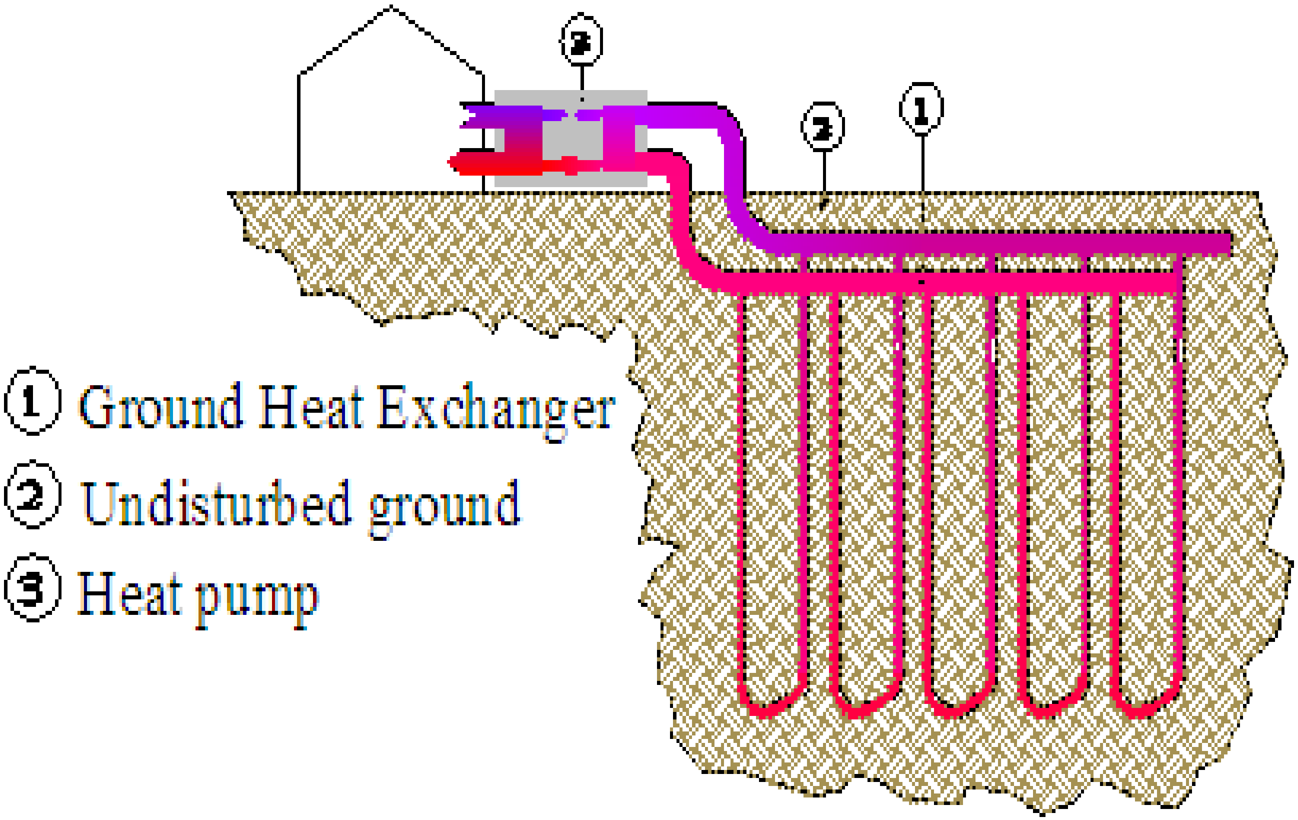
Vertical and Horizontal Ground Heat Exchanger Modeling



Multiple Vertical U-tube Ground Heat Exchanger

Earth heat exchangers are essential parts of the ground-source heat pumps and the accurate prediction of their performance is of fundamental importance.

- This presentation explains the development and validation of a numerical model for the simulation of energy flows and temperature changes in and around a ground heat exchanger.

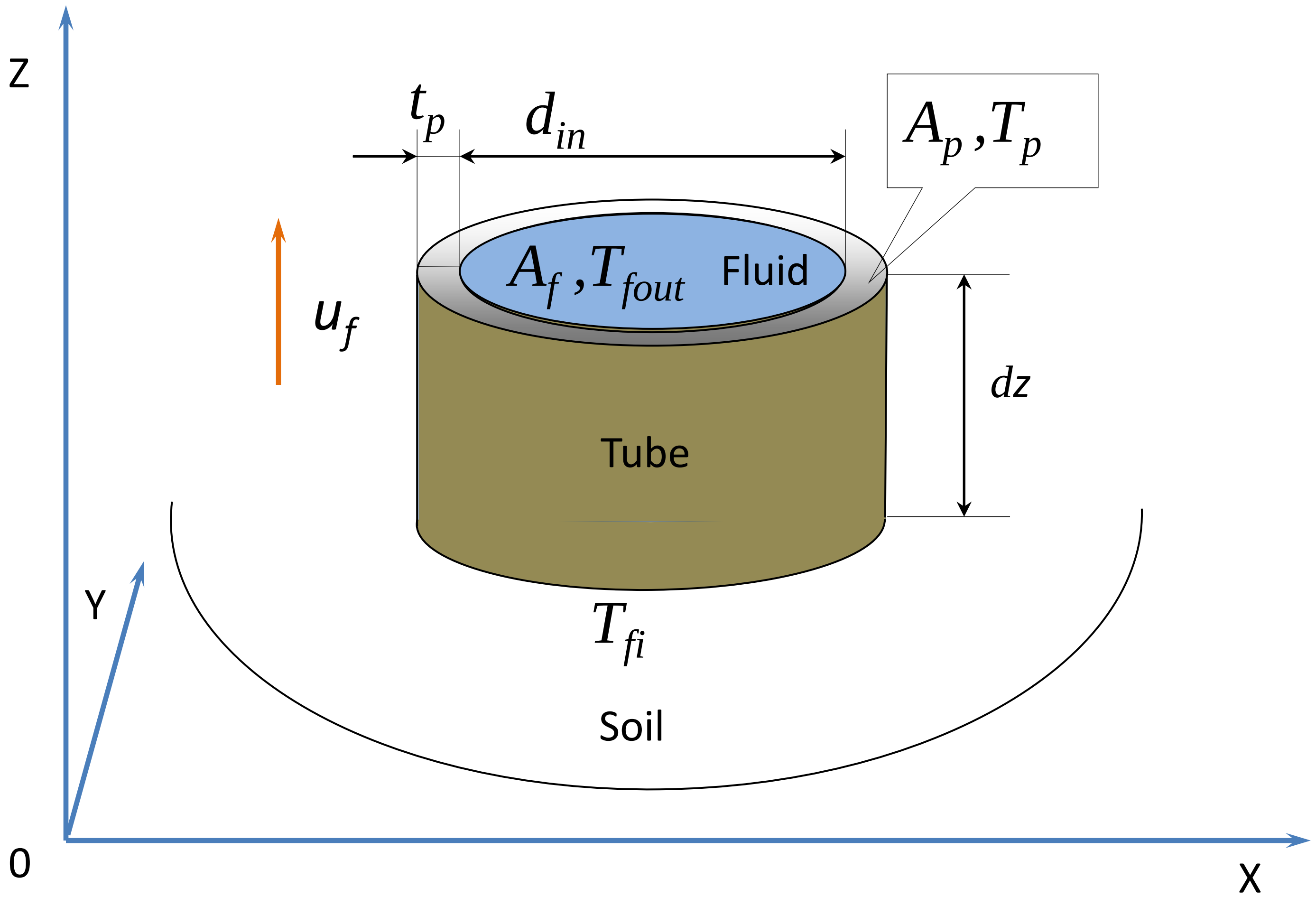
- The numerical model is based on the time-dependent convection-diffusion equation

