New expression to calculate quantity of recovered heat in the earth-pipe-air heat-exchanger operat-ing in winter heating mode

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Abstract A new expression is proposed to calculate the earth-energy of an earth-air-pipe heat exchanger during winter heating for three kinds of soil in France. An analytical model is obtained by using numerical computation developed in Scilab – a free open source software. The authors showed the comparison between their simple analytical model and experimental results. They showed the influence of different parameters to specify the size of the heat exchanger.

Keywords: Earth-pipe-air heat-exchanger; Analytical model; Air heating

Nomenclature

a_S – soil diffusivity, $m^2\ s^{-1}$
C_a – specific heat of air, $J\ kg^{-1}\ K^{-1}$
c_s – soil heat capacity, $J\ kg^{-1}\ K^{-1}$
D – diameter of the buried pipe, m
E – thickness of buried pipe, m
g_S – thermal conductance of soil for angle $\Delta\theta$, $W\ K^{-1}$ g_T – thermal conductance of pipe for angle $\Delta\theta$, $W\ K^{-1}$ h_{conv} – convective heat transfer coefficient, $Wm^{-2}\ K^{-1}$
k – annual space pulsation of soil, m^{-1}
L – length of buried pipe, m

ℓ'_0 – characteristic geothermal length (m) at a flow-rate Q
ℓ_0 – characteristic geothermal length (m) at a flow-rate Q_0
$\dot{m}_a$ – mass flow-rate of air entering buried pipe, kg s^{-1}
P – depth buried pipe, m

Q – volume flow-rate, m^3 h^{-1}
Q_0 – reference volume flow-rate, m^3 h^{-1}
Re – Reynolds'number
T_{air} – outside temperature, °C
T_{soil} – soil temperature, °C
T_θ – soil temperature at angle θ, °C
$T_2(x)$– air temperature inside pipe at the length x from inlet, °C
T_{2out}– air temperature at outlet, °C
$T_t(x)$– pipe temperature at the length x from inlet, °C
v – air velocity inside pipe, m s^{-1}
w – normalized recoverable energy
W_∞ – maximal recoverable energy by EPAHE during the heating period at a flow-rate Q_0 and at a depth 3 m, kWh
$W(L,Q,P)$ – recoverable energy by EPAHE during the heating period with a length L of buried pipe at a flow-rate Q and at a depth P , kWh
x – horizontal length along the pipe, m
z – depth of ground, m

Greek symbols

δ – annual skin length of the soil, m
ϕ_m – recoverable power of the EPAHE for the m-th month, W
Λ – normalized value of the length L
λ – air thermal conductivity inside the pipe section, Wm^{-1} K^{-1}
λ_S – soil heat conductivity, Wm^{-1} K^{-1}
μ – air dynamic viscosity, kg s^{-1} m^{-1}
ρ – air density, kg m^{-3}
ρ_S – soil volume density, kg m^{-3}

1 Introduction

The final energy consumed in French agriculture represents nearly 2.8% of the country energy in 2012 [1]. The use of renewable energies makes it pos-sible both to limit the consumption of fossil fuels and to reduce the carbon footprint of agricultural production. The use of geothermal energy allows using the inertial effect of the soil heat to increase recoverable energy. The use of a ground-to-air heat exchanger is well-adapted for greenhouses so that plantations do not undergo frosting.

Sizing a geothermal installation is difficult. There is no simple analytical formula for determining the length of buried pipes to know the recoverable energy. The transfer coefficient is an important parameter which is nonlinear. Therefore, it is necessary to use a numerical model. In this paper, authors give an empirical expression developed to calculate the energy re-covered by an earth-pipe-air heat-exchanger (EPAHE) in winter and spring heating conditions.

The analytical expression has been established by using a computer pro-gram developed in Scilab environment [2]. A simple model in static mode is also presented in this paper using the thermal conductance of the ground. The software developed by the authors, called HeatGround, uses soil prop-erties, technical data of EPAHE (depth P , length L, diameter D and flow Q), see Fig. 1, and climatic data (minimum temperature and maximum air temperature mean value). Numerical simulations lead the authors to de-fine a simple analytical expression for recoverable energy produced by the exchanger. Authors give for different French cities and for different kinds of soil, a table of recoverable energy produced by a pipe buried in the depth of 3 m.

