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Numerical Evaluation of Long-Term Performance of Borehole Heat Exchanger Fields

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INTRODUCTION

With reference to the heating and cooling of buildings, geothermal energy is being used with good results by means of ground coupled heat pumps (GCHPs).

GCHPs employ heat transfer between the ground and a fluid, typically a water-based solution, which flows in tubes buried into the soil.

Two different configurations are used: horizontal heat exchangers and vertical ones, also called Borehole Heat Exchangers (BHEs). The most common geometry for BHEs is composed of two U-bent polyethylene tubes, placed in a borehole which is then grouted.

AIMS OF THE WORK

- Study of the long-term performance of double U-tube BHEs with reference to some typical time-periodic working conditions and to three different BHE field configurations.

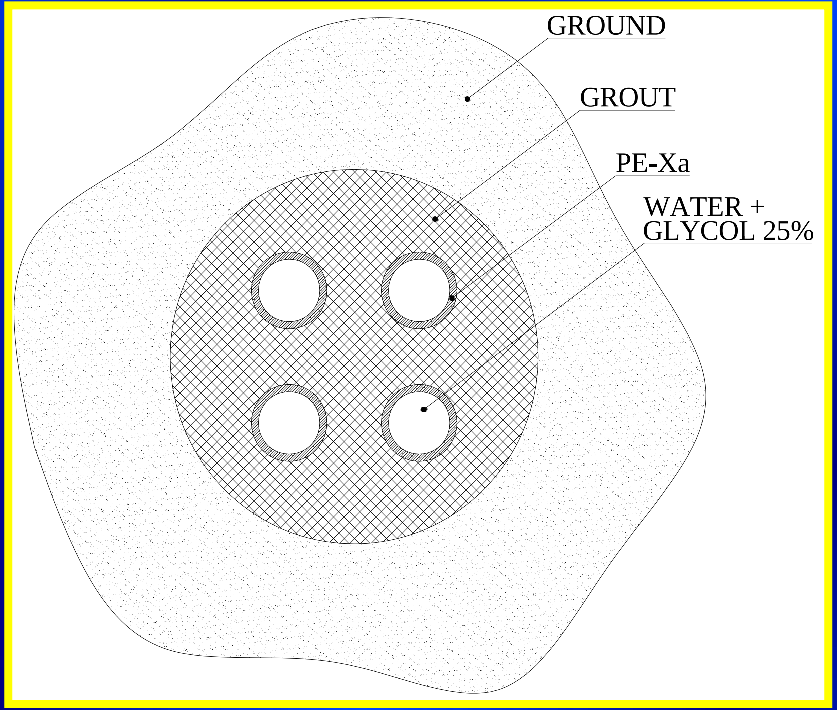
- Parametric analysis of the effects of BHEs spacing on the long-term performance of very large BHE fields.

The fluid mean temperature T_f in the BHE is determined as a function of time.

GEOMETRICAL MODEL

The temperature distribution along the vertical direction has a negligible influence on long-term BHE performance.

The problem is studied by means of a 2D conduction model, where the energy transfer due to water flow is replaced by a uniform, time dependent, heat generation.



Sketch of the double U-tube
BHE cross-section

GEOMETRICAL PARAMETERS, MATERIAL PROPERTIES, WORKING CONDITIONS

An effective thermal conductivity k_{peff} of the PE-Xa tube takes into account the thermal resistance due to the convective heat transfer between the water-glycol flow and the tube wall:

$$k_{peff} = \frac{\log(r_e/r_i)}{\frac{1}{r_i \cdot h} + \frac{1}{k_p} \cdot \log(r_e/r_i)}$$

h is the convection coefficient at the internal wall, $r = r_i$

Re = 2525, transition regime flow

Nusselt number by means of Churchill correlation (1977)

