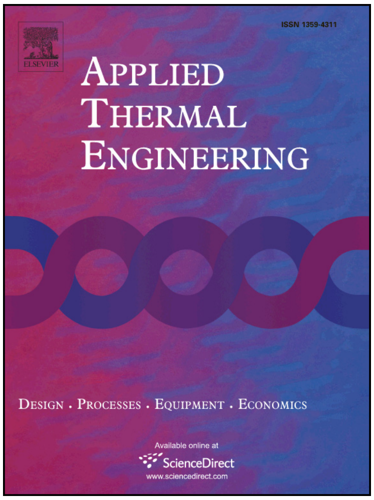

A Study on the Effect of Ground Surface Boundary Conditions in Modelling Shallow Ground Heat Exchangers

Marco Bortoloni, Michele Bottarelli, Yuehong Su

PII: S1359-4311(16)30720-7
DOI: http://dx.doi.org/10.1016/j.applthermaleng.2016.05.063
Reference: ATE 8278

To appear in: *Applied Thermal Engineering*

Received Date: 14 December 2015
Revised Date: 29 April 2016
Accepted Date: 10 May 2016

Please cite this article as: M. Bortoloni, M. Bottarelli, Y. Su, A Study on the Effect of Ground Surface Boundary Conditions in Modelling Shallow Ground Heat Exchangers, *Applied Thermal Engineering* (2016), doi: http://dx.doi.org/10.1016/j.applthermaleng.2016.05.063

A Study on the Effect of Ground Surface Boundary Conditions in Modelling Shallow Ground Heat Exchangers

MARCO Bortoloni[1,*], MICHELE Bottarelli[1], YUEHONG Su[2]
[1] Department of Architecture, via Quartieri 8, 44121 Ferrara, Italy
[2] Department of Architecture and Built Environment, The University of Nottingham, University Park, Nottingham NG7 2RD, UK

*Corresponding email: marco.bortoloni@unife.it

ABSTRACT

The effect on numerical solution of different thermal boundary conditions at the ground surface was analysed in modelling HGHEs. Boundary conditions of the 1st, 2nd and 3rd kind have been alternately tested by means of a finite element numerical code, solving the unsteady-state heat transfer problem in a 2D domain. An energy balance equation at the ground surface (3rd kind BC) has been developed and implemented in the numerical model. A preliminary simulation has been carried out in absence of the HGHE operating using real weather data. The solution has been validated with experimental data, and assumed as reference. The calibrated GSEB equation proved to properly predict the temperature in the soil. The resulting heat flux and temperature at the top of the domain have been considered respectively as the 2nd and 1st kind of equivalent boundary conditions for two new models. Finally, all three models have been solved with the supposed HGHE operating, to analyse how the different BCs affected the numerical solution. The results have been compared in terms of average temperature at the HGHE wall surface and in the ground. The use of a heat flux as BCs at the ground surface appeared as an extremely precautionary approach due to the resulting thermal drift in the soil. On the contrary, to assign an energy balance equation or a temperature as BCs on the ground surface seemed to have a limited effect in terms of temperature at the heat exchanger and in the soil.

KEYWORDS:
(Ground surface energy balance, ground heat exchangers, Numerical modelling, boundary conditions)

1. INTRODUCTION

Reduction of the building energy demand and greenhouse gases emissions are topics of great relevance in European policies of future planning. These policies sustain the spreading of renewable energy sources for space heating and cooling. Ground-coupled heat pumps (GCHPs) are regarded as a profitable and sustainable energy technology in this field, due to their high energy efficiency when the design is compliant with local environmental conditions [1-2]. In GCHPs the heat transfer is performed by means by means of ground heat exchangers, which can be installed vertically (VGHEs) or horizontally (HGHEs) as a loop placed in shallow diggings few meters deep in soil.

The performance of a GCHP system depends mainly on the thermo-kinetics coupling between the heat exchanger and soil. HGHEs use the ground as unsteady source/sink energy storage, related to the solar energy balance at ground surface. Although the close dependence on environmental conditions prevents thermal drifts after long-term operation [3], the seasonal temperature variation in shallow soil may lead to unfavourable working conditions for HGHEs, so the ground-coupling for a heat pump must be designed and sized accurately.

Several researches have been conducted to study the performance of HGHEs, following an analytical approach based on the line source theory and cylindrical heat transfer equations [4] or by means of numerical models. Anyway, attention should be paid to the correct assignment of the boundary condition at the ground surface, in order to treat realistically the effect of environmental conditions. The energy balance at the ground surface is usually reduced to a 1st kind boundary condition (BC). In [5] a sinusoidal temperature trend is assigned to the ground surface. A daily temperature time series is used as boundary condition in [6], as calculated by means of a ground surface energy balance using real weather data. The similar 1st BC has been numerically converted to the 2nd equivalent kind BC by means of a heat flux in [7], with the aim of considering the effect of the energy exploitation on the ground surface temperature. Despite the long computational time required, other numerical studies have been carried out including the mass transfer to take into account the effects of the soil moisture, as shown in [8] or developing an energy balance equation at the ground surface, i.e. 3rd kind BC. In [9] only the convective heat flux between air and ground is considered. The external environmental conditions are included in the models by means of energy balance equation validated against experimental data, taking into account the effect of solar radiation, latent and sensible heat transfer [10]. A ground surface heat balance is also used to study the performance of building foundation as heat exchanger in [11]. The simultaneous heat and moisture heat transfer at the ground surface has been considered in modelling an earth-air tunnel in a ventilation system in [12].