At last the authors compare the established analytical expression with results provided from scientific papers. The authors compare in few exam-ples the influence of main parameters on the design of EPAHE.

The difficulty for installers is to choose the length of the buried tube. Often, the diameter is already fixed. The calculation is limited to a tube length buried at a certain depth. Thus, the authors define a characteristic length ℓ'_0 depending on the nature of the soil and the flow in the pipe. The analytic relationship is characterized in normalized size for length and recoverable energy, with respect to ℓ'_0 and also with respect to the maximal energy recovery W_∞ during the winter seasons (in the case with infinite length).

2 Theoretical temperature distribution in ground

A scheme of EPAHE is presented in Fig. 1. The length taken into account L is the buried part of EPAHE and D represents the internal diameter of the pipe.

The soil temperature is given by an analytical expression deduced from resolving the equation of semi-infinite wall excited by a sinusoidal wave temperature. The air temperature varies between T_{min} and T_{max} during the year. The values of T_{min} and T_{max} are monthly averages for the coldest month and the warmest month of the year respectively for each French city studied in this paper. These values are obtained by JRC Europa Pvgis

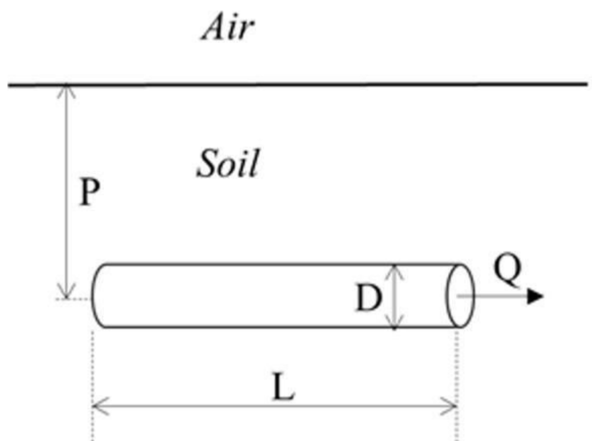

Figure 1: Description of the studied buried pipe.

software [3]. Assuming that the maximum temperature T_{max} is obtained on 1st August (the number d_M of that day of the year in the relationship (1) is equal to 214, with d_M = 1 given for 1st January and d_M = 365 given for 31th December), the soil temperature T_{soil} at the depth z and day d_M is given by:

$$T_{soil}(z, d_M) = T_0 + A(z) \cos\left(\frac{2\pi}{365}(d_M - 214) - k z\right), \quad (1)$$

where $A(z)$ is the magnitude of temperature wave at depth z:

$$A(z) = T_M e^{-k z}, \quad (2)$$

where T_M is the magnitude of temperature at the depth $z = 0$

$$T_0 = \frac{T_{min} + T_{max}}{2} \quad \text{and} \quad T_M = \frac{T_{max} - T_{min}}{2}. \quad (3)$$

Using the set of Eqs. (1)–(3), HeatGround computes for each month the air temperature and the soil temperature. The k coefficient is the wave number deduced from Fourier’s law. Its value is computed by using the soil diffusivity coefficient.

3 Application of HeatGround

The software HeatGround developed in the laboratory [2] uses thermal modeling in two dimensions, for cylindrical exchangers, as presented in

Fig. 2. The pipe, which constitutes the exchanger, is cut into slices. An electrical analogy is given to simulate the heat transfer between the pipe and the ground on a cylinder of radius R_S around the pipe. The radius R_S was arbitrarily chosen equal to 1 m so that it is less than the minimum depth *P* of 1.5 m for the simulation. Thus, the cylinder is slightly away from the air-ground interface. The software shows a maximum deviation of 3% of the results from a radius of 0.5 m. This result shows that the choice of numerical value of the radius in the simulation is not the most important parameter.