Geometrical data of double U-tube BHE		
r_i	13	Internal radius of PE-Xa tube [mm]
r_e	16	External radius of PE-Xa tube [mm]
r_b	78	External radius of grout layer [mm]
Thermal properties of high density polyethylene PE-Xa		
c_1	2300	Specific heat capacity [J kg^{-1} K^{-1}]
k_1	0.4	Thermal conductivity [W m^{-1} K^{-1}]
ρ_1	940	Density [kg m^{-3}]
Thermal properties of grout		
c_2	1600	Specific heat capacity [J kg^{-1} K^{-1}]
k_2	1.08	Thermal conductivity [W m^{-1} K^{-1}]
ρ_2	1000	Density [kg m^{-3}]
Thermal properties of ground		
$(\rho c)_3$	2.5	Heat capacity per unit volume [MJ m^{-3} K^{-1}]
k_3	1.8	Thermal conductivity [W m^{-1} K^{-1}]
Thermal properties adopted for water-ethylene glycol 25%		
c_{wg}	3823	Specific heat capacity [J kg^{-1} K^{-1}]
k_{wg}	1000	Thermal conductivity [W m^{-1} K^{-1}]
ρ_{wg}	1084.5	Density [kg m^{-3}]
μ_{wg}	6.31	Dynamic viscosity [mPa s]
Working conditions		
T_0	14	Initial water-glycol temperature [°C]
T_{gd}	14	Undisturbed ground temperature [°C]
$\dot{V}$	18	Water-glycol flow rate [dm^3 min^{-1}]
h	100.76	Convection coefficient [W m^{-2} K^{-1}]

TESTED THERMAL LOADS

$Q_{1,}$ (blue line): a BHE working both in winter and in summer, with a vanishing value of the total energy exchanged during one year (full compensation case);

$$Q_1 = A_1 \cdot \sin(\varphi \cdot \tau)$$

$Q_{2,}$ (red line): a BHE working both in winter and in summer, with a positive value of the total energy exchanged during one year (partial compensation case);

$$Q_2 = A_{2A} \cdot \sin(\varphi \cdot \tau) + \left| A_{2B} \cdot \sin(\varphi \cdot \tau) \right|$$

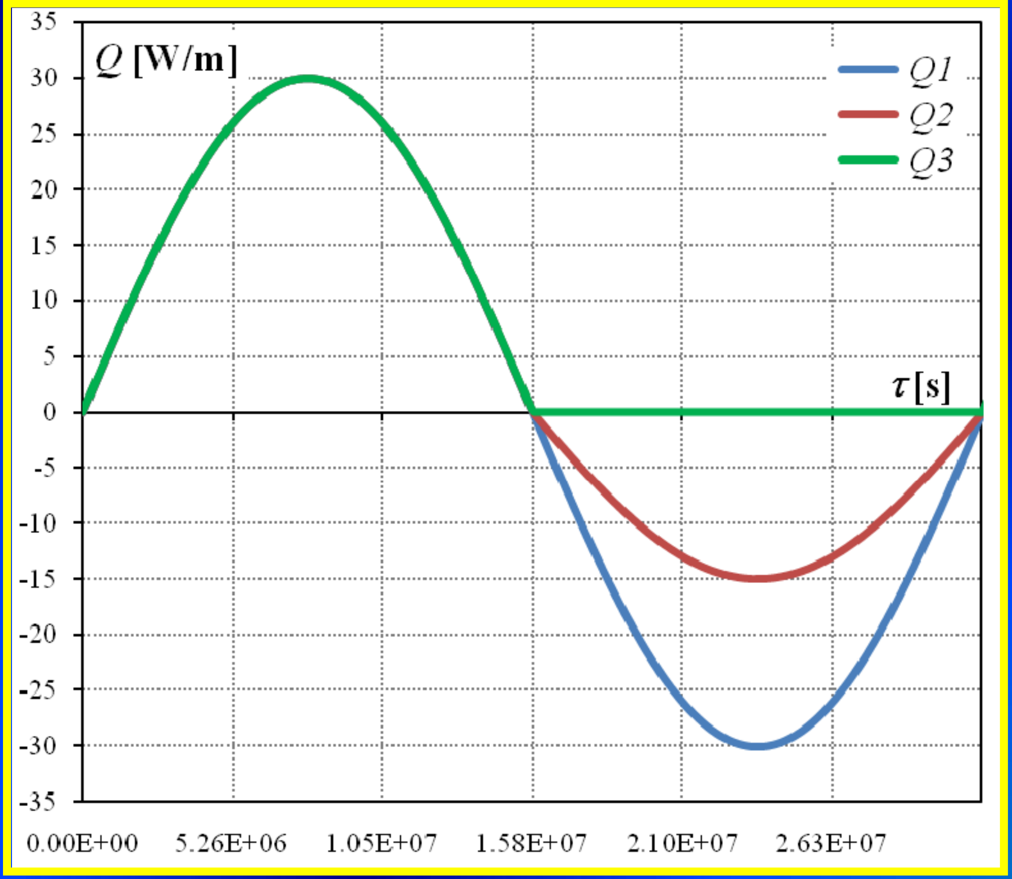
$Q_{3,}$ (green line): a BHE working only in winter (no compensation case).