This study aims to compare the effect on the solution of 1st, 2nd and 3rd kind BCs assigned at the ground surface in modelling HGHEs. A finite element numerical code has been applied solving the unsteady-state heat transfer problem in a

2D domain. An energy balance equation at the ground surface (3rd kind BC) has been developed, using real weather data and validated against experimental measurements. The resulting temperature and heat flux at the top of the domain have been considered respectively as the 1st and 2nd kind BCs for two other cases. Finally, an HGHE has been included in the simulations, applying alternately the different BCs.

2. NUMERICAL MODELLING

The commercial finite-element code COMSOL Multiphisycs V5.0 was used for the simulations, to solve the unsteady heat transfer problem in a 2D computational domain. A model of the energy balance at the ground surface has been developed, based on the ground surface properties (albedo and emissivity) and weather variables (solar radiation, air temperature, relative humidity, atmospheric pressure and wind speed). For a realistic simulation of the environmental conditions, weather data sets based on experimental data were used for simulations. A preliminary simulation was carried out to validate the proposed ground surface energy balance equation (GSEB) in absence of HGHEs, as described in the following. The simulated soil temperature has been compared with observed soil temperature at various depths, showing good agreement. Finally, simulations were carried out to test the energy performance of HGHE in heating and cooling, under the same environmental conditions. The GSEB equation, the resulting heat flux and temperature on ground surface have been used as boundary condition alternately, to analyse how the different BCs affected the numerical solution.

2.1. Model Domain

In this task, more attention was paid to the boundary conditions at the ground surface and to the modelling of the heat transfer induced by HGHEs in the soil. Hence, a 2D domain was modelled as a section of an HGHE and a large surrounding soil part (10 m wide and 10 m deep). A symmetric approach was applied to reduce the time required for calculations. The computational domain was taken to be sufficiently large to have a thermally undisturbed area by the HGHE operation. Here, the HGHE was assumed to be a flat-panel (FP), a novel type of ground exchanger invented at the University of Ferrara (Italy) that shows high energy performance, as reported in [13]. In the model domain, the FP was simplified as a vertical line and introduced as boundary condition. The supposed FP is 1 m high and lay within shallow soil, between a depth of 1 and 2 m. A scheme of the model domain is shown in Fig.1 together with the full mesh.

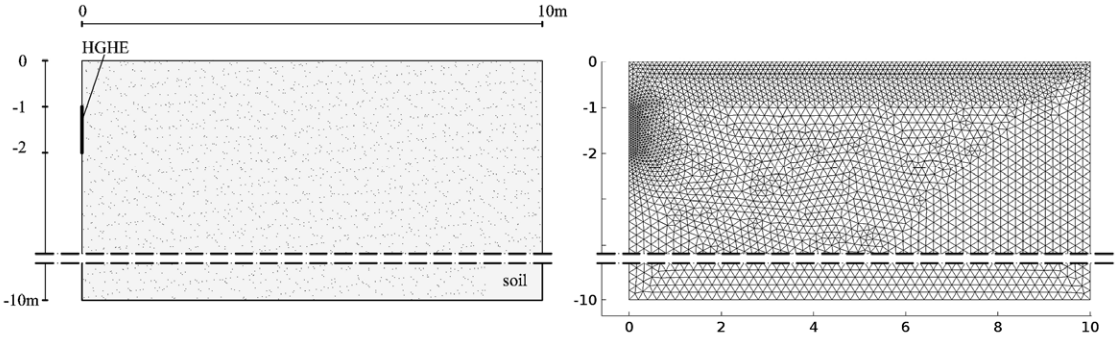

Figure 1: Sketch of the one-half symmetric model domain and mesh

To improve the solution, a higher concentration of elements is imposed near the FP and on the top edge of the domain (representing the ground surface) where higher temperature gradients are expected, and coarse in the outer domain. In order to check the grid independence of the solution, a preliminary analysis has been carried out. Different grid refinements have been simulated, progressively increasing the number of elements in the vicinity of the FP and of the top boundary, as well in the whole domain. The final mesh is composed by up to 10000 triangular linear elements.

The soil is supposed to be homogenous and isotropic over the entire domain. The thermo-physical properties of the soil were chosen according to [14], the recent Italian standard regulation about ground source heat pump systems. The properties of the ground surface were taken from those reported in [15] for a bare soil. The thermo-physical properties of the soil and of the ground surface are reported in Tab.1.

Table 1: Physical properties of soil

Thermal conductivity	Density	Specific heat	Surface albedo (α)	Surface emissivity
(W/mK)	(Kg/m^3)	(J/kgK)	(-)	(-)
1.5	1800	1700	0.15	0.95

3. BOUNDARY CONDITIONS

Only the heat transfer problem has been solved in the model domain, so thermal boundary conditions were assigned to the outer domain boundaries. At the top, boundary conditions of 1st, 2nd and 3rd kind have been alternately imposed at the ground surface in modelling HGHEs. A GSEB equation was firstly used as the 3rd kind BC in a preliminary model to assess the equivalent heat flux (2nd kind BC) and the equivalent ground surface temperature (1st kind BC). A heat flux time series has been set to the HGHE, representing the heating and cooling demand. Finally, an adiabatic condition was assigned to the side and bottom boundaries of the domain. Full details of the BCs at the ground surface and of the energy demand at the HGHE are given below, in section 3.1 and 3.3 respectively.

