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Thermodynamic analysis of building heating or cooling using the soil as heat reservoir

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Abstract

Soil can be used as heat reservoir for building heating or cooling purposes, as the underground temperature is different of the ambient air temperature. Ambient air is heated or cooled when flowing along a tube installed underground, and this air with changed temperature is introduced in the building. This problem can be studied in many ways, the main differences being the objectives and the considered details of the flow and temperature fields. In the present work a thermodynamic analysis is made, and important criteria are obtained in what concerns both the construction parameters (diameter and length of the tube installed underground) and the operation parameters (mass flow rate and heating or cooling effect). For such an analysis it is of crucial importance the consideration of the entropy generation minimization criterion which leads to the best thermodynamic performance of the system. Results are presented for three different specified operating conditions, which can be used for a better understanding of the heating or cooling systems using the soil as heat reservoir, as well as to give guidelines and limits when more detailed analysis are to be made.

1. Introduction

It is well known that underground temperature varies with depth, that it is not the same as the ambient air temperature, and that this difference can be used for heating or cooling purposes. In summer, underground temperature is lower than the ambient temperature, and in winter it is higher than the ambient temperature. Soil can thus be used as heat reservoir for heating (in winter) or cooling (in summer). Air taken from the ambient flows along a tube installed underground, and its temperature changes in the useful sense, both in winter and in summer. This air, with the so modified temperature, is introduced in the building, whose internal temperature is mainly conditioned by that of the entering air and by the heat exchanged with the exterior ambient surrounding it, through the roof and through the walls. This can be used to reach better comfort conditions in small rooms, small greenhouses, office buildings and residential buildings. Depending mainly on the ambient air temperature, soil could be the unique heat source or sink needed for heating or cooling purposes, respectively, during considerable periods of time along a year. This is the situation considered in the present work. If some more heat needs to be transferred to or from the building, in order to reach the desired comfort conditions, additional heating or cooling systems need to be considered, a situation that is not treated in the present work.

There is a strong interest in using alternative ways for building heating or cooling. One possible way is to use the soil as heat reservoir. Going in depth, it is possible to obtain very interesting underground temperatures for heating or cooling purposes, which change also from one place to other. Previous work in the field considers the underground tube and the surrounding soil, and an unsteady numerical study is conducted considering the temperature of the air in the tube, the heat and mass transfer in the soil, and the soil's natural thermal stratification [1]. Another numerical study of this type was conducted by Kumar et al. [2]. An analytical model for the same system, but

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Nomenclature

A	area
c_P	constant pressure specific heat
C_1, C_2	constants
D	tube diameter
f	friction factor
F, G	coefficients
h	convection heat transfer coefficient
k	thermal conductivity
L	length
m, n	exponents (heat transfer correlation)
$\dot{m}$	mass flow rate
M	exponent (friction factor correlation)
p	pressure
P	inner wetted perimeter
Pr	Prandtl number
R	length to diameter ratio, $R = L/D$
Re	Reynolds number
$\dot{S}$	entropy generation rate
T	temperature
x	longitudinal coordinate, along the tube

Greek symbols

Δ	difference value
θ	dimensionless temperature
ρ	density
τ	temperature ratio

Subscripts

a	air
c	interior compartment of the building
D	based on the tube diameter
gen	generation
i	intermediate point, before the building
ref	reference value
s	soil
1	referring the underground tube
2, 3	referring the building
*	dimensionless

without considering the mass transfer in the soil, is presented in Ref. [3]. In this study it is assumed that the system reaches a periodic quasi-steady-state behavior after some days of operation. Analysis of a system including the earth-tube system and the building has also been made by Sawhney et al. [4] and by Bojic et al. [5]. Other uses of the soil as heat reservoir can consider underground storage tanks [6–8], or the use of the soil or underground aquifers associated to the evaporator in heat pump based systems [9–11]. Aquifers can also be used for thermal energy storage as pointed in [12].

The pressure goes to increasingly low energy demands [13], or even to energy independent systems like the energy independent residential house (HARBEMAN house: HARmony BEtween Man And Nature) [14,15]. Natural ventilation systems are, as pointed by Fordham [16], another way towards less energy dependent systems for heating or cooling purposes. If a detailed analysis is conducted, conclusions can be obtained about how the soil temperature is affected by underground heat release [17], as well as how heat and mass transfer take place in the underground tube neighboring [18].

In the previously referred studies emphasis goes mainly to the thermal performance of the systems, and not to obtain design and/or operation criteria for such systems. In this work, considering a simplified lumped steady-state analysis, important guidelines and criteria are obtained, both in what concerns the construction parameters (diameter and length of the tube) and the operation parameters (mass flow rate and heating or cooling effects). The so obtained results are very useful for a better understanding of such systems, and also to give guidelines and construction and/or operation limits when more detailed analyses are to be conducted. These can include detailed local flow and temperature fields, as well as other relevant issues of the heating or cooling systems and processes.

2. Modeling

The system under analysis is presented in Fig. 1. A stream of ambient air enters a round tube, which is placed mainly underground. The underground temperature varies with depth, measured away from the earth surface, but it is taken as a constant in this work. As a temperature difference exists between the ambient air and the soil, the air stream is heated or cooled by the soil, and its temperature is T_i when entering the building. It is assumed that the temperature differences experienced by the air stream are small enough in order to take its physical properties as constant.

