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Initial stage of Thermal Response Tests combined with transient numerical model – a foundation of short-term ground storage of cold for effective cooling of office buildings.

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Abstract

The short-term storage of cold in borehole heat exchangers (BHE) is analysed to minimise the electricity consumption for air-conditioning in large commercial or office buildings in major cities. The cold is effectively produced during the night and stored in the ground. Next, during the day, the storage cold will be discharged with very low use of electricity by so-called free-cooling. Proper design of such short-term ground storage requires full knowledge of geological conditions provided locally by Thermal Response Test (TRT). The properties of rapid loading/unloading of BHE may come from the initial stage of TRT, when heat (cold) is locally transferred in transient, unsteady, non-equilibrium way. To handle such detail heat transfer phenomena a quick numerical model is designed and adjusted to interpret the TRT data. The solver, much quicker than detail Computational Fluid Dynamics (CFD) models, is validated with several TRT data. Finally, simulations of short-term cold storage in BHE is provided.

Keywords: BHE, Short-term storage, free-cooling, TRT, cold storage;

Introduction

According to the electricity demand forecast, in Poland limitations of energy supply in the coming years are to be expected. The problem of imbalance between supply and demand is even more visible when analysing the progress of daily electricity consumption where peaks in the day and valleys in the night can clearly be seen. The worst situation occurs in the summer when the capabilities of the transmission grid are limited by high temperatures, with simultaneous high demand for energy consumed by more and more popular cooling systems. This issue is critical for large commercial and office building in big cities, when the possibility of local electricity production with photovoltaic or wind-turbines is limited due to lack of space. Moreover, typical cooling demand of office or commercial buildings is high, exceeding the heat demand even by several times.

It is known that the efficiency of standard air-conditioning systems based on dry-coolers depend on the outside temperature. The higher the temperature outside, the worse the efficiency of the cooling system, and the increased consumption of electricity. Production of cold at night when the outside temperature is lower than in the daily demand peak, ensures that the system will still be working with higher efficiency than in the daily peak and relieving the network during the daylight peak. Moreover, usually cheaper tariffs of electricity are available at night, which amplify a measurable economic effect for the customer.

Favourable option is to produce cold during night and store it for day, mainly to discharge heat to borehole heat exchangers (BHE) in the form of e.g. vertical exchangers, normally used as a lower heat source of the heat pumps. Such a solution potentially gives excellent results (e.g. lowering condensing temperatures by more than 15 °C). The use of ground heat exchangers to power the ground with cold of plus temperature, can greatly improve the efficiency of cooling with the use of a heat pump (i.e. free cooling).

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The behaviour of BHE as a short-term storage for cold must therefore be known in order to make optimal decisions about the operation of the system and to estimate usable heat capacity of such a system in the short term. Unproper construction and size of the ground heat exchanger, or too much heat discharged into the ground can cause its heating increase of condensing temperature to an unprofitable value.

To address the challenge of designing the optimal ground heat exchangers for short-term storage of cold applicable for commercial or office buildings we improve and link well-established procedure of Thermal Response Test (TRT) with transient, non-equilibrium numerical modelling of heat transfer.

The TRT is valid and well-proved to correctly estimate the long-term thermal performance of the BHE, but it fails for short-term applications when dynamics loading/reloading are included. In standard approaches, the initial phase the TRT cannot be taken into account because non-equilibrium phenomena happened. Although the very first ten hours of the thermal response test provide the most valuable insight into the BHE loading in day-night time-scale, they are often neglected and removed from the analysis. Using these initial results of standard TRT to predict the efficiency of short-term energy storage requires a new, more complex approach when local phenomena inside the borehole itself have to be considered. In fact, solving transient, local and non-equilibrium heat transfer is essential for applications when a borehole heat exchanger is loaded and reloaded rapidly.