To calculate the GSEB and to determine the HGHE heat flux at hourly scale, a complete set of 2014 weather data of Ferrara, a city in northern Italy, were used in simulations. Several weather variables (solar radiation, air temperature, relative humidity, atmospheric pressure and wind speed) have been collected on an hourly basis by means of a Davis Vantage Pro2 Plus weather station installed since 2012 at the Department of Architecture in Ferrara. Measurements of the downward longwave radiation have been kindly provided by ARPA-EM (the meteorological service of the Emilia Romagna region). Moreover, the weather station has been equipped with four temperature probes since 2013, to monitor in real time the soil temperature at different depths (0.1, 0.8, 2.4, 4.2m). The sensors installed are thermistor with a resolution of ±0.5°C. The soil temperature time series for 2014 has been used to calibrate the parameters in the GSEB equation and to check the reliability of the model.

3.1. Energy Balance at the Ground Surface

The heat transfer between the ground surface and the underlying soil was supposed occurring only by conduction, in the model. The temperature in the soil is driven by the energy fluxes at the ground surface, so the heat flux deepening in soil is defined by the energy balance equation in a general and simplified form:

Equation 1: Energy balance at the ground surface.

$$G = R - H - LE$$

Where:

- G = soil heat flux (W/m^2)
- R = net radiative energy flux (W/m^2)
- H = sensible energy flux (W/m^2)
- LE = latent energy flux (W/m^2)

The effect of each component depends on the surface covering. A grassy surface was taken as reference to have comparability with the available measurements of soil temperature at different depths. The introduction of a vegetated layer has a major effects on the surface heat transfer, and consequently on the surface temperature. A detailed modelling of the effect of the grass on GSEB would require an additional equation to solve energy balance of the vegetated layer, as reported in [16-17]. To reduce the computational time, we opted for a simplification in modelling vegetation, neglecting a separate energy balance equation for vegetation and the underlying soil. The effect of the former one was introduced by means of appropriate coefficients of calibration for each energy flux. The surface temperature is mainly driven by the radiative component, especially during the summer. The net radiative energy flux R (W/m^2) consider absorption and reflection of the incident shortwave radiation solar radiation into its components direct and diffused, and the longwave radiation received and emitted by the surface. The amount of shortwave and longwave solar radiation reaching the ground surface and the outgoing longwave radiation as well, are reduced by the shading due to the grassy layer, so a coefficient of shading (a_1) was introduced. The net radiative energy flux at the ground surface is given by:

Equation 2: Net radiative energy flux.

$$R = a_1\left[(1-\alpha)Rs + Rl_d - \varepsilon_s \sigma T_s^4\right]$$

Where:

- a_1 = calibration coefficient of shading
- α = surface albedo
- Rs = shortwave solar radiation (W/m^2)
- Rl_d = downward longwave solar radiation (W/m^2)
- ε_s = surface emissivity
- σ = Stefan-Boltzmann constant (W/m^{2}K^4)
- T_s = surface temperature (K)

The convective energy flux between air and ground surface was calculated with Eq.3, where a coefficient of calibration (a_2) was introduced to take into account the sheltering effect of the vegetated layer as follows:

Equation 3: Convective energy flux.

$$H = a_2\left[h_{conv}\left(T_s - T_a\right)\right]$$

Where:

- a_2 = calibration coefficient of sheltering
- h_{conv} = convective heat transfer coefficient (W/m^{2}K)
- T_s = surface temperature (K)
- T_a = air temperature (K)

According to [18] the convective heat transfer coefficient at ground surface was calculated by means of the following empirical Jürges equations:

Equation 4: Convective heat transfer coefficient.

$$\begin{cases} h_{conv} = 5.8 + 3.9v; \left(v < 5m/s\right) \\ h_{conv} = 7.1v^{0.78}; \left(v > 5m/s\right) \end{cases}$$

Where:

- v = wind speed (m/s).

The evapotranspiration from the vegetated surface has been calculated following the FAO Penman-Monteith model that proved to be reliable for different climates and time step [19]. The equation allows the ET_0 evapotranspiration calculation for a reference grass crop well irrigated and completely shading the ground, using standard weather data. The evapotranspiration is then calculated in terms of mass by assuming a constant density of water. In calculating the latent heat flux at the ground surface, a calibration coefficient (a_3) was introduced, in order to take into account the characteristics of the vegetated layer, which is a not irrigated wild meadow. The coefficient a_3 is equivalent of the single crop coefficient K_c, which is usually calculated for different agricultural crops and crop growth stages [19]. In this model, variations in vegetation have not been considered due to the objective difficulties in knowing the different growth stages of a wild meadow as well as the watering. Therefore, we opted to assign a different name to the parameter. In view of this, the latent energy flux at the ground surface is given by:

Equation 5: Latent energy flux.

$$LE = a_3 \cdot \frac{lh \cdot \rho \cdot ET_0}{3.600}$$

where:

