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CONSTRUCTAL DESIGN OF ASSEMBLIES OF MULTI-SCALE HEAT PUMPS SERVED BY A SINGLE UNDERGROUND HEAT EXCHANGER

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Abstract. *The soil may provide inertial thermal energy for engineering applications such as underground heat exchangers for thermal comfort of buildings. This work presents the basis for design of high-order assemblies of multi-scale heat pumps that share a single underground heat exchanger in "U" shape. The method of Constructal Design was employed in order to explore the design possibilities under given constraints. The goal is the overall performance of heat-pumps assemblies of up to 4th order measured by the net enthalpy gain. The heat-pumps power requirements were represented by a fixed outlet temperature and variable mass flow rate of water that would leave the cycle evaporator and merges into the underground heat exchanger. Also, variable is the length of soil available to couple each heat-pump. A combinatorial set of configurations of heat-pumps typology was determined in order to illustrate the method. The physics of the study relies on the 3-D heat transfer by convection inside a buried tube and heat conduction in a finite portion of soil. Computational simulations were carried out in a commercial CFD software. Results showed the matter of designing assemblies from heat pumps that share a common underground heat exchanger is far from trivial and that this work puts forth the basis for such.*

Keywords: *Geothermal Energy, Constructal Design, District heating, underground heat exchanger.*

1. INTRODUCTION

Energy is an essential part of the great challenges of today's world. Renewable energy sources must be combined with energy rational and efficiency solutions. Energy use for residential thermal comfort of buildings has become significant part of today's energy use (near 20 %). Urban occupations have become progressively dense and so has the energy demand for residential needs. Geothermal energy, more specifically, inertial thermal energy, presents itself as viable source of renewable energy (Molavi and McDaniel, 2016). Any solution that allows the use of such energy source and combines rational applications (meets end use with source as in exergy efficiency) is worth exploring either for fully or partially replacement of grid power.

Earlier works have originally conceived this possibilities and model (Errera et al., 2013; Errera et al., 2014).

In this work we explore the possibilities of harnessing thermal energy from the soil to heat pumps in a range of power size and terrain availability. There may be large heat pumps with little soil available or vice-versa. This work then presents the basis for design of high-order assemblies of multi-scale heat pumps that are connected to a single underground heat exchanger in "U" shape. The method of Constructal Design was employed in order to explore the design possibilities under given constraints. The better designs tend to be the ones that promote greater access from the heat pumps to the thermal energy of the soil. The ultimate goal is the overall performance of heat-pumps assemblies of up to 4th order measured by the net enthalpy gain.

2. THE MODEL

Briefly the new system is modelled as illustrated by Fig.1. The soil is modelled as a sufficiently large and long parallelepiped in which lies a buried "U-loop" pipe along its length, and water flows through it. Water flowing out from heat pumps merges in the loop on the right-side branch at positions associated to the respective heat pumps. On the return branch, the same respective mass flowrate is collected by the respective heat pump. Figure 2 shows the model is further simplified by removing the vertical pipes. The junctions ("T" connections) were "virtualized" mathematically. They are shown by apparent sections in Fig. 2. The whole domain is connected mathematically. The dimensions adopted in the model are shown. This model was validated earlier (Errera et al., 2013).

The method of Constructal Design allows to identify the multitude of configurations (designs) that assemblies of heat pumps may become and the overall performance. For instance, one may consider 4 heat pumps that may harness the thermal energy independently (disconnected to the others) or in pairs, in combinations of trios or assembled together in four. There will be times when separated heat pumps may provide better overall performance, others not. The issue in hand is to know when and why the use of geothermal energy viable.

Assemblies (configurations) are explored by random selecting configurations for up to 4th order from a set of combinatorial possibilities. Typology of heat pumps are presented in Fig. 3. The size (or heat power) required by each heat pump is represented by the mass flow rate and the fixed inlet temperature, T_0. The size is given by the Pe_D number in the nondimensional presentation. Three orders of magnitude are considered. Spatial availability in lots had the same height and width. They differ in the dimensionless length, namely 25, 10, 100, 200 and 400 compared to the diameter for the buried pipe. Seven typologies of heat pumps are devised in order to perform the study. For instance, the heat pump type "D" is the smallest in both its size and its available soil for heat exchange, while the type "E" is the largest in both features.

The heat transfer model takes into account heat convection in water inside the pipe with sudden mixing at the junctions (inlets and outlets) shown in Fig. 2. The flow is laminar, incompressible and considered uniform. The laminar regime is warranted by using the maximum Pe_D of 10^4, which for Pr = 7 (water) sets a maximum Re_D of 1430, and thus below 2300. The pipe is coupled with a homogenous and isotropic portion of soil with uniform constant heat conductivity. All is in steady-state regime to represent the continuous use of the heat pumps. The boundary conditions are specified far field temperature T_∞ on the side walls ($y = \pm S/2$) and bottom e top walls ($z = \pm H/2$). The ends ($x = 0$, $x = L$) are not disturbed (Neumann type). The junctions were virtualized mathematically in order to prevent solving unnecessary developing fluid dynamics.