In the present work, we propose an extended procedure of analysing TRT data, based on transient numerical modelling focused on the short time phenomena. We describe the in-house model, validate it with the results of benchmark thermal response tests, and compare with detail Computational Fluid Dynamics solution from the OpenFOAM code. Sensitivity analysis proved that the model is capable of predicting the results of the thermal response tests, both in short-term and in long-term. Finally, we present the monthly simulations of thermal energy storage in a day-night cycle with various demands from the commercial or office buildings.

2. Thermal Response Tests

Results from three standard thermal response tests are used in this work. The benchmark TRT test comes from Vienna as a joint effort of Central European project called Geoplasma-CE. In this well-documented borehole three group of researchers conducted TRT and interpreted their results. The other thermal response tests have been performed in Warsaw, in Vistula River Valley and in Koprki, outside Warsaw where Euros Energy headquarter is. The TRT test were conducted with commercially available specialised devices GERT designed to conduct TRT by UBeG company.

The following table summarized the parameters of TRT tests that were used in this work.

Table 1. Parameters of the thermal response tests.

Location	Heat load [W]	Length [m]	Mass flow rate [kg/s]	Initial borehole temperature [°C]	BHE type	Fluid
Koprki	8590	100	0.44	10.9	1U 40x3	Water
Warsaw	8730	100	0.47	9.3	1U 40x3.7	Glycol
Vienna	5130	150	0.36	12.4	1U 40x3.7	Water

3. Numerical solver and modelling

Early mathematical and numerical approaches treat BHE as two separate regions, the inside of the borehole (fluid, pipe and grout) and the outside of the borehole (ground). One-dimensional (1D) models [1] and [2] describe temperature in the ground using an analytical function, where [3] a simplified finite difference model of heat conduction is presented. The thermal capacities of the fluid, pipe and grout are neglected to simplify the model. This operation is commonly known as the quasi-steady state. It means that heat transfer inside borehole is always considered as time-independent, or that the thermal equilibrium is reached. As a result, those models are appropriate for long-term simulations only. The doctoral thesis [1] states that for times lesser than $5{r_b}^2/\alpha_s$ models are inaccurate, where r_b means radius of borehole and α_s denotes thermal diffusivity of soil (ground).

In order to simulate the short-term heat pump workloads, a more complex model of the transient heat conduction in the inside of BHE must have been implemented during work on Heat Exchanger Numeric Solver (HENS). This model, based on the [4], is composed of two parts: the outside and the inside linked via borehole heat loading.

3.1. The outside part of the model HENS

The outside part of the BHE model is a 2D axisymmetric heat conduction with Neumann boundary condition at borehole wall and Dirichlet boundary condition at far-field boundary. The ground temperature is obtained by solving the energy equation in the cylindrical coordinate system:

$$\frac{1}{a_s}\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2} \tag{1}$$

Partial differential equation is transformed to algebraic linear system of equation using finite volume method discretization. Due to stability, time derivative is transformed using fully implicit method. As mentioned before, boundary condition at borehole wall and far-field radius are established upfront – Neumann type $\dot{T}\,[K/m]$ (where $\dot{T} = \dot{q}/(2\pi k_s)\,[K/m]$) and Dirichlet type $T_{ff}\,[K]$ respectively. Rest of boundary conditions are arbitrary. The far-field boundary radius can be estimated by Eskilson [1] assumption $r_f = 3\sqrt{a_s t_{max}}$.

The mesh cells size in vertical direction should be refined at top and bottom boundaries. Such operation improves stability and reduces computational error. In case of mesh in radial direction the smallest cell should be at borehole and its size may vary from $r_b/6$ to $r_b/3$. Mesh size may increase along radius.

3.2. The inside part of the model HENS

Inside part of the BHE model works as a modified MTRCM [5] model considering thermal resistances and capacities of all components/regions. There are 3 regions – fluid, pipe and grout. Moreover, the grout region is split into three sections. One corresponding to the section of grout between the pipes and two sections between each pipe and borehole. To be able to simulate transiency of heat conduction each grout sections can be divided by a specific number of segments.

The vertical heat conduction and fluid mass transfer were calculated using a finite difference method. Boundary conditions are as follows: BHE heat load [W] and borehole wall temperature [K].

