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Assemblies of heat pumps served by a single underground heat exchanger

M.R. Errera [a], S. Lorente [b], A. Bejan [c,*]

[a] Federal University of Paraná, Department of Environmental Engineering, Curitiba, Paraná 81531-980, Brazil
[b] Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, avenue de Rangueil, F-31 077 Toulouse Cedex 04, France
[c] Duke University, Department of Mechanical Engineering and Materials Science, Durham, NC 27708-0300, USA

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ABSTRACT

In this paper we document the relationship between complex flow architecture and global performance for assemblies of heat pumps coupled thermally with the ground through a single U-shaped loop with circulating fluid. The assemblies vary according to heat pump numbers, sizes and locations along the loop. They are classified in a systematic way, and their performance is documented in three classes of designs: assemblies of heat pumps of the same size, heat pumps distributed equidistantly, and large numbers of heat pumps distributed almost continuously on a long loop. The work is based on numerical simulations, and on an analysis that holds in the limit of heat pumps distributed continuously. The relationship between flow architecture and global performance (heat transfer density) serves as guide for the energy design of high-density urban settlements in the future.

1. Introduction

There is an increasing interest in the future of urban design as a growing vasculature with high-density transport ranging from building energy design (heating, air conditioning) to power distribution, transportation, and communications. The future points toward thicker urban settlements, and this means even higher densities of transport.

One important class of high-density designs are buildings connected thermally to the ground [1–25]. The connection is effected by heat pumps that deposit or extract heat through fluid loops buried in the ground. As neighborhoods become denser, and as the inhabited space expands vertically (above and below ground), the land area with which the buildings are coupled becomes essential. This is why in Ref. [26] we proposed the idea of coupling two heat pumps in a single underground heat exchanger. We showed how the heat exchanger interacts with the soil volume, and that heat pumps of different sizes may operate better when they share a single underground loop. We also reported the effect of the pressure losses and overall performance of the design.

In this paper we consider the design of assemblies of multiple heat pumps that operate while connected to a straight single loop underground heat exchanger (Fig. 1). The degrees of freedom of the design are the sizes of the heat pumps and the positions of their connections along the loop.

We first consider assemblies with equal-size heat pumps and with variable connecting locations along the loop. We then position the heat pumps equidistantly along the loop and vary their sizes. The number of heat pumps varies from 1 to 4. Finally, we consider assemblies in the limit of large numbers of heat pumps distributed almost continuously on a long loop. In accord with constructal design [27,28] we seek the trends in how the global performance of the design depends on the flow architecture of the assembly.

2. Model

Consider a group of buildings that use heat pumps to extract heat from the ground by sharing the same underground heat exchanger (Fig. 1). The limiting case is a single heat pump operating with its own heat exchanger (configuration 1A1 in Table 1). More complex assemblies consist of two or more heat pumps distributed along longer heat exchangers.

We model the buried heat exchanger as a hairpin-shaped pipe. Heat pumps are connected to the loop on one leg for intake, and on the opposite location on the other leg to retrieve the working fluid. Therefore, in the intake leg the mass flow rate increases along the direction from the first to the nth heat pump, as more fluid is added in each. The mass flow rate decreases after the stream passes the U-turn (Fig. 2).

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* Corresponding author. Tel.: +1 919 660 5309; fax: +1 919 660 8963.
E-mail address: dalford@duke.edu (A. Bejan).

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Nomenclature

c_P	specific heat of the fluid, J/kg K
D	diameter of the buried pipe, m
f_j	mass flow rate ratio defined as $f_j = \dot{m}_{\mathrm{HP}j}/\dot{m}_{\mathrm{HP1}}$
H	height of the soil portion, m
k_f	thermal conductivity of the fluid, W/m K
k_s	effective thermal conductivity of soil, W/m K
L_{en}	equal distance between heat pumps, m
L_j	length of the soil position and one of the legs associated to heat pump j, m
L_{nT}	length of the soil portion and one of the leg of the entire piping assembly, m
L_{sat}	saturation length for enthalpy gain, m
l_j	the position along the x-axis at which the heat pump j is connected to the pipe, m
$\dot{m}_{\mathrm{HP}j}$	mass flow rate of the heat pump j, kg/s
$\dot{m}_{\mathrm{HPnU}}$	mass flow rate in the pipe after the last node n, kg/s
Pe_D	Peclet number at the first stretch between junction 1 and 2, as Eq. (11′)
$\tilde{Q}_{\mathrm{HP}j}$	dimensionless enthalpy gain of heat pump j
$\dot{Q}_{j,j+1}$	heat flow from the soil to the pipe between the junctions j and $j + 1$, W
$\tilde{Q}_{\mathrm{HP}nT}$	dimensionless total enthalpy gain of all heat pumps of n-assembly
Re_D	Reynolds number with respect to the pipe diameter
S	spacing between the two straight pipes, m
t	residence time, L/U_{avg}
$\tilde{t}_{sat}$	dimensionless saturation time, $\tilde{t}_{sat} \sim \tilde{L}_{sat}/Pe_D$, based on the saturation length
T_∞	far field soil temperature, K
T_f	temperature field in the pipe fluid, K
T_{inlet}	temperature at which heat pumps connects to the pipe, K
T_m	mean temperature of the flow in the pipe, K
$T_{m,out,j}$	mean temperature of the flow at the heat pump j intake, K
T_s	temperature field in the solid, K
u	fluid velocity component in the x direction, m/s
V	volume of soil in which the pipes are buried, m^3
W	width of soil volume, m
x, y, z	coordinates, m