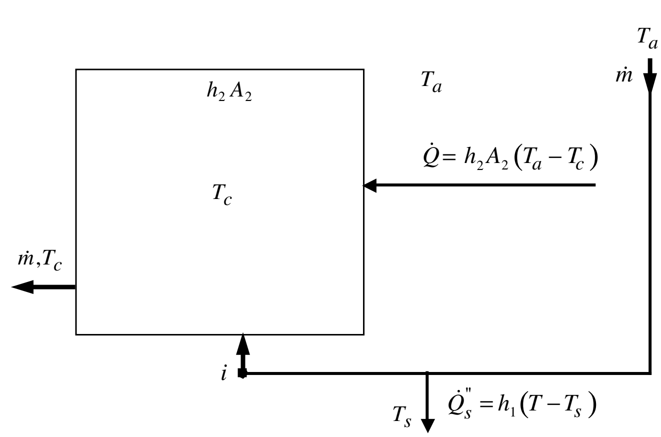

Fig. 1. Physical model.

2.1. Energy conservation analysis

Energy conservation equation applied to the air stream flowing inside the tube gives

$$T_{\mathrm{i}} = T_{\mathrm{s}} + (T_{\mathrm{a}} - T_{\mathrm{s}})\exp\left(-\frac{h_1 P_1 L}{\dot{m}c_P}\right) \tag{1}$$

where h_1 is the convection heat transfer coefficient between the air stream and the inner tube wall, P_1 is the inner wetted perimeter of the tube and L is its total length underground. It is assumed that the inner wall tube temperature is very close to the soil temperature in order to have a manageable model when analyzing the entropy generation associated to this heat transfer process [19,20]. Conduction heat transfer through the tube wall is thus not taken into account, the validity of this assumption being mainly related with the thermal conductivity and wall thickness of the tube. It is to be retained, however, that the main scope of the present work concerns the thermodynamic analysis of the overall system, and that the main interesting conclusions can be obtained from the simplified physical model adopted. Ambient air is considered to be dry air, only forced convection heat transfer exists between the air stream and the inner wall of the tube, and no eventual moisture phase changes (evaporation/condensation) inside the tube are taken into account.

Building receives the air stream at temperature T_{i}, which leaves it at its inner temperature, T_{c}. Through its surface, of area A_2, the building exchanges heat by convection with the environment at temperature T_{a}, with an averaged convection heat transfer coefficient h_2. It is assumed that the floor of the building is perfectly insulated, and thus that there is no direct heat exchange between the building and the soil. The radiation heat transfer is negligible or treated in a combined way with convection, h_2 being a combined convection–radiation coefficient in that case [21]. Energy conservation equation applied to the building leads to

$$T_{\mathrm{c}} = T_{\mathrm{a}} - \frac{\dot{m}c_P}{h_2 A_2 + \dot{m}c_P}(T_{\mathrm{a}} - T_{\mathrm{s}})\left[1 - \exp\left(-\frac{h_1 P_1 L}{\dot{m}c_P}\right)\right] \tag{2}$$

A real situation is unsteady in nature, with changes on the ambient air temperature along a day. Only minor changes occur in the soil temperature along a day, and the temperature variation of the ambient air and of the soil along a year are not relevant for the present purposes. Evaluation of the unsteady behavior of the system needs to take into account additional information for each individual component, and the so obtained results and conclusions depend on the particular situation considered. The main conclusions can be obtained considering the simplest steady-state situation, which must be taken into account when more elaborate and refined analysis, including unsteady effects, are to be conducted.

Variables can be made dimensionless taking the following reference values for temperature, length and mass flow rate

$$\Delta T_{\mathrm{ref}} = T_{\mathrm{s}} - T_{\mathrm{a}}, \quad L_{\mathrm{ref}} = \frac{h_2 A_2}{k}, \quad \dot{m}_{\mathrm{ref}} = \frac{h_2 A_2}{c_P} \tag{3}$$

It is thus assumed that the surface area of the building is known, A_2, as well as its corresponding averaged convection heat transfer coefficient, h_2, product h_2A_2 being a measure of the building heat transfer conductance [19,20]. Another dimensionless parameter of interest is the ratio between the tube length and its diameter

$$R = \frac{L}{D} \tag{4}$$

When the flow inside the tube (of smooth inner walls at constant temperature T_{s}) takes place in turbulent regime, and it is hydrodynamically and thermally developed, the convection heat transfer coefficient h_1 can be evaluated using the Dittus–Boelter correlation as [21]

$$h_1 = 0.023\frac{k}{D}Re_D^m Pr^n \tag{5}$$

with $m = 0.8$. In what concerns exponent n, it must be $n = 0.4$ for stream heating and $n = 0.3$ for stream cooling [21].