Each inlet adds $\dot{m}_{HPj}$ to the stream in the pipe (Fig. 1) along the right branch and the outlets lie on the return branch.

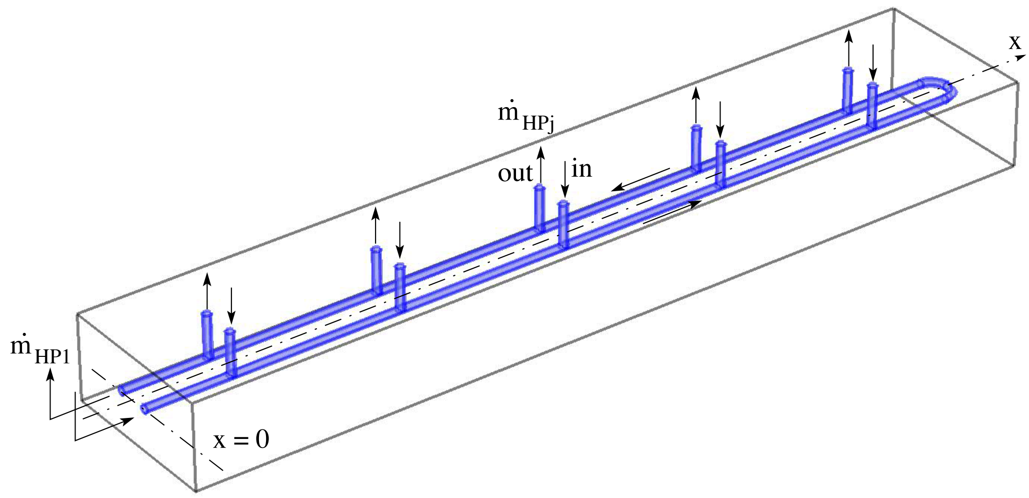

Figure 1. Model of "U-loop" underground heat exchanger that serves multiple heat pumps coupled to parallelepiped portion of soil, after Errera et al., 2014.

The physical model results a system of partial differential equation (PDEs) that in turn are solved by commercial software (COMSOL Multiphysics, 2019). It is based on the finite element method and it allows pre- and post-processing, and specially, it allows "virtualization" of the junctions as illustrated in Fig. 2. Further details on the numerical model, implementation, meshing and validation can be found in Errera *et al.*, 2013.

For the sake of conciseness, we illustrate the model with two 4th order assemblies of heat pumps, namely, {F,E,G,D} and {F,G,C,A}. We set possible combinations among them and the possibility of replacement of one of the heat pumps. Performance of conceivable designs is compared with respect to the maximum enthalpy flow an assembly could extract from the soil thermal energy reservoir.

Simulations conditions are set as $\tilde{S} = 15, \tilde{W} = 40, \tilde{H} = 20$ and $D = 0.1$ m. The working fluid is water with properties at 283 K, namely, heat conductivity $k_f = 0.58$ W·m^{-1}·K^{-1}, specific mass $\rho_f = 10^3$ kg·m^{-3}, heat capacity $c_{Pf} =$ 4192 J·kg^{-1}·K^{-1}, viscosity $\mu_f = 0.001$ Pa·s. The soil properties are heat conductivity 2 W·m^{-1}·K^{-1}, the heat capacity $c_P = 870$ J·kg^{-1}·K^{-1} and the specific mass $\rho = 10^3$ kg·m^{-3}. All heat pumps discharge water at $T_{inlet} = 278$ K into the pipe. The far field temperature is $T_\infty = 288$ K.

