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ON THE DESIGN OF EARTH-WATER HEAT EXCHANGERS FOR VENTILATION SYSTEMS IN BUILDINGS

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ABSTRACT

In this paper a design methodology is proposed for earth-water heat exchangers. These systems are emerging as an alternative to the well known earth-air heat exchangers for passive houses. Earth-air heat exchangers are often used for passive cooling means of ventilation air. As an alternative earth-water systems are now starting to get used, as they offer a lot of advantages. Up till now no clear design methodology has been proposed. In this paper a methodology is developed based on optimizing thermal performance in relation to pressure drop.

INTRODUCTION

Energy use reduction in buildings is a target set by a lot of governments around the world. As on average 40% of energy use in developed countries is dedicated to creating comfort in buildings [1], new technological developments are stimulated to emerge on the marked.

Passive houses and net zero energy buildings are coming into scope all around the globe as the standard for the future building stock [2].

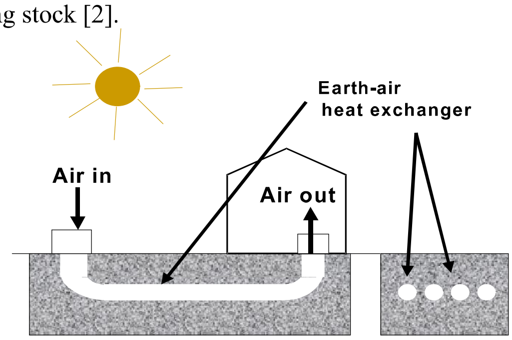

Figure 1 : Earth-air heat exchangers coupled to a building

In order to reduce cooling and heating needs and avoid overheating of these highly insulated buildings, more attention is paid to using passive means. A well known concept is the use of earth-air heat exchangers to pre-cool or pre-heat building ventilation air (Figure 1). Tubes (diameter 0.2 tot 1 m) are put into the ground, through which ventilation air is drawn. Because of the high thermal inertia of the soil, the temperature fluctuations at the ground surface exposed to the exterior climate, are damped deeper in the ground. Furthermore a time lag occurs between the temperature fluctuations in the ground and at the surface. Therefore at a sufficient depth the ground temperature is lower than the outside air temperature in summer and higher in winter. When fresh ventilation air is drawn through the earth-air heat exchangers the air is thus cooled in summer and heated in winter.

Several studies have been published in the passed about the performance of these earth-air heat exchangers [3-8]. Often this is done in relation to the building energy use. Several software codes are available with which the behaviour of the earth-air heat exchanger can be simulated. De Paepe and Janssens published a simplified design methodology for earth-air heat exchangers, based on thermal to hydraulic performance optimisation [5]. Through dynamic simulations and measurements it was shown that the methodology is quite conservative [7-8].

Earth-air heat exchangers represent a relatively high investment cost for the installation (ground works) and the surroundings of the building have to allow for the laying of the tubes. During construction great care has to be taken. Firstly, it is not always easy to dig deeply and collapsing of the pit walls has to be avoided. Secondly, during summer operation condensation inside the tubes will occur. Tubes thus have to be tilted to evacuate the water (which with long and bent tubes is not an easy task), in order to avoid mould growth inside the tubes.

As an alternative, earth-water heat exchangers are being considered. In these systems water is circulated to a matrix of small diameter tubes (diameter 2 tot 5 cm) which are put into the ground. These tubes are coupled to a water-air battery placed in the ventilation inlet, thus obtaining the same effect as earth-air heat exchanger. Little or no information is available on the performance of these systems and no design method has been suggested.

