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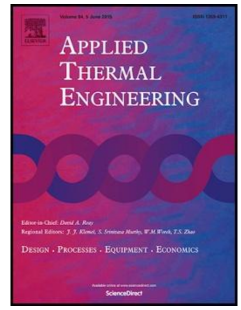

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Optimal operation of ground heat exchangers in presence of design anomalies: an approach based on second law analysis.

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Highlights

- Two vertical U-tube GHEs systems are considered for three different users.
- Transient model is applied to the ground, boreholes and the energy requirement.
- GHEs are analysed in different operating conditions.
- Boreholes ovalization, fouling and groundwater level are taken into account.
- Entropy generation minimization is used to discover the optimal configuration.

Abstract

Geothermal systems often experience non homogeneous behavior between the various boreholes, due to possible local differences in the ground stratigraphy or installation problems. This may create important inefficiencies or operational issues, particularly in the case of small systems. These problems can be partially corrected through optimal operation. In this paper, parametric analysis of the global entropy generation is proposed for the optimization of the overall performances of two vertical U-tube ground heat exchangers during operation. When the system is already installed, the design variables, such as the tube diameter and the installation depth, cannot be modified to contrast the effects of anomalies. The mass flow rate distribution between the boreholes is the design variable that can be changed during the operation in order to select the best configuration.
The possible anomalous scenarios that are considered include boreholes ovalization, fouling or different thermal proprieties in the stratigraphy of soil surrounding the GHE system and different boreholes depths. The analysis shows that significant improvements in term of recovered exergy up to 1.6% in the examined scenarios, can be achieved thought proper operation.

Keywords: Ground heat exchangers; Optimal operation; Entropy generation; Exergy; Heat transfer.

Nomenclature

Ex	Exergy (W)		
$\dot{S}'_{gen}$	Entropy Generation rate for unit length (W/m K)	*Subscript*	
$\dot{S}_{gen}$	Entropy Generation rate (W/K)	*1*	First Vertical U-tube GHE
$\overline{\dot{S}}_{gen}$	Time average Entropy Generation rate (W/K)	*2*	Second Vertical U-Tube GHE
$\dot{m}$	Mass flow rate (kg/s)	*av*	Average
c_p	Specific heat (J/kg K)	*b*	Bulk
$\dot{q}$	Heat Transfer rate for unit length (W/m)	*d*	Borehole depth
$\dot{Q}$	Heat Transfer rate (W)	*ex*	Outer radius of U-tube
f	Friction factor	*,f*	Friction losses contribution
h	Heat transfer coefficient (W/m^2 K)	*g*	Grouth
k	Thermal conductivity (W/m K)	*g,tot*	Global system
L	Installation depth (m)	*i*	Inner radius of U-tube
p	Pressure (Pa)	*in*	Inlet of U-tube
Pr	Prandtl number	*loc*	Hydraulic local resistance contribution
Re	Reynolds number		
r	Radial Coordinate (m)	*nom*	Nominal
T	Temperature (K)		
U	Global heat transfer coefficient (W/m2 K)	*opt*	Optimal
Δp	Pressure Drop (Pa)	*out*	Outlet of U-tube
		p	Vertical U-tube
		rec	Recovered
Greek symbols		*ref*	Reference
Ψ	Recovered work rate (%)	*s*	Soil
λ	Ratio between Two Lengths	*t*	Thermal contribution
ρ	Density (Kg/m^3)	*tot*	Total
μ	Mass flow rate distribution (%)	*w*	Water

1. Introduction

The direct-use of geothermal energy to supply heating, cooling and domestic hot water has rapidly increased in 45% in the five years[1]. This is marked by the diffusion of small ground heat exchanger systems because they offers several benefits. The overall advantages of these systems are due to the reduction in primary energy consumption using fossil energy sources, due to low operating, maintenance, and life cycle costs and due to a longer life expectancy than most conventional systems [2]. Geothermal source may be the ground, groundwater or surface water. The most common heat pump system based on geothermal energy is the ground coupled heat pump (GCHP) system [3]. This is constituted by a closed loop circuit buried in the ground where a process fluid, in the heating mode, transfers heat from the ground to tubes. The process fluid, usually glycol water, transfers heat to the heat pump in the evaporator. In cooling mode the process fluid receives heat in the condenser and exchanges it to the ground. Vertical boreholes with one or two U-tubes are typically used as the ground heat exchangers (GHE) [4,5]. Experimental and theoretical analysis have been conducted to elaborate a solid base for the design and the performance evaluation and for thermal analysis of BHE systems [6]. The heat transfer process may usually be investigated in two separated regions. One is the solid soil/rock outside the borehole, where the heat conduction can be treated as a transient process [7]. Since the borehole depth is much larger than its diameter, this process is often formulated by the one-dimensional line-source or cylindrical-source theory [8]. A transient two-dimensional implicit finite volume model is used to develop non-dimensional short time-step temperature response factors in vertically ground-coupled heat exchangers [9]. A two-dimensional model of the finite line-source has also been proposed in order to consider the axial heat flow in the ground for longer durations [10,11]. The other region is the inside the borehole, including the backfilling, the U-tubes and the circulating fluid inside the pipes. The heat transfer in this region is generally assumed to be in steady-state due to the much smaller dimensions and thermal capacity. Because diameters are smaller than lengths, borehole is often treated as one-dimensional pipe heat exchanger neglecting the heat transfer in the direction of the borehole axis [12]. An expression of the equivalent diameter is proposed for the heat transfer of a vertical U-tube heat exchanger and the thermal processes in the borehole is represented by a single borehole resistance [13,14]. A response-test method is used for the determination of borehole thermal resistance [15].

Performances of GHE systems depend on both the design and operating conditions [16-18]. However most of the works in literature are focused on the optimal design of GHEs while only few studies consider the optimal operation after installation. The Taguchi technique has been employed to optimize the design parameters of GHEs but also the operating temperatures of the condenser and evaporator [19,20].

Second law analysis, in the forms of exergy analysis and entropy generation minimization (EGM), has the characteristics to be successfully used to fill this gap as revealed by the design studies available in the literature. In [21], exergy analysis is used for the optimum size of GHE while in [22] the exergetic efficiency of a GCHP system is evaluated as a function of depth boreholes for heating season. A peculiar characteristics of EGM method [23] is the possibility to distinguish between irreversibilities due to heat transfer and friction losses. This feature has been used to select the optimal length and the optimal diameter of the ground the heat exchanger and to select the optimal velocity of the working fluid [24,25]. In recent studies, the optimal design of vertical U-Tubes ground heat exchangers is performed by combining EGM and genetic algorithms in single or multi-objective optimization strategies. The high sensitive parameters, i.e. the number of boreholes, the borehole depth, the outer pipe diameter, the borehole radius and the circulating fluid mass flow rate per pipe have been considered as the free design variables [26,27].

Optimal operation allows one to properly consider the annual variations in the thermal load as well as possible mismatch between expected and actual performance due to anomalies occurred during installation or operation. When the system is already installed, it is not possible to modify the lengths or diameters in order to maximize the energy performance.

In this paper, optimal operations of small GCHP systems in different scenarios that can occur after installation are investigated. These scenarios are borehole ovalization, variations in the heat transfer between borehole and ground due to fouling, boreholes at different level etc. The effects of these anomalies and the benefit of optimal operation are more significant in the case of small GHEs.

