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One underground heat exchanger for multiple heat pumps

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ABSTRACT

A heat pump that is coupled thermally with the ground extracts heat from the soil in winter, and discharges heat in the summer. The coupling is made through a buried heat exchanger. In this paper we explore the idea of using a single heat exchanger that serves more than one heat pump. Each heat pump draws its mass flow rate from the heat exchanger and, in addition, a background flow rate circulates permanently through the heat exchanger. The places where the heat pumps are connected to the exchanger vary. The objective of the design is to select the configuration of the multi-component system such that the total enthalpy flow rate delivered to the heat pumps is larger and the total pumping power is smaller. The paper documents the effect of geometry (the connections) and the relative sizes (mass flow rates of heat pumps) on the total enthalpy flow rate. The paper shows the parametric domain in which the design with a single heat exchanger is superior in comparison with the classical design where each heat pump is connected to its own heat exchanger.

1. Introduction

The need to maintain thermal comfort in buildings accounts for nearly 12% of the energy consumption in industrialized countries [1,2]. The partial or complete replacement of electricity or fuel as the driver for thermal comfort can be achieved through the use of geothermal heat pumps [3–9]. Underground heat exchangers facilitate the flow of energy between the ground and the heat pumps [10]. Ground heat exchangers can work in open or closed loop. The closed loop system consists of a fluid flowing in buried pipes that can be installed horizontally or vertically in the available terrain [3,6,11–16]. Ground heat exchangers were traditionally designed as single pipes or channels with array of loops or serpentines [15,17–19]. Most of these developments were based on empirical work [7,12,20–22].

The Constructal Law [23,24] has shed new light on the configuration (tree, serpentine) of a stream immersed in a solid [25–28]. That applies, for instance, to a single heat pump that interacts with a finite volume in the ground. In this paper we rely on the Constructal Law to configure a single heat exchanger that serves more than one heat pump, that is, the buried heat exchanger serves several buildings at the same time. At first, this is promising because the common heat exchanger uses less ground space, and it requires less pumping power. This is the beginning of the investigation of heat pumps assemblies and the effect of size scale on the evolution of the design of underground heat exchanger.

2. Model

Several heat pumps operate with heat transfer to and from a single heat exchanger buried in the ground. In the simplest model, the heat exchanger is a hairpin-shaped pipe embedded in a parallelepipedic volume of soil. The boundaries of the volume are at uniform temperature, T_∞. The soil is modeled as a homogenous solid with constant, uniform and isotropic properties. The pipe is round, with diameter D. The thermal resistance of the pipe wall is negligible because the wall is assumed to be sufficiently thin and its material has a high enough thermal conductivity.

The objective of the paper is to determine the configuration (the layout) of the heat exchanger and multiple heat pumps so that the performance of the whole assembly is increased. We begin with a heat exchanger that is shaped as the letter *U*, and focus on the region close to the end turn where a new heat pump is connected. We then consider more complex configurations.

Assume that a heat pump is connected at $x = 0$ (Fig. 1a). There a baseline mass flow rate $\dot{m}_0$ that comes from the pre-existing piping (from the left in Fig. 1), enters in one leg and returns along the other. The heat pump is connected such that the fluid intake is on one leg and the outflow is in the opposite location on the other leg. The heat pump position is at $x = l$, which varies as a design parameter. The pipes reside in the horizontal plane $x - y$ with