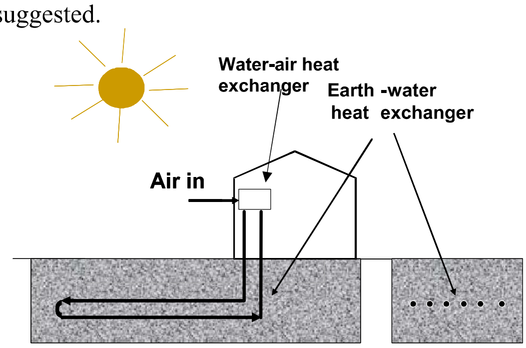

Figure 2 : Earth-water heat exchangers coupled to a building

In this paper the thermo-hydraulic performance characteristics of these earth-water heat exchangers are described and analyzed. Based on these results a design methodology is proposed.

NOMENCLATURE

c_p	[J/kgK]	Thermal capacity
D	[m]	Tube diameter
f	[-]	Friction coefficient
h	[W/m²K]	Convective heat transfer coefficient
k	[W/m²K]	Overall heat transfer coefficient
L	[m]	Tube Length
$\dot{m}$	[kg/s]	Mass flow rate
n	[-]	Number of tubes in parallel
Δp	[Pa]	Pressure drop
$\dot{Q}$	[W]	Thermal power
T	[K]	Temperature
V	[l/min]	Volume flow rate
v	[m/s]	Velocity

Special characters

ε	[-]	Heat exchanger effectiveness
λ	[W/mK]	Thermal conductivity
ρ	[kg/m³]	Density

Subscripts

air	Air
aw	Air to water heat transfer
In	Inlet of the tube
out	Outlet of the tube
s	Soil influence area
soil	Of the soil/ground
t	Tube wall
water	Water
ws	Water to soil

DESIGN METHODOLOGY FOR EARTH-WATER HEAT EXCHANGERS LINKED TO A VENTILATION SYSTEM

Dimensions of the heat exchanger

The earth-water heat exchanger should be sized in order to meet certain design requirements. For instance, during cold weather the ventilation air should be heated above the freezing point to prevent ice formation on other heat recovery components in the ventilation system. The ventilation air should also cover the entire building cooling load during a design summer day or at least a part of it. These design requirements are achieved by heating or cooling the ventilation air in the air-water heat exchanger. This is a fin-and-tube type heat exchanger with a fixed effectiveness (ε_{aw}).

For the ventilation air the following parameters are specified:

$\dot{m}_{air}$: the air mass flow rate

$T_{air,in}$: the inlet air temperature

$T_{air,out}$: the desired outlet air temperature after the heat exchanger, thus setting the heating/cooling load

For the design of the water tubes the mass flow rate and temperature change over the water-air unit have to be selected in the design problem. The only parameter given by the boundary conditions is the soil temperature. The soil temperature is defined by the external climate and by the soil composition, its thermal properties and water content. The soil temperature fluctuates in time, but the amplitude of the fluctuation diminishes with increasing depth, converging to a practically constant value throughout the year at a given depth. Optimal depths are in the range of two to four meter (IEA Annex 28 1999 [9]). Thus the parameters of the problem are :

$\dot{m}_{water}$: the water mass flow rate

$T_{water,in}$: the inlet water temperature in the tubes

$T_{water,out}$: the outlet water temperature after the tubes

T_{soil} : the soil temperature

ε_{aw}: the air-water heat exchanger effectiveness

Performance evaluation criteria

For a designer these parameters have to be determined in such a way that the boundary conditions and the heat exchanger performance are met. This means that the location, the available space, the building design and economics induce restrictions to the choice of the tube length and the number of tubes as well as the air-water battery. It is important to be able to evaluate the influence of the parameters on the performance. Different combination of these parameters can lead to the same thermal performance. So a second design criterion has to be introduced. Pressure loss of the flow through the air-water heat exchanger and pressure loss for the water flowing through the tubes is directly linked to fan and pump energy use.