- a_3 = calibration coefficient
- lh = latent heat of evaporation (J/kg)
- ρ = density of water (1.000 kg/m^3)
- ET_0 = reference evapotranspiration (l/m^{2}h)

3.2. Validation of the model

The GSEB equation (Eq.1) was validated with the observed soil temperature data at different depths in 2014. The Eq.1 has been properly implemented in COMSOL to be tested as boundary condition at the ground surface, and a preliminary numerical simulation was carried out for a whole year in unsteady state. In this model, the heat flux representative of the HGHE was set to zero, so the variation in the soil thermal field was determined by the environmental conditions only. The weather conditions observed at the test field in 2014 were converted in hourly scale time series and used as input in Eq.2-5. The soil temperature was monitored with an hourly time step at different depths. The measured soil temperature data has been compared to the simulated temperature at the same depth to calibrate the parameters a_1, a_2 and a_3 in Eq.1 and thus to analyse the reliability of the model in predicting the soil temperature. Finally, a soil temperature profile for the 1st day of 2014 was obtained from the available soil temperature data and set as the initial condition for simulations.
The values of the three calibration parameters were set to reduce the difference between the simulated (*s*) and the measured (*m*) temperature in the soil. The calibration coefficient of shading (a_1) was set to 0.30. It represents the view factor between the ground surface and the sky/sun. It was assumed that the 70 % of both incoming shortwave and longwave radiation were absorbed by the vegetated layer on the ground surface. The coefficient of sheltering (a_2) was set to 0.35. Finally, to account for the lack of a system of irrigation, the latent heat flux was reduced setting a_3 equal to 0.25.
The daily averaged values of soil temperature observed and simulated are reported in Fig. 2. Four temperature probes were considered (*T1*, *T2*, *T3* and *T4*) at four different depths (0.1, 0.8, 2.4, 4.2 m respectively). Deviations are detectable

mainly for shallow probes *T1* and *T2*, where fluctuations in temperature are greater. For shallow probes, the relationship between measured and simulated temperature is more stable in winter, when the radiative heat flux is low and the latent heat flux is nearly zero. In this case the simulated temperatures are slightly higher than measured ones with a maximum error of 1.47 °C. The model showed less accuracy in the estimating shallow soil temperature in summer, with a maximum error of 2 °C. This could be a variation in the energy balance due to the natural growth cycle of the grass covering the ground surface, not accounted in the model, such as the rain. Finally, the temperatures are in good correspondence for both deep probes (T3 and T4) for the entire period of simulation.

A scatter plot of the simulated soil temperatures versus the equivalent measured are shown in Fig. 3 for probe T1 (depth 0.1 m) and in Fig. 4 for probe T2 (depth 0.8 m), where the central line represents a perfect relationship between measured and simulated values, and the two others a span of 2 °C. In both cases the slope of the relationship is close to 1:1, although slightly dispersion occurs for a temperature higher than 20 °C. The overall mean root square error (RMSE) has been calculated for the entire simulation period, and reported in Tab. 2 for each temperature probes.

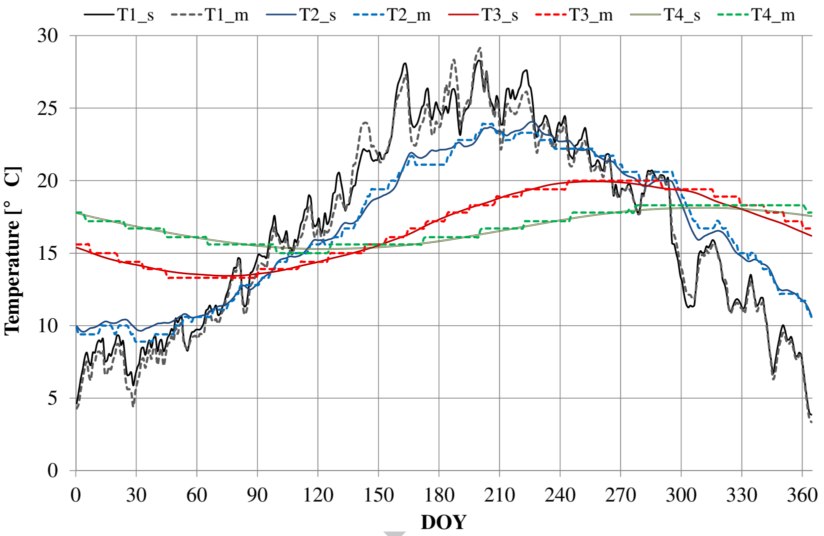

Figure 2: Daily averaged soil temperature at different depth (0.1, 0.8, 2.4, 4.2m): simulated (s) and measured (m).