The dimensionless temperature of the building, Eq. (2), can be obtained as

$$\theta_{\mathrm{c}} = \frac{\dot{m}_*}{1+\dot{m}_*}\left[1 - \exp\left(-FRD_*^{(1-m)}\dot{m}_*^{(m-1)}\right)\right] \tag{6}$$

where F is a constant dimensionless parameter given by

$$F = 0.023\pi(4/\pi)^m Pr^{(n-m)} \tag{7}$$

Noting the way as temperature is made dimensionless, θ_{c} is positive in both cases of heating or cooling, that is, in the case of $\theta_{\mathrm{c}} = (T_{\mathrm{c}} - T_{\mathrm{a}})/(T_{\mathrm{s}} - T_{\mathrm{a}}) = (>0)/(>0) > 0$ or $\theta_{\mathrm{c}} = (T_{\mathrm{c}} - T_{\mathrm{a}})/(T_{\mathrm{s}} - T_{\mathrm{a}}) = (<0)/(<0) > 0$, respectively. It is also to be noted that the influence of exponent n is contained in coefficient F, as given by Eq. (7).

If, instead, the fluid flows inside the duct in the laminar regime, a similar treatment can be made, and the relevant changes in the foregoing expressions are that $m = 0$, $n = 0$, and the coefficient 0.023 present in Eqs. (5) and (7) must be replaced by 3.66 [22]. The evaluation of the flow regime is made comparing the value of the Reynolds number with 2300, the Reynolds number in the present context being obtained as $Re_D = 4\dot{m}/(\pi D\mu)$, or

$$Re_D = \frac{4}{\pi}Pr^{-1}\dot{m}_* D_*^{-1} \tag{8}$$

2.2. Entropy generation analysis

The entropy generation minimization is an important criterion to find the best thermodynamic operating conditions of fluid and thermal systems [19,20], and it is also crucial in the problem under analysis to obtain well defined design and operation criteria.

In what concerns the heat transfer process taking place in the tube, a local entropy balance leads to

$$\frac{\mathrm{d}\dot{S}_{\mathrm{gen},1}}{\mathrm{d}x} = \frac{h_1 P_1 (T_\mathrm{s} - T)^2}{T_\mathrm{s} T} \tag{9}$$

This expression must be integrated along the total length of the tube underground, and the obtained result can be made dimensionless to give

$$\frac{\dot{S}_{\mathrm{gen},1}}{h_2 A_2} = \dot{m}_* \left\{ \tau[1 - \exp(-FRD_*^{(1-m)} \dot{m}_*^{(m-1)})] + \ln\left[\frac{1 + \tau \exp(-FRD_*^{(1-m)} \dot{m}_*^{(m-1)})}{1+\tau}\right] \right\} \tag{10}$$

The building heat transfer conductance, given by product h_2A_2, has been used to made the entropy generation rate dimensionless, and it has been introduced the dimensionless temperature ratio

$$\tau = \frac{T_\mathrm{a} - T_\mathrm{s}}{T_\mathrm{s}} = -\frac{\Delta T_{\mathrm{ref}}}{T_\mathrm{s}} \tag{11}$$

It should be noted that for the heating operation it is $T_\mathrm{s} - T_\mathrm{a} > 0$, $\Delta T_{\mathrm{ref}} > 0$ and $\tau < 0$, and that for the cooling operation it is $T_\mathrm{s} - T_\mathrm{a} < 0$, $\Delta T_{\mathrm{ref}} < 0$ and $\tau > 0$. It is also to be noted that Eq. (10) makes sense only for $\tau > -1$, a condition that is always satisfied.

The fluid flowing through the duct is viscous, and its pressure decreases as it flows along the duct. A local entropy balance for this process gives

$$\frac{\mathrm{d}\dot{S}_{\mathrm{gen},2}}{\mathrm{d}x} = \frac{\dot{m}}{\rho T}\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right) \tag{12}$$

In this case, an expression is needed to obtain $(-\mathrm{d}p/\mathrm{d}x)$ as function of the involved variables and parameters. The answer for this question starts noting that

$$\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right) = 2f\frac{(\dot{m}'')^2}{\rho D} \tag{13}$$

where $\dot{m}''$ is the (constant) mass flux flowing along the tube, and f is the friction factor [20]. In the present notation, it can be obtained that

$$\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right) = \frac{32}{\pi^2}(h_2A_2)^{-3}\frac{k^5}{\rho c_P^2}\dot{m}_*^2 D_*^{-5} f \tag{14}$$

When the fluid flows in the turbulent regime in a tube of smooth inner walls, in hydrodynamically developed conditions, the friction factor can be obtained as

$$f = 0.046 Re_D^M \tag{15}$$

with $M = -0.2$ [20,22]. It is thus obtained that

$$\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right) = 0.046\frac{32}{\pi^2}\left(\frac{\pi}{4}\right)^{-M}(h_2A_2)^{-3}\frac{k^{(5+M)}\mu^{-M}}{\rho c_P^{(2+M)}}\dot{m}_*^{(M+2)} D_*^{-(M+5)} \tag{16}$$