The simulation neglects the caloric supply in the soil. Only the 'temperature' parameter is taken into account. This choice can be improved if the simulation is dynamic taking into account the capacity of the soil. The exchange coefficient in the pipe h_{conv} uses the Dittus-Boelter correlation which depends of the position *x* inside the pipe.

The temperature T_{soil} is calculated for each month of the year in the program using Eq. (1). The two temperatures T_{air} and T_{soil} are monthly average values. Assuming that the variation of the temperature T_{air} as a function of time over a year is sinusoidal and a time period of 1 year, then T_{soil} is deduced from Eq. (1).

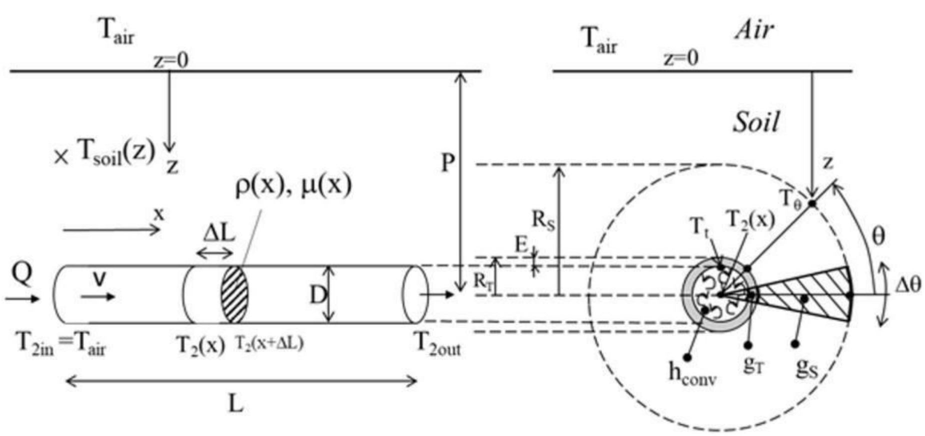

Figure 2: Description of the studied buried pipe used in the HeatGround software.

Amitrano has developed a tutorial to assist in the design of an air-ground exchanger [4]. The simulations using the present software made it possible to obtain a simplified analytical relation which will be compared with that of Amitrano. Therefore, the authors compared the results of this author to design simple analytical formulations for sizing a heat exchanger. The idea is to provide a simple analytical method based on experiments and simulations. Soil parameters are quite variable and nonlinear. Three types of soil are taken into account, compare Tab. 1, according to [5]. Only the value of k, obtained by using Eqs. (4) and (5) is useful in our formulation.

Table 1: Characteristics of 3 soils used, (Soil A – wet sandy soil, Soil B – wet clay soil, Soil C – moist peat).

	ρ_s	c_s	λ_s	a_s	k	$\delta = 1/k$
Units	kg m^{-3}	J K^{-1} kg^{-1}	W K^{-1} m^{-1})	m^2 s^{-1}	m^{-1}	m
Soil A	2000	1480	2.2	7.43 10^{-7}	0.37	2.74
Soil B	2000	1550	1.58	5.10 10^{-7}	0.44	2.27
Soil C	1100	3650	0.5	1.25 10^{-7}	0.89	1.12

The soil diffusivity is given by

$$a_s = \frac{\lambda_s}{\rho_s c_s} . \quad (4)$$

The coefficient k is defined as the inverse of the annual skin length of the soil δ

$$k = \frac{3.15\ 10^{-4}}{\sqrt{a_s}} , \quad \delta = \frac{1}{k} . \quad (5)$$

Thus, the important parameters are, in order of importance: flow rate Q, depth P , temperatures T_{min} and T_{max} , length L, diameter D. Considering the low thickness E of EPAHE, the nature of the material is not very significant for the recoverable energy.

4 Sizing an air-ground heat exchanger

4.1 Definition of the recoverable energy

At shallow depth, the average annual soil temperature is identical to the air temperature. But during the winter season, the temperature of the soil is higher than the outside air temperature.

The maximal recoverable energy, W_∞ , by EPAHE, was obtained by the HeatGround software. The energy transferred in the exchanger is cal-culated when the temperature of the soil is higher than the temperature of outside air.