A parametric analysis is performed to identify the minimum of entropy generation and so the corresponding best configuration.

A system composed by two single vertical U-tube GHEs is analyzed for three domestic users that differ in thermal load profile. Heat transfer between the vertical U-tube and the ground is analyzed as 1-D cylindrical coaxial heat exchanger. Finite difference method is used to evaluate the time evolution of ground temperature around the borehole, while a logarithmic mean temperature is adopted to calculate the time evolution of the fluid in the borehole. The variation of the annual thermal load, which is usually approximated as a series of continuous rectangular heating or cooling pulses, is accounted in the simulation of the heat exchange [9,28].

The analytical expression of global entropy generation for the two vertical U-tube GHEs is considered to account heat transfer, friction losses and hydraulic local resistance losses due to pipe section variations and due to control valves. This expression is then applied to the parametric analysis of various operating conditions that may be caused by possible anomalies occurred during the installation or during the operation.

2. Description of the GHE system and of cases studied

The Ground Heat Exchangers analyzed in this paper, consist of two vertical U-tubes, as shown in Figure 1, installed for residential use. The U-tubes are in polyethylene with an inner diameter of 0.029 m and an outer diameter of 0.033 m. The borehole diameter is 0.1 m. The circulating fluid consists of a 25% propylene/glycol water solution for a total mass flow rate of 0.9 kg/s. The geometric and the thermo-physic characters of the system are listed in the Table 1.

In winter operation, the working fluid flows in the U-tubes and gains heat from the ground and transfers it to the evaporator of the heat pump. During summer operation, the working fluid receives heat from the condenser of the heat pump and transfers it to the ground. The borehole inlet temperature is set to 9°C for the entire winter period, while the outlet temperature is about 12°C, with almost negligible variations during operating condition.

Soil temperature varies from month to month as a function of incident solar radiation, rainfall, seasonal swings in overlying air temperature, local vegetation cover, type of soil, and depth. Nevertheless, in shallow installations, the soil temperature is relatively constant below 15 m, where it can be roughly assumed equal to the mean annual temperature of air [1]. For this application, the soil temperature under 15 m of depth is assumed at 15°C and it is coincident with the undisturbed soil temperature (i.e. far from the boreholes).

GHEs are designed to fulfil the thermal requests of three buildings with different volume and thermal energy demand. The characteristics of the three domestic users are shown in Table 2. User *A* is characterized by a volume of 300 m^3 and it relative heat demand is plotted in Figure 2. The other curves are obtained by scaling this curve on the basis of the building volumes (240 m^3 for user *B* and 210 m^3 for user *C*). As the fluid temperatures in the GHE do not depend significantly on time, the GHE operates at almost constant thermal power, therefore the daily operating time directly depends on the daily energy requirements.

In the case of user *A*, ground heat exchanger is installed at 150 m of depth. In the basic (homogeneous) design this corresponds to two equal boreholes reaching a maximum depth of 150 m. In the case of user *B*, the plant has boreholes installed at 100 m. For last user *C*, the boreholes depth is 50 m.

The aim of this work is to find the optimal configuration of GHEs in different operating conditions for several plant sizes and to show the effect of the size in the optimization results. This study regards three different cases of anomalies that are summarizes in the Table 3 in order to give a clearer understanding of the issues treated:

CASE 1: The GHEs installation is characterized by two vertical boreholes with different lengths. Such anomaly typically occurs because of local non-homogeneous of the ground hardness. This leads to difficulties in the drilling operations. As a result, the length of the boreholes may differ from the design value. In Case 1 the residential user with the highest heating load (user *A*) is considered. The optimal operation is investigated for different lengths of installation L_1 and L_2 of the two boreholes, while the total length in depth, L_1+L_2, is kept fix to 300 m. The length ratio L_1/L_2 is indicated as λ. The Table 4 summarizes this case specifying each λ value considered.

CASE 2: The installation is characterized by an anomaly that affects the overall heat transfer coefficient of the GHEs. This is usually caused by fouling inside one of the pipes or because of different thermal proprieties in the stratigraphy of soil surrounding the system. For Case 2 the plant of the user *A* is analyzed and the two boreholes are installed at the same depth (150 m). The operating condition simulated for this study is a reduction of its nominal heat transfer coefficient U_{1nom}. in the first vertical U-tube GHE. The reference heat transfer coefficient is evaluated in nominal operating conditions when there are no anomalies. The heat transfer coefficient of the second vertical U-tube is considered as unaffected, thus remaining equal to the nominal value. Table 5 reports the heat transfer coefficient reductions analyzed in the study. Only limited variations in the global heat transfer coefficient have been considered, in order compare scenarios where the daily energy requirements of each building is still fulfilled despite the anomaly. In fact, the daily operating time of the GHE is strictly correlated with the daily energy demand of the buildings, therefore a reduction in heat transfer coefficient involves a longer operating time. A large variation in U, e.g. 50% U_{1nom} , would require an operating time larger than 24 h, which would make the comparison difficult to perform.

CASE 3: For each of the three domestic users, one of two vertical U-tube boreholes is considered affected by an obstruction or an ovalization generated during installation. This consists in a reduction of tube cross section in a tube due to distortion and crushing during installation [29].

Ovalization is treated as an hydraulic local resistance loss. The corresponding equation for local loss factor k_{los} is available in literature [30]. Ovalization is considered in the 1^{th} vertical U-tube while boreholes have the same depth (150 m for each one for the domestic user *A*, 100 m for the domestic user *B* and 50 for the domestic user *C*). In the Table 6, the design and operating conditions are listed for this latter case.

3. Mathematical modelling

3.1 Thermal model

The vertical U-tube GHE is represented as a cylindrical coaxial heat exchanger and it is analyzed using a one-dimensional model. The 1-D model includes fluid core, an equivalent convective resistance layer, tube layer, grout layer that is surrounded by the ground. Consequently, four radiuses are identified, which dimensions are reported in Table 2: r_i (inner u-tube radius), r_{ex} (outer u-tube radius), r_g (borehole radius) and r_s (ground). The ground radius is chosen sufficiently large to consider the corresponding temperature equal to the unperturbed one. Figure 3 shows the domain and the various radiuses. The main parameters of the ground properties (density, thermal conductivity, etc.) are supposed constant at all depths and temperatures considered.
The temperature distribution in the soil around the vertical U-tube GHE is given by the solution of 1-D heat conduction equation in cylindrical coordinates:

$$\rho_s c_{ps} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (k_s r \frac{\partial T}{\partial r}) \tag{1}$$

Moreover, as illustrated in Figure 3, the U-tube GHE is discretized along its entire length (equal to twice the borehole depth) and Eq.1 is solved for each element of the discretization. This approach allows one to account for the variation of the fluid temperature along the GHE. As a consequence of this assumption, heat transfer in the axial direction occurring at the bottom of the borehole is neglected, but this contribution is roughly less than 2.5% of the total.
Central finite difference is used to discretize spatial derivatives while implicit backward Euler scheme is adopted for time integration.
The initial condition is given by undisturbed soil temperature:

$$T(0, r) = T_s \tag{2}$$

The type of boundary condition on the inner surface ($r=r_g$) depends on the energy requirement: if domestic users need energy, the GHEs are used to satisfy the energy requirement and the boundary condition is given by Robin boundary condition (Eq.3):

$$k_s \left. \frac{\partial T(t, r)}{\partial r} \right|_{r=r_g} = h_w (T - T_{av}) \tag{3}$$

where the convective heat transfer coefficient h_w and the mean temperature T_{av} refer to the propylene/glycol water solution that flows in the vertical U-tube GHE.
In the case of no energy requirement the system is considered adiabatic and the relative boundary condition is given by Neumann boundary condition (Eq. 4). On the outer surface ($r=r_s$), unperturbed temperature is prescribed (Eq.5).

$$k_s \left. \frac{\partial T(t, r)}{\partial r} \right|_{r=r_g} = 0 \tag{4}$$

$$T(t, r_s) = T_s \tag{5}$$

Figure 3 also shows where boundary conditions are applied.