Eq. (12) is integrated along the tube length L, and the obtained result can be made dimensionless as

$$\frac{\dot{S}_{\mathrm{gen},2}}{h_2A_2} = \left[\frac{G}{F}\frac{(h_2A_2)^{-2}}{T_\mathrm{s}}\right]\dot{m}_*^{(M-m+4)} D_*^{-(M+5)+m}\left\{FRD_*^{(1-m)}\dot{m}_*^{(m-1)} + \ln\left[\frac{1+\tau\exp(-FRD_*^{(1-m)}\dot{m}_*^{(m-1)})}{1+\tau}\right]\right\} \tag{17}$$

where the dimensional factor G, of units $\mathrm{W}^2\,\mathrm{K}^{-1}$, is obtained as

$$G = 0.046\frac{32}{\pi^2}\left(\frac{\pi}{4}\right)^{-M}\frac{k^{(4+M)}\mu^{-M}}{\rho^2 c_P^{(3+M)}} \tag{18}$$

It should be noted that factor $(G/F)[(h_2A_2)^{-2}/T_\mathrm{s}]$ in Eq. (17) is dimensionless, and that also Eq. (17) makes sense only for $\tau > -1$.

If, instead, the flow is laminar, similar expressions apply but it is $M = -1$ and the 0.046 coefficient in Eqs. (15), (16) and (18) must be replaced by 16 [20,22].

The entropy balance for the building gives

$$\dot{S}_{\mathrm{gen},3} = h_2A_2\frac{(T_\mathrm{a} - T_\mathrm{c})^2}{T_\mathrm{a}T_\mathrm{c}} \tag{19}$$

This equation can be worked in order to include the variables and parameters relevant for the present analysis, and its dimensionless version becomes

$$\frac{\dot{S}_{\mathrm{gen},3}}{h_2A_2} = \frac{\left\{\tau\frac{\dot{m}_*}{1+\dot{m}_*}[1-\exp(-FRD_*^{(1-m)}\dot{m}_*^{(m-1)})]\right\}^2}{(1+\tau)\left\{(1+\tau) - \tau\frac{\dot{m}_*}{1+\dot{m}_*}[1-\exp(-FRD_*^{(1-m)}\dot{m}_*^{(m-1)})]\right\}} \tag{20}$$

The dimensionless global entropy generation rate in the overall process is

$$\frac{\dot{S}_{\mathrm{gen}}}{h_2A_2} = \frac{\dot{S}_{\mathrm{gen},1}}{h_2A_2} + \frac{\dot{S}_{\mathrm{gen},2}}{h_2A_2} + \frac{\dot{S}_{\mathrm{gen},3}}{h_2A_2} \tag{21}$$

The foregoing equations can be solved for some relevant cases, in order to obtain the most relevant information about the operating and construction conditions and criteria for the heating or cooling processes. Three different cases are considered, namely the operation at the maximum cooling or heating effect, the operation at a specified cooling or heating effect other than the maximum, and the operation at a specified mass flow rate.

3. Operation at the maximum cooling or heating effect

Analysis of the problem and of Eq. (6) indicates that a given mass flow rate exists leading to a maximum value of θ_c. In fact, a small value of $\dot{m}_*$ leads to a situation corresponding to a nearly null effect of the soil temperature over the compartment temperature, which tends to be equal to the ambient temperature, T_a. If, instead, the mass flow rate is high, the temperature of the air entering the compartment is very close to the ambient temperature, as its value is only slightly affected by the underground temperature. In both cases, $\theta_\mathrm{c} \approx 0$. The value of $\dot{m}_*$ leading to $\theta_\mathrm{c} = \theta_{\mathrm{c,max}}$ is obtained imposing the condition

$$\frac{\partial \theta_c}{\partial \dot{m}_*} = 0 \tag{22}$$

The obtained condition for such maximum is

$$\exp(-FRD_*^{(1-m)}\dot{m}_*^{(m-1)})[1-(m-1)FRD_*^{(1-m)}\dot{m}_*^{(m-1)}(1+\dot{m}_*)]-1=0 \tag{23}$$

Assuming that the value of $\theta_c = \theta_{c,max}$ is specified, from Eq. (6) it is obtained that

$$\exp[-FRD_*^{(1-m)}\dot{m}_*^{(m-1)}] = 1-\theta_c\frac{1+\dot{m}_*}{\dot{m}_*} \tag{24a}$$

$$-FRD_*^{(1-m)}\dot{m}_*^{(m-1)} = \ln\left(1-\theta_c\frac{1+\dot{m}_*}{\dot{m}_*}\right) \tag{24b}$$

where it is noted that it must be $1-\theta_c[(1+\dot{m}_*)/\dot{m}_*] > 0$, that is, it must be $\dot{m}_* > \theta_c/(1-\theta_c)$. Introduction of the results of Eqs. (24a) and (24b) into Eq. (23) leads to

$$\left(1-\theta_c\frac{1+\dot{m}_*}{\dot{m}_*}\right)\left[1+(m-1)(1+\dot{m}_*)\ln\left(1-\theta_c\frac{1+\dot{m}_*}{\dot{m}_*}\right)\right]-1=0 \tag{25}$$

which is the equation to obtain the value of $\dot{m}_*$ once specified the value of $\theta_c = \theta_{c,max}$.