Assuming the density of air ρ_A is equal to 1.25 kg m^{-3} and the specific heat capacity of air C_A is equal to 1004 Jkg^{-1}K^{-1}, the recoverable power ϕ_m (given in watts) is given by the following expression

$$\phi_m = \frac{\rho_A C_A}{3600} Q\,(T_{2out} - T_{air}) \approx 0.34 Q\,(T_{2out} - T_{air})\,. \quad (6)$$

Thus, energy (given in kilowatts) computed for the winter season, for the months between October and April inclusive, is given by

$$W = \sum_{m=1}^{4} \phi_m \frac{24}{1000} N_m + \sum_{m=10}^{12} \phi_m \frac{24}{1000} N_m \,, \quad (7)$$

where N_m is the number of days in the mth month. If the length L is very long, then the temperature T_{2out} approaches T_{soil}, and W approaches W_∞.

4.2 Results from HeatGround of the recoverable energy

Table 2 shows values of the temperatures T_{min} and T_{max}, and the recoverable energy for 3 types of soils for an EPAHE buried at 3 m depth and for a flow rate of 120 m^{3}h^{-1}. The standard requires to have a maximum flow of 1.3 m^{3}h^{-1}m^{-2} for the French RT2005 standard in the case of individual dwelling, and the French standard BBC of low energy building in the case of tertiary use in building renovation. Knowing the average surface area of approximately 100 m^2 for individual cases, we took a reference rate value of 120 m^{3}h^{-1}. For the German Passiv-Haus standard, the number of air changes per hour for all types of buildings, under renovation as well as new buildings, should be less than 0.6 h^{-1}. Taking a 100 m^2 house, to heat the volume of 250 m^3, we must have a turnover of less than 150 m^3 h^{-1}. W_∞ (in kWh) is given to a depth of 3 m and P_0 for a volume flow-rate inside the pipe Q_0 = 120 m^{3}h^{-1}. Energy W_∞ is obtained using the Eq. (7) for depth P = 3 m (soil temperature T_{soil}) and the air temperature T_{air} (obtained for P = 0 in Eq. (1) and Eq. (2)) for each months of heating.

If you change the parameters λ_S , ρ_S , and C_S by 20%, then the values of W_∞ can change by less than 7%.

4.3 Analytical model of the recoverable heat energy

Thus, the foregoing analytical model is sufficient to assess the recoverable energy W for the heating season (October to April inclusive) by the air-

Table 2: Energy recoverable W_∞ (kWh) at 3 m depth for different French cities for 3 types of soil and a flow rate of 120 $m^3 h^{-1}$.

City	T_{min} , °C	T_{max} , °C	W_∞ , kWh		
			Soil A	Soil B	Soil C
Lille	4.1	18.7	721	779	821
Paris	4.1	19.7	770	832	878
Rennes	6.2	19.3	647	699	737
Tours	5.0	20.2	750	810	855
Strasbourg	1.9	20.2	903	976	1030
Bordeaux	7.1	21.4	706	763	805
Lyon	3.6	21.3	874	944	996
Marseille	8.1	24.4	805	869	917
Perpignan	8.4	23.9	765	826	872
Nice	8.4	24.1	775	837	883

ground heat exchanger. If we want to implement a pipe of length L to a depth P , diameter D, and through which an air change rate of Q, then the authors propose their formulas, see Eq. (11).

The maximal recoverable energy W (for a very long length L) is equal to W_∞ and is proportional to Q. The formula (11) is obtained by correlation with the simulation with HeatGround, see Fig. 3. For example, the authors [6] propose a formula for energy proportional to the term $1 - e^{-\frac{\pi D h_{conv}}{\dot{m}_a C_a} L}$ by using the notations of this article, but the difficulty is that h_{conv} is not constant along the pipe. The correlation of Dittus-Boelter gives

$$h_{conv} = 0.023 \frac{\lambda}{D} \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} , \quad (8)$$

where Re depends of the characteristics of air inside the pipe

$$\mathrm{Re} = \frac{\rho v}{\mu} D . \quad (9)$$

The Prandtl number is calculated by the following second order analytic expression:

$$\mathrm{Pr} = 7.16\ 10^{-1} + 1.39\ 10^{-4}\ T_2(x) - 3.57\ 10^{-7}\ T_2(x)^2 , \quad (10)$$