Therefore a good criterion to evaluate the performance is to maximize the following PEC:

$$PEC = \frac{\dot{Q}}{\frac{\dot{m}_{air}}{\rho_{air}} \Delta p_{air} + \frac{\dot{m}_{water}}{\rho_{water}} \Delta p_{water}} \quad (1)$$

$$\dot{Q} = \dot{m}_{air} c_{p,air} \left(T_{air,in} - T_{ait,out}\right) = \dot{m}_{water} c_{p,water} \left(T_{water,in} - T_{water,out}\right) \quad (2,\text{a and b})$$

This implies that for a given heat load, the problem is transformed into a question of minimization of the pressure drop over the system. As the pressure drop over the air battery is fixed by its geometry, the pressure drop of the water tubes has to be minimized.

Effectiveness – NTU

In [5] the concept of heat exchanger effectiveness was introduced and coupled to pressure drop in order to optimize the design of an earth-air heat exchanger. The thermal performance of the heat exchanger is characterized by means of the steady state effectiveness of the tube ε_{ws}. The soil temperature T_{soil} is taken at distance r_s from the tube center, as illustrated in Fig. 3. This distance is often selected as the penetration depth in the ground for a 24h periodic flux variation.

$$\varepsilon_{ws} = \frac{T_{water,out} - T_{water,in}}{T_{soil} - T_{water,in}} = 1 - \exp\left(- \frac{\pi k L D}{\dot{m}_{water} c_{p,water}} \right) \quad (3)$$

$$NTU = \frac{\pi k L D}{\dot{m}_{water} c_{p,water}} \quad (4)$$

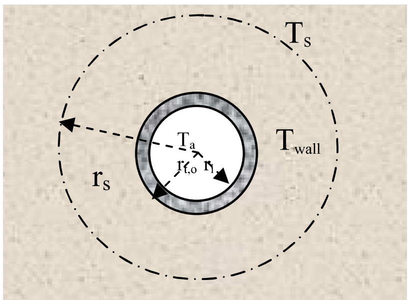

Figure 3 : Temperatures in a earth-air heat exchanger

In the NTU the overall heat transfer coefficient k is the most influencing parameter. The overall heat transfer coefficient is the inverse of the thermal resistance occurring between the air or water inside the tube and the ground. In essence the thermal resistance is composed of convective transfer resistance between air or water and tube wall, and of the conductive heat transfer resistance through the tube wall and in the ground (Eq. (5)).

$$\frac{1}{k} = \frac{1}{h_i} + \frac{\ln\left(r_{t,o} / r_{t,i} \right)}{\lambda_t / r_{t,i}} + \frac{\ln\left(r_{t,o} / r_s \right)}{\lambda_s / r_{t,i}} \quad (5)$$

The length L is an independent parameter influencing the NTU. There is a linear variation of NTU with length. Changing the diameter D or the mass flow rate will change the fluid velocity inside the tube. This results in a changing Reynolds number, which in turn affects the pressure drop and heat transfer through the non-dimensional friction factor and Nusselt number, (see the Appendix for the equations). The diameter D and water mass flow rate have no independent influence on NTU. In Figure 4 the contour plot of NTU/L is shown as function of flow rate and diameter. In Figure 5 the influence of flow rate and diameter is shown on the overall heat transfer coefficient k (with wall thickness of the tube of 5mm and soil penetration depth of 0.17m).

For low flow rates the flow is laminar and the influence of this is clearly seen in k as the convective resistance becomes dominant. For higher flow rates the overall heat transfer is no longer influence by raising the flow rate further for a given diameter as the convective resistance is negligible.
Raising the diameter lowers the overall heat transfer coefficient as the thermal resistance of the ground becomes larger.
As the influence of flow rate on overall heat transfer coefficient is relatively limited a small influence of flow rate on NTU is seen in Figure 4. Higher flow rates augment heat transfer, but at the same time also pressure drop.
In general lowering D lowers NTU and thus effectiveness. This effect is more pronounced if the flow rate is high.