- The FlexPDE software package is employed to solve the resulting equations of the model

- The mathematical model is validated through a comparison with data obtained from experiments with real borehole set-ups in Cyprus

- The validated model is used to study the heat flow and the temperature variation in various configurations of heat-exchangers and extract conclusions

Geometry of a unit element of the problem



For time-dependent convection-diffusion the representative one dimension equation is

$$\frac{\partial \varphi}{\partial t} + u\frac{\partial \varphi}{\partial x} - \frac{\partial}{\partial x}\left(D\frac{\partial \varphi}{\partial x}\right) = S, \qquad (1)$$

where D = mass diffusion coefficient, u =velocity, ϕ = function under consideration, S = source or sink term

For an incompressible fluid of unit volume the 1D energy conservation equation is:

$$\rho\, c\, \frac{\partial T}{\partial t} + \frac{\partial}{\partial z}\left(-\lambda\frac{\partial T}{\partial z}\right) + \frac{4}{d_{in}} h\left(T_f - T_p\right) = \rho\, c\, u\frac{\partial T}{dz}. \qquad (2)$$

Internal Energy | Conduction | Convection | Supplied heat

Applying a 1D energy conservation equation for a unit tube volume :

$$\rho_p\, c_p\, \frac{\partial T}{\partial t} + \frac{\partial}{\partial z}\left(-\lambda_p\frac{\partial T}{\partial z}\right) + \frac{h}{t_p}\left(T_p - T_f\right) = 0. \qquad (3)$$

The heat equation representing the heat flow in the borehole and ground material per unit volume is:

$$\rho_g\, c_g\, \frac{\partial T}{\partial t} + \frac{\partial}{\partial z}\left(-\lambda_g \frac{\partial T}{\partial z}\right) = 0, \qquad (4)$$

The convection heat transfer coefficient *h* can be estimated from:

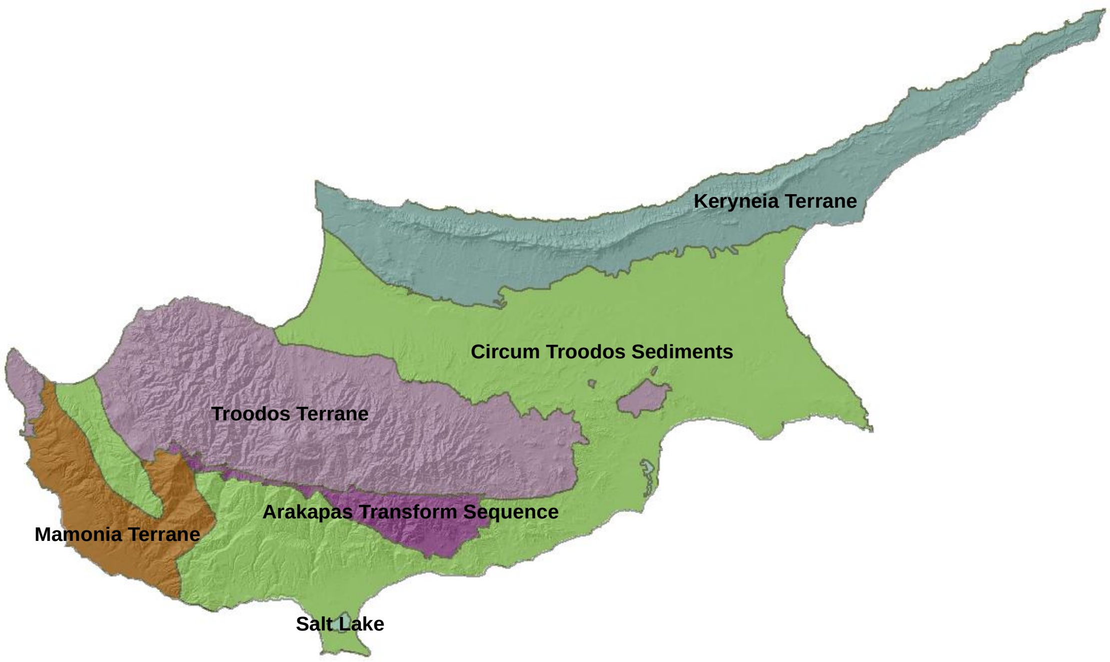
$$h = \frac{\lambda}{D_H} Nu, \qquad (5)$$

where D_H = hydraulic diameter (in this case the tube-inside diameter) and
Nu = Nusselt number.

The Nusselt number in this case can be expressed through the Dittus-Boelter correlation as:

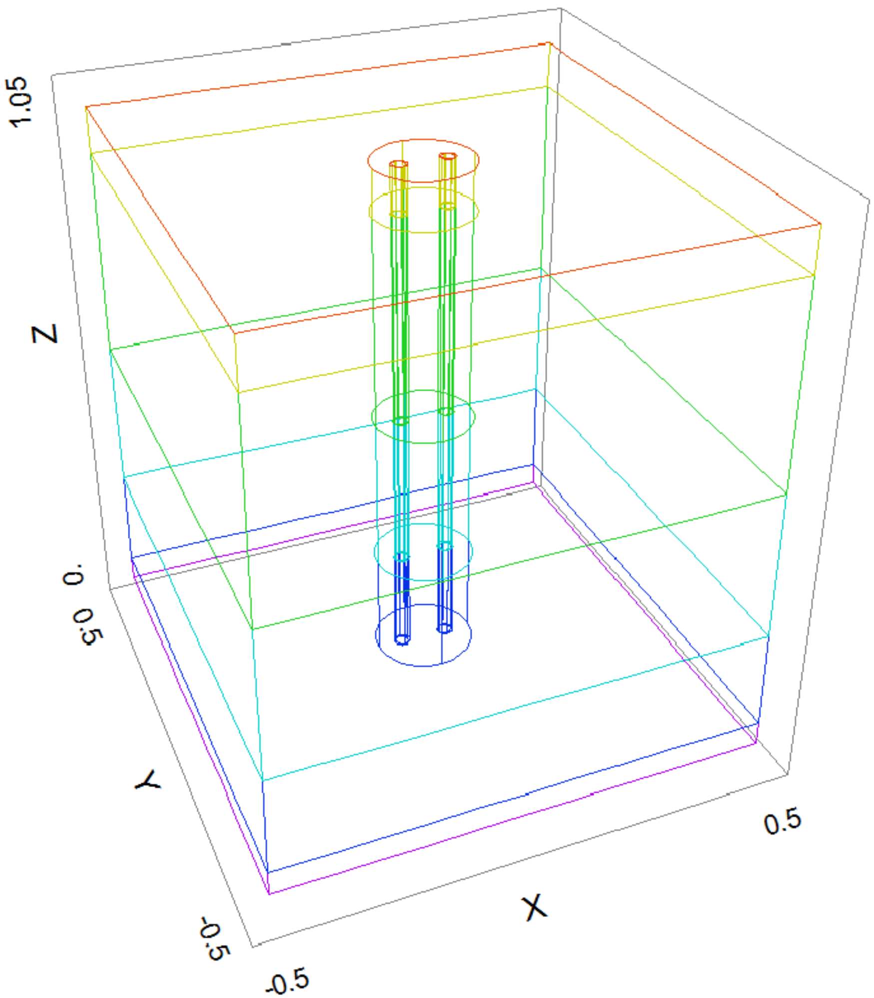
$$Nu = 0.023\, Re^{0.8}\, Pr^{n}, \qquad (6)$$

where Pr = Prandtl number (= $\mu c/\lambda$), Re = Reynolds number (= $\rho c d_{in}/\mu$), μ = dynamic viscosity, and n = 0.4 for heating (wall hotter than the bulk fluid) and 0.33 for cooling (wall cooler than the bulk fluid).

