

GEOHERMAL HELICAL HEAT EXCHANGER

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ABSTRACT

This paper presents helical heat exchangers for geothermal use. The differences with more widespread geothermal exchangers are given, and a complete thermal model for the underground such as for the exchanger is developed, including the local freezing of water contained in the underground when temperatures are lower than 0°C. This model is compared with published data and with experimental results.

In a second part, the model is applied to the heating and the cooling of buildings. The choice was made to consider that the thermal energy needed was directly extracted from the underground, so that results do not depend on the model of heat pump.

INTRODUCTION

Helical heat exchangers belong to geothermal exchangers which are said to be *compact*. Contrary to vertical exchangers – or *borehole heat exchangers* (BHE) –, they are buried in the first dozen of meters under the ground surface, in order to reduce the installation costs. Several geometries and ways of burying these exchangers exist. In this paper, we consider an exchanger “Terra-Spiral”, which height is $H = 2.4$ m, radius $R = 0.5$ m, and pitch $p = 0.08$ m. The upper part of the exchanger is buried at around 1 meter depth: $z_{up} = -1$ m, with a vertical Z-axis going upwards. The ground surface serves as the reference $z = 0$.

According to Philippe (2010), the vertical heat exchangers are widespread over the world. Geothermal horizontal exchangers are quite common in France: the installation costs is reduced since they are buried at around 1 meter depth on large surfaces (typically between once and twice the area to be heated/cooled). That is the reason why many thermal models exist for these exchangers (Philippe (2010)).

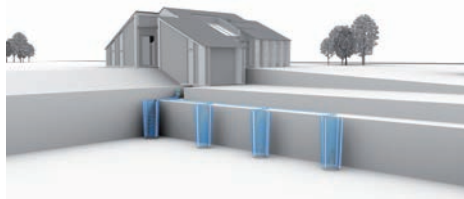


Figure 1: A house connected with four spiral heat exchangers (courtesy of RYB-Terra)

Helical heat exchangers constitute an alternative to

these exchangers: compared to horizontal exchangers, they require few place on the ground; and compared to BHE, the installation costs are significantly reduced. Few thermal models exist: at our knowledge, the main work was done for energy storage in arid zones (Doughty et al. (1991), Rabin et al. (1991), Rabin and Korin (1996)). These studies concern objects of 6 m height which upper part is buried at 4 m depth. The encountered problematic is not exactly the same as our, since our goal is to use these exchangers in order to heat and to cool buildings in western Europe, where the climate and even the underground is different.

In this paper, we adapt an existing model, presented by Rabin and Korin (1996), in order to make it usable with our objectives. This model is 2D axisymmetric, with the vertical axis of axisymmetry being the axis of the helical heat exchanger.

THERMAL MODEL OF THE UNDERGROUND

Temperatures not disturbed by the exchangers

The first step is to model the underground. The geothermal gradient does not need to be taken into account since the depths are quite low. We consider as upper boundary condition the temperature of the ambient air. We denote h_{tot} ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) the heat transfer coefficient between the air and the ground surface. Moreover, we assume constant values of thermal conductivity λ and heat capacity ρc_p of the ground, considered as homogeneous and semi-infinite. Heat conduction is considered to be the only transfer of thermal energy occurring in the underground. These hypothesis are widespread in geothermal studies (Doughty et al. (1991), Rabin et al. (1991), Nebali and Makhoul (2007), Rabin and Korin (1996), Deveughele and Vercamer (1983)): Rabin and Korin (1996) insist on the difficulty to take into account all phenomena, and Doughty et al. (1991) show an example of thermal parameters depending on temperature and humidity: the results are not significantly improved while the calculation is more complex and time-consuming.

Let consider the air temperature variation:

$$T_{ext}(t) = T_{moy} - \tilde{T}_{amp,atm} \cos(\omega(t - t_c)) \quad (1)$$

The mathematical solution for the undisturbed temperature in the underground $\tilde{T}(z, t)$ is given as the sum of

four sinusoids with the same pulse ω :

$$\begin{aligned} \check{T}(z, t) = T_{moy} - \frac{\check{T}_{amp, atm}}{1 + \alpha^4} \exp\left(z\sqrt{\frac{\omega}{2a}}\right) \times \\ \left[\alpha^0 \cos\left(\omega(t - t_c) + z\sqrt{\frac{\omega}{2a}}\right) \right. \\ + \alpha \cos\left(\omega(t - t_c) + z\sqrt{\frac{\omega}{2a}} + \frac{\pi}{4}\right) \\ + \alpha^2 \cos\left(\omega(t - t_c) + z\sqrt{\frac{\omega}{2a}} + \frac{\pi}{2}\right) \\ \left. + \alpha^3 \cos\left(\omega(t - t_c) + z\sqrt{\frac{\omega}{2a}} + \frac{3\pi}{4}\right) \right] \end{aligned}$$

where $a = \frac{\lambda}{\rho c_p}$ is the thermal diffusivity of the underground and $\alpha = \frac{-\sqrt{\lambda \rho c_p \omega}}{h_{tot}}$.