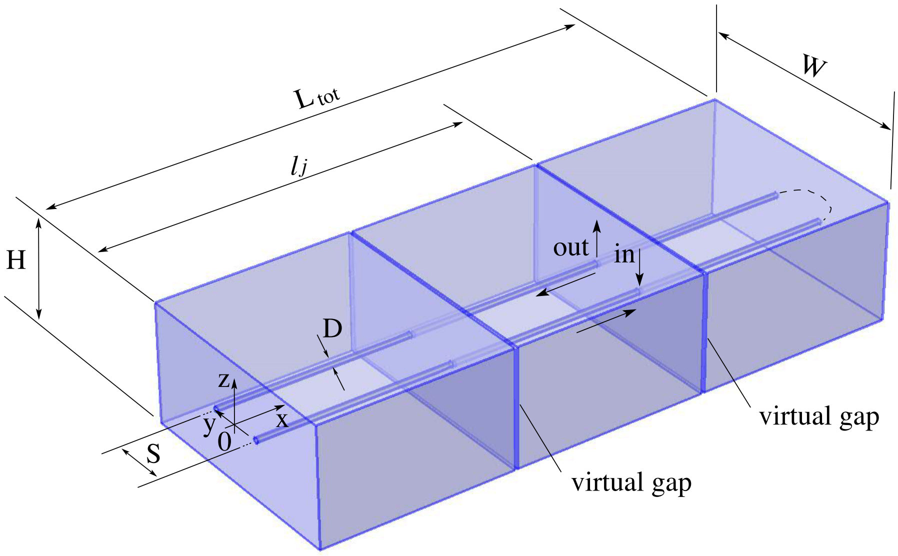

Figure 2. Numerical domain showing the replacement of junctions by their virtualizations. The mesh nodes of the soil are mirrored onto the opposite side while the flow in the pipes are corrected by the mass balance of the inlet and outlets, after Errera et. al, 2014.

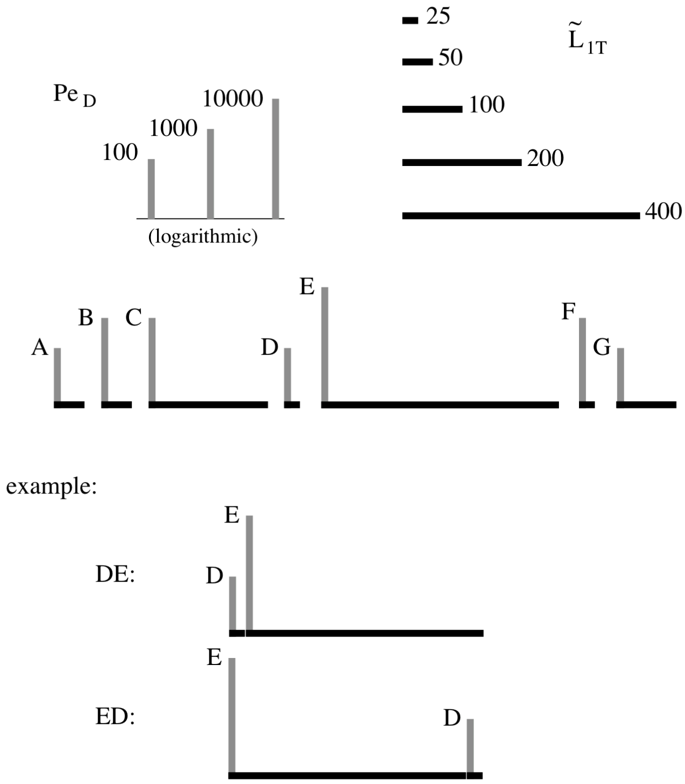

Figure 3. Typology of assorted heat pumps and assemblies. The size (or heat) required by each heat pump is represented by the mass flow rate and the fixed inlet temperature, T_0, thus given by the Pe_D number in the nondimensional presentation, after Errera et al., 2014.

3. RESULTS AND DISSCUSSION

The overall dimensionless performance, Q_{HP4T}, of combinatorial 4th order assemblies of heat pumps of the two sets is shown. The sets show a clear different range of performance, and the {F,G,C,A} is superior. The range of performance varies from 0,6 to 0,87 and it shows the evolution of design of assemblies is far from trivial. The assemblies FG+CA and FGC+A performs nearly the same, meaning the sequence and the combination of size and soil availability prevail in the overall performance. Also, it is worth noting the presence of heat pump "E" in the assembly pulls down the performance range regardless if combined with heat pump "D".

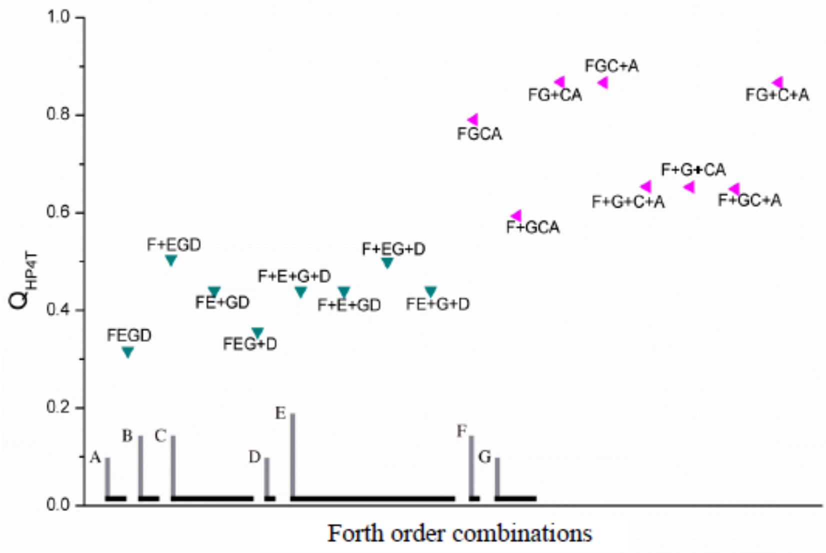

Figure 4. Overall dimensionless performance, Q_{HP4T}, of 4th order assemblies of heat pumps {F,E,G,D} and {F,G,C,A}.