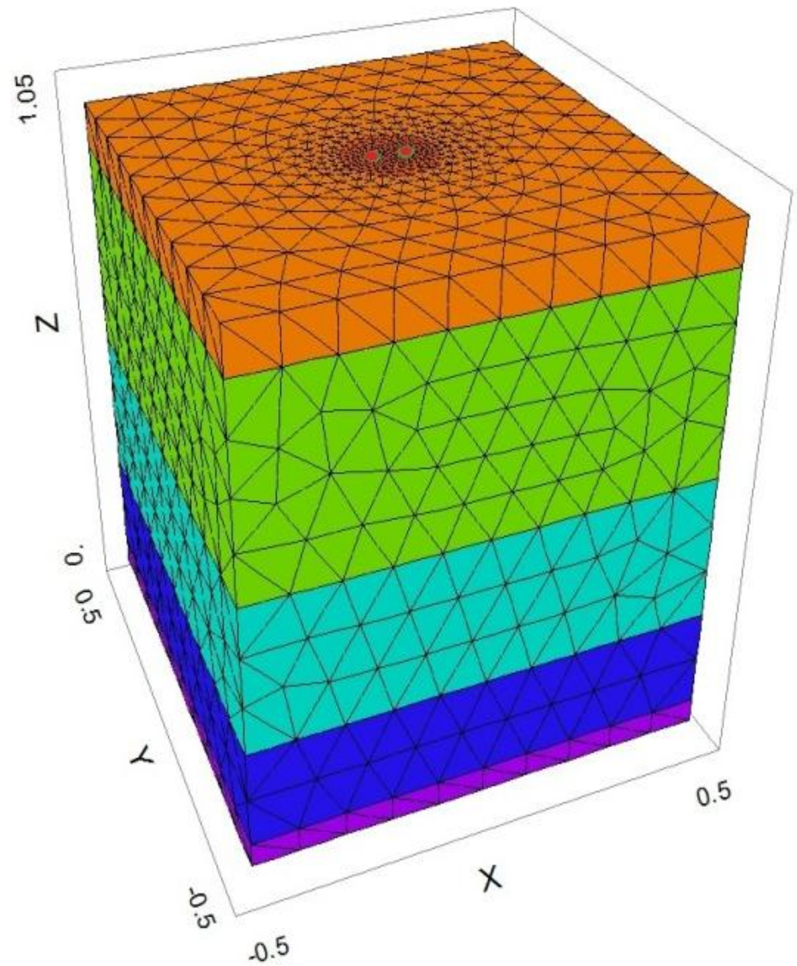


Major geological terranes of Cyprus and rock thermal properties

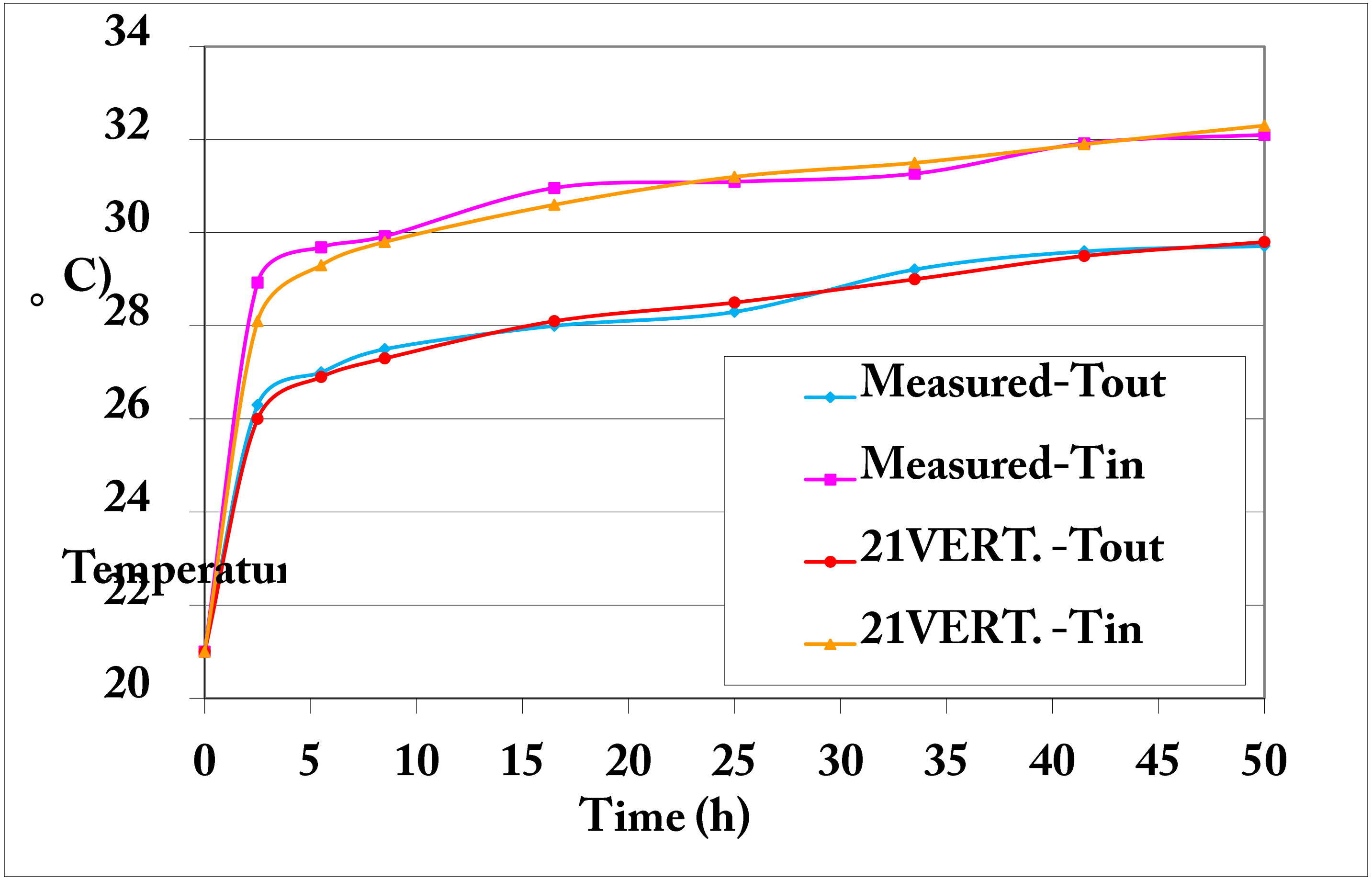
Formation/ Lithology	λ W m^{-1} K^{-1}	c_p J kg^{-1} K^{-1}	ρ kg m^{-3}	α ×10^{-6} m^2 s^{-1}	Condition
Tera limestone	1.22	654	2232	0.835	dry
	1.74	906	2347	0.818	saturated