$$Q_3 = A_3 \cdot \sin(\varphi \cdot \tau) + \left| A_3 \cdot \sin(\varphi \cdot \tau) \right|$$

A_1 = 30 W/m;
A_{2A} = 22.5 W/m, A_{2B} = 7.5 W/m;
A_3 = 15 W/m.

$$\varphi = \frac{2\pi}{P} = 1.9924 \cdot 10^{-7} \text{ s}^{-1}$$

φ: pulse of oscillation,
P = 1 year = 31536000 s: period,
τ: time



TESTED BHE FIELD CONFIGURATIONS

- Case I: a single BHE surrounded by infinite ground
- Case II: a square field of 4 BHEs, with a spacing of 6 m, surrounded by infinite ground
- Case III: the limiting case of a square field of infinite BHEs, with a spacing of 6 m

MODEL EQUATIONS

For the polyethylene tubes, the grout and the ground, the equation to be solved is the Fourier equation without generation:

$$\rho_j c_j \frac{\partial T}{\partial \tau} = k_j \nabla^2 T \quad , \quad j = 1, 2, 3$$

where ρ_j, c_j and k_j are the density, the specific heat capacity and the thermal conductivity of the j-th solid material.

In the solid which replaces the water-glycol solution, the equation to be solved to obtain the temperature distribution T_f is

$$\rho_{wg} c_{wg} \frac{\partial T_f}{\partial \tau} = k_{wg} \nabla^2 T_f + q_{gi}$$

where q_{gi} is the power generated per unit volume, given by

$$q_{gi} = -\frac{Q_i}{4 \cdot \pi r_i^2} \quad , \quad i = 1, 2, 3$$

Q_1, Q_2, Q_3 are the heat fluxes per unit length.

INITIAL CONDITION

The BHE and the ground are in mutual thermal equilibrium at temperature T_0

BOUNDARY CONDITIONS

In order to grant that the results are independent of the chosen domain size:

- *CASES I* and *II*: two boundary conditions have been considered at the external circular surface: uniform and constant temperature $T=T_{gd}$; zero heat flux.
- *CASE III*: two different conditions have been imposed on the external square boundary and compared: periodic condition and adiabatic condition.

In all cases, the check gave the same results for both boundary conditions up to 5 significant digits.

A period of 15 years of operation is considered and a uniform time step of 1 day is adopted in computations.

Simulations have been performed by means of the linear system solver (Direct UMFPACK) available in COMSOL Multiphysics 3.4, with default tolerance settings.