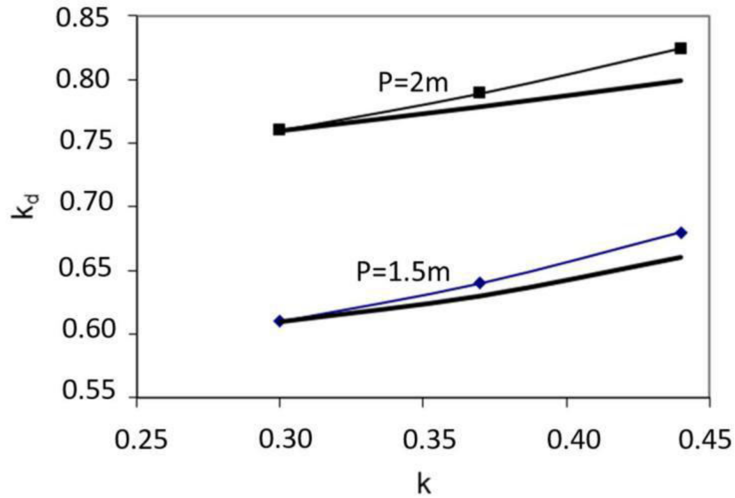

Figure 3: Shape of k_d ***versus*** k for 2 depths (1.5 m and 2 m) with P_0 = 3 m.

$$W(L,Q,P) = W \frac{Q}{Q_0} k_d \left(1 - e^{-L/\ell_0 \sqrt{Q/Q_0}}\right). \tag{11}$$

The length ℓ_0 is a characteristic length whose the value is computed by HeatGround. These empirical relationships are established by using the results of the simulation.

The coefficient k_d takes into account variation of the depth according to Eq. (13). For example, if we take P = 0, the recoverable energy is zero. The relationship does not depend on the type of pipe. The authors [7] experimentally show that the choice of steel or PVC does not influence the results of the extractable energy.

The new value of W_∞ for a flow rate different from Q_0 and a depth different than P_0 becomes $W_\infty(Q/Q_0)k_d$. If $\ell'_0 = \ell_0 \sqrt{Q/Q_0}$, then

$$W(L,Q,P) = W \frac{Q}{Q_0} k_d \left(1 - e^{-L/\ell'_0}\right). \tag{12}$$

By correlation with the work [4], we have shown a linear relationship between k_d, k, and P

$$k_d = \frac{1 - e^{-kP}}{1 - e^{-kP_0}}, \tag{13}$$

and by using a normalized value $\Gamma = kP$ and $\Gamma_0 = kP_0$

$$k_d = \frac{1 - e^{-}}{1 - e^{-}{}_{0}} \quad . \tag{14}$$

If $P < 3$ m, the coefficient k_d is like a depreciation factor which reduces the maximal recoverable energy.

For soil A and B, the relationship (14) for k_d is a good assumption. However, for soil C with $k = 0.89$, it is necessary to simulate the exact value of W_∞. The k_d coefficient is equal to 0 if $P = 0$, and its value is equal to 1 if $P = P_0$. It may be convenient to use a reduced-form Eq. (16) using the formulation of authors normalized function

$$f_{AM}(\Lambda) = 1 - e^{-\Lambda} \tag{15}$$

with $\Lambda = L/\ell'_0$.