The term $\exp\left(z\sqrt{\frac{\omega}{2a}}\right)$ reflects the fact that the amplitude of high-frequency air temperature variation decreases significantly with the depth. If the period of the sinusoid is equal to 1 day (it is colder at dawn than in the late afternoon) and if the diffusivity is $a = 10^{-6} \text{ m}^2/\text{s}$, values of $z \leq -0.4 \text{ m}$ imply $\exp\left(z\sqrt{\frac{\omega}{2a}}\right) < 0.1$; values of $z \leq -0.8 \text{ m}$ imply $\exp\left(z\sqrt{\frac{\omega}{2a}}\right) < 0.01$. That is the reason why a mean temperature over the day is sufficient to describe the temperatures at the depths of the exchangers.

With this assumption, 1-order atmospheric temperature model is sufficient. From now on, ω is set to the annual pulse. An order of magnitude is $\alpha = \frac{\sqrt{\lambda \rho c_p \omega}}{h_{tot}} \simeq 0.06$, ranging from 0 to 0.2, depending on the type of underground and of its upper "insulation". Except for special cases with really specific conditions and high accuracy of measurement, it is reasonable to consider that the undisturbed temperature of the ground can be written as:

$$\check{T}(z, t) = T_{moy} - T_{amp} \exp\left(z\sqrt{\frac{\omega}{2a}}\right) \cos\left(\omega(t - t_c) + z\sqrt{\frac{\omega}{2a}}\right) \quad (2)$$

with $T_{amp} \simeq \check{T}_{amp, atm}$ the amplitude of the temperature on the ground surface.

EQUATION 2 was already used by Doughty et al. (1991) in this form. Indeed, the author consider that the temperature of the ground surface is the same as the atmospheric temperature (what we actually equally did when considering $\alpha = 0$); and since their geothermal heat exchanger is buried deep enough in the underground, they consider that this temperature can not be disturbed by its use.

Boundary condition expressed with heat flux

EQUATION 2 suffices to give the initial temperature condition in the underground. The derivative with respect to z — multiplied by $(-\lambda)$ — indicates the cor-

responding heat flux:

$$\begin{aligned} \tilde{\varphi}(z, t) = -\lambda \frac{\partial \check{T}}{\partial z} \\ = \begin{cases} E\sqrt{\omega} T_{amp} \exp\left(\sqrt{\frac{\omega}{2a}} z\right) \\ \times \cos\left(\omega(t - t_c) + \sqrt{\frac{\omega}{2a}} z + \frac{\pi}{4}\right) \end{cases} \quad (3) \end{aligned}$$

with $E = \sqrt{\lambda \rho c_p}$ the thermal effusivity of the underground.

Moreover, if the temperature of the ground surface differs from the undisturbed one, an additional flux must appear on this place, which value is $h_{tot}(T(r, 0, t) - \check{T}(0, t))$. h_{tot} takes into account the natural convection such as the (linearized) radiation. According to Rabin et al. (1991), we can consider that a reasonable value with a low wind condition is $h_{tot} = 15 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$.

Summary

The underground is described with a 2D axisymmetric way. It is modeled as a cylinder, with a height going from $z_\infty < 0$ to 0 and a radius ranging from 0 to r_∞ . z_∞ and r_∞ are chosen "far enough" from the exchanger — depending on the simulation done —, so that the temperatures at these limits remain undisturbed by the exchanger. Typical values are $z_\infty = -10 \text{ m}$ and $r_\infty = 7 \text{ m}$. The conditions applied to the underground are:

1. Initial condition at $t = t_{ini}$

$$\begin{aligned} T(z, t_{ini}) = T_{moy} - T_{amp} \exp\left(z\sqrt{\frac{\omega}{2a}}\right) \\ \times \cos\left(\omega(t_{ini} - t_c) + z\sqrt{\frac{\omega}{2a}}\right) \end{aligned} \quad (4)$$