MESH INDEPENDENCE TEST

3 unstructured meshes have been tested for each configuration;

a comparison of the results is illustrated in the Table, where the values of T_f, for the case of adiabatic boundary condition with heat flux Q_3, are reported for some time intervals after start-up;

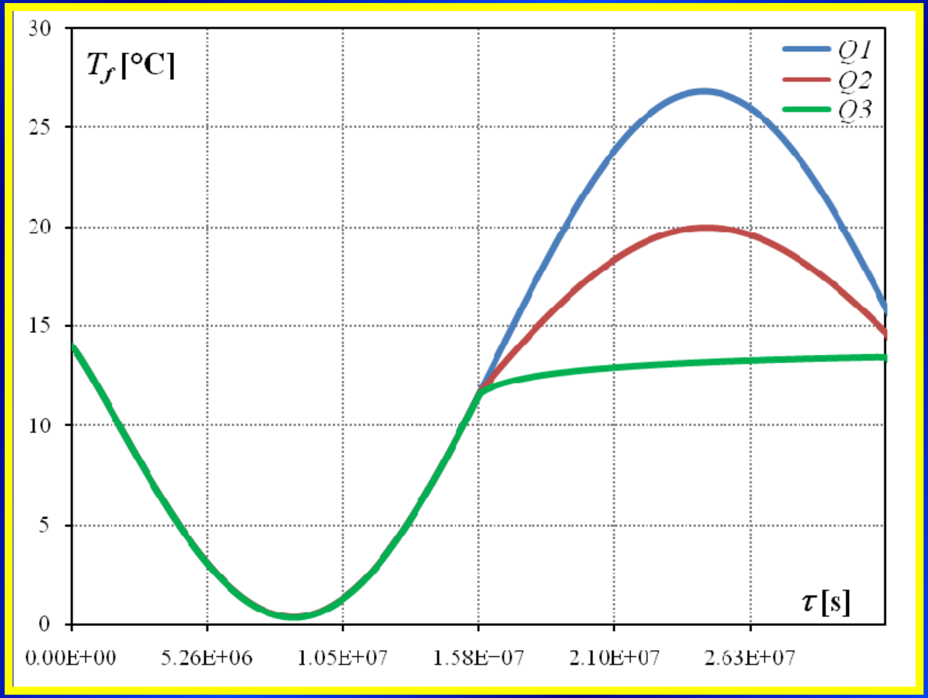
the results show a good agreement among the tested meshes and in particular between Mesh 2 and Mesh 3;

thus, Mesh 2 has been adopted for the final computations.

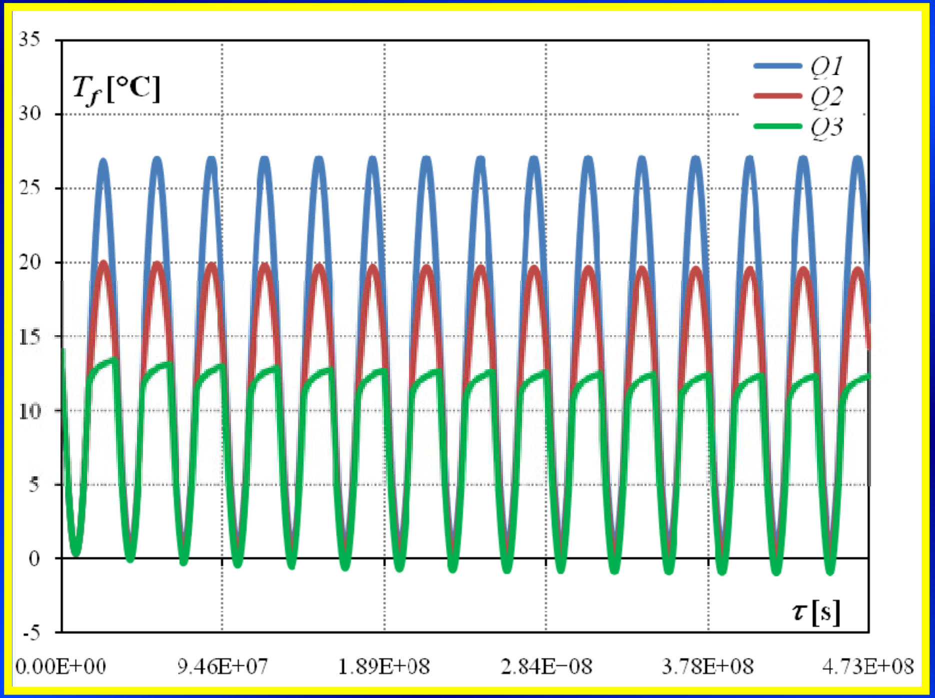
T_f [°C], case I			
Time	***Mesh 1 (4436)***	***Mesh 2 (7442)***	***Mesh 3 (9612)***
1 year	13.42	13.42	13.40
5 years	12.80	12.81	12.81
10 years	12.48	12.49	12.51
15 years	12.38	12.38	12.38
T_f [°C], case II			
Time	***Mesh 1 (8186)***	***Mesh 2 (11020)***	***Mesh 3 (14146)***
1 year	12.55	12.56	12.55
5 years	10.51	10.47	10.45
10 years	9.37	9.37	9.41
15 years	8.75	8.78	8.78
T_f [°C], case III			
Time	***Mesh 1 (3954)***	***Mesh 2 (6950)***	***Mesh 3 (9212)***
1 year	10.64	10.63	10.61
5 years	-2.90	-3.22	-3.30
10 years	-20.04	-19.96	-19.95
15 years	-36.92	-36.61	-36.70