The temporal distribution of soil temperature at borehole interface is evaluated using Eq.1. This value represents the source temperature, with infinity heat capacity, that exchanges heat with the inlet fluid in the borehole. Temporal evolution of outlet fluid temperature in borehole is calculated by relating the heat flux with a logarithmic temperature difference between ground (at radius r_s) and process fluid (propylene/glycol water solution). This implies the fact that transient behavior of the borehole is neglected, which is a reasonable approach considering that the characteristic time here is of the order of few minutes and much smaller than the characteristic time in the ground and the timeline adopted for the analysis. Such approach allows one to reduce the computational efforts but it is not suitable for applications such as control system design (see for example [31]). The heat transfer coefficient referred to inner tube surface is expressed as:

$$U = \frac{1}{\frac{1}{h_w} + ln(\frac{r_{ex}}{r_i})\frac{r_i}{k_p} + ln(\frac{r_g}{r_{ex}})\frac{r_i}{k_g} + ln(\frac{r_s}{r_g})\frac{r_i}{k_s}} \quad (6)$$

3.2 Thermal model validation

The model has been tested through a comparison between experimental data and calculated data with the model itself. The available experimental data refer to a plant with 51 geothermal boreholes of 100 m (double U De32 mm) divided into 3 circuits each one with 17 boreholes. The measurements relate to the inlet temperature and outlet temperature of the fluid circulating in the plant and the mass flow rates of each circuit. These measures are available every hour during the winter heating season for the winter season 2012-2013. The thermal model has been used to calculate the temperature of the fluid at the outlet of one of the 17 boreholes belonging to the first circuit. Figure 4 reports the data computed by the model and the experimental data. The comparison between the two curves confirms a good accuracy of the model.

3.3 Parametric analysis of Entropy Generation

Parametric analysis of entropy generation is performed for the three cases illustrated in Sect. 2 to identify optimal operation when anomalies occur.

Entropy generation rate $\dot{S}_{gen}$ in a borehole GHE is due to viscous friction and heat transfer, namely:

$$\dot{S}_{gen} = \dot{S}_t + \dot{S}_f \quad (7)$$

In the case of closed loop GHE with a single U-tube, the pipe flow is considered as turbulent and fully developed. Thus, the entropy Generation rate per unit length is given by [32]:

$$\dot{S}'_{gen} = \frac{43.48\, q^2}{\pi k T_b^2 \, \Pr^{0.4}} \mathrm{Re}^{-0.8} + 0.00144 \, \mathrm{Re}^{4.8} \frac{\pi^3 \mu^5}{\rho^2 T_b^2 \, \dot{m}} + \frac{\dot{m}\Delta p_{loc}}{\rho T_b} \quad (8)$$

where the first term represents the source of irreversibility due to heat transfer, while the irreversibility due to viscous friction $\dot{S}_f$ appearing in Eq. 7, is here separated in two contributions: friction losses (second term in eq. 8) and the hydraulic local resistance losses due to obstructions or ovalizations (third term in eq. 8). T_b is the bulk temperature of the fluid.

In the present work, the global entropy generation rate (W/K) is calculated as sum of entropy generation of each vertical U-Tube ground heat exchanger during seasonal operation:

$$\dot{S}_{gen,tot} = \dot{S}_{gen,1} + \dot{S}_{gen,2} \tag{9}$$

The simulations with the thermal model, include the transient operating mode of the geothermal system; consequently, entropy generation rate is a function of the time. For this reason, the corresponding time-averaged value

$$\overline{\dot{S}}_{gen,tot} = \frac{1}{\tau}\int_0^{\tau} \dot{S}_{gen,tot}(t)\,dt \tag{10}$$

over seasonal operation is investigated in the parametric analysis. Optimal geometric parameters can be freely chosen only during the design stage. On the contrary, after installation only operational parameters can be modified. In each of the cases investigated, the geothermal heat pump system is considered after its installation. Thus, tube length and pipe diameter are not considered design variables free to vary in the parametric analysis of entropy generation. On the contrary, the mass flow rate distribution defined as:

$$\mu = \frac{\dot{m}_1}{\dot{m}_{tot}}\% \tag{11}$$

is varied during the parametric analysis in order to identify the optimal operating condition that minimizes the entropy generation in the system; $\dot{m}_{tot}$ is the constrained variable. The μ value is varied in a range 40-60 % since a preliminary steady state analysis that showed that optimal value is obtained in this range [33].

In order to evaluate the effects of entropy generation in terms of energy consumption units, the concept of exergy can be introduced. Exergy is the maximum amount of work which can be produced by a system interacting with the external environment through an ideal transformation from the current state to the complete equilibrium with the external environment. This quantity is a measure of the quality of energy flows exchanged by the system.

Entropy generated in each optimal operating condition can be converted into exergy destruction, which represents the work rate that is not obtained by the system or the deviation between the ideal work rate and the actual work rate. A comparison between the exergy destruction in the reference condition and in the optimized condition provides an evaluation of the recovered work rate. This quantity can be referred to the exergy associated with the heat flux Ex_{heat} exchanged by the GHE, namely:

$$\Psi_{rec} = \frac{T_0 \overline{\dot{S}}_{gen,tot_{ref}} - T_0 \overline{\dot{S}}_{gen,tot_{opt}}}{Ex_{heat}} \tag{12}$$

Reference conditions refer to a mass flow rate distribution equal to 50%.

For Case 1, the parametric analysis is repeated for different lengths of the two boreholes in order to investigate optimal operation when anomalies due to drilling occur, as detailed in Sect. 2. Table 4 reports each scenario analyzed for Case 1. Table 5 summarizes for Case 2 all the scenarios subjected to the parametric analysis in the case of anomalous reduction of thermal transmittance. For Case 3, ovalization of the first vertical U-tube is investigated. Specifically, a localized cross section reduction of 60% is considered. Furthermore, in Case 3 parametric analysis is performed for each domestic user (i.e. energy demand). A detailed description of this latter study is reported in the Table 6.