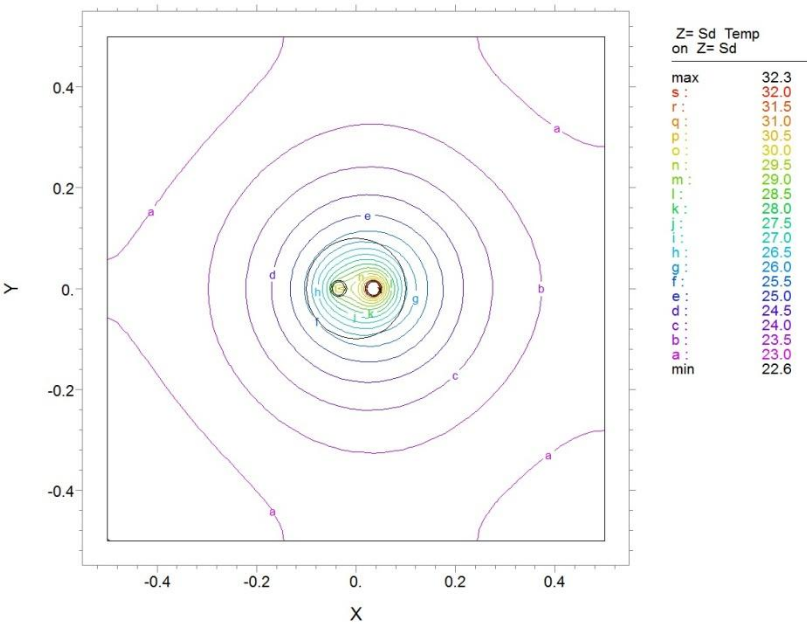
(a) A drawing showing the geometry of the vertical heat exchanger in FLEX PDE.



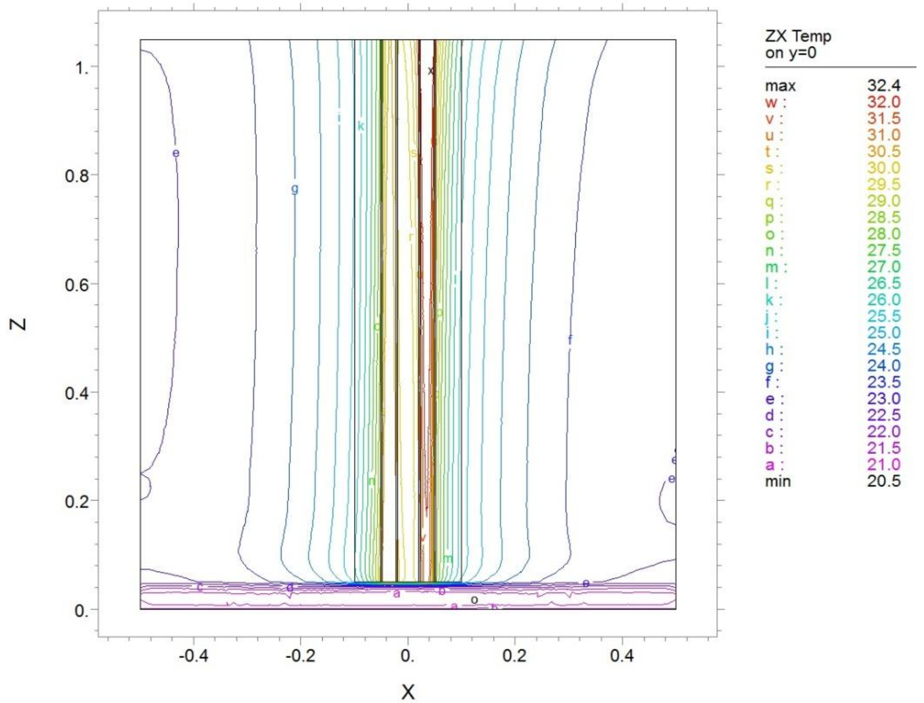
(b) The resulted final 3D-mesh used to check the effect of the layers on the temperature in the tubes of the GHE.



Comparison of the simulated fluid temperature to the actual recorded temperatures, for a 32mm U-tube and



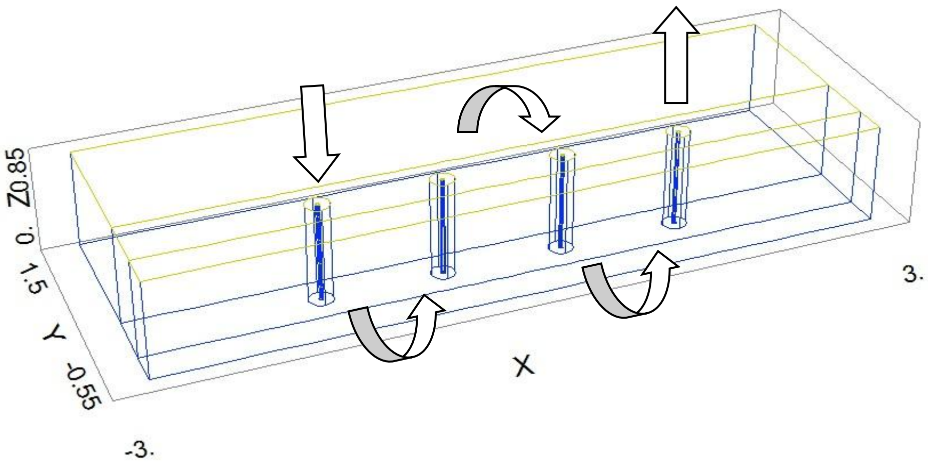
(a)



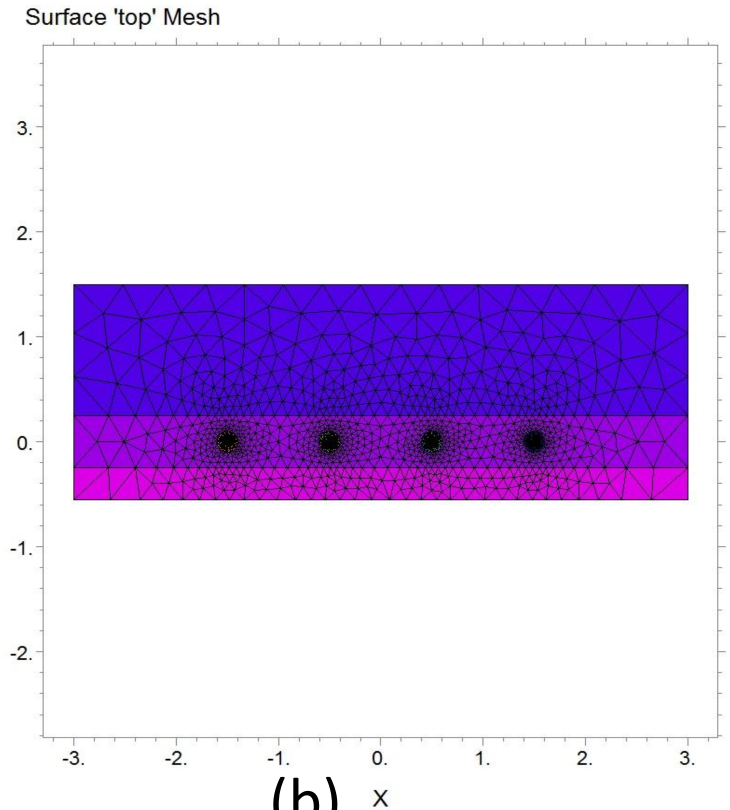
(b)

(a) Cross-sectional temperature distribution around the borehole at the surface (z = 105 m) after 50 h of operation of the vertical GHE.