The idea of modelling inside part of the BHE comes from Hellström [6], who presented a 2D quasi-steady-state model. He introduced dependencies of fluid, grout and borehole temperature as thermal resistances ("delta circuit").

The number of temperature data points in one layer of the model may vary depending on the grout segments division. The number of cells in the vertical direction is related to the outside part of the model.

3.3. Solving procedure

The simulation procedure include the following steps:

1) Preprocessing data:
   a) Input thermophysical, geometrical and simulation parameters.
   b) Create a mesh.
   c) Calculate the resistances and capacities of the inside part of the model.
   d) Create initial temperature fields.
   e) Create matrices for inside and outside part of the model.
   f) Create RHS vectors for inside and outside part of the model, based on initial conditions.
2) Solving loop:
   a) Solve an algebraic system of equations of the inside part of the model.
   b) Solve an algebraic system of equations of the outside part of the model.
   c) Retrieve borehole heat load $\dot{q}\,[W/m]$
   d) Retrieve borehole temperature $T_b\,[K]$.
   e) Update RHS vectors for both part using new temperature fields and heat load and borehole temperature.
   f) Save temperature fields.
   g) Update timestep.

3.4. Initial validation with the result of CFD

To validate the solver a series of analyses has been performed. The first one is a comparison with detail computational fluid dynamics (CFD) numerical model optimized to simulate BHE. The CFD model allows simulating 3D transient heat conduction. The main tool used to perform analyses is OpenFOAM's chtMutliRegionFoam solver. The momentum equation for the fluid is solved before heat transfer simulation using simpleFoam solver. The obtained fluid velocity field is transferred to the heat conduction model to reduce calculation time. The chtMultiRegionFoam solves energy equations for all regions simultaneously. Such CFD model gives results comparable to real-life TRT's. The main disadvantage is high demand for computational power which leads to long time simulation duration. The CFD mesh has over 2.4 million cells, HENS has around 2000 cells only. The calculation speedup is expected while using a simplified model.

To determine speedup, the same case has been performed using both models. It took over 4708 seconds on average to evaluate 3D simulation results and 29 seconds on average using HENS. So the speedup reaches around 162 times, as shown in Fig. 1. Moreover, the error between obtained results is lesser than ±0.3 [K].

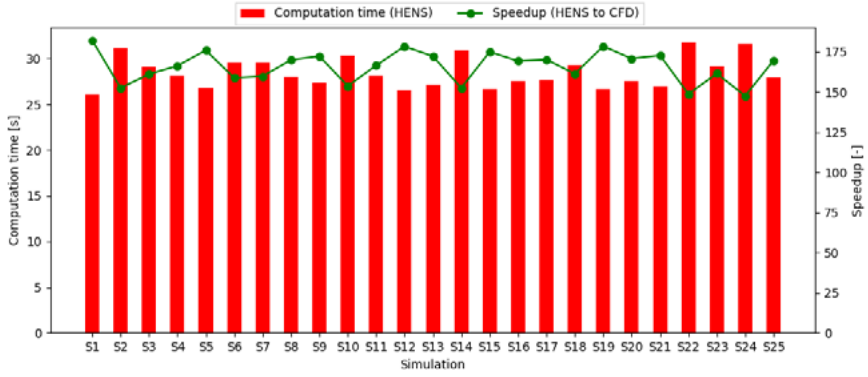


Fig. 1. Speedup of HENS solver, compare to the CDF solver in OpenFOAM.

4. Results - sensitivity analysis

4.1. Results from the TRT in Vienna, Austria

The reference thermal response test was carried on borehole heat exchanger located nearby Vienna City Centre area. This is a benchmark location to conduct TRT by various group, with well-determined geological parameters and properties od the borehole itself. The data from the TRT test is described in [7].
In Fig. 2 we summarised the results of the sensitivity analysis performed with different values of the thermal diffusivities of the ground (soil) and inject (cement). In this figure, and similar figures of the other TRT, the values of the temperature errors are presented. The errors are calculated as at each time step as a difference between the temperature directly measured during TRT and temperature computed with corresponding numerical simulation performed with HENS. We separately calculated errors based on temperature probed from the inlet and the outlet of the BHE.
The results with the minimum errors are presented in the centre sub-figure in Fig. 2. In the surrounding sub-figures errors are plotted for different values of thermal diffusivities of ground and cement, as specified in Table 2.