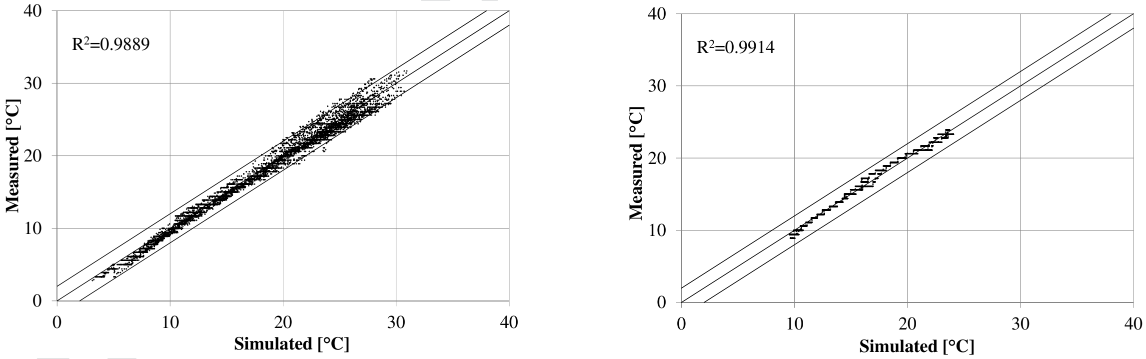

Figure 3: Scatter plot of the simulated and measured hourly temperature 0.1 m deep in soil

Figure 4: Scatter plot of the simulated and measured hourly temperature 0.8 m deep in soil

Table 2: Soil temperature simulation accuracy at different depths

Depth (m)	0.1	0.8	2.4	4.2
RMSE (°C)	0.79	0.46	0.29	0.25

The calibrated GSEB equation proved to properly predict the temperature in the soil. The discrepancies between the measured and simulated values were considered satisfactory. Furthermore, the error was reduced with increasing depth and then the thermo-physical properties of soil considered were plausible.

Fig. 5 shows the energy partition between each component of the GSEB, for 3 days in winter and summer. Both in winter and in summer, the conductive heat flux in soil (*G*) has a strong dependence on the net radiation (*R*) because the ground surface was supposed to be only partially shaded by the vegetation above. The convective heat flux (*H*) is low on average due to the sheltering effect by the vegetated layer. Moreover, the convective heat transfer coefficient is affected by the dependence on the low wind speed, here representative of an urban area. *H* is relatively stable and varies between +25 and -15 W/m^2 depending on the temperature difference between air and surface. As expected, the heat loss from the surface due to the latent heat flux (*LE*) is nearly zero in winter. It is related to the air temperature and soil heat flux, thus an increase is observed in summer, with a daily oscillation between 25 and 5 W/m^2 during daytime and nighttime.

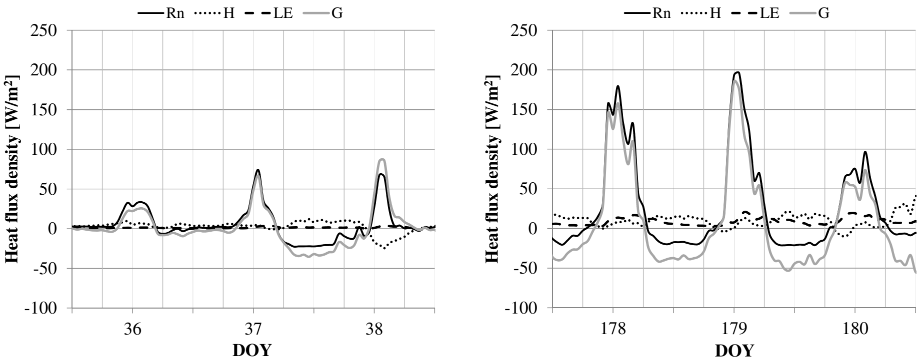

Figure 5: Energy partition of heat fluxes at ground surface during winter and summer.

A further case was simulated to analyse the relationship between the air temperature near the ground and the surface temperature. The hourly scale time series for the air temperature near ground in 2014 was used as 1st kind BC. The resulting daily averaged values of soil temperature are reported in Fig. 6, in comparison with the equivalent soil temperature data at different depths, observed in 2014. The relationship between measured and simulated temperature is more stable during the first 90 days of winter, when the radiative heat flux is low. As the temperature increases, deviations are detectable in all probes and the estimated temperature at different depths is always lower than the measured one. This could be related to the fact that the energy budget at the ground surface is normally affected by solar radiation daytime although, in the case of partial vegetation cover, the ground surface is partially shaded. During the day, the surface is heated up by incident solar radiation therefore, the temperature at the surface can be higher in comparison to the air temperature. By assuming the ground surface temperature to be equal to that of the air, the former effect of radiative heat transfer cannot be taken into account. The air temperature is not directly applicable as BC, and a reliable correlation between the air and surface temperature could be a simple method to define a reliable BC at the ground surface in modelling HGHEs.

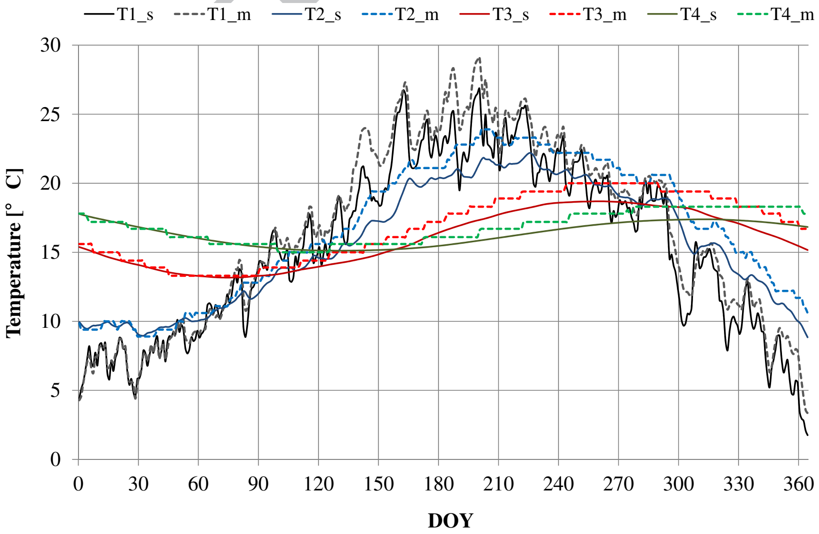

Figure 6: Daily averaged soil temperature at different depth: simulated (s) and measured (m).