Once obtained the value of $\dot{m}_*$ from Eq. (25), for any value of D_* the value of R can be evaluated from Eq. (24b) as

$$R = -\frac{1}{FD_*^{(1-m)}\dot{m}_*^{(m-1)}}\ln\left(1-\theta_c\frac{1+\dot{m}_*}{\dot{m}_*}\right) \tag{26}$$

From Eq. (25), as for $\theta_c = \theta_{c,max}$ $\dot{m}_*$ is a function of θ_c only, from Eq. (26) it must be

$$RD_*^{(1-m)} = -\frac{1}{F\dot{m}_*^{(m-1)}}\ln\left(1-\theta_c\frac{1+\dot{m}_*}{\dot{m}_*}\right) = C_1 \tag{27}$$

Taking present the equation defining R, Eq. (4), it can be concluded that, in this case,

$$L = C_1[k/(h_2A_2)]^{(m-1)}D^m = C_2D^m \tag{28}$$

where $C_2 = C_1[k/(h_2A_2)]^{(m-1)}$ is a dimensional constant of units $m^{(1-m)}$. When the flow takes place in turbulent regime, it is thus concluded that the construction parameters L and D must be related as $L = C_2D^{0.8}$ in order to operate at $\theta_c = \theta_{c,max}$.

In what concerns the entropy generation, once specified $\theta_c = \theta_{c,max}$ (and thus $\dot{m}_*$), T_s, $(G/F)(h_2A_2)^{-2}/T_s$ and τ, it can be concluded that

$$\frac{\dot{S}_{gen,1}}{h_2A_2} = \text{constant}, \quad \frac{\dot{S}_{gen,2}}{h_2A_2} \propto D_*^{-(M+5)+m},$$
$$\frac{\dot{S}_{gen,3}}{h_2A_2} = \text{constant} \tag{29}$$

and the overall entropy generation is

$$\frac{\dot{S}_{gen}}{h_2A_2} \propto D_*^{-(M+5)+m} \tag{30}$$

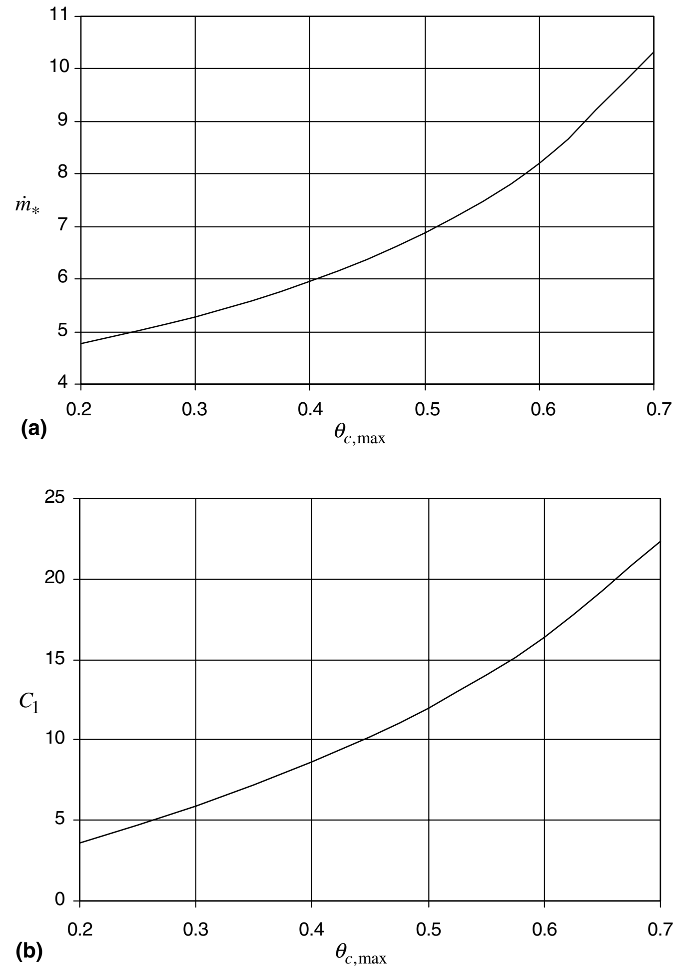

Fig. 2. Dependence of the results for the maximum cooling or heating effects on the dimensionless temperature: (a) mass flow rate and (b) constant C_1 as given by Eq. (27).

that is, the entropy generation monotonically decreases as the tube diameter increases, with $-(M+5)+m = -4$ when the flow takes place in the turbulent regime. In this case, the entropy generation analysis says us that a higher value of the tube diameter should be used in order to have a lower entropy generation, but it is not obtained a criterion from it, in the form of an equation or a well defined condition.

Some results are presented in Fig. 2a and b, closely the same for both cases of heating or cooling operations. The only difference is in the value of exponent n, included in the F coefficient, which is $n = 0.4$ for heating operation and $n = 0.3$ for the cooling operation. It can be seen in Fig. 2a that the required mass flow rate increases as increases the heating or cooling effect, given by the dimensionless compartment temperature, θ_c, and that higher maximum heating or cooling effects require higher mass flow rates. It is seen from Fig. 2b that the numerical value of constant C_1 increases as increases the dimensionless compartment temperature θ_c, and that its dependence on θ_c is similar to that of $\dot{m}_*$ on θ_c. For example, for $\theta_c = 0.5$ and $h_2A_2 = 1000$ W K^{-1}, from Eq. (28) it can be obtained that $L \approx 100D^{0.8}$. It can be seen that, in this case, the constructive solution for the operation at the maximum heating or cooling effect leads to a tube with a length/diameter ratio $L/D \approx 100D^{-0.2}$, noting that constant 100 has units of $m^{0.2}$. In what concerns the required mass flow rate, once again for the situation for which $\theta_c = 0.5$ and $h_2A_2 = 1000\ \mathrm{W\ K^{-1}}$, it is $\dot{m} \approx 6.9\ \mathrm{kg\ s^{-1}}$, a considerably high value for this parameter.