This function is a normalized value energy w, where w is equal to the energy W divided by the maximal recoverable energy $W_\infty(Q/Q_0)k_d$, see Figs. 4 and 5 with x-log-scale. The energy is calculated by:

$$W(L,Q,P) = W \frac{Q}{Q_0} k_d f_{AM}(\Lambda) \,. \tag{16}$$

4.4 Influence of parameters

From analytical formulations, we have given the influence of the parameters Q, L, P , and D. We took a rest variation around the following points: City of Lille, $Q = Q_0 = 120$ m^{3}h^{-1}, $P = P_0 = 3$ m, $D = 0.15$ m, soil A. The analytic relationship has given us the total differential

$$dW = \frac{\partial W}{\partial Q} dQ + \frac{\partial W}{\partial L} dL + \frac{\partial W}{\partial P} dP + \frac{\partial W}{\partial D} dD \,. \tag{17}$$

This allowed us to obtain the relative changes of energy with the relative relationship parameters Q, L, P , and D

$$\frac{dW}{W} = \frac{\partial W}{\partial Q}\frac{dQ}{Q}\frac{Q}{W} + \frac{\partial W}{\partial L}\frac{dL}{L}\frac{L}{W} + \frac{\partial W}{\partial P}\frac{dP}{P}\frac{P}{W} + \frac{\partial W}{\partial D}\frac{dD}{D}\frac{D}{W} \,, \tag{18}$$

$$W\% = \frac{\partial W}{\partial Q} Q\% \frac{Q}{W} + \frac{\partial W}{\partial L} L\% \frac{L}{W} + \frac{\partial W}{\partial P} P\% \frac{P}{W} + \frac{\partial W}{\partial D} D\% \frac{D}{W} \,, \tag{19}$$

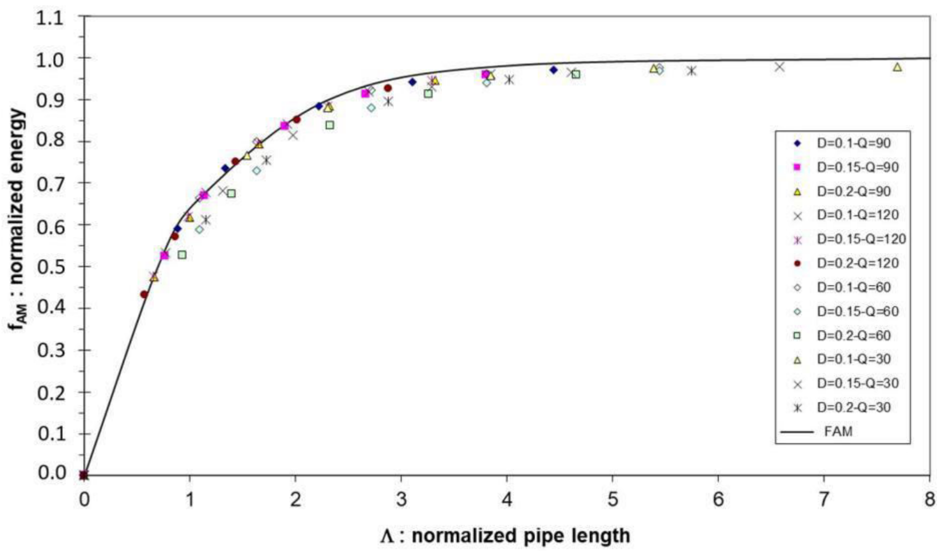

Figure 4: Normalized energy $\boldsymbol{w}$ obtained by the software HeatGround and analytical model $f_{\boldsymbol{AM}}$.

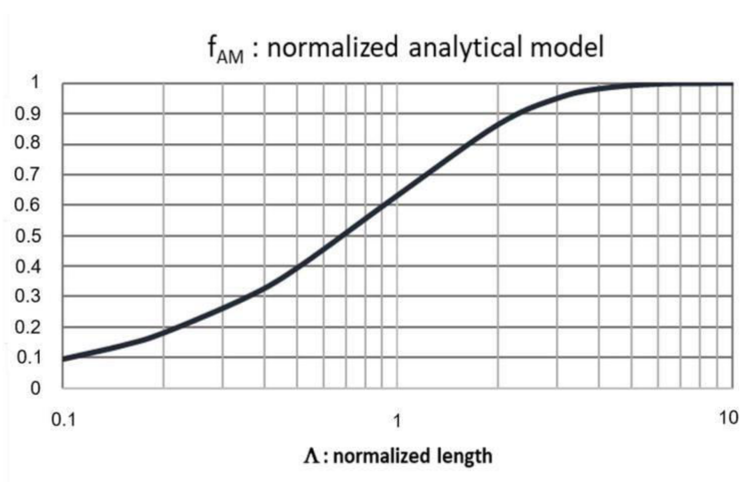

Figure 5: Function $f_{\boldsymbol{AM}}$ with x-log-scale.