2. Boundary conditions:

- axial symmetry at $r = 0$;
- adiabatic condition at $r = r_\infty$;
- heat flux condition at $z = z_\infty$

$$\begin{aligned} \varphi(z_\infty, t) = E\sqrt{\omega} T_{amp} \exp\left(\sqrt{\frac{\omega}{2a}} z_\infty\right) \\ \times \cos\left(\omega(t - t_c) + \sqrt{\frac{\omega}{2a}} z_\infty + \frac{\pi}{4}\right) \end{aligned} \quad (5)$$

- heat flux condition at $z = 0$

$$\begin{aligned} \varphi(0, t) = E\sqrt{\omega} T_{amp} \cos\left(\omega(t - t_c) + \frac{\pi}{4}\right) \\ + h_{tot}(T(0, t) - \check{T}(0, t)) \end{aligned} \quad (6)$$

Freezing of the underground

The underground contains water, which will freeze if temperatures goes below 0°C . We model this freezing considering the following hypothesis for numerical reasons:

1. Gas contained in the underground (air) can flow out during the freezing, when the water expands, so that there is no variation of volume of the underground;
2. Water is liquid over 0°C and solid below -1°C . A smooth Heaviside function gives the ratio η of liquid water between these temperatures.

The local thermal conductivity of the underground such as its local volumetric thermal capacity ρc_p are affected by this transition. We assume that these properties depend only and directly on the local amount of solid/liquid water. Denoting κ the water content of the underground and $1 - \eta$ the amount of ice in the total water (η varies between 0 and 1), we assume that the thermal conductivity of the underground is given by

$$\lambda_{mix} = (1-\kappa)\lambda_{mat} + \kappa\left((1-\eta)\lambda_{ice} + \eta\lambda_{liq.wat}\right) \quad (7)$$

The same applies for volumetric thermal capacity:

$$\begin{aligned} (\rho c_p)_{mix} &= (1 - \kappa)(\rho c_p)_{mat} \\ &+ \kappa\left((1 - \eta)(\rho c_p)_{ice} + \eta(\rho c_p)_{liq.wat}\right) \end{aligned} \quad (8)$$

Moreover, latent heat is released during this change of state. Mathematically, the heat capacity of the underground seems to be affected by this change of state. The heat equation is

$$(\rho c_p)_{mix} \frac{\partial T}{\partial t} = \nabla \left(\lambda_{mix} \nabla T \right) - \frac{\partial \eta \kappa}{\partial t} (\rho L)_{liq.wat}$$

that is:

$$\nabla \left(\lambda_{mix} \nabla T \right) = \left((\rho c_p)_{mix} + \frac{d\eta}{dT} \kappa (\rho L)_{liq.wat} \right) \frac{\partial T}{\partial t}$$

Thus, the equivalent heat capacity of the underground can be defined with:

$$(\rho c_p)_{mix,eq} = (\rho c_p)_{mix} + \frac{d\eta}{dT} \kappa (\rho L)_{liq.wat} \quad (9)$$

One can keep the classical aspect for the heat equation:

$$\nabla \left(\lambda_{mix} \nabla T \right) = (\rho c_p)_{mix,eq} \frac{\partial T}{\partial t}$$

MODEL OF THE HEAT EXCHANGER

Forewords

Junctions between the heat pump and the extremities of the exchangers are not taken into account. It is generally assumed that the heat transfer fluid flows from the upper to the lower bound of the spiral coil. In other words, the outlet to the heat pump is downside and the inlet upside.

The thermal resistance between the underground and the heat transfer fluid is calculated through the geometry of the wall, the thermal properties of the material constituting the exchanger, the thermal conductivity of the heat transfer fluid, and the Nusselt number. The total thermal resistance of the object modeled has to be the same as the thermal resistance of the real object, *i.e.* the sum of the thermal resistance of the pipe, $R_{th,wall}$, and of the flow, $R_{th,flow}$:

$$R_{th,wall} = \frac{\ln\left(\frac{r_e}{r_i}\right)}{2\pi L_{tot} \lambda_{wall}} \quad (10)$$

$$R_{th,flow} = \frac{1}{\pi \text{Nu} L_{tot} \lambda_f} \quad (11)$$

with λ_{wall} the thermal conductivity of the wall, r_i (respectively, r_e) the internal (respectively, external) radius of the pipe, λ_f the thermal conductivity of the heat transfer fluid and L_{tot} the helical length of the exchanger.

Moreover, there exists a thermal resistance of external contact $R_{th,ext}$, due to the potential development of an air layer between the pipe and the underground, inherent to freezing and thawing cycles during extraction. Considering the other thermal resistances, we assume that this resistance can be neglected.