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Nomenclature

c_P	specific heat of the fluid, J/kg K
D	diameter of the buried pipe, m
f,	friction coefficient for flow in pipes
H	height of the soil portion, m
h_T	specific total head loss in the heat exchanger with one heat pump, kJ/kg
h_{2T}	specific total head loss in the heat exchanger with two heat pumps, kJ/kg
$h_{0l}^{\rightarrow}, h_{0l}^{\leftarrow}$	specific head loss in the heat exchanger in the stretch $(0,l)$, kJ/kg
$h_{lL}^{\rightarrow}, h_{lL}^{\leftarrow}$	specific head loss in the heat exchanger in the stretch (l,L), kJ/kg
h_{UL}	specific head loss in the U-turn of the heat exchanger (l,L), kJ/kg
h_{ref}	specific head loss in the heat exchanger with one separate heat pump, kJ/kg
h_{ref2}	specific head loss in the heat exchanger with two separate heat pumps, kJ/kg
$\tilde{h}$	relative head loss, as defined by Eq. (32)
$\tilde{h}_2$	relative head loss, as defined by Eq. (35)
k_f	thermal conductivity of the fluid, W/m K
k_s	effective thermal conductivity of soil, W/m K
L	length of the soil portion and one of the leg of the pipe, m
l	the position along the x-axis at which the heat pump is connected to the pipe, m
$\dot{m}_{HP}$	mass flow rate of the heat pump, kg/s
$\dot{m}_0$	baseline mass flow rate, kg/s
n	exponent, as Eqs. (32)–(35)
Pe_D	Peclet number, as Eq. (14')
$\tilde{Q}_{HPj}$	dimensionless enthalpy gain of heat pump j, W
$\tilde{Q}_{HP,tot}$	dimensionless total enthalpy gain of all heat pumps, W
$\dot{Q}_{HP}$	enthalpy gain retrieved by single heat pump, W
Re_D	Reynolds number with respect to the pipe diameter
r_j	mass flow rate ratio as $r_j = \dot{m}_0/\dot{m}_{HPj}$
S	spacing between straight pipes, m
T_∞	far field soil temperature, K
T_f	temperature field in the pipe fluid, K
$T_{HP,inlet}$	temperature at which heat pumps connects to the pipe, K
$T_{inletj,m}$	mean temperature of the flow where heat pump j connects to the pipe, K
T_m	mean temperature of the flow in the pipe, K
$T_{m,out}$	mean temperature of the flow at the heat pump intake, K
T_s	temperature field in the solid, K
u	fluid velocity component in the x direction, m/s
$\overline{U}_0$	mean velocity of the fluid in the pipe when only the baseline flow is present, m/s
U_{avg}	local mean velocity, m/s
$\overline{U}_{tot}$	mean velocity when baseline and heat pump flow rates are present, 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, kg/s/m
ρ	fluid density, kg/m^3
Θ	dimensionless temperature, as Eq.(13)
$\Theta_{HPj,out,m}$	dimensionless mean temperature at the heat pump j intake
$\tilde{\nabla}^2$	dimensionless Laplacian operator

Superscripts

$(\sim)$	dimensionless

centers at $y = \pm S/2$. The heat pump feeds the buried pipe with a mass flow rate of $\dot{m}_{HP}$ at a specified temperature T_{inlet}. The heat pump retrieves the flow rate $\dot{m}_{HP}$ at a higher temperature.

The ground volume ($V = L \times W \times H$) is shown in Fig. 1b. The heat transfer through the soil is modeled as steady-state heat conduction,

$$\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} + \frac{\partial^2 T_s}{\partial z^2} = 0 \quad (1)$$

where $T_s(x,y,z)$ is the temperature field in the soil. The fluid flow is modeled as incompressible and uniform with nearly constant properties.

We are interested in the design of the underground heat exchanger and in how to position the heat pumps along it. Therefore we assume that the connections between a heat pump and the U pipe can be modeled as sudden mixing. The pipe flow at the point where the stream arrives from the heat pump is described as

$$0 \leqslant x \leqslant l^{(-)}, \quad u = \overline{U}_0 = \frac{4r\dot{m}_{HP}}{\rho\pi D^2} \quad (2)$$

$$l^{(+)} \leqslant x \leqslant L, \quad u = \overline{U}_{tot} = \frac{4(r+1)\dot{m}_{HP}}{\rho\pi D^2} \quad (3)$$

The flow condition on the opposite leg of the U, at the point where the heat recovers its stream, is given by

$$0 \leqslant x \leqslant l^{(-)}, \quad u = \overline{U}_0 = -\frac{4r\dot{m}_{HP}}{\rho\pi D^2} \quad (4)$$

$$l^{(+)} \leqslant x \leqslant L, \quad u = \overline{U}_{tot} = -\frac{4(r+1)\dot{m}_{HP}}{\rho\pi D^2} \quad (5)$$

Parameter r is the ratio between two mass flow rates,

$$r = \frac{\dot{m}_0}{\dot{m}_{HP}} \quad (6)$$

where $\dot{m}_0$ is the background mass flow rate in the underground heat exchanger in the absence of $\dot{m}_{HP}$.

The temperature field in the pipe $T_f(x,y,z)$ is determined by solving Eqs. (1)–(6) and the energy equation [29]

$$u\frac{\partial T_f}{\partial x} = \frac{k_f}{\rho c_P}\left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial z^2} + \frac{\partial^2 T_f}{\partial y^2}\right) \quad (7)$$

where k_f is the thermal conductivity W/m K, ρ is the density kg/m^3 and c_P is the specific heat [J/kg K] of the fluid flowing in the pipe. The boundary conditions on the faces located at $x = 0$ and $x = L$ are:

$$\frac{\partial T}{\partial x} = 0, \quad \text{on the solid zy faces at } x = 0 \quad \text{and} \quad x = L \quad (8)$$

The far-field condition is modeled as $T = T_\infty$ on the side boundaries of the volume of solid. The continuity of heat flux at the pipe-solid wall interface is

$$k_f\frac{\partial T_f}{\partial n}\bigg|_{walls} = k_s\frac{\partial T_s}{\partial n}\bigg|_{walls} \quad (9)$$

where k_s is the effective thermal conductivity W/m K of the soil, and k_f is the fluid thermal conductivity. One additional equation is nec-