3.3. Energy Requirements at the HGHE

The energy requirement for space heating and cooling is defined as the amount of energy needed to maintain a constant target value of the building indoor temperature. In GCHPs, the thermal energy is extracted/transferred from/to the ground by means of the ground heat exchanger.

To define an hourly energy requirement in heating and cooling mode we applied the methodology reported in [19] where the energy requirement of a building was related to an outdoor air temperature time series. In this case, the real outdoor temperature of Ferrara in 2014 has been reduced to a sinusoidal and negative exponential variation of air temperature with Eq. 6:

Equation 6: Outdoor air temperature.

$$T_a(D) = T_M - A \cdot \cos\left[\frac{2\pi}{365}(D - D_0)\right]$$

where:

- T_a = daily average outdoor air temperature at Julian day D (C°)
- D_0 = Julian day with the lowest temperature
- T_M = annual average air temperature
- A = average annual amplitude of the air temperature

The parameters in Eq. 6 were chosen according to the available weather data. Then, the temperature time series on an hourly scale was obtained superimposing to the daily time series a sinusoidal oscillation ranging between the daily minimum and maximum air temperatures (night/day) in winter and summer. The indoor, the outdoor temperature (calculated with Eq. 6) and the real outdoor temperature are shown in Fig.7 at a daily scale.

The building was simplified to a homogenous lumped and closed thermodynamic system whose internal energy variation only occurred owing to the heat transfer through its envelope only, as reported in [20]. The heating season is supposed from October 16th to April 30th, the cooling one from May 1st to October 15th. In the model, the heating/cooling system was set to operate for reaching and maintaining a defined target indoor temperature (20 °C in winter and 24 °C in summer). A time scheduling was supposed to represent typical working conditions for a residential building in a mild climate: 5-10 AM and 4-12 PM during working days, and 6 AM to 12 PM on the weekends. Furthermore, it has been supposed that the heating and cooling power of the system could not exceed 40 W for a cubic metre of building when it is turned on.

The energy building demand (W/m^3) for heating/cooling was calculated for a unit of building gross volume (1 m^3) at hourly scale. In the 2D model domain, the FP was treated as a boundary condition of the 2nd type, having a heat transfer surface of 1 m^2 (the FP is 1 m high) therefore, the former heating and cooling time series was assumed to be the specific energy requirement at the FP (W/m^2). In view of this, the maximum thermal load at the FP is 80 W/m^2, due to the symmetrical domain. The daily energy demand at the FP is reported in Fig.7.

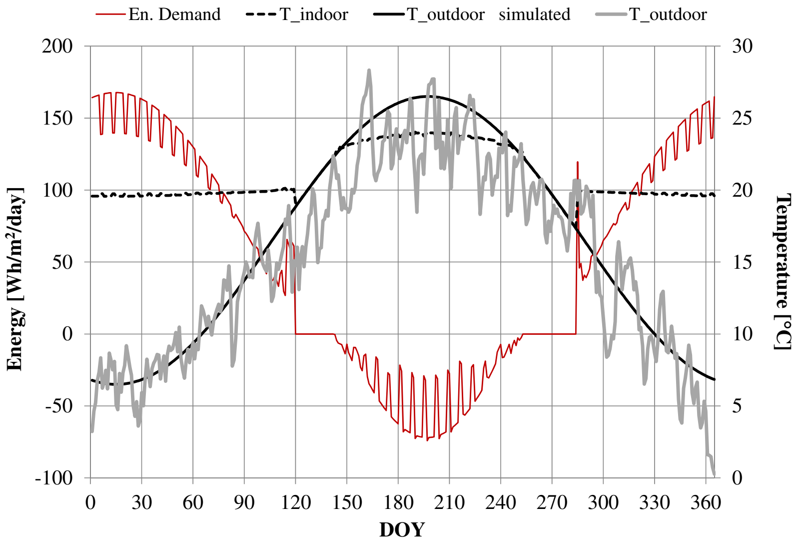

Figure 7: Outdoor air temperature, indoor temperature and energy requirements for space heating and cooling.

4. RESULTS

The effect of 1st, 2nd and 3rd kind BCs imposed at the ground surface in modeling HGHEs have been analysed. The proposed GSEB equation, the equivalent heat flux and temperature have been considered as BCs in three new simulations. As for preliminary analysis, a complete set of weather data of Ferrara for 2014 were considered. The soil temperature profile for the 1st day of 2014 was set as the initial condition. Simulations have been carried out with the supposed HGHE operating, for two consecutive years in each case, to check the thermal drift of the domain.

According to the simplifications and assumptions considered, the results were compared in terms of average temperature at the HGHE wall surface. This could be considered as the average temperature of the working fluid, and therefore it is representative of the HGHE performance with the different boundary conditions at the ground surface. Moreover, the temperatures in the surrounding soil were calculated by means of point probes at different depths to evaluate the evolution of the thermal field.