4. Results

4.1 Case 1

Figure 5 shows, for each scenario listed in Table 4, the optimal mass flow distribution μ that leads minimum entropy generation. The mass flow rate results equally distributed (50%) between the two boreholes when these are installed at the same depth (λ=1). When λ increases, i.e. the first borehole is deeper than the second ($L_1 > L_2$), the optimal operating condition is characterized by mass flow rate $\dot{m}_1$ smaller than $\dot{m}_2$. In fact, a larger L_1 brings an increase of the friction losses and of the corresponding contribution to the entropy generation. Consequently, a smaller mass flow rate in the deeper tube is required to counteract the increase in entropy generation due a larger installation depth. The reduction of $\dot{m}_1$ is significant when the length ratio is very different from one. For λ=2, the optimal μ is about 40%. The same kind of result is obtained when L_2 is larger than L_1. For λ = 0.5, the minimum value of entropy generation occurs when mass flow rate distribution is equal to 60 %.

Figure 6 reports time averaged entropy generation rate due to heat transfer $\overline{\dot{S}}_t$ and fluid friction $\overline{\dot{S}}_f$ in the optimal operating conditions. Both these terms depend on the borehole length and the circulating mass flow rate, therefore they change in the parametric analysis. In the reference case (λ =1) the entropy generation terms are the same for the two boreholes due to the equal lengths and mass flow rates. The global entropy generation for the reference case is 0.039 W/K.

When the installation depths of the two boreholes are different, the optimal mass flow rate distribution is obtained by making the two pressure drops similar, but without penalizing the corresponding heat transfer terms. As a result, the entropy generation terms increase in the longer tube and decrease in the other one.

Starting from the scenario with λ=1 and decreasing λ, the total entropy generation slightly increases for λ>0.85 and then decreases. In the scenario characterized by λ=0.5 it is particularly evident the fact that the total entropy generation is smaller than the reference scenario. This is due to the non-linear behavior of friction with respect to the velocity and the prevailing effect of entropy generation due to friction.

If an equal mass flow rate distribution were maintained, the total entropy generation would be larger. The main reason is that a different pressure drop would occur in the two boreholes, therefore an additional fluid dynamic resistance should be provoked in the tube with the smaller pressure drop and a consequent entropy generation term would arise. As an example, in the scenario λ=0.5, the total entropy generation in the optimal distribution is about 0.037 W/K, while in the case of equal distribution this term would be 0.053 W/K.

For Case 1 the recovered exergy obtained in the optimal configurations, is about 1.6%.

4.2 Case 2

Figure 7 shows the optimal mass flow rate distribution corresponding to heat transfer coefficient reduction. A progressive reduction of U_1 does not affect the value of μ that remains equal to 50% because the two vertical U-tubes have the same length. The effect of the heat transfer coefficient on time averaged heat transfer rate is shown in Figure 8. A reduction of the heat transfer coefficient leads to a decrease in the heat transfer rate exchanged by the 1st vertical U-tube. To contrast this effect, the second Vertical U-tube must exchange a larger heat transfer rate. When the heat transfer coefficient reduction occurs, the operation time necessary to satisfy the daily energy demand is larger than in the nominal case because the parametric analysis is conducted considering the same energy demand for each scenario.

Entropy Generation is plotted in Figure 9. $\overline{\dot{s}}_t$ in the first borehole, increases with the exchanged thermal power. However, entropy generation due to heat transfer can be considered negligible respect to entropy generation due to friction losses. $\overline{\dot{s}}_f$ is constant, as mass flow rate does not change and it is independent on heat transfer.

4.3 Case 3

The optimal configuration, when ovalization occurs, is plotted in Figure 10 and it is characterized by a lower mass flow rate in the U-tube GHE affected by ovalization. This arises from the direct relation between the entropy generation and the hydraulic local loss. However, the effect of ovalization is more significant for the user with shorter vertical U-tubes. In fact the optimal μ is about 44% for the *C* user and 47% for the user *B*. On the contrary, the optimal value of μ is about 50% in the case of longer tubes (user *A*). This occurs because the relative effect of local resistance compared to distributed friction losses is smaller for longer pipes. The entropy generation contributions are reported in Figure 11. For the user *C*, the ovalization contribution causes an entropy generation equal to 0.0012 W/K while the entropy generation due to friction losses is about 0.006 W/K. For the user *B*, the contribution due to ovalization increases to 0.0015 W/K, because of the larger mass flow rate in the first tube while the entropy generation due to friction losses is about 0.012 W/K.

For the user *A*, friction losses are dominant and the effect of obstruction is negligible. The relative contribution of ovalization to the global entropy generation varies from 6.2% for shorter boreholes to 2.9% for longer ones. For this case the recovered exergy is about 1.2%. This relative contribution decreases with the length because, in this application, ovalization is treated as local resistance. Obstruction could be a distributed friction losses with a certain extension along the pipe and consequently it would affect significantly optimization results also for long boreholes.

5. Conclusions

In this paper, the parametric entropy generation analysis of small geothermal systems affected by anomalies due to imperfect installation has been proposed, with the goal of optimizing their operating conditions. The investigated system consists in two vertical U-tube ground heat exchangers. Three different heat demands profiles have been considered. The analysis is carried out through an unsteady 1D thermal model that accounts for the heat transfer in the ground and the working fluid. Three types of anomalies have been considered: 1) boreholes with different lengths caused by drilling imperfections; 2) reduction in the overall heat transfer coefficient, and 3) ovalization of one of the vertical tubes. Mass flow rate distribution between the two vertical U-tubes is chosen as operational parameter free to vary in the parametric entropy generation analysis. The entropy generation analysis proves to be efficient in the case of anomalous operating conditions of GHEs.

The results show that, when no design anomalies affect the system ,the minimum entropy generation is achieved by a mass flow rate equally distributed between the two vertical U-tubes. In contrast, when the length of the two boreholes differs, a smaller mass flow rate should be directed to the longer borehole in order to achieve minimum entropy generation in the system. This occurs because entropy generation due to fluid friction is dominant compared to the contribution due to heat transfer. In the optimal configurations, the recovery exergy is about 1.6%.

The parametric analysis suggests that an even distribution of mass flow rate between the two vertical U-tubes leads minimum entropy generation in the case of anomalous reduction in the overall heat transfer coefficient in one of the tubes.

The last anomalous scenario is, the ovalization treated as a hydraulic local resistance. Ovalization mainly affects entropy generation in the case of short boreholes. So its relative effect is more relevant for shorter tubes. Mass flow rate repartition should be characterized by a lower mass flow rate in the pipe affected by ovalization and the recovered exergy is about 1.2%. In the case of long boreholes, entropy generation due to distributed friction losses is dominant and the effect of ovalization is negligible, unless the reduced cross-section extends for a significant length. That is, minimum entropy generation is achieved by a homogenous distribution of mass flow rate between the two vertical U-tubes. Depending on the obstruction extent, this can cause much larger pressure losses, making it necessary an optimization process also for the case of deeper installations.

In conclusion, this study shows the use of entropy generation analysis as an effective tool to identify the optimal operation for a geothermal heat pump system. For the first time the effect of anomalies related to the installation of the system on entropy generation has been addressed. In particular, parametric entropy generation analysis allows one to identify possible ways to mitigate the effect of the anomalies on the performance of the system. This is an important outcome, since the small geothermal systems often experience installation imperfections.

References

[1] Lund J. W., T.L. Boyd. Direct application of geothermal energy: 2015 Worldwide review. Proceedings of World Geothermal Congress 2015. Melbourne, Australia, April 19-25, 2015.