(b) Axial (along the center of the GHE tubes) temperature distribution after 50 h of operation of the vertical GHE.



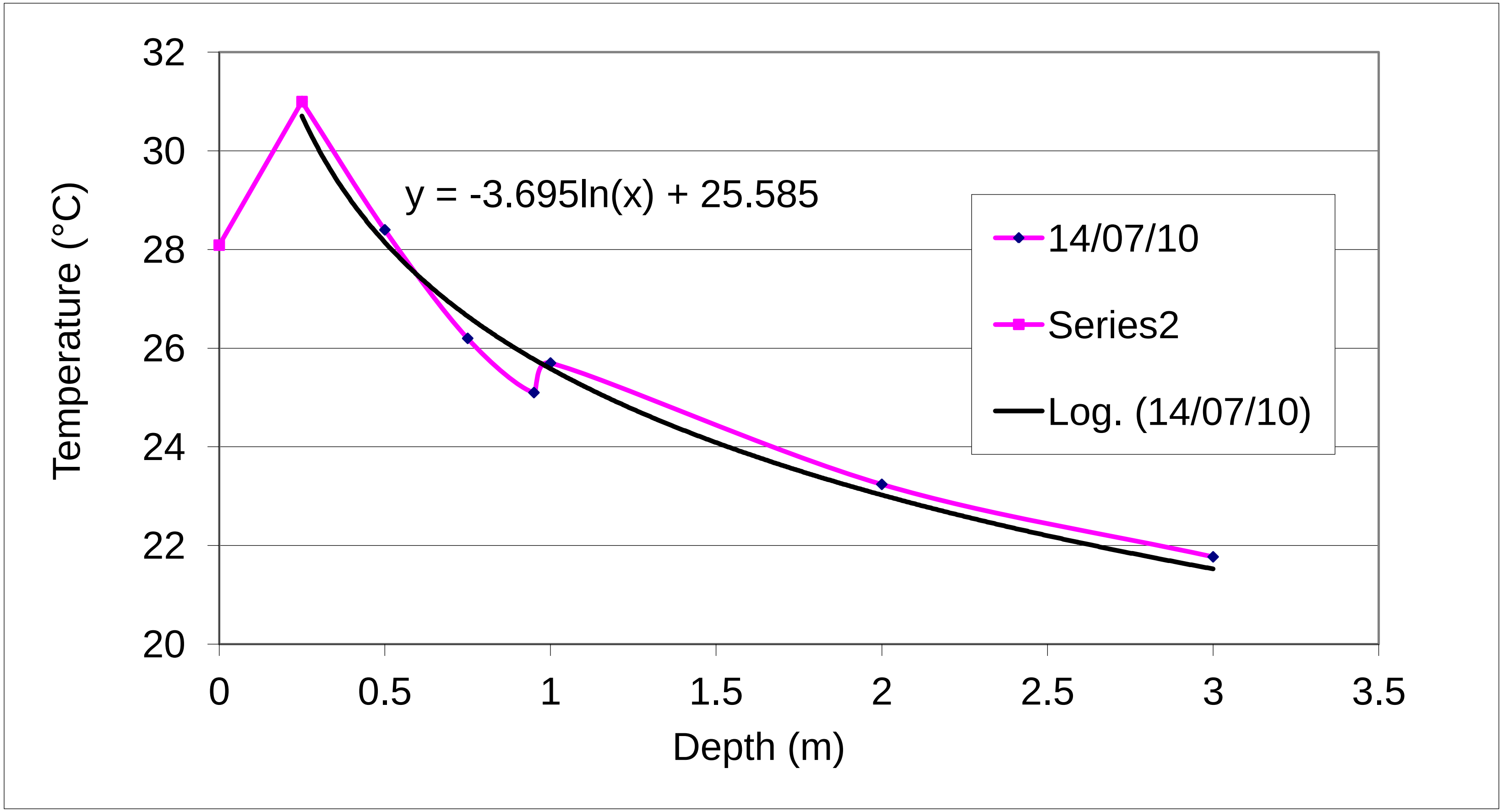
(a)



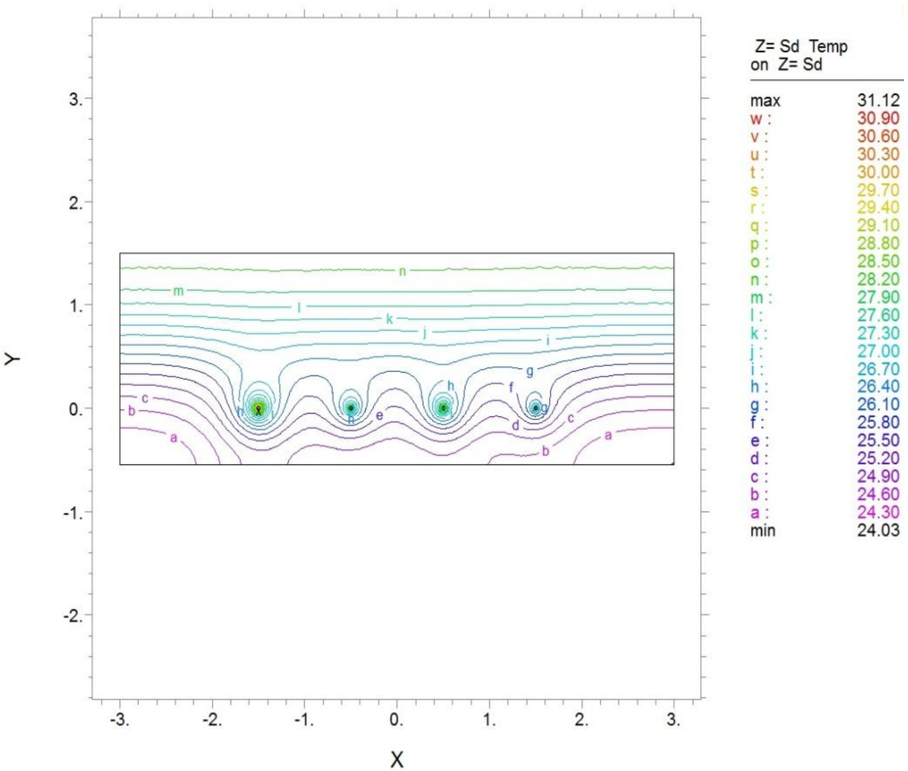
(b)

(a) The scaled geometry of the horizontal GHE.