The resulting time series for each BCs of the daily average temperature at the HGHE wall are shown in Fig.8. For completeness, a weekly detail of the hourly HGHE operation, when the minimum temperature is reached in the heating period, has been included. In the diagram, an entire year is presented, starting in October, when heating season begins.

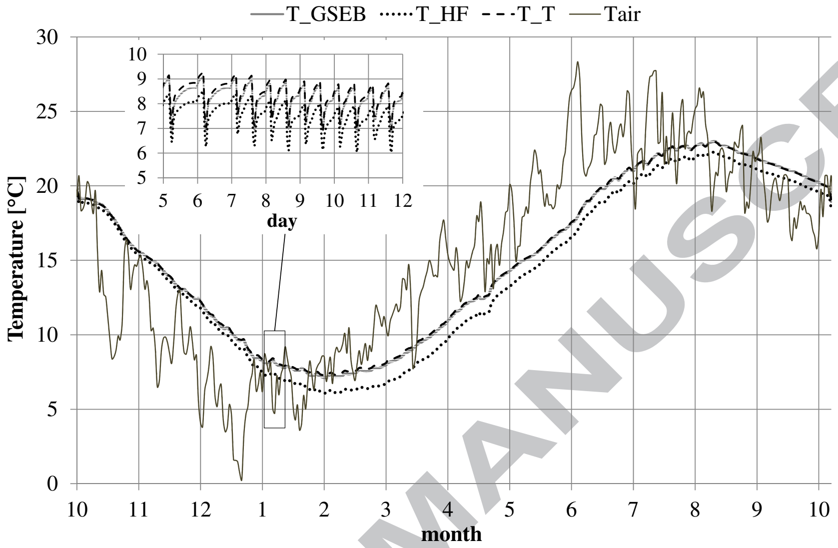

Figure 8: Daily average temperature on the HGHE surface for the three BCs and a week with hourly data.

The initial average temperature is around 20°C, and then it rapidly decreases. After two months of heat extraction, the temperature at the HGHE is 2.5°C lower than the equivalent undisturbed. The minimum temperature is reached in all three cases in the second half of February, with a lag of 45 days in comparison with the temperature at ground surface and that of air. The temperature drops more rapidly with the equivalent heat flux assigned to the surface (case *HF*) and shows a maximum difference of 1.3 °C compared to the other two cases. Moreover, unlike the other cases (*GSEB* and *T*), a thermal drift of 0.6 °C is detected after a year in HF, because the equivalent heat flux does not balance the heat demand of HGHE operating. On the contrary, a negligible discrepancy is observed between the case *GSEB* and *T*. Therefore the use of 1st kind boundary conditions could be considered an acceptable simplified boundary condition. Finally, it is noted that the daily average air temperature has more favourable values than soil temperature late in winter and in summer. As a consequence, it could be considered as an alternative energy source for the heat pump in space heating and cooling.

Fig. 9 shows the hourly time series of soil temperature at two different points. The first temperature probe is above the HGHE, 0.8 m deep in soil. The second probe is positioned at the average depth of the HGHE and 1 m far from it. In the former one, the maximum difference between the case *HF* and the two other cases is 1.8 °C. Moreover, a significant negative difference is maintained over the entire year. As for the temperature at the HGHE wall, the soil thermal field is comparable for *GSEB* and *T*.

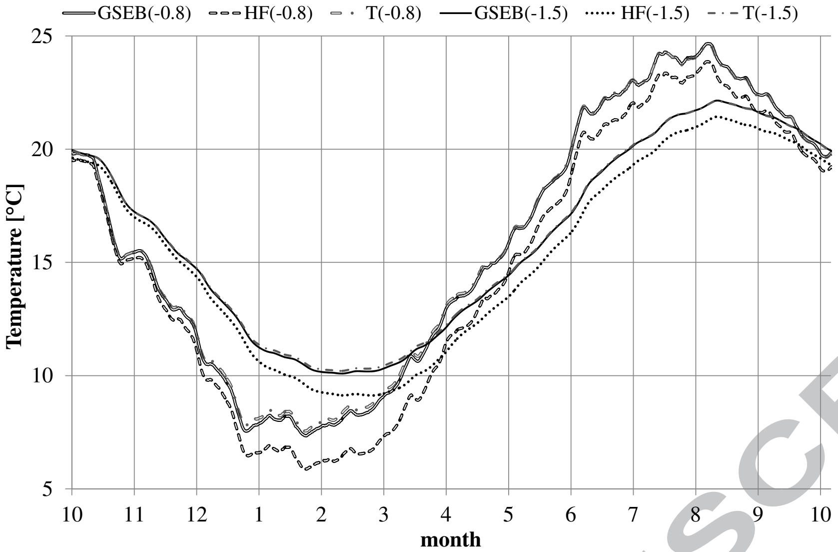

Figure 9: Average temperature in the soil for the three BCs.

5. REMARKS

The effect on numerical solution of different boundary conditions at the ground surface was analysed in modelling of HGHEs. The commercial software COMSOL Multiphysics was used to solve the unsteady heat transfer problem in a 2D computational domain. A model of the energy balance at the ground surface (GSEB) based on the ground surface properties and weather variables was developed, and properly implemented in COMSOL to be tested as boundary condition at the ground surface. For a realistic simulation of the environmental conditions, weather data sets based on experimental data were used for simulations. It was validated with the observed soil temperature data at different depths in 2014, proving to properly predict the temperature in the soil.