[2] Benli H. A performance comparison between a horizontal source and a vertical source heat pump systems for a greenhouse heating in the mild climate Elaziğ, Turkey. Applied Thermal Energy 2012; 50: 197-206.

[3] Sung Lok Do, Jeff S. Haberl, A review of ground coupled heat pump models used in whole-building computer simulation programs. Proceedings of the 17th Symposium for Improving Building Systems in Hot and Humid Climates, Austin Texas, August 24-25, 2010.

[4] Yang H., Cui P., Fang Z. Vertical-borehole ground-coupled heat pumps: A review of models and system. Applied Energy 2010; 87: 16–27.

[5] Murat H., Sisman A. Experimental and computational investigation of multi U-tube boreholes. Applied Energy 2015; 145: 163-171.

[6] Atam E, Helsen L. Ground-coupled heat pumps: Part 2-Literature review and research challenges in optimal design. Renewable and Sustainable Energy Reviews (2015), http://dx.doi.org/10.1016/j.rser.2015.07.009.6

[7] Zeng H., Diao N., Fang Z. Heat transfer analysis of boreholes in vertical ground heat exchangers. International Journal of Heat and Mass Transfer 2003; 46: 4467–4481.

[8] Bandos TV, Montero A, Fernándeza E, Santandera JLG, Isidro JM, Péreza J, et al. Finite line-source model for borehole heat exchangers: effect of vertical temperature variations. Geothermics 2009;38::263–70.

[9] Li M., Lai A. Review of analytical models for heat transfer by vertical ground heat exchangers (GHEs): A perspective of time and space scales. Applied Energy 2015; 151:178-191.

[10] Zeng H. Y., Diao N. R., Fang Z. H. A finite line-source model for boreholes in geothermal heat exchangers. Heat Transfer-Asian Research 2002; 31: 558 567.

[11] Atam E., Helsen L. Ground-coupled heat pumps: Part 1–Literature review and research challenges in modeling and optimal control. Renewable and Sustainable Energy Reviews 2015. http://dx.doi.org/10.1016/j.rser.2015.10.007.

[12] Wołoszyn J., Gołas A. Modelling of a borehole heat exchanger using a finite element with multiple degrees of freedom. Geothermics 2013; 47: 13-26.

[13] Florides G., Kalogirou S. Ground heat exchangers-A review of systems, models and applications. Renewable Energy 2007; 32: 2461–2478.

[14] Gu Y, O'Neal DL. Development of an equivalent diameter expression for vertical U-Tubes used in ground-coupled heat pumps. ASHRAE Trans 1998; 104: 347–355.

[15] Claesson, J., Eskilson, P. Conductive heat extraction from a deep borehole. Thermal analysis and dimensioning rules. Energy 1988; 13: 509–527.

[16] Sisman A., Aydın M. Experimental and computational investigation of multi U-tube boreholes. Applied Energy 2015; 145: 163–171.

[17] Beier R. A., Holloway W.A. Changes in the thermal performance of horizontal boreholes with time. Applied Thermal Engineering 2015; 78: 1–8.

[18] Kohl T., Brenni R., Eugster W. System performance of a deep borehole heat exchanger. Geothermics 2002; 31: 687-708.

[19] Sivasakthivel T., Murugesan K., Sahoo P.K. Optimization of ground heat exchanger parameters of ground source heat pump system for space heating applications. Energy 2014; 78: 573-586.

[20] Esen H., Tugurt E. Optimization of operating parameters of a ground coupled heat pump system by Taguchi method. Energy and Buildings 2015; 107: 329–334.

[21] Kord A. S, Jazayeri S. A. Optimization and analysis of a vertical ground-coupled heat pump. International Journal of Renewable Energy Research 2012; 2: 1.

[22] Esena H., Inallib M., Esena, Pihtilib K. Energy and exergy analysis of a ground-coupled heat pump system with two horizontal ground heat exchangers, Building and Environment 2007; 42: 3606–3615.

[23] Bejan A. Entropy generation minimization: The new thermodynamics of finite-size devices and finite-time processes. Journal of Applied Physics 1996; 79: 1191-1218.

[24] Marzbanrad J., Sharifzadegan A., Kahrobaeian A. Thermodynamic optimization of GSHPS heat exchangers. International Journal of Thermodynamics 2007; 10: 107-112.

[25] Min Li, Alvin C.K. Lai. Thermodynamic optimization of ground heat exchangers with single U-tube by entropy generation minimization method. Energy Conversion and Management 2013; 65: 133–139.

[26] Huang S., Ma Z., Cooper P. Optimal design of vertical ground heat exchangers by using entropy generation minimization method and genetic algorithms. Energy Conversion and Management 2014; 87: 128–137.

[27] Huang S., Ma Z., Wang F. A multi-objective design optimization strategy for vertical ground heat exchangers. Energy and Buildings 2015; 87: 233–242.

[28] Fang Z., Diao N., Cui P. Discontinuous Operation of Geothermal Heat Exchangers. Tsinghua Science And Technology 2002; 7: 194 - 197.

[29] Del Mastro R., Noce G. GSHP Deep Boreholes: a case history: le perfezioni geotermiche più profonde d'Italia. Lozzolo, Edizioni GEOenergia, 2010.

[30] Idel'chik I.E. Handbook of Hydraulic Resistance (2nd edn.). Hemisphere, New York, 1986.

[31] G. Espinosa-Paredesa, A. Morales-Dıazb, U. Olea-Gonzàlezc, J.J. Ambriz-Garcia Application of a proportional-integral control for the estimation of static formation temperatures in oil wells. Marine and Petroleum Geology 2009; 26: 259; 26.

[32] Bejan, A. Method of entropy generation minimization, or modeling and optimization based on combined heat transfer and thermodynamics. Revue Générale de Thermique 1996; 35: 637-646.

[33] Cosentino S., Verda V., Sciacovelli A. Optimal operation of small geothermal systems through entropy generation analysis. Proceeding of ESDA2014: ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis. Copenhagen, Denmark, June 25-27, 2014.

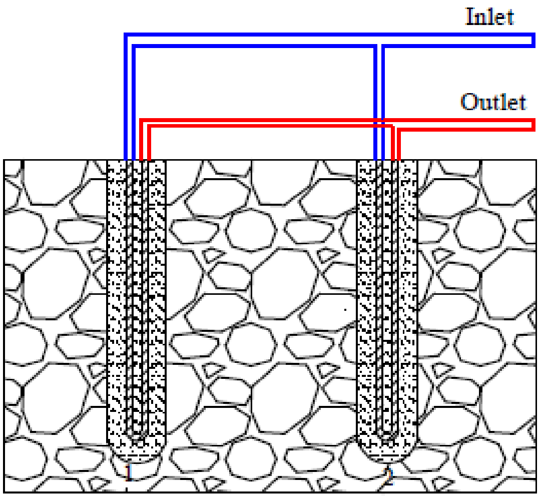

Fig. 1. Two Vertical single U-Tube Ground Heat Exchangers.