4. Operation at a specified cooling or heating effect

In this case, a value of the compartment temperature is specified, but not the condition of $\theta_c = \theta_{c,\max}$. Thus, starting from

$$\theta_c = \theta_{c,\text{specified}} \tag{31}$$

it is to be noted that Eqs. (24a), (24b) and (26) hold also in this case.

Inspecting on equations giving the entropy generation terms, Eqs. (10), (17) and (20), it is concluded that

$$\frac{\dot{S}_{gen,1}}{h_2A_2} = f_1(\dot{m}_*), \quad \frac{\dot{S}_{gen,2}}{h_2A_2} = D_*^{-(M+5)+m} f_2(\dot{m}_*),$$
$$\frac{\dot{S}_{gen,3}}{h_2A_2} = \text{constant} \tag{32}$$

where functions f_1 and f_2 depend only of $\dot{m}_*$.

The question now is to investigate if a value of $\dot{m}_*$ exists that minimizes the entropy generation, once specified the values of θ_c, $(G/F)(h_2A_2)^{-2}/T_s$, τ, and D_*. Such a value of $\dot{m}_*$ exists, and once it has been evaluated the value of R can be evaluated using Eq. (26). In a graphical form, the dependence of $\dot{S}_{gen}/(h_2A_2)$ on D_*, and the existence of such a minimum with respect to $\dot{m}_*$ is sketched in Fig. 3. In this case, once specified the value of θ_c, the minimization of entropy generation gives a well defined criterion, from which it is possible to specify the operation parameter $\dot{m}_*$, as well as the ratio between the diameter and length of the tube (the construction parameters).

Some results are presented in Fig. 4a and b, for $h_2A_2 = 1000\ \mathrm{W\ K^{-1}}$, $T_s = 290\ \mathrm{K}$ and $|\tau| = 0.05$. The obtained results for the cooling and for the heating operations exhibit only slight differences, and a detailed analysis is conducted for the cooling operation results only. This is a common feature and procedure followed in this work for the remaining results' analysis. It is to retain that the heating or cooling situations differ only through exponent n in Eq. (5) and through the value of τ, which is positive for the cooling operation and negative for the heating operation.

It is seen from Fig. 4a that the mass flow rate imposed by a specified compartment temperature is nearly constant for a small the tube diameter. For intermediate values of D_* it is observed a decrease of $\dot{m}_*$ with D_*, for the same value of θ_c. For high values of D_*, $\dot{m}_*$ reaches a new and lower constant value for each specified value of θ_c. Globally, it is observed that the mass flow rate decreases as decreases the specified value of θ_c. For example, for $\theta_c = 0.5$ and for small values of D_* the mass flow rate is $\dot{m} \approx 1.1\ \mathrm{kg\ s^{-1}}$. In what concerns the variation of parameter R with the tube diameter, it can be observed in Fig. 4b. For example, for $\theta_c = 0.5$ and $D_* \times 10^6 \approx 7$ ($D \approx 0.27$ m) it is $R \approx 335$, that is, a tube with a ratio $L/D \approx 335$. Surprisingly, R does not vary monotonically with D_*. For each value of θ_c it exists a given value of D_* that minimizes the value of R. Higher or lower values of D_* lead to higher values of parameter R. Once specified the heating or cooling effect, the system must be designed with the minimum L/D ratio, as presented in Fig. 4b for the specified parameters.

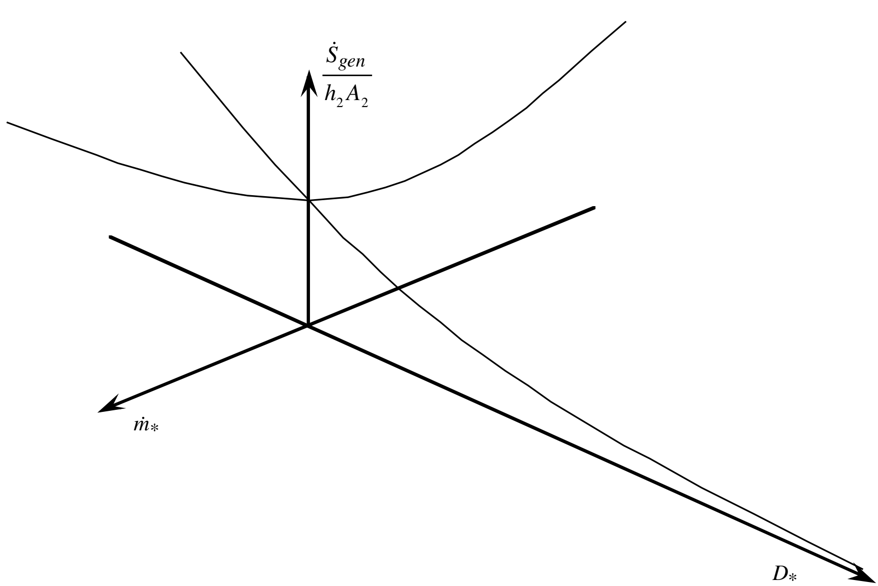

Fig. 3. Dependence of the entropy generation on the mass flow rate and on the tube diameter when operating under a specified heating or cooling effect, and the existence of a minimum with respect to $\dot{m}_*$.