$$W\,\% = W_{(\boldsymbol{Q})}\% + W_{(\boldsymbol{L})}\% + W_{(\boldsymbol{P})}\% + W_{(\boldsymbol{D})}\%\,, \tag{20}$$

where $dW/W = W\%$ and $W_{(\boldsymbol{x})}\% = x\%\, f_{\boldsymbol{x}}$,

$$W\% = Q\%\, f_{\boldsymbol{Q}} + L\%\, f_{\boldsymbol{L}} + P\%\, f_{\boldsymbol{P}} + D\%\, f_{\boldsymbol{D}} . \tag{21}$$

The influence of main parameters is given below. The relation (21) is composed of 4 terms depending on the relative variations of *Q*, *L*, *P* , and *D*. The first 2 terms are the most important parameters. The relation

$$W_{(\boldsymbol{Q})}\% = Q\% \; 1 - \frac{\Lambda}{2}\frac{e^{-\Lambda}}{1 - e^{-\Lambda}} \tag{22}$$

represents the relative changes in energy by the parameter *Q*%. The rela-tion

$$W_{(\boldsymbol{L})}\% = L\% \,\frac{\Lambda e^{-\Lambda}}{1 - e^{-\Lambda}} \tag{23}$$

represents the relative variations of energy by the parameter *L*%. For a type of soil, a depth and a diameter given, the relative influence of main parameters *L* and *Q* depends of the value of Λ. Usually the depth *P* and the diameter of the pipe are often imposed, the relations on $f_{\boldsymbol{P}}$ and $f_{\boldsymbol{D}}$ are not presented in this article.

The depth and diameter are usually fixed. The flow rate and the length of the pipe are parameters that the installer must choose in order to obtain the energy optimum. From Fig. 6, the relative influence of the pipe length and the flow rate are identical for Λ values between 0.5 and 1. The installer will have to make in situ measurements to determine the length ℓ'_0.

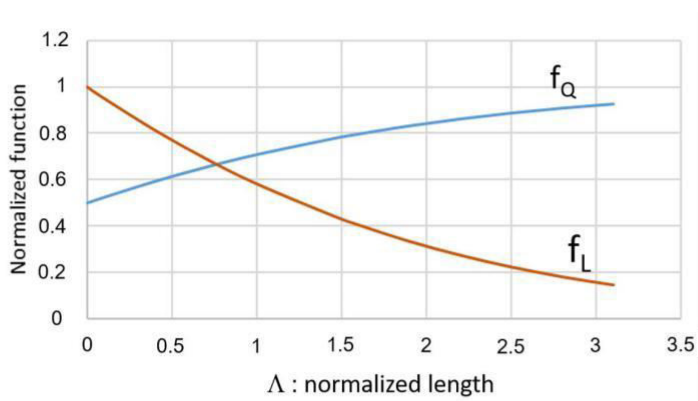

Figure 6: Shape of normalized function $f_{\boldsymbol{Q}}$ and $f_{\boldsymbol{L}}$ ***versus*** normalized length Λ.

5 Comparison

This section compares results obtained from different methods, including the use of the HeatGround software, the numerical methods of Amitrano, and the analytical method that the authors propose.

By using HeatGround, with L = 25 m, P = 2 m, D = 0.2 m, Q = 120 m^3h^{-1}, and with the characteristics of the soil ρ_S = 2000 kgm^3, λ_S = 2 $Wm^{-1}K^{-1}$, C_S = 900 $Jkg^{-1}K^{-1}$. The temperature T_{min} = −2 °C and T_{max} = 23.5 °C.

The length ℓ'_0 is obtained in [2] by using Eq. (12) and energy recovered to determine f_{AM} with a great value of Λ. We obtain ℓ'_0 = 17.2 m by using relation

$$\ell'_0 = \frac{-L}{\ln(1 - f_{AM})} . \tag{24}$$

and then Λ = 1.45.