Simulations were carried out to test the HGHE energy performance in heating and cooling, under the same environmental conditions. The GSEB equation, the resulting heat flux and temperature on ground surface were alternately used as boundary condition (BC) of the 1st, 2nd and 3rd kind in simulations. The solution of the equivalent heat flux at the ground surface diverged from the other two cases, and appeared as an extremely precautionary approach. On the other hand, to assign the temperature resulting from the energy balance on the ground surface has the significant limit to block the thermal effect of the heat exchanger on the surface. Consequently, to use a 3rd kind boundary condition in modelling HGHE is an acceptable approach to the problem, not affecting the calculation time. However, the correct estimation of surface temperature is of great importance also in this case, and a preliminary simulation with a GSEB could be required.

Finally, a simulation was conducted assigning the air temperature as 1st kind BCs at the ground surface. Although a tendency to underestimate the shallow soil temperature has been identified, a correlation between ground surface and air temperature could be developed in the future to determine more quickly a feasible boundary condition in modeling HGHEs.

ACKNOWLEDGEMENT

The research was funded by the University of Ferrara with funds: “Giovani Ricercatori, 5 per mille assegnato all’Università degli Studi di Ferrara - dichiarazione dei redditi dell’anno 2011”.

REFERENCES

[1] Chiasson, A.D., 1999. Advances in modeling of ground-source heat pump systems. M.Sc. Thesis, Oklahoma: Oklahoma State University.

[2] Mustaf, O.A., 2008. Ground-source heat pumps systems and applications. Renewable and Sustainable Energy Reviews, 12/2, 344-371.

[3] Gan, G., 2013. Dynamic thermal modelling of horizontal ground-source heat pumps. International Journal of Low-Carbon Technologies, 8, 95-105.

[4] Kavanaugh S.P., Rafferty K., 1997. Ground source heat pumps-Design of geothermal systems for commercial and institutional buildings. ASHRAE Applications Handbook.

[5] Lee, K.H., Strand, R.K., 2008. The cooling and heating potential of an earth tube system in building. Energy and Buildings, 40, 486-494.

[6] Fujii, H., Yamasaki, S., Maehara, T., Ishikami, T., Chou, N., 2013. Numerical simulation and sensitivity study of double-layer Slinky-coil horizontal ground heat exchangers. Geothermics, 47, 61-68.

[7] Bottarelli, M., Bortoloni, M., Su, Y., Yousif, C., Aydin, A.A., Georgiev, A., 2014. Numerical analysis of a novel ground heat exchanger coupled with phase change materials. Applied Thermal Engineering, In press.

[8] Piechowsky M., 1999. Heat and mass transfer model of a ground heat exchanger: validation and sensitivity analysis. International Journal of Energy Research, 23, 571–588.

[9] Kupiec, K., Larwa, B., Gwadera, M., 2015. Heat transfer in horizontal ground heat exchangers. Applied Thermal Engineering, 75, 270-276.

[10] Demir, H., Koyun, A. and Temir, G., 2009. Heat transfer of horizontal parallel pipe ground heat exchanger and experimental verification. Applied Thermal Engineering, 29, 224-233.

[11] Nam, Y., Chae, H.,0 2014. Numerical simulation for the optimum design of ground source heat pump system using building foundation as horizontal heat exchanger. Energy, 1-10.

[12] Gan, G., 2014. Dynamic interactions between the ground heat exchanger and environments in earth-air tunnel ventilation of buildings. Energy and Building, 85, 12-22.

[13] Bottarelli, M., Di Federico, V., 2012. Numerical comparison between two advanced HGHEs. Int. Journal of Low-Carbon Technologies. 7/2, 75-81.

[14] UNI 11466, 2012. Heat pump geothermal systems - Design and sizing requirements, s.l.: s.n.

[15] Herb, W.R., Janke, B., Mohseni, O., Stefan, H. G., 2008. Ground surface temperature simulation for different land covers. Journal of Hydrology, 356, 327-343.

[16] Deardorff, J.W., 1978. Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation. Journal of Geophysical Research, 83, 1889-1903.

[17] Best, M.J., 1998. A model to predict surface temperatures. Boundary-Layer Meteorology. 88, 279-306.

[18] Nam, Y., OOka, R., Hwang, S., 2008. Development of a numerical model to predict heat exchange rates for a ground-source heat pump system. Energy and Buildings, 40, 2133-2140.

[19] Allen, R.G., Pereira, L.S. Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper, 56, Rome: FAO.

[20] Bortoloni, M., Bottarelli, M., 2015. On the sizing of a Flat-Panel ground heat exchanger. International Journal of Energy and Environmental Engineering, 6, 55-63.

1. Different boundary conditions have been simulated at the ground surface in modelling HGHEs.

2. The unsteady-state heat transfer problem has been solved in a 2D domain.

3. An energy balance equation at the ground surface (3^{rd} kind BC) has been developed.

4. The equivalent heat flux at the ground surface appeared as a precautionary approach.

5. The energy balance equation and the equivalent temperature showed similar results.