An order of magnitude of the volumetric flow rate in an exchanger is 4 L/min, that is $q_v \simeq 67 \cdot 10^{-6} \text{ m}^3/\text{s}$. The heat transfer fluid is mono-propylene glycol, so that the kinematic viscosity should remain between $2 \cdot 10^{-6}$ and $10 \cdot 10^{-6} \text{ m}^2/\text{s}$, with high viscosity when the fluid is cold and concentrated. Through a cross section $2r_i = 20.4 \cdot 10^{-3} \text{ m}$, the Reynolds number is $\text{Re} < 2000$: the flow in the exchanger is assumed to be laminar, as in Rabin et al. (1991).

We use $\text{Nu} = 4.36$: it matches a constant flux condition. Indeed, this hypothesis is realistic: assuming a steady state for the heat pump, the temperature of the heat transfer fluid along the depth is approximately a straight line.

Annular cylindrical conduit

This model appears in Doughty et al. (1991), Rabin et al. (1991) and in Rabin and Korin (1996) but is not detailed. This is the goal of this part.

Geometry

For usual geometries, this model leads to an increase of the exchange area between the exchanger and the underground. The cylinder has the same (mean) radius and the same height as the exchanger, so that the underground volume in the middle of the exchanger correspond to the real one.

The flow section is chosen so that that the volume of the heat transfer fluid is kept. This is the only influence of the pitch.

The thickness of the wall is not very important, as long as it is small when compared to the radius of the cylinder. The value of the thermal conductivity of the cylinder walls is such that the total thermal resistance between the heat transfer fluid and the underground is equal to the one of the helical heat exchanger.

Heat transfer fluid flow

Since the model is 2D axisymmetric, the flow cannot have an orthoradial component. Its velocity is vertical. It corresponds to the vertical component of the velocity of the heat transfer fluid inside the real helical exchanger. Since the height is kept, the transit time is kept.

Moreover, since the fluid volume is kept, the volumetric flow rate is kept too.

The boundary conditions are quite easy to express. At each time step, two parameters are needed:

- the geothermal power P to be extracted from the underground;
- the outlet temperature T_{out} (computed at the lower side of the cylinder).

Both parameters enable the calculation of the inlet temperature T_{in} to be applied on the upper side of the cylinder:

$$T_{in} = T_{out} - \frac{P}{(\rho c_p)_f q_v} \quad (12)$$

with P the geothermal power, positive when the exchanger extracts energy from the underground (heating mode for the building), q_v the volumetric flow of the heat transfer fluid, and $(\rho c_p)_f$ its volumetric heat capacity.

VALIDATION OF THE MODEL

Comparison with published results

At first, we use the same conditions as Rabin and Korin (1996). The test consist in storing heat in the underground by injecting hot water at 70°C for 150 days, before recovering it by injecting water at 20°C . This simulation is done using two undergrounds with different thermal properties (case 1 and case 2). The main difference between both models is the use of a thermal resistance between the heat transfer fluid and the underground: moreover, this resistance is quite low so that results should have the same orders of magnitude. Figure 2 shows the temperatures at the outlet for both models. The coherence is really good.

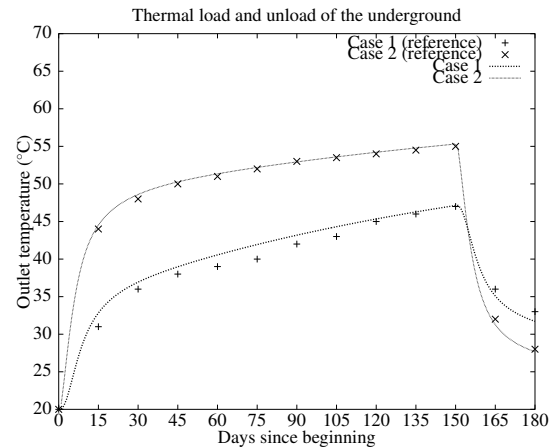


Figure 2: Outlet temperatures for two cases (references given by Rabin and Korin (1996))

Comparison for the freezing model

Numerical approach

To prove the interest of taking into account the freezing of the underground water, three simulations are done. At the beginning, the underground temperature is homogeneous (10°C). A constant cooling power, high enough to make the underground freeze, is continuously extracted during 3 days. Then the heat extraction is stopped, but the fluid circulation still works during 11 additional days (relaxation time).

Three soils are simulated, each of them containing a different volumetric ratio of water (0%, 20%, 50%). These soils are chosen so that the thermal parameters are the same when the whole water content is liquid. Figure 3 shows how the outlet temperature evolves (the inlet temperature is nearly 3.5 K lower than the outlet temperature during the heat extraction).