RESULTS

Case I: a single BHE surrounded by infinite ground



(a)

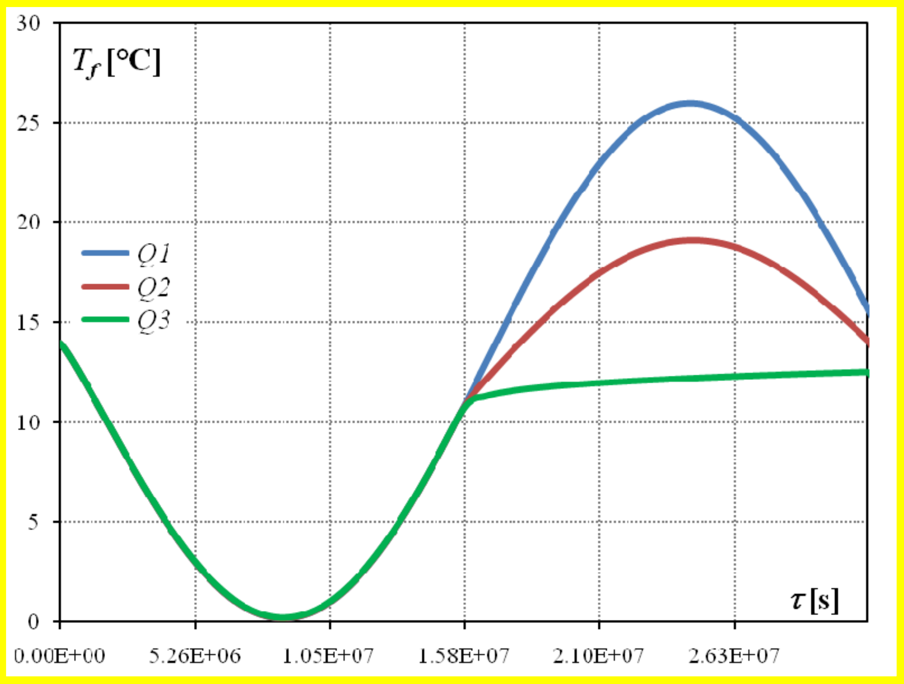


(b)

Fluid temperature T_f versus time, for the heat fluxes Q_1, Q_2, Q_3:
(a) time interval of 1 year;
(b) time interval of 15 years.