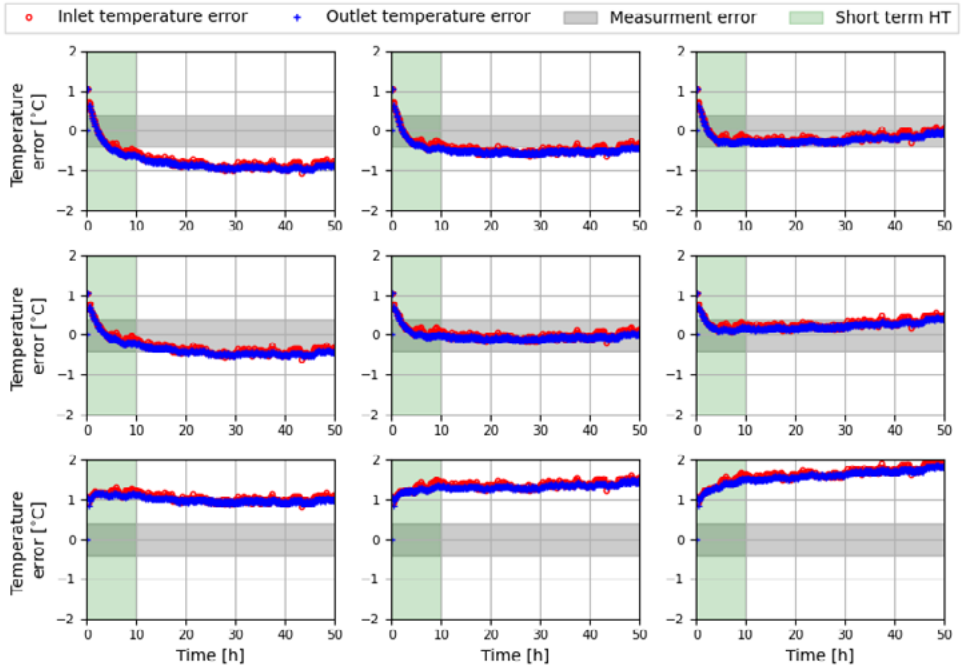


Fig. 2. Sensitivity analysis for the Vienna TRT. Each plot presents a temperature error plotted for the first 50 hours of TRT test, for the values of thermal diffusivity that corresponds to the layout in Table 2.

Table 2. The values of the thermal diffusivities of each subplots.

			Left column	Central Column	Right column
Upper row	α_s	$\left[\frac{m^2}{s}\right]$	$0.98 * 10^{-6}$	$1.09 * 10^{-6}$	$1.20 * 10^{-6}$
	α_c		$5.66 * 10^{-7}$	$5.66 * 10^{-7}$	$5.66 * 10^{-7}$
Middle row	α_s		$0.98 * 10^{-6}$	$1.09 * 10^{-6}$	$1.20 * 10^{-6}$
	α_c		$6.29 * 10^{-7}$	$6.29 * 10^{-7}$	$6.29 * 10^{-7}$
Lower row	α_s		$0.98 * 10^{-6}$	$1.09 * 10^{-6}$	$1.20 * 10^{-6}$
	α_c		$6.92 * 10^{-7}$	$6.92 * 10^{-7}$	$6.92 * 10^{-7}$

The initial temperature error converges to 0 in about 5 hours. It is worth to mention, that for this TRT the data was written every 10 minutes, so the exact time of the beginning of the test remains uncertain to this limit. That time shift may influence the temperature error values, especially when the temperature rises quickly. Such a situation occurs at the beginning of the TRT test. The overall behaviour of temperature error plots remains as stated before.