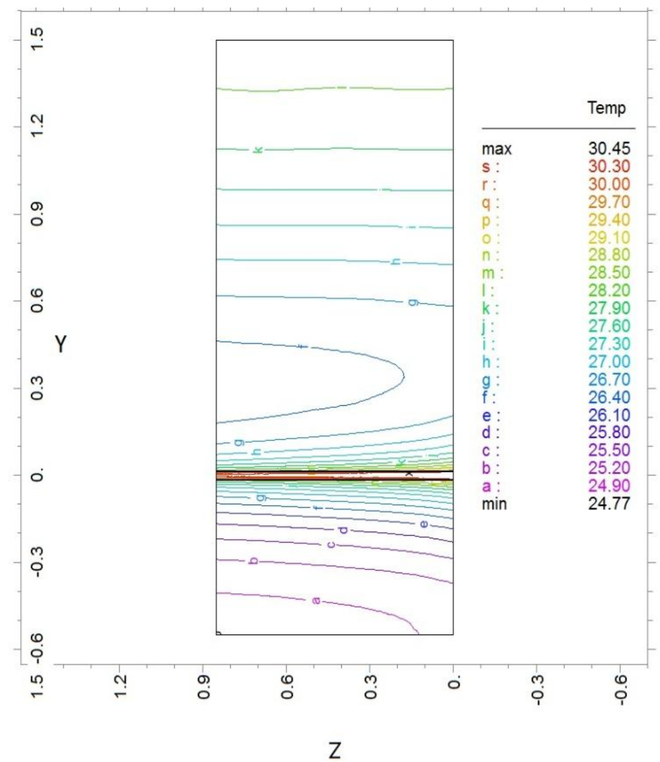
(b) The resulting final 3D-mesh used to check the efficiency of the horizontal GHE.



June recorded temperature at the Prodromi borehole. Also shown is the best fit equation for imposing temperature profile in the ground



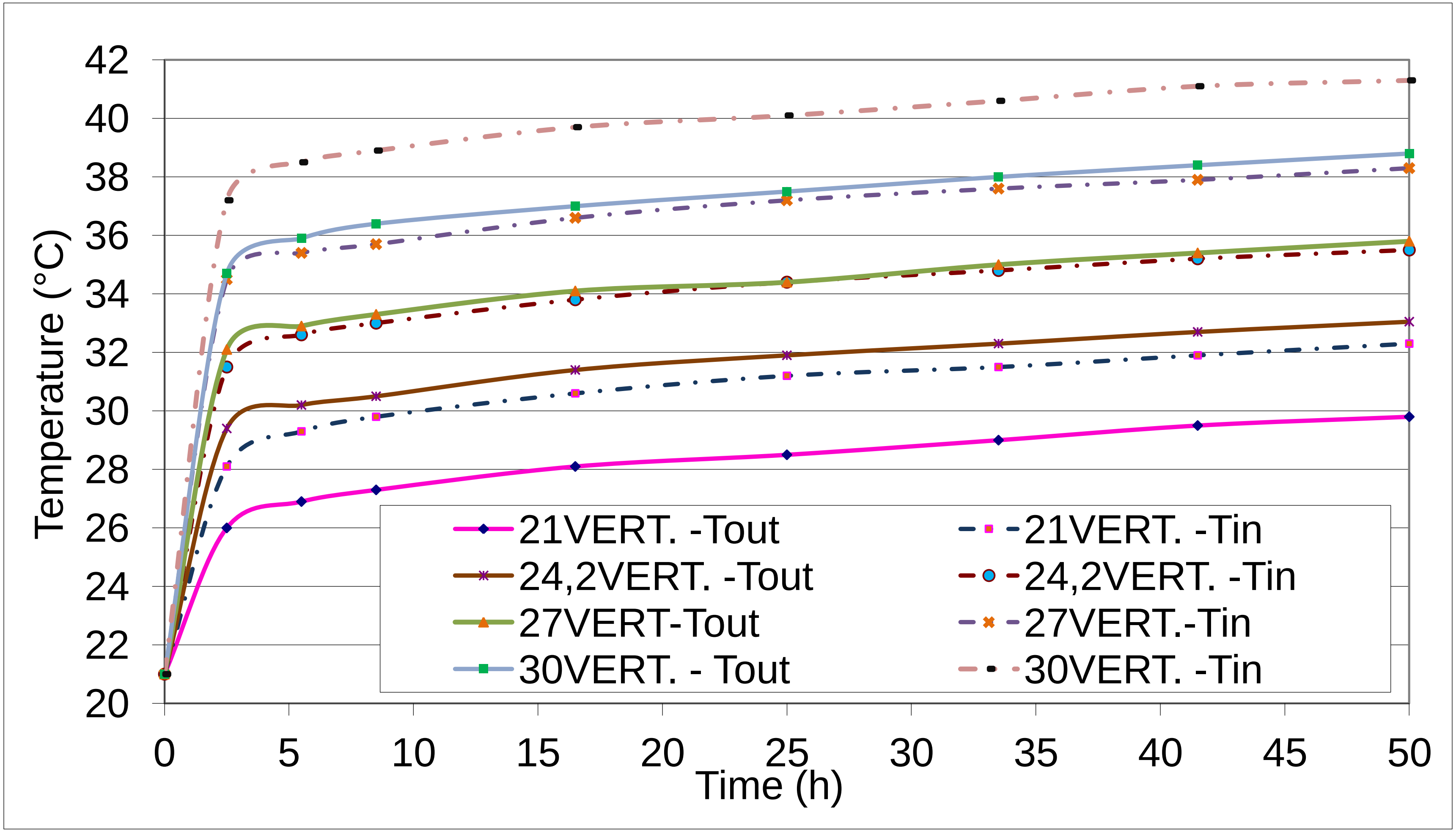
(a)



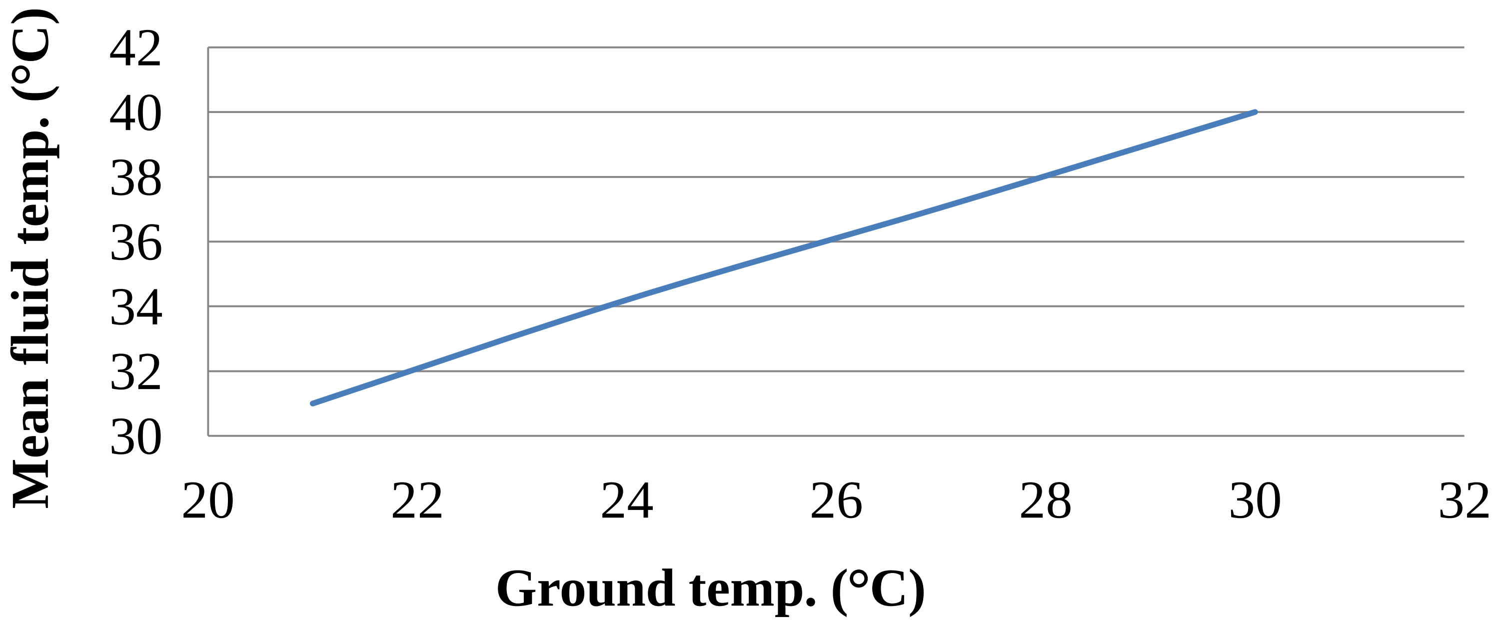
(b)