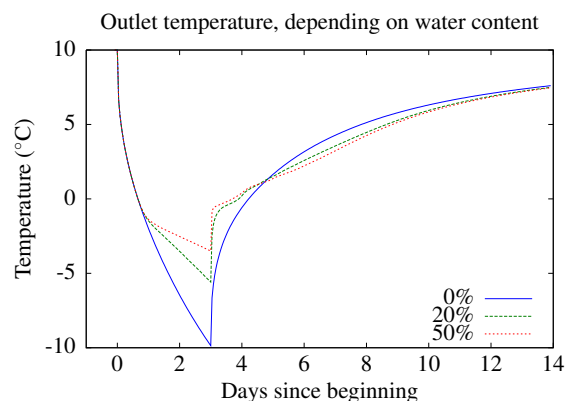


Figure 3: Influence of underground freezing on outlet temperatures

It can be noted that the outlet temperatures after 3 days strongly depend on this freezing phenomenon. This phenomenon also occurs in standard condition and has to be taken into account when modeling the underground: it would not suffice to consider only the thermal parameters of the underground at the beginning, when the entire water content is liquid.

Experimental approach

An experimental platform was created some kilometers away from Chambéry (Savoy, French Alps). Helical heat exchangers were connected to a heat pump. The exchangers are $H = 2.4$ m high and $R = 0.5$ m large. The platform is a dozen meters away from a river, the *Leysse*, and the underground is mainly composed of silt and sand. Water was found at a depth of 3.5 m or 4 m, just below the lowest part of the exchanger. As a consequence, it can be assumed that there is a high water content in the underground. According to van Genuchten (1980) and Wösten et al. (1999), we first estimate the volumetric water content to $\kappa = 40\%$.

For this experiment, the heat pump worked continuously during several days, until temperatures below 0°C could be reached. Temperatures were measured with 4-wired Pt100 and the geothermal power was calculated thanks to the flow rate. This power was then used as a working condition for the model.

Moreover, the values of atmospheric temperatures over a “mean” year were used to obtain the values of T_{moy} , T_{amp} and t_c . We measured variation of natural temperatures in the underground in order to estimate its average diffusivity using EQUATION 2: $a \simeq 1.1 \cdot 10^6 \text{ m}^2/\text{s}$.

Besides, the thermal effusivity of the underground was estimated experimentally. This led to $\lambda = 2.6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ and $\rho c_p = 2.3 \cdot 10^6 \text{ J}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$; these values were used in the simulations. The value of thermal conductivity is slightly high according to Verein Deutscher Ingenieure (2000), but is reasonable.

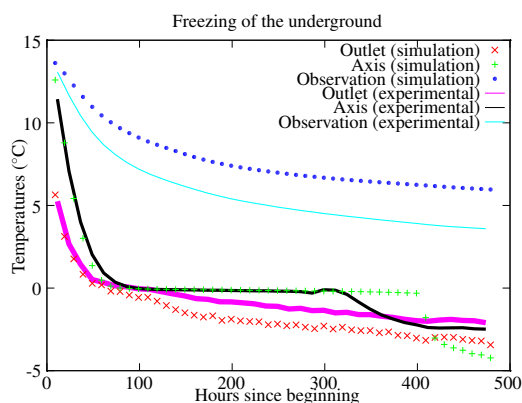


Figure 4: Comparison between simulation and experimental work

Figure 4 compares the experimental and simulated temperatures at following points: “outlet” of the heat transfer fluid, “axis” (at middle-height), “observation” at 1 m from the axis (at middle-height).

The temperatures on the axis keep a value of 0°C during a long time (more than 200 hours). This can be bound with the release of latent heat in the underground. This proves the necessity of taking into account the effect of freezing.

We probably overestimated the water content, since the simulated temperatures on the axis remain at 0°C for a higher time in the simulation than in reality. At a distance of 1 m of the axis, the model overestimates the temperatures: this effect can be tied to a bad estimation of the thermal properties for the underground. Conversely, the model underestimates the outlet temperatures when the water freezes. This may be a consequence of the way we modeled the freezing of water, between 0°C and -1°C : indeed, experimental and simulated outlet temperatures converge again when all the water is solid (after 400 hours). We could not check this hypothesis by reducing this interval, because of a lack of computer memory.

The model is not perfect and should be improved; moreover, the thermal parameters are not precisely known. Nevertheless, a good adequateness can be found with experimental results.