4.2. Results from the TRT in Warsaw, Poland

TRT test in Warsaw was carried on the Vistula River Shore area.

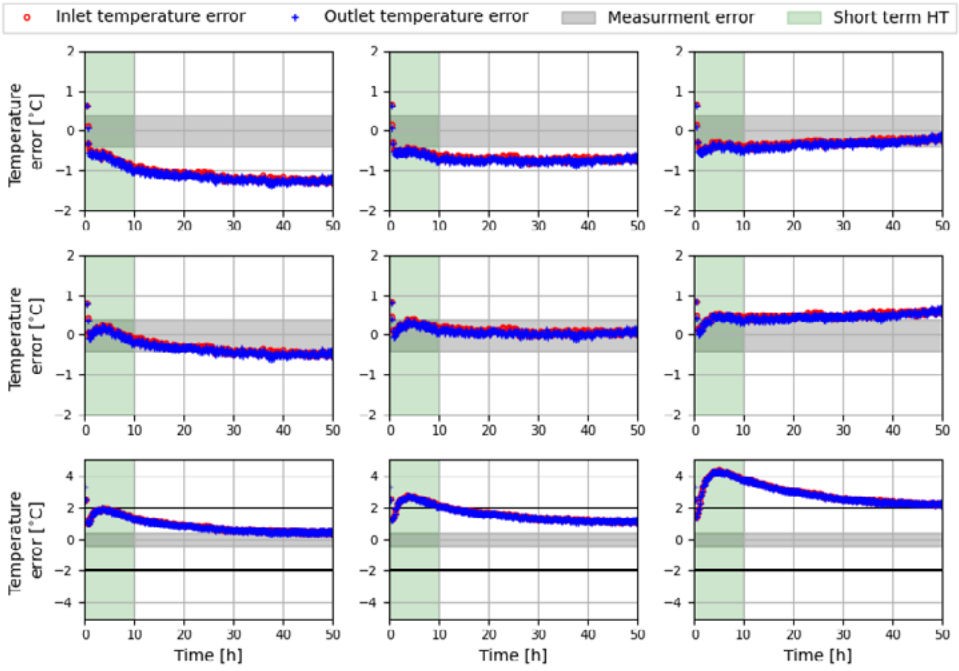


Fig. 3. Sensitivity analysis for the Warsaw TRT. Each plot presents a temperature error plotted for the first 50 hours of TRT test, for the values of thermal diffusivity that corresponds to the layout in Table 3. Note that the y-axis in the third row is expanded.

Table 3. The value of the thermal diffusivities of each subplots.

			Left column	Central Column	Right column
Upper row	α_s	$\left[\frac{m^2}{s}\right]$	$1{,}14 * 10^{-6}$	$1.27 * 10^{-6}$	$1.40 * 10^{-6}$
	α_c		$3.78 * 10^{-7}$	$3.78 * 10^{-7}$	$3.78 * 10^{-7}$
Middle row	α_s		$1{,}14 * 10^{-6}$	$1.27 * 10^{-6}$	$1.40 * 10^{-6}$
	α_c		$4.20 * 10^{-7}$	$4.20 * 10^{-7}$	$4.20 * 10^{-7}$
Lower row	α_s		$1{,}14 * 10^{-6}$	$1.27 * 10^{-6}$	$1.40 * 10^{-6}$
	α_c		$4.62 * 10^{-7}$	$4.62 * 10^{-7}$	$4.62 * 10^{-7}$

The result in lower right sub-plot is out of visible range. Despite different heat-carrying fluid, the behaviour of the results is similar.

4.3. Results from the TRT in Koprki, Poland

Next analysis presents the temperature influence of grout and soil thermal diffusivities on the accuracy of matching to TRT tests. The following figure shows the change in the differences between TRT and HENS inlet and outlet temperatures. The best matching result is shown in the centre subplot in Fig 4.

TRT test was carried on nearby the Euros Energy headquarters.