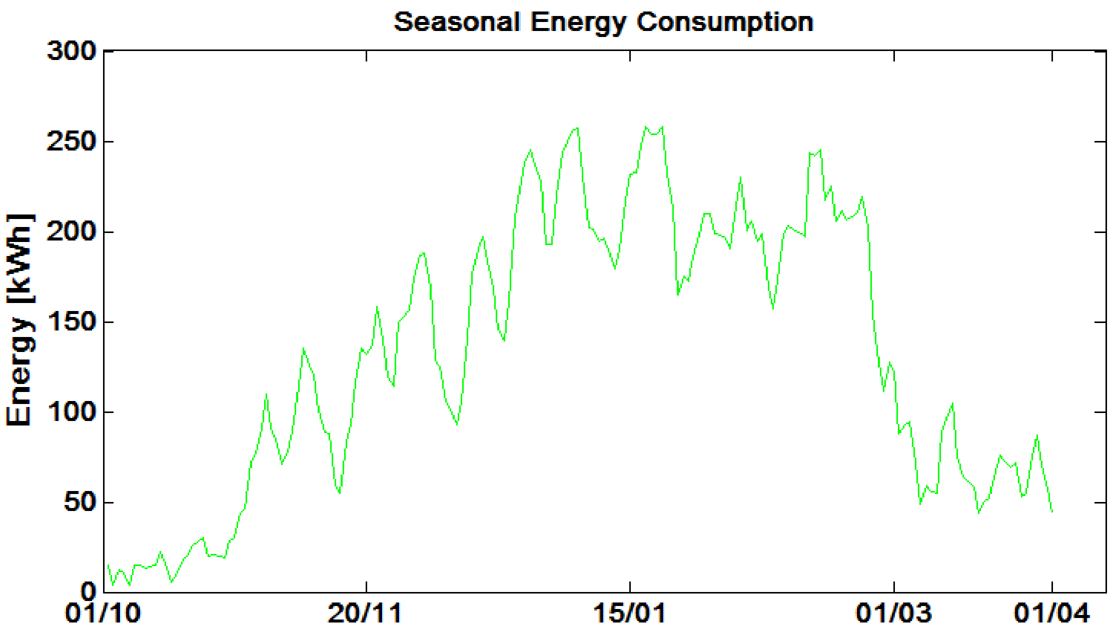

Fig. 2. Seasonal Energy demand for the domestic user *A*.

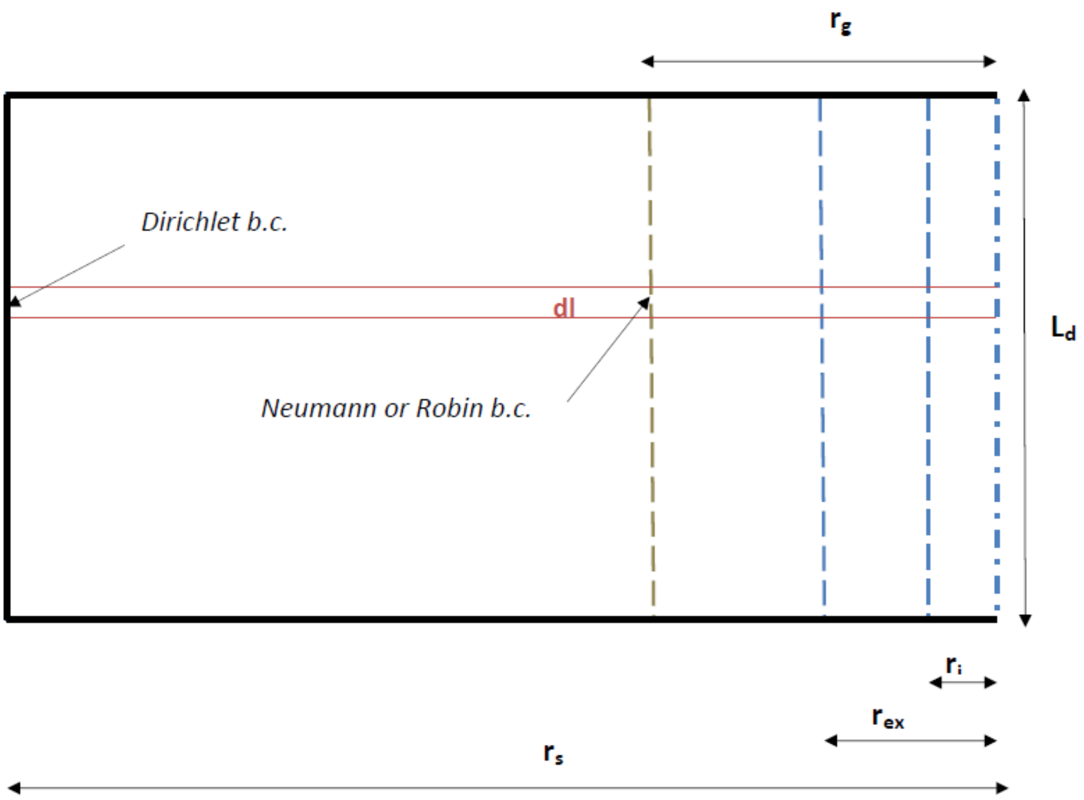

Fig. 3. System representation

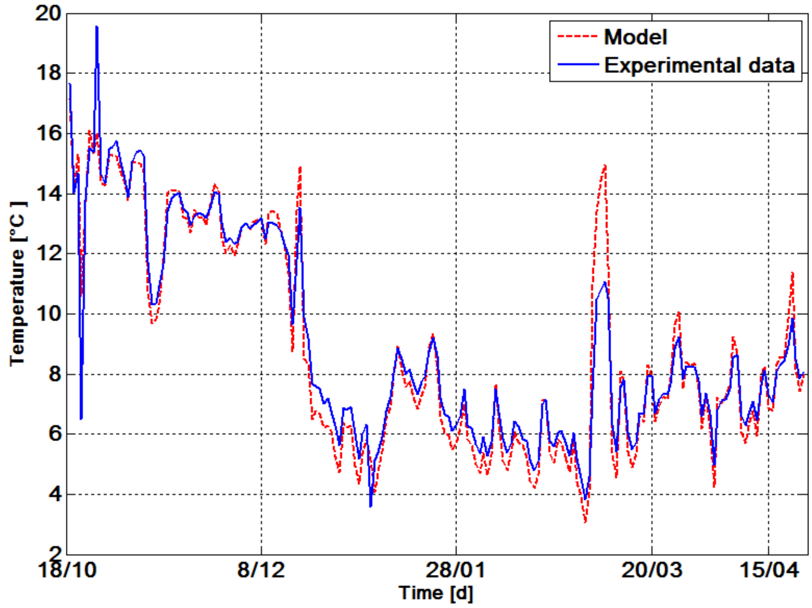

Fig. 4. Temperature of the outlet fluid from the Boreholes.