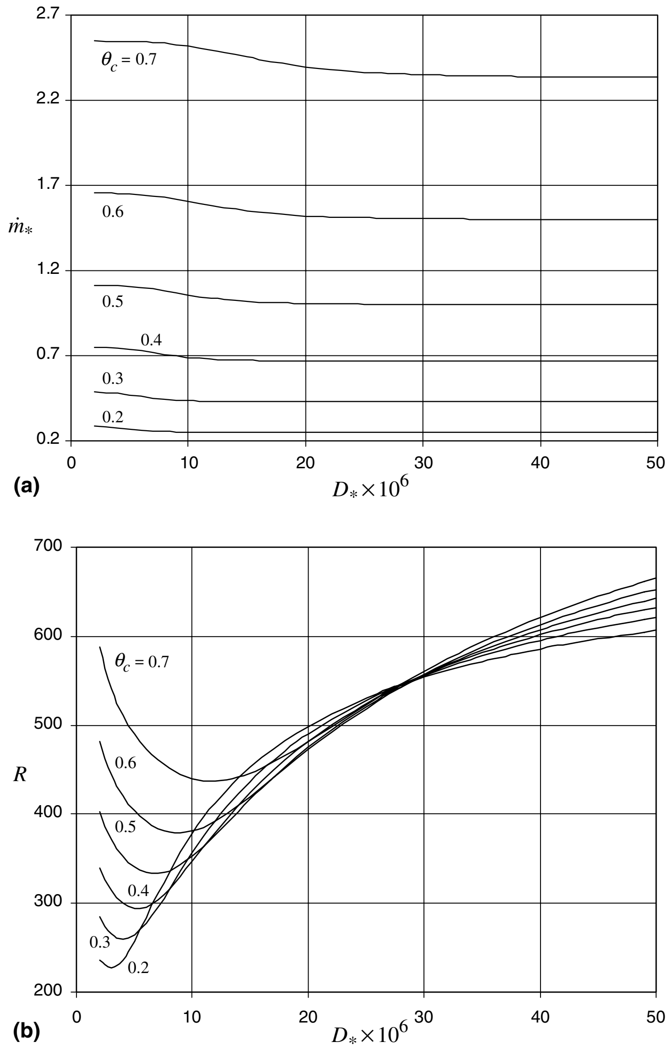

Fig. 4. Dependence of the results for the cooling operation under a specified cooling effect: (a) dimensionless mass flow rate and (b) length to diameter ratio.

5. Operation at a specified mass flow rate

In this case, it is the operation parameter $\dot{m}_*$ that is specified. Starting from

$$\dot{m}_* = \dot{m}_{*,\text{specified}} \tag{33}$$

it is to be investigated if a value of D_* exists that minimizes the entropy generation, for specified values of $\dot{m}_*$, T_s, $(G/F)(h_2A_2)^{-2}/T_s$, τ, and R. This value exists, and once it has been obtained the corresponding value of θ_c is obtained using once again Eq. (6). In a graphical form, the dependence of $\dot{S}_{gen}/(h_2A_2)$ on R, and the existence of such a minimum with respect to D_* is sketched in Fig. 5.

Results for this situation, corresponding to the cooling operation, are presented in Fig. 6a and b for $h_2A_2 = 1000\ \text{W K}^{-1}$, $T_s = 290$ K, and $|\tau| = 0.05$. Only the obtained results for the cooling operation are presented, as those for the heating operation exhibit only slight differences when compared with that corresponding to the cooling operation. From Fig. 6a it is observed that, for a specified mass flow rate, the length of the tube monotonically increases as increases the diameter of the tube. Higher mass flow rates lead to higher tube diameters. For example, for $\dot{m}_* = 1$ ($\dot{m} \approx 1\ \text{kg s}^{-1}$) and $R = 200$ it is $D_* \approx 22.5$, that is, $D \approx 0.86$ m and $L \approx 171$ m. In what concerns the dependence of he compartment temperature on the involved parameters, it is observed in Fig. 6b that it increases considerably for small values of R, and that it tends to a constant value as R increases. Higher mass flow rates lead to higher compartment temperatures. For example, once again for $\dot{m}_* = 1$ and $R = 200$, it is $\theta_c \approx 0.46$.