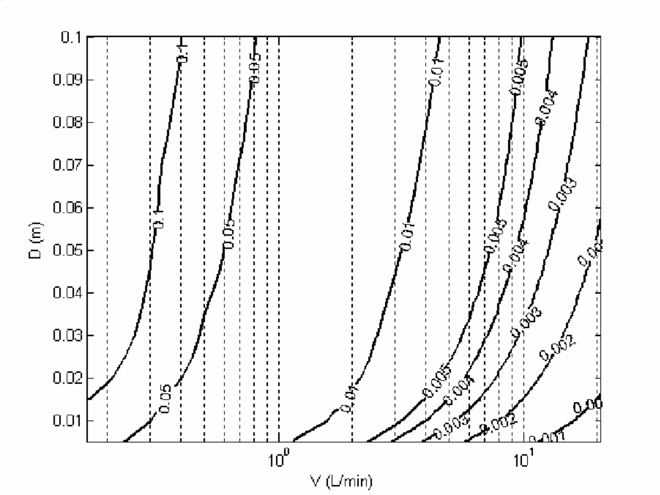

Figure 4 : NTU/L as function of D and volume flow rate

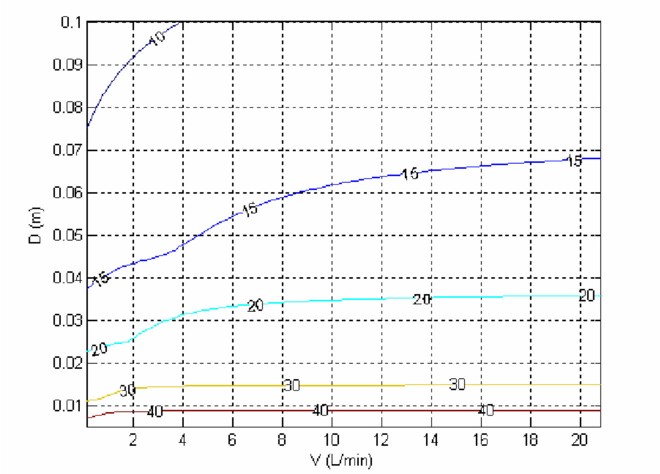

Figure 5 : k as function of D and volume flow rate

Pressure drop

$$\Delta p = 4 \cdot f \cdot \frac{L}{D} \cdot \frac{\rho_{water} v_{water}^2}{2} \quad (6)$$

The tube length L is again an independent parameter linearly influencing the pressure drop. Diameter and volumetric flow rate have a combined influence. In Figure 6 the contour plots of pressure drop per unit of length $\Delta p/L$ for varying diameter and flow rate are shown. Having a small flow rate per tube and a large diameter results in the lowest pressure drop.

Based on the earlier presented PEC, this would favour using many tubes, with a large diameter. This is in conflict with the thermal demand of a small diameter. In both cases a large number of tubes is beneficial, increasing the surface area and lowering the velocity. The tube length and diameter combination have to be optimized.

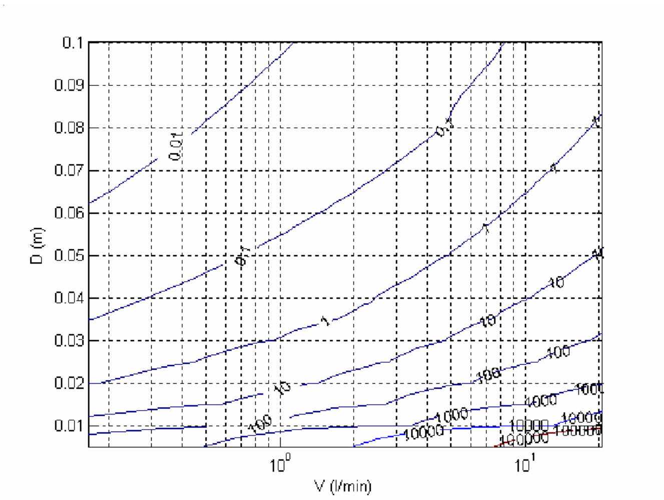

Figure 6 : Δp/L as function of D and volume flow rate

Specific pressure drop

As both NTU and pressure drop behave in linear fashion with tube length, the parameters NTU/L and Δp/L are only dependent on diameter and volume flow rate. These two parameters can now be used to optimize thermal to hydraulic performance. The specific pressure drop can be define as :