RESULTS

<u>Case II</u>: a square field of 4 BHEs, with a spacing of 6 m, surrounded by infinite ground



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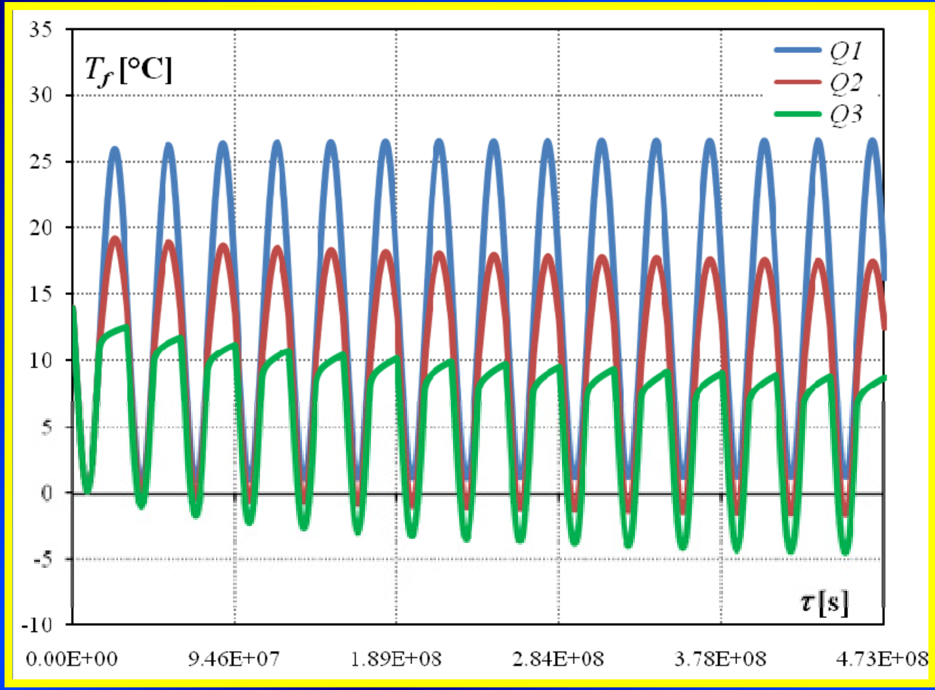
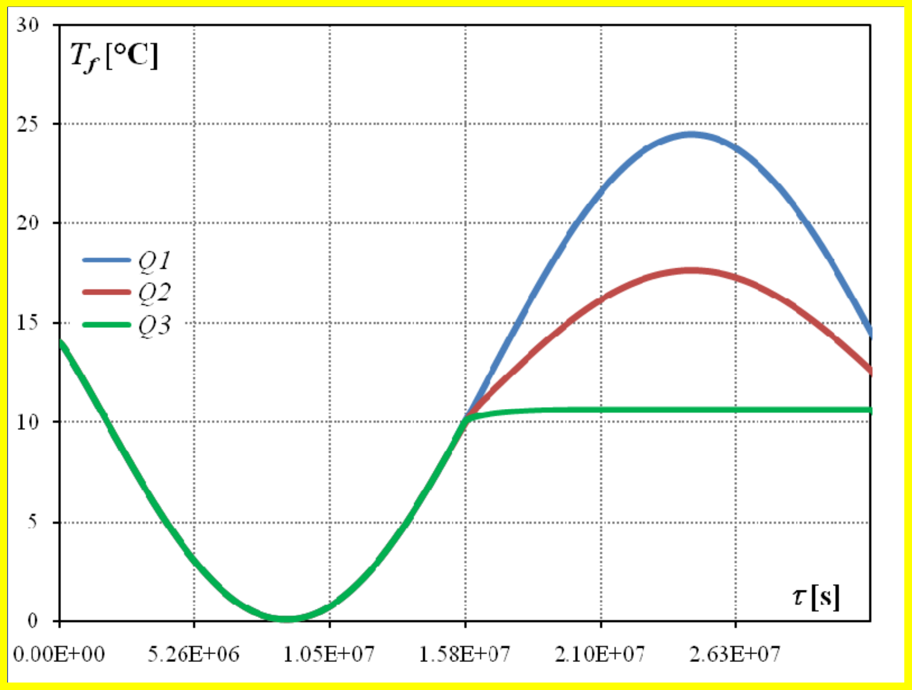