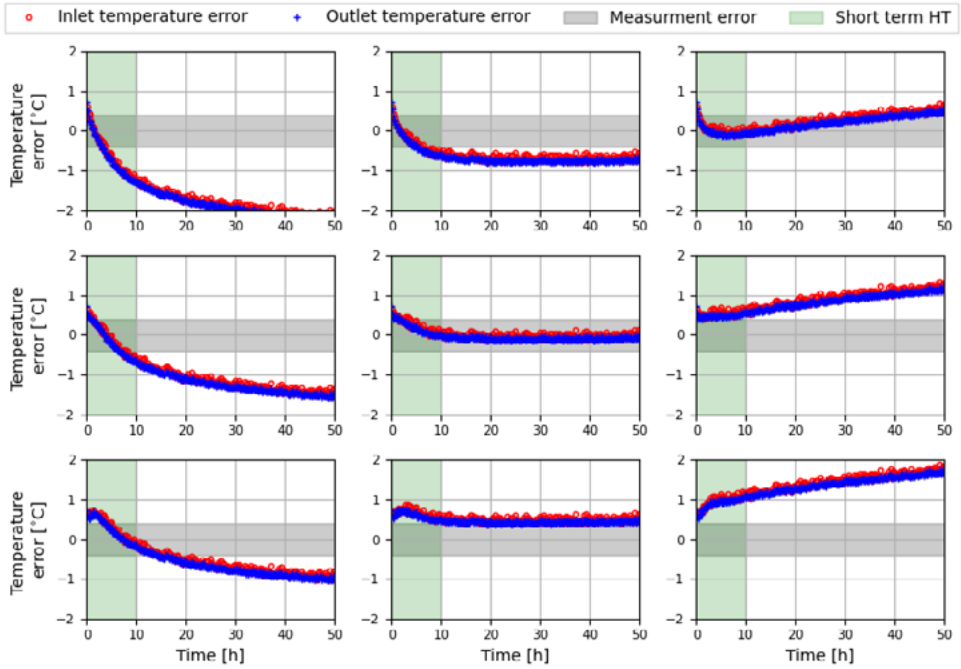


Fig. 4. Sensitivity analysis for the thermal response test in Koprki, nearby Warsaw. Each plot presents a temperature error plotted for the first 50 hours of TRT test, for the values of thermal diffusivity that corresponds to the layout in Table 4.

Table 4. The values of the thermal diffusivities of each subplots.

			Left column	Central Column	Right column
Upper row	α_s	$\left[\frac{m^2}{s}\right]$	$1.09 * 10^{-6}$	$1.21 * 10^{-6}$	$1.33 * 10^{-6}$
	α_c		$3.30 * 10^{-7}$	$3.30 * 10^{-7}$	$3.30 * 10^{-7}$
Middle row	α_s		$1.09 * 10^{-6}$	$1.21 * 10^{-6}$	$1.33 * 10^{-6}$
	α_c		$3.67 * 10^{-7}$	$3.67 * 10^{-7}$	$3.67 * 10^{-7}$
Lower row	α_s		$1.09 * 10^{-6}$	$1.21 * 10^{-6}$	$1.33 * 10^{-6}$
	α_c		$4.04 * 10^{-7}$	$4.04 * 10^{-7}$	$4.04 * 10^{-7}$

The results lead to the conclusion that soil thermal diffusivity determines the long term accuracy of temperature (the smaller the diffusivity value is the less heat is conducted through soil region and fluid temperature raise). Grout thermal diffusivity value specifies the rate of heat transfer in the short-term period.

5. Results – day/night cycles

Two four-weeks-long simulations present the simulated operation of the heat pump using different cycle schemes. Both tests are based on Koprki TRT parameters. The first one presents borehole heat load inversion every 12 hours. The second one shows a more complicated week-long cycle, during which there are 60 hours of heat delivery, 60 hours of heat extraction and 48 hours of idle.