(a) Cross-sectional temperature distribution around the tubes of the horizontal heat exchanger after 50 h of operation.

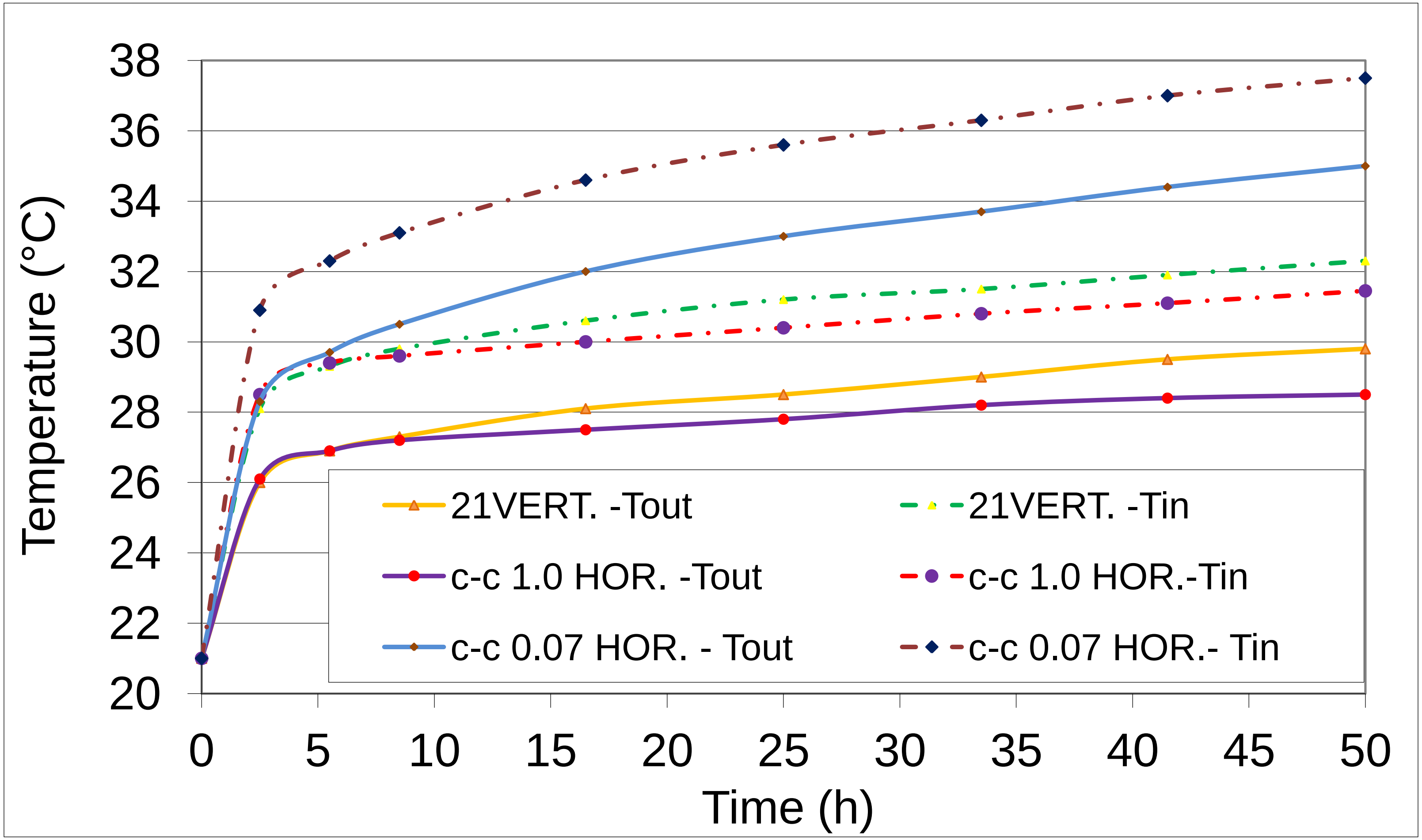
(b) Axial (along the center of a GHE tube) temperature distribution after 50 h of operation.



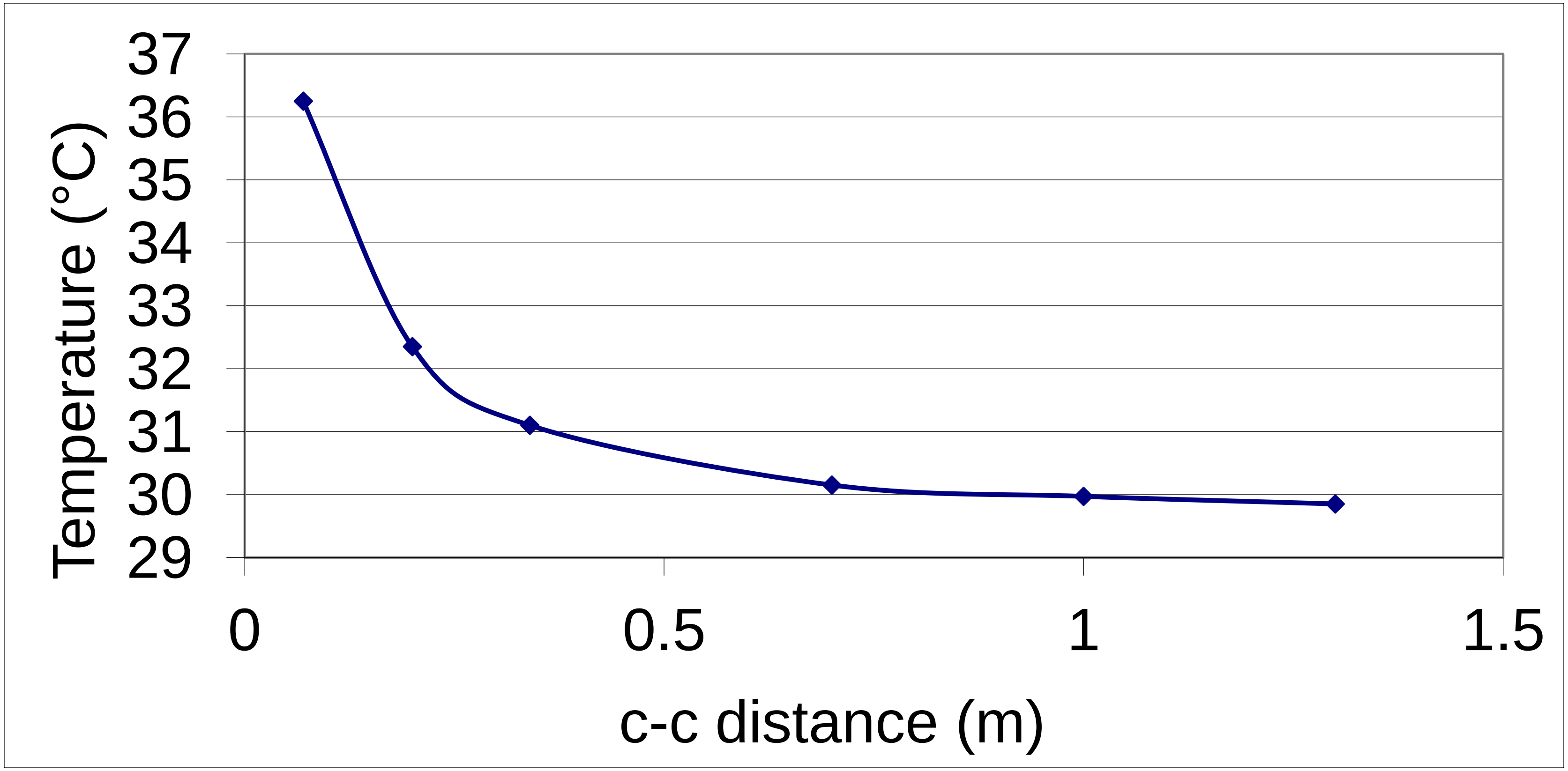
Effect of the ground temperature on the inlet and outlet fluid temperature of the vertical GHE