(b)

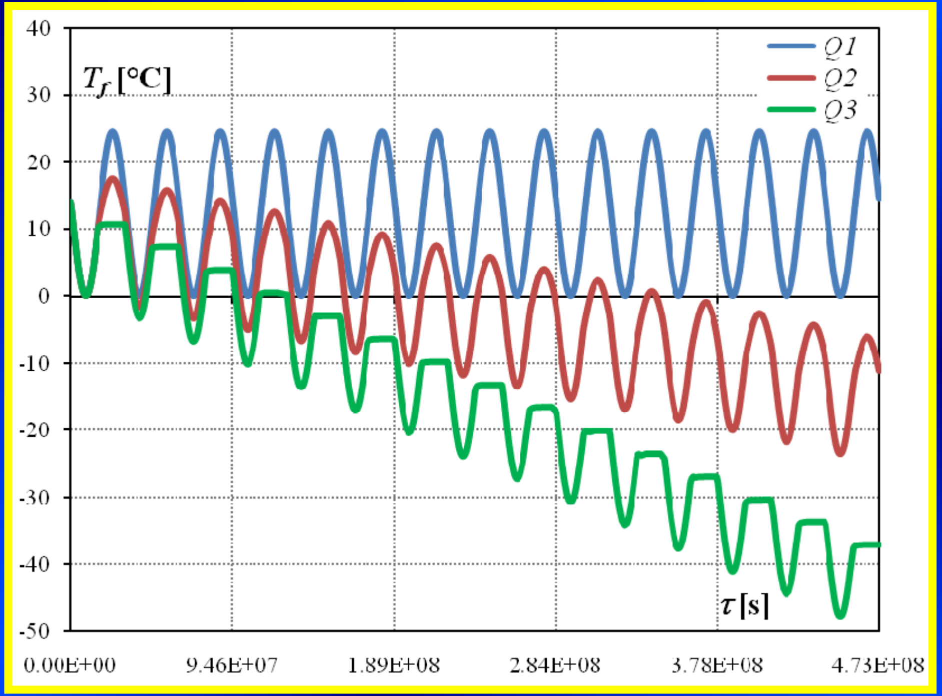
Fluid temperature T_f versus time, for the heat fluxes Q_1, Q_2, Q_3:
(a) time interval of 1 year;
(b) time interval of 15 years.

RESULTS

Case III: the limiting case of a square field of infinite BHEs, with a spacing of 6 m



(a)