COUPLING WITH A LOW-ENERGY HOUSE

The thermal energy need of a low-energy house was simulated besides. It handles on daily-mean values required for heating and cooling a 120 m^2 compact building located in Savoy (France). The underground is supposed to have a thermal conductivity $\lambda = 1.7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, a volumetric thermal capacity $\rho c_p = 2.5 \cdot 10^6 \text{ J}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$, and a volumetric water content $\kappa = 20\%$. These values are representative for many types of undergrounds which would not be dried. 3 helical heat exchangers are connected in parallel: we assume that they do not have any thermal effect on each other.

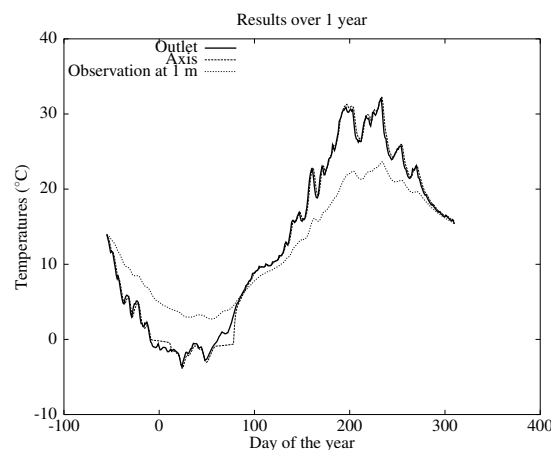


Figure 5: Coupling with a low-energy building over 1 year

In the following, the energy required for the building is assumed to be extracted from the underground on a continuous way. Different temperatures evolutions are

represented on Figure 5: the outlet temperature, the temperature on the axis at nearly mid-height of the exchanger, and the temperature at 1 m of the axis at the same depth.

The temperatures of the ground, and in particular the spatial extension of the freezing zone, appear on Figure 6 at the day when the ice has the maximal extension. The solid line represents the isotherm -1°C : inside it, water is frozen. The dashed line represents the isotherm 0°C : outside, the water remained liquid.

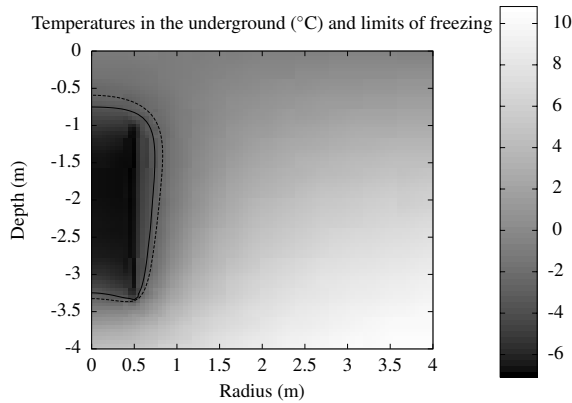


Figure 6: Temperatures in the underground and maximal volume of ice

Inside the exchanger, the underground is completely frozen. Conversely, ice propagates slowly outside.

Figure 7 represents the outlet temperatures over 10 years, when the exchangers are only used to cope with the heating needs. It shows that the natural load of the underground suffices to get similar temperatures over years.

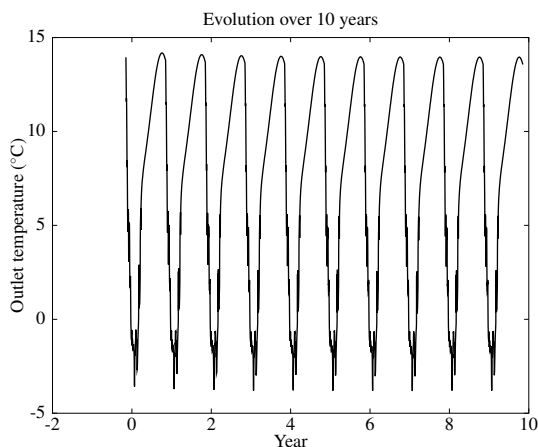


Figure 7: Simulation over 10 years

EFFECT OF CYCLING

Let define the *medium temperature of the heat transfer fluid* as the mean value between inlet and outlet temperatures. Figure 8 shows this temperature for three cases:

1. one with a steady operating mode with constant power (labelled *Steady*).

2. a second one with an operating mode “15 minutes on / 45 minutes off” each hour: the circulator works during both periods (labelled *On*).
3. a third one with an operating mode “15 minutes on / 45 minutes off” each hour: the circulator does *not* work during the second period (labelled *Off*).

The powers are chosen such that the energy extracted over an hour is the same for the three cases.