$$J = \frac{\Delta p}{NTU} \qquad (7)$$

J is a measure for the pressure drop necessary in order to realize one unit of NTU. Figure 7 gives the plot of J as function of D and volumetric flow rate (V).

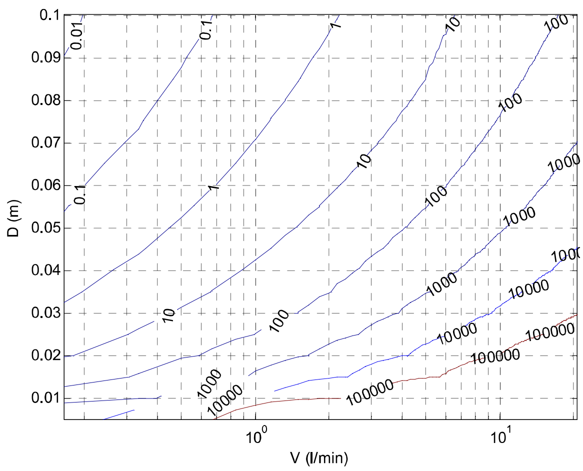

Figure 7 : J as function of D and volume flow rate

If the desired effectiveness ε_w of the heat exchanger is given (based on the temperature program), then the required NTU can be determined using Eq. (3). This NTU value is then the minimally desired NTU. Considering that the pump circulating the water can only accept a maximum pressure drop (e.g. 0.5 bar), provides the maximum allowable specific pressure drop :

$$J_{MAX} = \frac{\Delta p_{MAX}}{NTU_{\min}} \quad (8)$$

In fig. 7 this J_{MAX} defines a zone that is not allowed for D and V. Using Fig. 4 and 5 the most effective heat exchanger can then be selected as having the smallest allowable tube diameter and flow rate.

GRAPHICAL DESIGN METHOD

Flow rate and length as function of J

For a given effectiveness of the heat exchanger a plot can be created linking the specific pressure drop to tube length and flow rate for selected diameters. This is shown in Fig. 8 for an effectiveness of 80%, which is a typically accepted value for these type of heat exchangers [9]. The lower part of the figure gives the relation between the water flow rate and J while the upper part gives the relation between L and J; The lines in both graphs are lines of constant D. So starting from the abcis (J) if a given tube diameter is selected , the flow rate and the tube length can be determined to give the desired heat exchanger effectiveness.

This graph can now be used to select a suitable heat exchanger.