5.1. Day cycle (12/12)

The 28 days of operation using 12/12 cycle plot presents high comparability of the results. Heat is delivered and extracted from a single BHE, with rate of 5 kW. During one cycle 60 KWh of energy is stored and restored out of the ground. There are no visible heat loss. An oscillating inlet temperature reaches 13.2 °C at peaks and

drops down to -9.2 °C. The lower plot visualizes the temporal values of coefficient of performance (COP). During the loading stage, when cold is stored in the BHE, the COP values drop from initial 8 to 5. The COP of cooling stage is divided into two components – the free-cooling part and regular cooling with heat pump. Free-cooling takes place when inlet temperature is smaller than 12 °C. The total cooling energy achieved by reusing cold stored in BHE reaches up to 43 kWh daily. The free-cooling COP is estimated by dividing total cooling energy by the electrical energy estimated to be used by fan coils and circulating pumps.

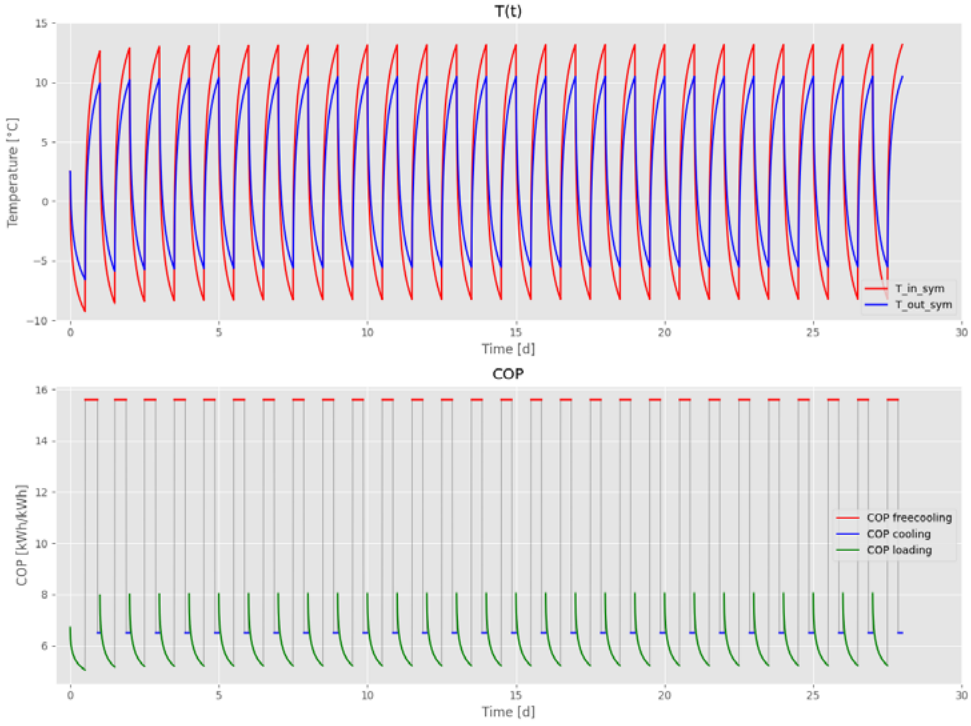


Fig. 5. Month simulation of the day/night cycle of loading and unloading the ground cold storage designed as a source of cooling of Euros Energy headquarter in Koprki.

5.2. Week cycle (12/9)

The second one shows a week-long cycle, during which there are 60 hours of heat delivery, 60 hours of heat extraction and 48 hours of idle. The details of cycle is specified in Table 5.

Table 5. Loading and unloading scheme. Notation: +Q states heat delivery; -Q states heat extraction; 0 states idle

	00^{00}-7^{00}	7^{00}-8^{00}	8^{00}-20^{00}	20^{00}-22^{00}	22^{00}-23^{59}
MON	+Q	0	-Q	0	+Q
TUE	+Q	0	-Q	0	+Q
WED	+Q	0	-Q	0	+Q
THU	+Q	0	-Q	0	+Q
FRI	+Q	0	-Q	0	
	00^{00}-7^{00}		7^{00}-19^{00}	19^{00}-23^{59}	
SAT	0		0	+Q	
SUN	+Q		0	+Q	

The week long cycle results plot presents that temperatures plots remain almost the same in case of comparing them week by week. The simulations starts on Friday at 20:00. During the weekdays inlet temperature at picks increases due to unbalanced heat energy supplied and received out of the BHE. The 12/9 cycle represents the

workload of a heat pump systems in an office building. The energy that is stored during nights and weekend can be retrieved during working hours at work days. Koprki's example presents 300 kWh of energy converted in BHE throughout one week. The COP of loading varies from 5.5 to 7.6. The free-cooling phase COP reaches 20.2, while conventional cooling phase coefficient of performance equals to 6.5.