The energy increases when Q parameters, L and P increase in the first order. But it's second order if D parameters decreases then energy in-creases. If the Q is fixed, Tab. 3 shows that the choice of the length of the pipe is important. The analytical relation gives results of the same order of magnitude. In Tab. 4, when the length is larger (L = 50 m), the effect of Q is greater.

Table 3: Results for HeatGround, Amitrano method, and analytical method.

W %	HeatGround	Amitrano	Analytical method
$W_{(Q)}$ %	**Q**% 0.836	**Q**% 0.884	**Q**% 0.777
$W_{(L)}$ %	**L**% 0.337	**L**% 0.412	**L**% 0.444
$W_{(P)}$ %	**P** % 0.656	**P** % 0.636	
$W_{(D)}$ %	**D**% -0.229	**D**% -0.274	

6 Results and discussion

Take the case of the paper [7]. The study was conducted in Western India. The authors show that for a speed of 2 m s^{-1}, the yearly energy gain is 423 kWh. With a coefficient k = 0.848 and a pipe of length L = 23.42 m,

Table 4: Results for HeatGround, relative influence for city of Lille and Soil A, $Q = Q_0$ = 120 m^3 h^{-1} , $P = P_0$ = 3 m, D = 0.15 m.

W %	***L*** = 35 m	***L*** = 50 m
$W_{(Q)}\%$	***Q***% 0.87	***Q***% 0.93
$W_{(L)}\%$	***L***% 0.25	***L***% 0.12
$W_{(P)}\%$	***P*** % 0.54	***P*** % 0.54
$W_{(k)}\%$	***k***% -0.22	***k***% -0.11
$W_{(D)}\%$	***D***% -0.11	***D***% -0.06

for a diameter of D = 0.15 m, at a depth of P_0 = 2.7 m, we found ℓ_0 = 32 m and Λ = 0.73. If we take k_d = 1, then $f_{AM} W_\infty$ = 423 kWh, f_{AM} = 0.52 and W_∞ = 813 kWh.

The authors give a speed of 5 m s^{-1}, for which energy gain is 846 kWh.

As the speed is 2.5 times greater, then the length is multiplied by $\sqrt{2.5}$, hence ℓ'_0 is 50.6 m, Λ = 0.46 and f_{AM} = 0.37. If energy is multiplied by a factor $\frac{Q}{Q_0} f_{AM}(\Lambda)$ = 0.925, there is energy gain of 752 kWh, which is less by 11% than that given by the authors. We have taken this simulation, for the climate of Jaipur, T_{min} = 15.2 °C and T_{max} = 33.2 °C.

A judicious choice of the length L is to assume a value of approximately $2\ell'_0$. For a gap of 0.4 m between each pipe and a length equal to $2\ell'_0$, it gives the surface energy of 35 kWh per square meter of the building projection area. According to [7], there is no influence between the use of PCV or steel for the tube. The author [2] presented a table with simulation data.

7 Conclusion

The authors showed that it is possible to propose a simple analytical formula to determine the recoverable energy by a ground-air heat exchanger for the heating season.

(i) A simple formula (see Eq. (16)) gives an order of magnitude of the percentage of recoverable energy in the soil.

(ii) Knowledge of the soil (see Tab. 1) is essential to exploit the approxi-mate analytical formula.

(iii) Parameters influencing the recoverable energy can be determined an-alytically by an analytic formula (see Eq. (21)).

(iv) If the length of the pipe is too long, the flow will be the most influential term (see Fig. 6).

(v) The analytical formula makes it possible to obtain the variation of the various parameters (*L, Q*) and their influence on the recoverable energy, but for that the use of HeatGround is necessary to obtain the characteristic length ℓ'_0 by Eq. (24).

Installers usually know the depth, soil type, then it is interesting to see the influence of the diameter and length to optimize the entire system. The next step in this work is to formulate a similar relationship for cooling in summer in the south of France. An economic study may be associated with this work in the case of optimization of the choice of the pipe length, for example.

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