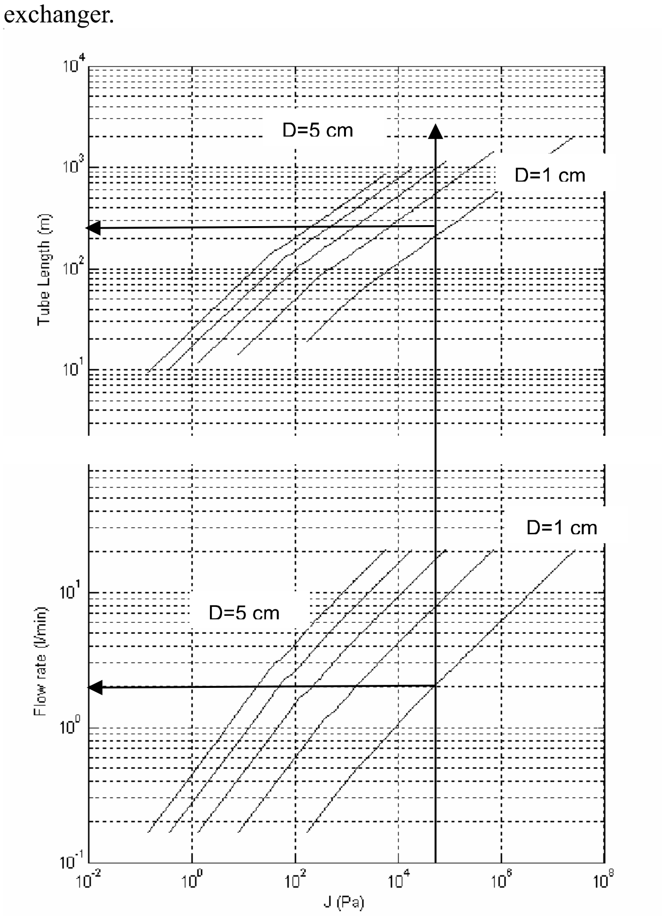

Figure 8 : Design graph for earth-water heat exchangers with effectiveness 80 %

Example

For a small office building with an air flow rate of 750 m^3/h an earth-water heat exchanger has to be designed. Due to space constraints the length of the tube cannot exceed 100 m.

If the pressure drop over the tubes has to be limited to < 0.5 bar then for a desired effectiveness of 80% the J_{Max}=31250 Pa.

Different solutions can then be found in Figure 7 and are summarised in Table 1.

D (cm)	L (m)	V (l/min)	v(m/s)	Δp (bar)
1	170	1.7	0.35	0.016
2	441	6,3	0.33	0.48
3	785	14.7	0.34	0.49
3	89	1.33	0.031	0.0013

The first 3 solutions are possible solutions for the J_{MAX}. All of them are within the needed pressure drop limit of 0.5 bar. All 3 of them result in a fairly large flow rate and a fairly long tube. In order to be able the install the heat exchanger the tube will have to be bended in a serpentine form.

Tubes with diameters above 3 cm are not suited. For these diameter the J value needed can no longer be achieved with an acceptable flow rate and an acceptable tube length.

The forth solution is a solution which is using a tube which will fit in the available space and gives a J value smaller than J_{MAX}. This solution will also fulfil the desired NTU. The flow rate has been reduced a lot.

From this example it is clear that using an earth-water heat exchanger with a small diameter and a low flow rate gives the best solution to the problem.

CONCLUSION

In this paper a clear analysis is made of the design problem of a earth to water heat exchanger.

A design methodology is proposed in order to be able to select the proper tube diameter and tube length within the constraints of maximum pressure drop and thermal performance.

For this the J-NTU method is proposed and illustrated.

Using an earth-water heat exchanger with a small diameter and a low flow rate gives the best solution to the problem.

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APPENDIX : HEAT TRANSFER AND PRESSURE DROP CORRELATIONS

In order to create a continuous heat transfer model for the heat transfer from the tube wall to the fluid following set of equations are used (in accordance with Schlünder/Hausen en Gnielinski) :

$$Nu_{lam} = \left[3.66^3 + 1.61^3 \cdot \left(\frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot \mathrm{D}}{\mathrm{L}}\right)\right]^{1/3}$$

$$Nu_{turb} = \frac{f_{turb} \cdot (\mathrm{Re} - 1000) \cdot \mathrm{Pr}}{2 \cdot \left(1 + 12.7 \cdot \sqrt{\frac{f_{turb}}{2}} \cdot \left(\mathrm{Pr}^{2/3} - 1\right)\right)}$$

$$f_{turb} = (1.58 \cdot \ln \mathrm{Re} - 3.28)^{-2}$$

$$f_{lam} = 16/\mathrm{Re}$$

$$Nu = \left(Nu_{lam}^5 + Nu_{turb}^5\right)^{1/5}$$

$$f = \left(f_{lam}^5 + f_{turb}^5\right)^{1/5}$$