6. Conclusions

Soil can effectively be used as a heat reservoir for building heating or cooling purposes. Using a simplified steady

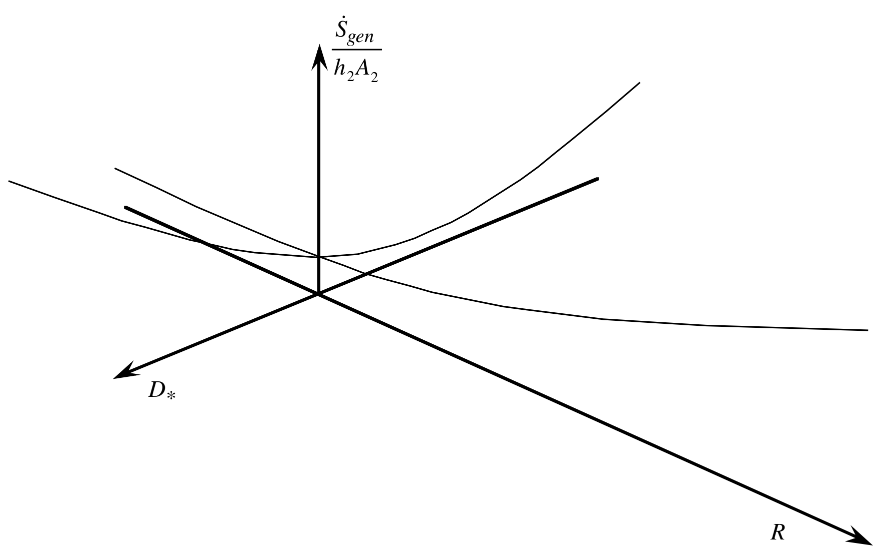

Fig. 5. Dependence of the entropy generation on the tube diameter and on the length to diameter ratio when operating under a specified mass flow rate, and the existence of a minimum with respect to D_*.

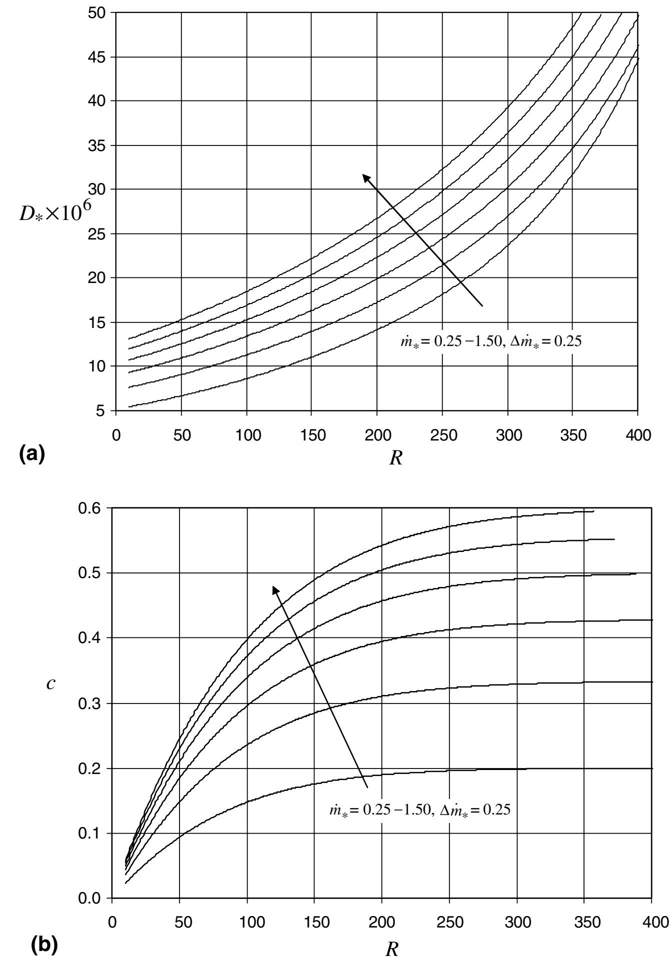

Fig. 6. Dependence of the results for the cooling operation under a specified mass flow rate: (a) dimensionless tube diameter and (b) dimensionless compartment temperature.

thermodynamic analysis, a better insight related to these systems is obtained, and important criteria can be obtained in what concerns their constructing and operating parameters. For that, it is of crucial importance the consideration of the entropy generation minimization criterion.

Previous works on similar systems concern mainly on the thermal performance of the systems, and not on design and operation criteria for such systems. Situations exist for which the entropy generation minimization criterion clearly leads to design and/or operation criteria. This is the way followed in this work both for the heating or cooling operations under specified heating or cooling effects, or under specified mass flow rate. When operating at the maximum heating or cooling effect, the entropy generation monotonically decreases as increases the tube diameter, and a design or operating criterion of the same type cannot be obtained in this case. However, a design criterion is obtained in this case, in the form of an equation relating the tube diameter and the tube length. When operating at a specified heating or cooling effect, an optimal (minimum) ratio exists between the tube length and the tube diameter, a result that only the entropy generation minimization can give, and that is unknown if only the energy analysis is conducted. Another relevant conclusion is that the heating and cooling situations exhibit very similar results, with slight differences only, and that the results for one situation can be used for both the situations.

With this study, a better understanding of the heating and cooling systems based on the underground soil temperature is given, and clear and useful criteria are obtained both for the construction and operation parameters. Such criteria can be useful by themselves, or they can give very useful limits and guidelines when more elaborate and refined analysis are to be conducted.

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