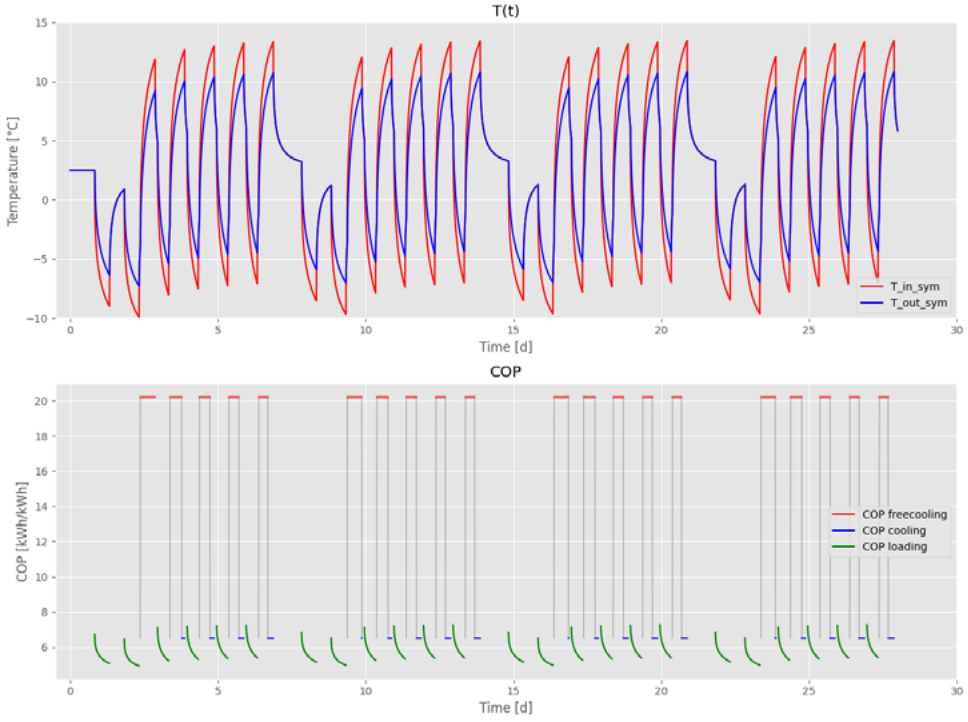


Fig. 6. Month simulation of the day/night cycle of loading and unloading the ground cold storage with weekends included.

6. Conclusions

The HENS model allows to solve complex heat conduction problem with relatively high accuracy. It is a great pre-processing tool to quickly evaluate the range of ground and soil thermophysical parameters. The correctness with three different TRT test proves that HENS can be highly applicable in research on heat pumps systems. Using HENS opens the possibility of investigation of long-term storage of heat or cold with defined workloads, including short-term cold storing with rapid loading/unloading. Moreover, a custom heat load may be specified. It allows to optimise cooling system for commercial of office buildings with specified energy tariff. Short-term heat storing takes place when the conditions are beneficial i.e. low energy tariff. Energy may be reused later to air condition buildings with free-cooling mode.

Nomenclature

r	Radius (m)	t	Time (s)
α	Thermal diffusivity (m^2/s)	Subscripts	
Q	Heat load (W)	b	Borehole
T	Temperature (K)	f	Fluid
q	Borehole heat load (W/m)	ff	Far-field
z	Depth (m)	g	Grout
k	Thermal conductivity (W/m/K)	s	Soil

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