The highest enthalpy gain observed in the simulations was for the assembly {FG+CA}. In this configuration, the first heat pump of the first pair demands 10 times greater heat then the following heat pump. In the first pair {FG}, the first has 4 times shorter length of soil at its disposal do extract heat, while in the second pair, {CA}, while the first has at its disposal 4 times more length. This points to a trend to seek pairings of large demand followed by small demand.

In Table 8 we show the overall performance for an assembly of the type {FG+CA}. The outlet temperatures of each one heat pump do not reach the maximum possible of 14.85 ºC (288 K). The enthalpy gain considers an established mass flow rate of water that exchange heat with the evaporators of the heat pumps and a return temperature, T_{inlet}, of 4.85 ºC (278 K). The harnessed heat is similar for all four heat pumps showing a certain balance. The heat output of the respective heat pumps, $Q_{HPout,j}$, would be more than enough for a heating load of 1.65 kW for an typical room in the winter in Curitiba based on COP of 5.2 (contemporary heat pump). The use of the soil is expressed by the volumetric power density of the soil expressed at the last column of the table. The highest density of heat extraction is observed in heat pump A.

Table 1. Performance indicators of each heat pump in an assembly {FG+CA}. Inlet temperature for all heat pumps at 4,85 ºC, retrieve temperature, $T_{out,j}$, heat harnessed from the heat exchanger to the evaporator, $Q_{HPj} = Q_L$, useful heat output, $Q_{HPout,j} = Q_H$, soil volume and volumetric power density. Adopted COP = 5,2.

Heat Pump	$T_{out,j}$ [ºC]	$Q_{HP,j} = Q_L$ [kW]	$Q_{HPout,j} = Q_H$ [kW]	Soil Volume [m³]	Volumetric Density [kW/m³]
F	13.04	0.34	1.77	100	0.018
G	12.74	0.36	1.87	80	0.023
C	14.44	0.40	2.08	200	0.010
A	13.54	0.39	2.03	40	0.051

Results pointed out that the evolution of design of systems like those is a complex issue and that it requires further and systematic studies in order to the take advantage of the renewable energy that inertial thermal energy from soil may provide.

4. CONCLUSIONS

This paper addressed the possibility to harness inertial thermal energy from the soil by a underground "U" pipe that is shared by multiple heat-pumps with different heat loads and availability of soil. The physical model was simplified and solved numerically by consolidated mathematical formulation that in turn was solved in a commercial software in order to accommodate the variety of tested configurations and the possibility of virtualization. The method of Constructal Design was employed in order to explore the main evolution trends in which assemblies of heat pumps can be devised with the goal to harness energy with higher performance and low environmental impact.

Given the simplifications and considerations, this is a solid starting point to explore particular and specific cases of interest with more detailed calculations. Technical and economic issues are to be taking into account. Hopefully this clean renewable energy becomes more accessible.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Bejan, A., 1993. *Heat Transfer*. John Wiley & Sons, New Jersey.

Bejan, A., 2013. *Convection Heat Transfer.* John Wiley & Sons, New Jersey, 4nd edition.

COMSOL Multiphysics, 2019. "COMSOL Multiphysics® v. 5.3a", COMSOL AB, Stockholm, Sweden. <http://www.comsol.com>

Errera, M., Lorente, S., Anderson, R., Bejan, A., 2013. "One underground heat exchanger for multiple heat pumps". *International Journal of Heat and Mass Transfer*, vol. 65, pp. 727-738.

Errera, M., Lorente, S., Bejan, A., 2014. "Assemblies of heat pumps served by a single underground heat exchanger". *International Journal of Heat and Mass Transfer*, vol. 75, pp.327-336.

INCROPERA, F. et al. 2008. *Fundamentos de transferência de calor e de massa*. : LTC , Rio de Janeiro, 6ª edition.

Isolani, P. et al. 2008. *Eficiência energética nos edifícios residenciais*. European Comission. Lisboa

Molavi J., McDaniel J., 2016 "A review of the benefits of Geothermal heat pump systems in retail buildings". *Procedia Engineering*, v. 145, pp. 1135-1143.

Paludetto, D., Lorente, S., 2016. "Modeling the heat exchanges between a datacenter and neighboring buildings through an underground loop". *Renewable Energy*, vol. 93, pp. 502-509.

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