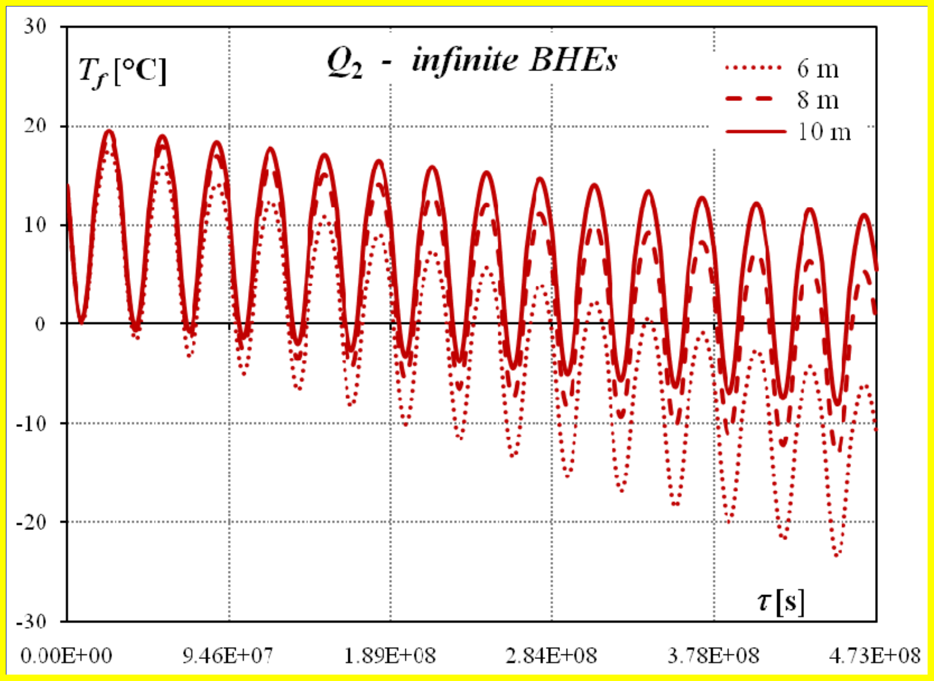


(b)

Fluid temperature T_f versus time, for the heat fluxes Q_1, Q_2, Q_3:
(a) time interval of 1 year;
(b) time interval of 15 years.

RESULTS

Effects of BHEs spacing on the long-term performance of very large BHE field



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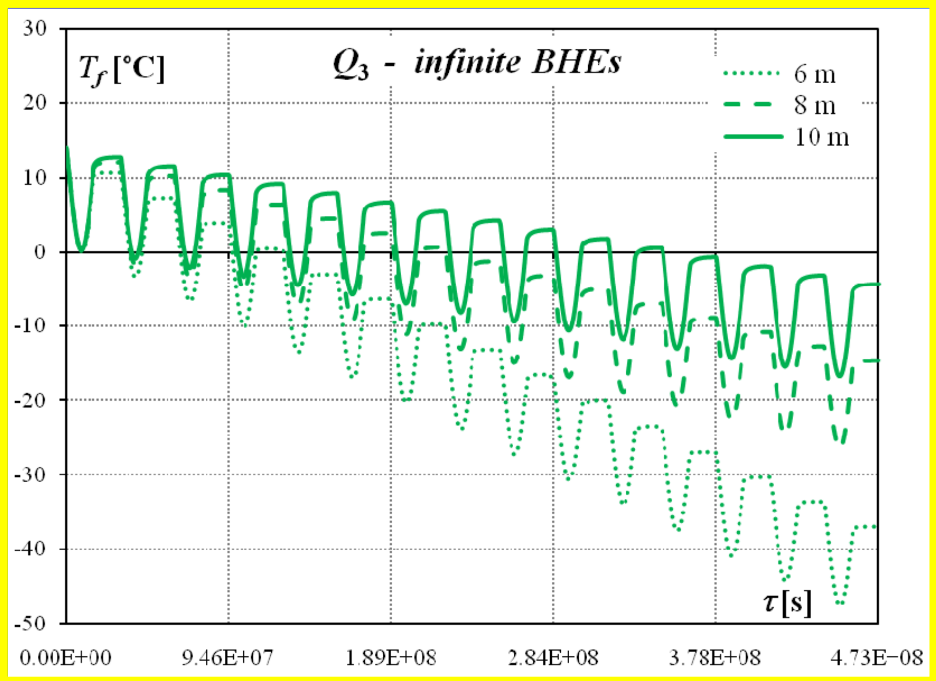

(b)

Fluid temperature T_f versus time for field of infinite BHEs, with different spacing between adjacent BHEs (6, 8, 10 m):
(a) partial compensation load Q_2;
(b) no compensation load Q_3.

CONCLUSIONS

The following main conclusions have been drawn:
in the case of *no groundwater movement into the ground*

- for a single BHE, no compensation between winter and summer loads is necessary;

- for a small field of 4 BHEs with a spacing of 6 m, a partial compensation of the winter load by means of an opposite-sign summer load with 50% peak power is sufficient to grant an acceptable long term performance;

- for a very large and square BHE field, the only solution is an almost complete seasonal compensation of the thermal load for all tested spacing.

Thank you for your kind attention!