Greek symbols

μ	viscosity, Pa s
ρ	fluid density, kg/m^3
Θ	dimensionless temperature, as Eq. (12)
$\Theta_{\mathrm{HP}j,out,m}$	dimensionless mean temperature at the heat pump j intake
$\tilde{\nabla}^2$	dimensionless Laplacian operator
ζ_j	dimensionless position of heat pump j measured from the U end of the loop
ζ	dimensionless longitudinal coordinate

Subscripts

j	index of an unspecified heat pump
j, $j + 1$	index relating to the stretch between nodes j and $j + 1$

Superscript

($\sim$)	dimensionless

All heat pumps feed the loop with a mass flow rate $\dot{m}_{\mathrm{HP}j}$ at the same temperature, T_{inlet}, and retrieve the fluid in local mean junction temperature, $T_{m,out,j}$, which resulted from the heat transfer from the soil to the fluid (Fig. 2).

The heat exchanger interacts thermally with a volume of soil shaped as parallelepiped (Fig. 3). The side boundaries of the volume are modeled as surfaces at uniform temperature, T_∞. We consider the volume as homogenous solid with constant, uniform and isotropic properties. The U-shaped pipe with diameter D has sufficiently thin wall and high enough thermal conductivity such that its wall thermal resistance is negligible.

The first heat pump (HP1) is connected at $x = 0$ (Fig. 3). The other heat pumps are located at $x = l_j$. The two legs of the U are laid in the horizontal plane x–y with centers at $y = \pm S/2$. The mass flow

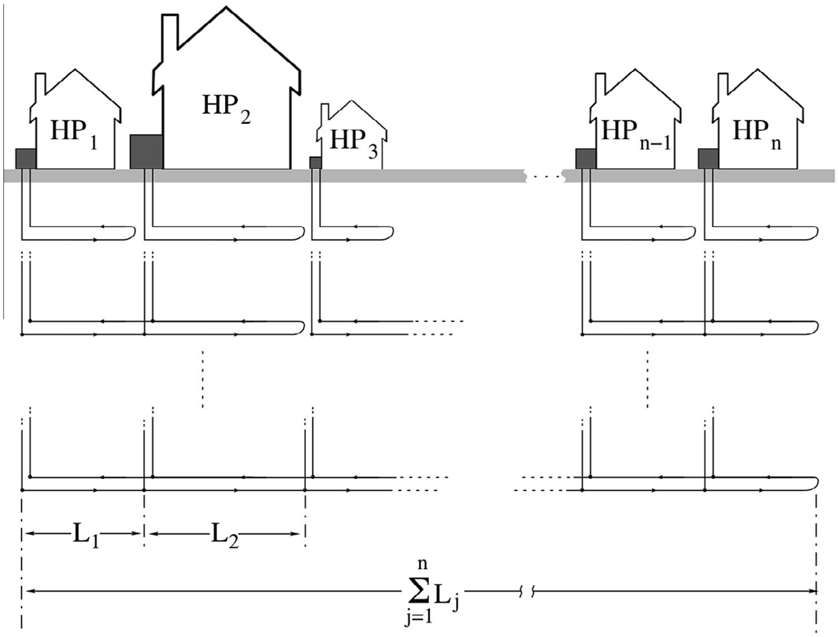

Fig. 1. Groups of buildings (heat pumps) that interact thermally with the ground: from isolated heat exchangers to assemblies of heat pumps served by a single loop.