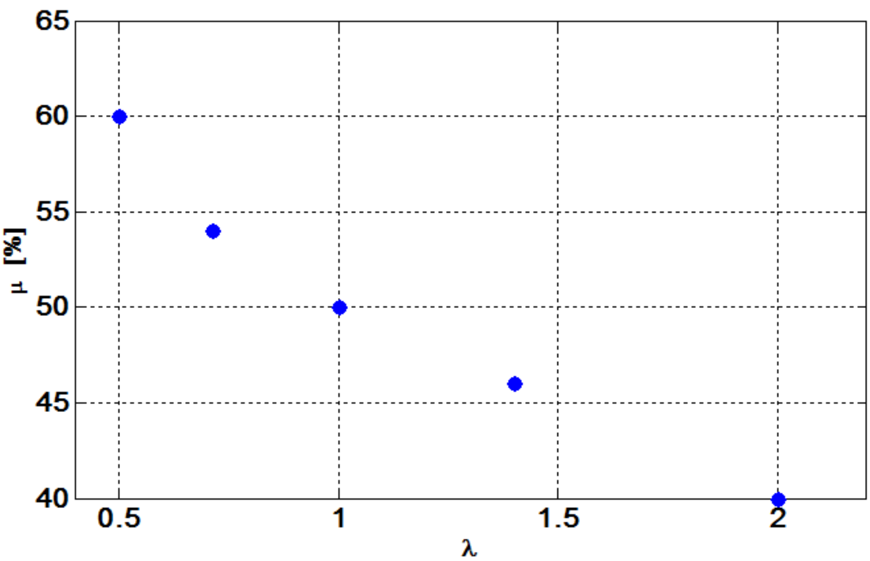

Fig. 5. Optimal Mass Flow Rate Distribution in Case 1.

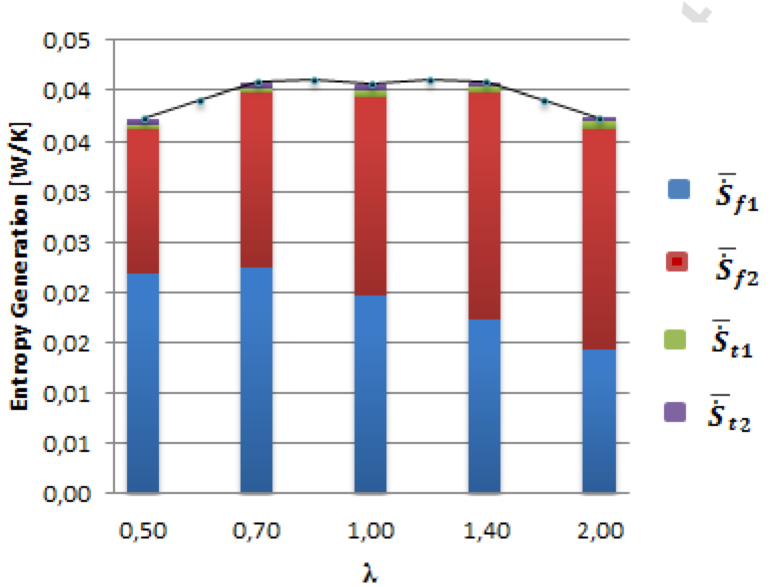

Fig. 6. : Entropy Generation contributions in Case 1.

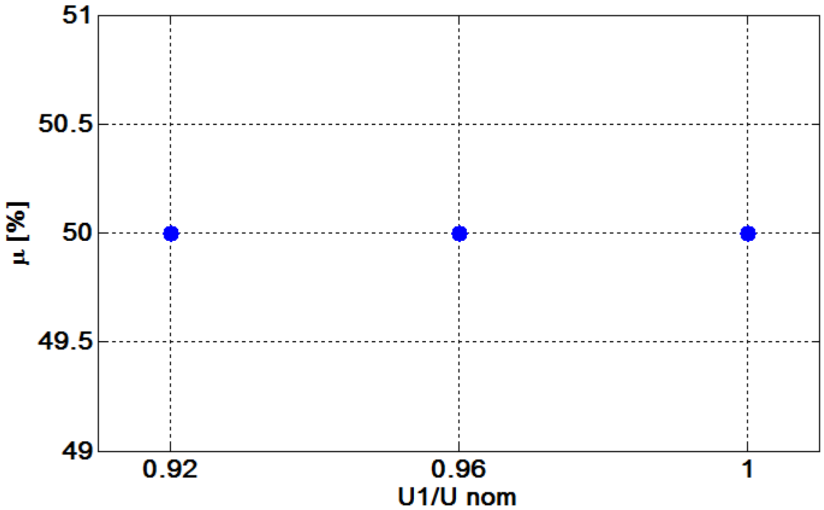

Fig. 7. Optimal Mass Flow Rate Distribution for Case 2.

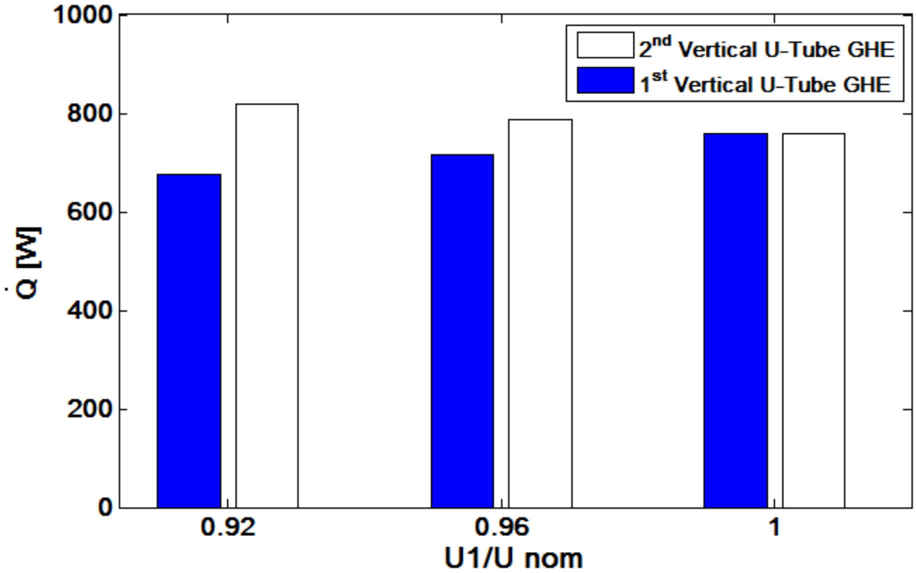

Fig. 8. Time Average heat transfer rate for Case 2.

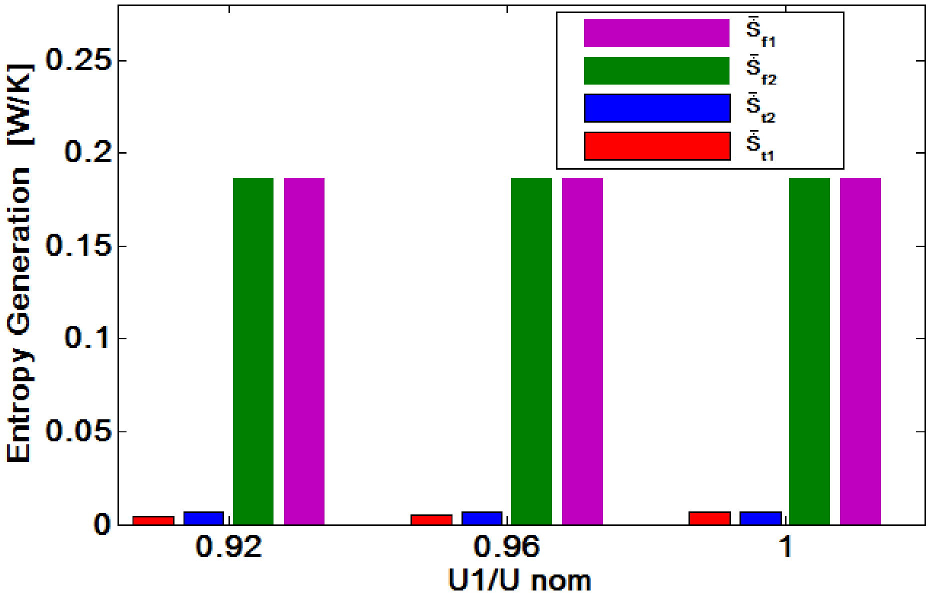

Fig. 9. Entropy Generation in Case 2.