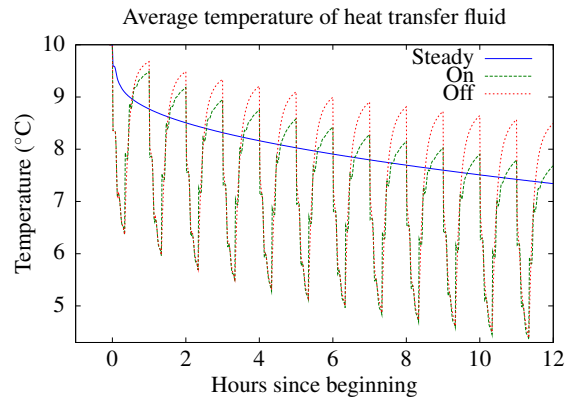


Figure 8: Evolution of the mean heat transfer fluid temperature over 12 hours

Figure 8 shows the inconvenience of short cycling: the temperatures of the heat transfer fluid are lower when extracting geothermal power. Two effects play a major role in this phenomenon:

- the energy is extracted next to the exchanger (there is not enough time for the underground to homogenize temperatures on a further distance);
- the gap between the temperature of heat transfer fluid and the temperature of the underground outside the exchanger is increased, due to the thermal resistance R_{th} presented above.

Therefore, better coefficient of performance (COP) can be reached with long cycles. Moreover, the two cases “cycling” show no major differences on outlet temperatures when geothermal heat is extracted. There is apparently no use in making the circulator work when no heat is required.

INFLUENCE OF SEVERAL PARAMETERS

The results presented in this section are done with the thermal needs of another house. It would correspond to a 120 m^2 house built at the same place as the previous one, with thermal norms corresponding to year 2005. For the same reasons as previously, the heat pump is not modeled and the energy needed for the building is supposed to correspond to the energy extracted from the underground. For the reference case, six exchangers are connected in parallel and are used to heat and to cool the building.

Results over 1 year

Figure 9 shows the outlet temperatures, for the case of reference (heating and cooling) and for the case “heating only”. Once again, the natural thermal load during

summer is good, whatever the use of the geothermal exchangers.

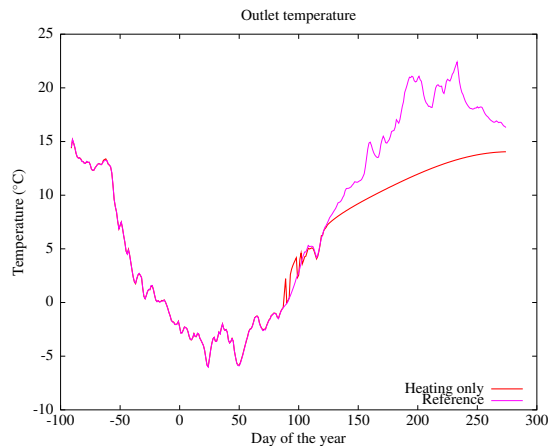


Figure 9: Outlet temperature over 1 year

Influence of the pitch

On Figure 10, we made the pitch grow from 0.08 m (reference case) to 0.2 m, keeping values for radius R and height H constant. The outlet temperature variations increase with the increase of the pitch, mainly because of the greater thermal resistance R_{th} (the total length is reduced).

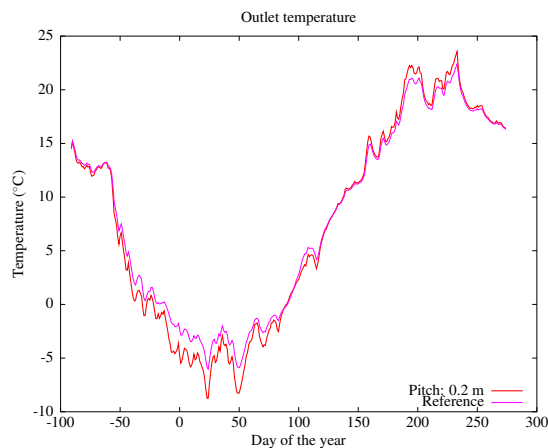


Figure 10: Outlet temperature, making the pitch vary

Influence of height and radius

On figure 11, the number of exchangers was reduced to $N = 5$, and the total flow rate “at the heat pump” was kept constant. On a first model, the height was multiplied by 1.2; on a second one, the radius was multiplied by this same value. It appears that the temperatures are nearly the same for the three cases. As a first approximation, the thermal resistance of the whole installation is the same as in the reference case, and the outlet temperatures evolve on a similar way when the product $N \times H \times R$ is kept constant.