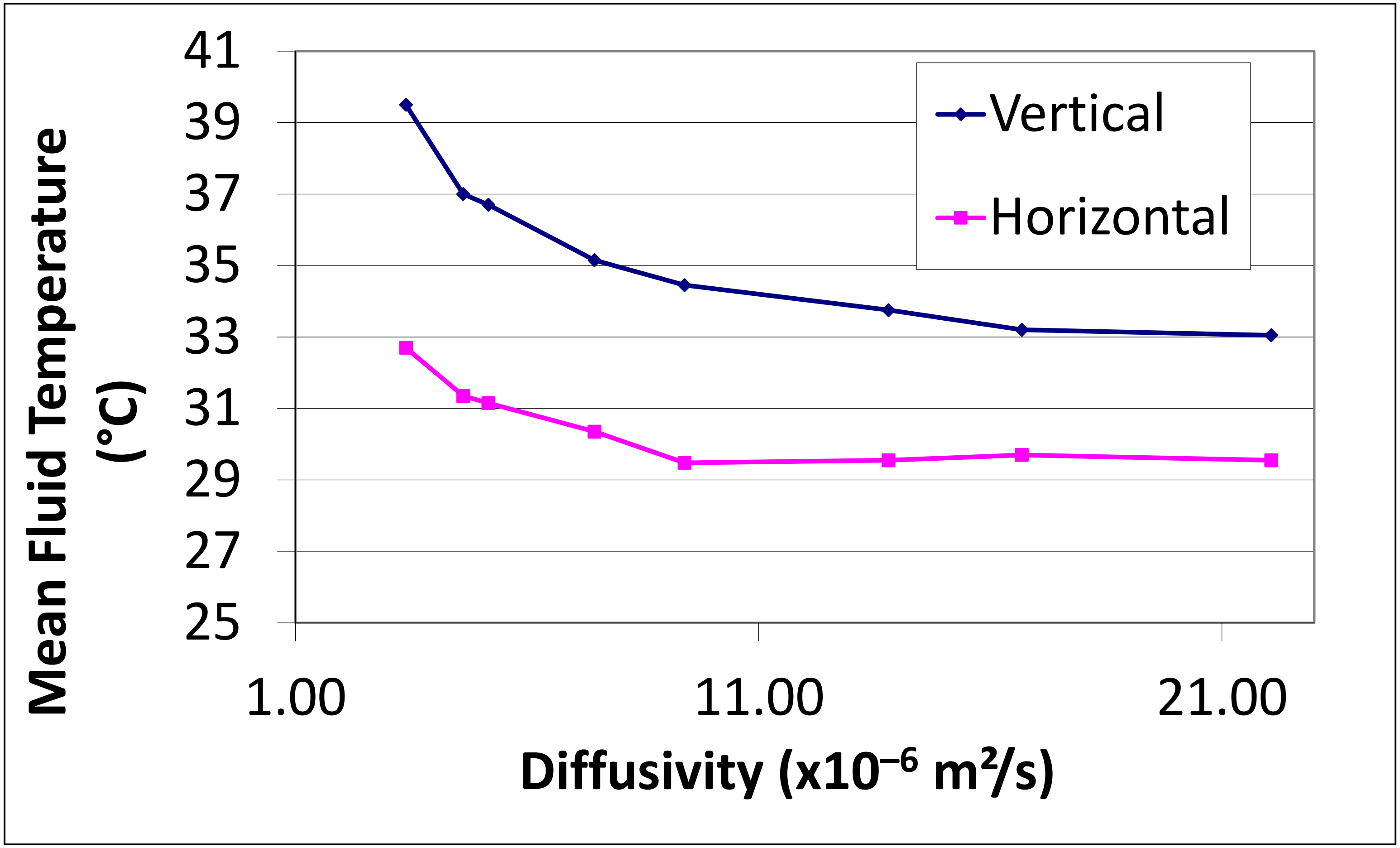
Effect of initial ground temperature on the mean fluid temperature of a 100-m vertical GHE.



Comparison of the inlet and outlet fluid temperature of the vertical and horizontal GHEs



Effect of centre to centre tube distance of a horizontal HE on the mean fluid temperature after 50h of operation



Ground diffusivity effect on the mean fluid temperature of the vertical and horizontal GHE

CONCLUSIONS

- The development and validation of a numerical model for the energy flow and temperature change in and around a borehole heat exchanger was presented.
- The model has combined a 3D conduction with a 1D mass flow and 1D convective heat transfer within the carrier fluid.
- The model was tuned, after taking into account experimental results.
- Cyprus with a large variety of lithologies, ranging from igneous to sedimentary, served as testing field for measuring the thermal properties and initial temperatures.
- Examining the effect of the initial ground temperature on the mean fluid temperature of a vertical GHE it was shown that a nearly linear relation exists under the conditions examined.
- A horizontal GHE will produce a hotter outlet fluid than a vertical one if the center-to-center tube distance is kept the same as for the vertical GHE. If this distance is increased enough then the horizontal GHE may produce a lower temperature than the vertical one.
- It was shown that thermal diffusivities above 16×10^{-6} m^2 s^{-1} are not additionally effective for the vertical GHE. Below that value diffusivity is very important as the lower the value the greater the temperature of the GHE. For the horizontal GHE the critical value is about $9\times t10^{-6}$ m^2 s^{-1}.

THANK YOU FOR YOUR ATTENTION