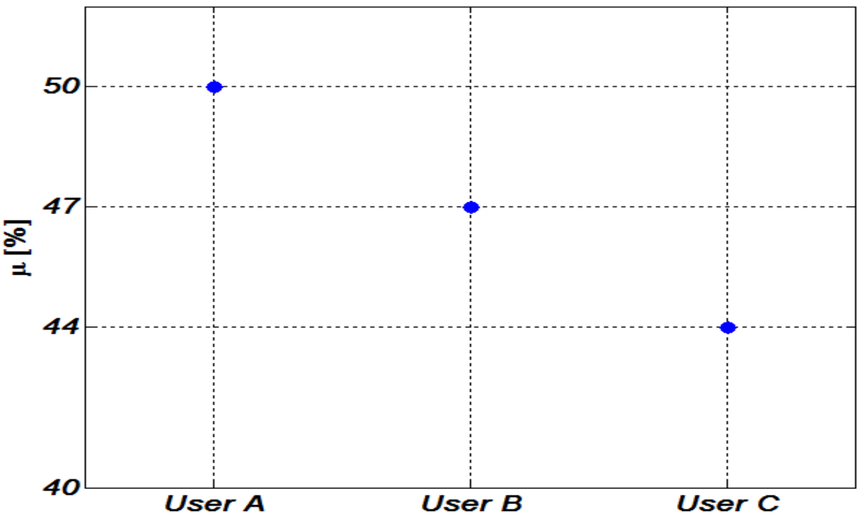

Fig. 10. Optimal Mass Flow Rate for Case 3.

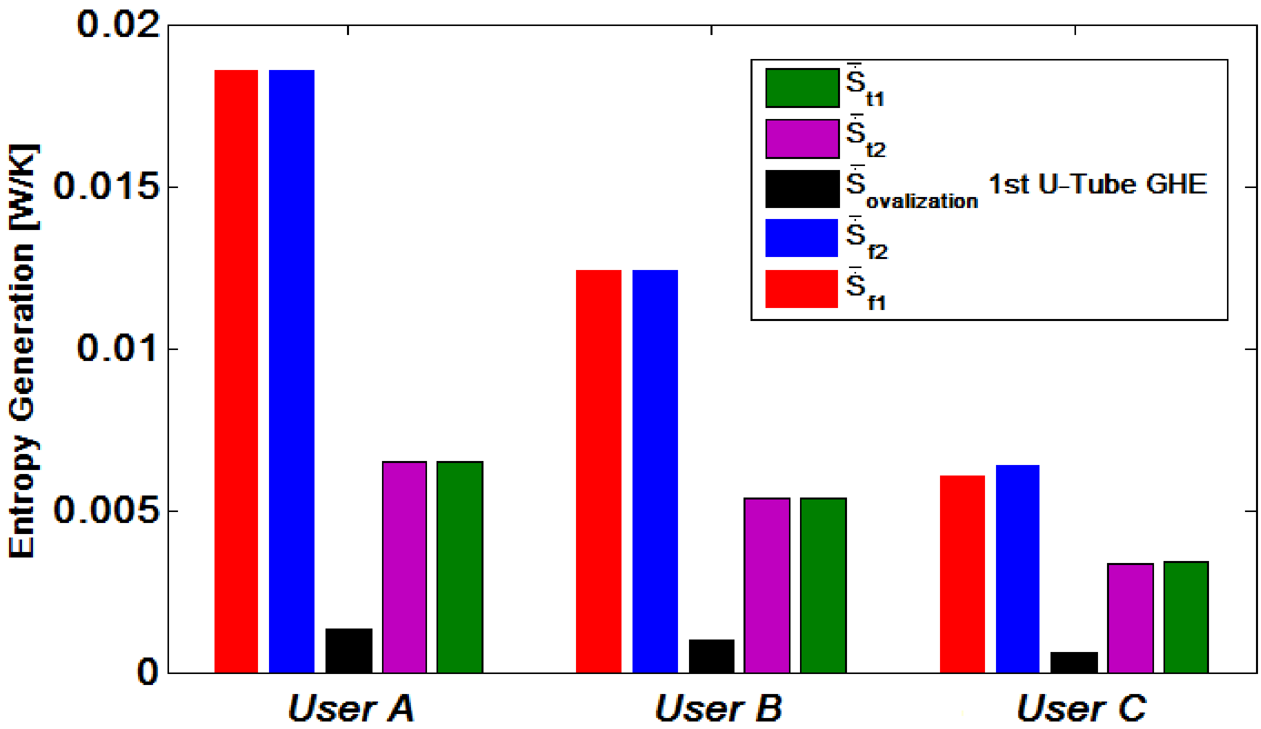

Fig. 11. Entropy Generation contributions in Case 3.

Material	Heat Conductivity [W/m K]	Diameter [m]
U-tube PE100	0.33	0.029 inner 0.033 outer
Grout Saturated Sand	1.8	0.1
Soil	2.5	4

Table 1 Geometric and thermo-physic characters of the zone around the U-Tube Heat Exchanger.

Users	Volume [m^3]	Depth of the Vertical U-Tubes [m]	Thermal Power of GHE [kW]
A	300	150	1.4
B	240	100	1.2
C	210	50	1

Table 2 Volume of domestic users and relative design variables of GHE plant

	Domestic User considered	Anomalous Scenario
Case 1	Domestic User *A*	Different depths of boreholes installation
Case 2	Domestic User *A*	Different heat transfer coefficient of the two boreholes.
Case 3	Domestic Users *A*,*B* and *C*	Ovalization in one of the two vertical U-tubes.

Table 3 Cases analyzed.

Domestic User considered	Depth of the 1st Vertical U-Tube [m]	Depth of the 2nd Vertical U-Tube [m]	Length ratio λ	Design Variable
A	100	200	0.5	μ
A	125	175	0.71	μ
A	150	150	1	μ
A	175	125	1.4	μ
A	200	100	2	μ

Table 4 Fixed parameters and design variable for Case I.

Domestic User considered	Depth of the Vertical U-Tubes [m]	Transmittance reduction	Design variable
A	150	0.92	μ
A	150	0.96	μ
A	150	1	μ

Table 5 Fixed parameters and design variable for Case 2

Domestic User considered	Depth of the Vertical U-Tubes [m]	Ovalization [%]	Design variable
A	150	60	μ
B	100	60	μ
C	50	60	μ

Table 6 Fixed parameters and design variable for Case 3