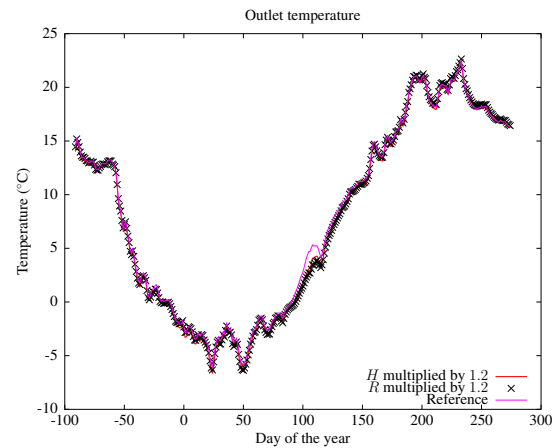


Figure 11: Outlet temperature, making geometry vary

Influence of the ground

On figure 12, the ground is supposed to be wet sand ($\lambda = 2.4 \text{ W.m}^{-1}.\text{K}^{-1}$). The temperatures gain in stability (a greater volume around the exchanger is used).

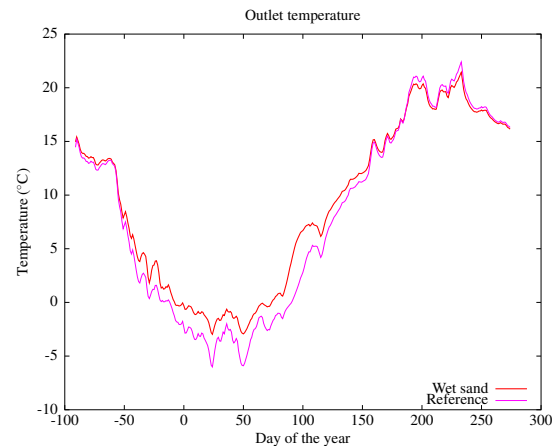


Figure 12: Outlet temperature, making ground vary

CONCLUSION

This paper presented a reliable model of geothermal heat exchangers. This model may be used to define the geometry of exchangers and to size an installation. Besides, it pointed out the fact that temperatures were about the same over years (no thermal unload of the underground can be measured).

We showed that the influence of the thermal resistance existing between the heat transfer fluid and the underground had to be taken in account, in particular when defining the pitch. Moreover, the influence of the cycling was explained: if possible, short cycles are to be avoided.

A limit of this model is the freezing of water, which is considered to occur at constant volume. Moreover, no mechanical effect is taken into account: for example, the freezing/thawing cycles may create an air layer between the exchanger and the underground, increasing the thermal resistance over years.

NOMENCLATURE

Latin letters

a	Thermal diffusivity ($\text{m}^2.\text{s}^{-1}$)
c_p	Specific heat ($\text{J}.\text{kg}^{-1}.\text{K}^{-1}$)
E	Thermal effusivity ($\text{J}.\text{s}^{-1/2}.\text{m}^{-2}.\text{K}^{-1}$)
h_{tot}	Total heat transfer at the ground surface ($\text{W}.\text{m}^{-2}.\text{K}^{-1}$)
L	Specific latent heat ($\text{J}.\text{kg}^{-1}$)
L_{tot}	Helical length of the exchanger (m)
N	Number of helical heat exchangers (-)
Nu	Nusselt number (-)
P	Geothermal power (W)
q_v	volumetric flow rate ($\text{m}^3.\text{s}^{-1}$)
r	Radius (m)
r_e	Exterior radius of the pipe (m)
r_i	Interior radius of the pipe (m)
R_{th}	Thermal resistance ($\text{K}.\text{W}^{-1}$)
t	Date (s)
t_c	Coldest date (s)
T	Temperature (K)
T_{moy}	Mean temperature over the year (K)
T_{amp}	Amplitude of temperature on the ground surface (K)
$\tilde{T}_{amp,atm}$	Amplitude of temperature of the atmosphere (K)
z	Depth (m)

Greek letters

α	Auxiliary coefficient (-)
η	Ratio of water at liquid state (-)
κ	volumetric ratio of water in the underground (-)
λ	Thermal conductivity ($\text{W}.\text{m}^{-1}.\text{K}^{-1}$)
ρ	Mass density ($\text{kg}.\text{m}^{-3}$)
φ	Heat flux density ($\text{W}.\text{m}^{-2}$)
ω	Annual pulse ($\text{rad}.\text{s}^{-1}$)

Subscripts

ext	External side
f	Heat transfer fluid
$flow$	Flow
ice	Solid water
in	Inlet
$liq.wat$	Liquid water
low	Lower part
mat	“Dry matrix” of the underground
mix	Multi states
out	Outlet
up	Upper part
$wall$	Wall of the exchanger

Accentuation

~ Undisturbed by the exchanger

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