance were investigated.

- Correlations were proposed to evaluate the mean fluid temperature. The applicability of the correlations has been checked under any kind of working condition (Summer/Winter/TRT), both in quasi-stationary and in transient regime, for different diameters of the BHE.

List of Publications in International Journals:

- E. Zanchini, A. Jahanbin. *Correlations to determine the mean fluid temperature of double U-tube borehole heat exchangers with a typical geometry*. ***Applied Energy*** *(2017).*

- E. Zanchini, A. Jahanbin. *Effects of the temperature distribution on the thermal resistance of double u-tube borehole heat exchanger.* ***Geothermics*** *71 (2018) 46-54.*

- E. Zanchini, A. Jahanbin. *Finite-element analysis of the fluid temperature distribution in double U-tube Borehole Heat Exchangers.* ***Journal of Physics*** *Conference Series745 (2016) 0320032.*

- A. Jahanbin, E. Zanchini. *Effects of position and temperature-gradient direction on the performance of a thin plane radiator.* ***Applied Thermal Engineering*** *105 (2016) 467-473.*

END

Thanks for your attention