International Journal of Thermal Sciences 96 (2015) 227–235

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Review

Energy design for dense neighborhoods: One heat pump rejects heat, the other absorbs heat from the same loop

A. Almerbati [a], S. Lorente [b], A. Bejan [a, *]

[a] Duke University, Department of Mechanical Engineering and Material Science, Durham, NC 27708-0300, USA
[b] University of Toulouse, INSA, 135 Avenue de Rangueil, 31077 Toulouse, France

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form
21 May 2015
Accepted 22 May 2015
Available online 26 June 2015

Keywords:
Energy
Urban design
Dense neighborhoods
Heat pumps
Ground heat exchangers

ABSTRACT

This paper documents the joint performance of heat pumps that are served by a common loop buried in the ground, and which operate simultaneously: one heat pump absorbs heat from the buried loop whereas the other one rejects heat. A background flow is circulated in the underground loop even when the two heat pumps are not operating. The objective is to determine the performance and the manner in which it is affected by the way in which the two heat pumps are connected to the loop. The performance measures are the heat transfer rates into and out of the heat pumps, and the total pumping power required by the assembly. The paper documents the individual performance of the heat pumps, and their relative performance, which is the ratio of heating absorbed by one pump to the heating rejected by the other pump.

1. Introduction

Ground coupled heat pumps draw heat from and reject heat to the ground, depending on diurnal and seasonal conditions and geographic orientation of the building. Even on the same day and in the same neighborhood, a building facing the sun may need cooling, while a neighboring building facing away from the sun may need heating. The thermal coupling between the heat pump flow system and the ground is influenced by a buried loop through which the heat pump fluid circulates. Heat pumps that provide cooling to the building reject heat to the loop and the ground. Heat pumps that heat the building extract heat from the loop and the ground.

This is an active field of research. Specifically, ground heat exchangers can work in open or closed loops. Here we focus on the closed loop design, which consists of a stream flowing in buried pipes installed horizontally or vertically in the available terrain [1–7]. Ground heat exchangers are traditionally designed as single pipes or channels with arrays of loops or serpentines [6–11]. Closely related to this field, and with impact on a greater scale, is the extraction from geothermal energy from shallow subsurface flow loops. The state of the art in this domain is presented by Vienken et al. [12]. Optimization methods for such designs are described by de Paly et al. [13], Bayer et al. [14] and Daróczy et al. [15]. The energy policy significance of this field is outlined by Hähnlein et al. [16].

The growth of thickly settled neighborhoods pushes the ground coupled design toward multiple heat pumps that are served by the same loop buried in a shared land area. When the heat pumps operate in unison—all rejecting, or all absorbing—the design challenge is to accommodate all the heat pumps by using the same loop. As the density of urban settlement increases further, the multiple heat pump assembly acquires a new feature: some heat pumps reject heat to the ground while at the same time neighboring heat pumps absorb heat from the ground. In this paper we focus on this feature of thickly settled design, and analyze the simultaneous operation and performance of heat pumps that reject and absorb heat from the ground. The simplest such design is shown in Figs. 1–4.

2. Model

We chose the simplest possible model in order to highlight the goal of this work, which is to discover the relationship between the flow configuration and the performance of the combination of two heat pumps. To begin with, we assumed that the heat

---

* Corresponding author.
E-mail address: abejan@duke.edu (A. Bejan).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.05.007
1290-0729/

Nomenclature

c_{turb}	factor, Eq. (28)
c_P	specific heat of the fluid, J kg^{-1} K^{-1}
D	diameter of the buried pipe, m
f	friction factor for flow in pipe
h	conduction equivalent heat transfer coefficient, W m^{-2} K^{-1}
L	length of duct, m
$\dot{m}_0$	background mass flow rate, kg s^{-1}
$\dot{m}_a$	total mass flow rate through the T_a pipe, kg s^{-1}
$\dot{m}_b$	total mass flow rate through the T_b pipe, kg s^{-1}
$\dot{m}_H$	mass flow rate of HT pump, kg s^{-1}
$\dot{m}_L$	mass flow rate of LT pump, kg s^{-1}
N	number of heat transfer units for the buried pipe
p	perimeter of duct, m
P	pressure, Pa
q_H	heat rejected by HT pump, W
q_L	heat absorbed by LT pump, W
r	mass flow rate ratio, $\dot{m}_L/\dot{m}_H$
r_H	mass flow rate ratio, $\dot{m}_0/\dot{m}_H$
r_L	mass flow rate ratio, $\dot{m}_0/\dot{m}_L$
T_H	high temperature, K
$T_{H,end}$	fluid temperature at the end of T_a pipe (Figs. 2 and 3), K
$T_{H,in}$	temperature of fluid which enters the loop from HT pump, K
$T_{H,out}$	temperature of fluid that exits the loop toward HT pump, K
T_L	low temperature, K
$T_{L,end}$	fluid temperature at the end of T_b pipe (Figs. 3 and 4), K
$T_{L,in}$	temperature of fluid which enters the loop from LT pump, K
$T_{L,out}$	temperature of fluid that exits the loop toward LT pump, K
T_∞	soil temperature, K
Greek symbols	
ΔP	pressure difference, Pa
ΔT	temperature difference, K
ε	dimensionless factor, Eq. (8)
ρ	density, kg m^{-3}
τ	dimensionless temperature difference, Eq. (17)
Subscripts	
HT	high temperature heat pump
in	inflow
LT	low temperature heat pump
out	outflow

exchanger loop is horizontal (subsurface), not in a vertical hole, even though in high density neighborhoods the available ground area is scarce. An infinite medium is assumed: the effect of the boundaries of the round area is neglected, and so are the diurnal and seasonal temperature trends of the surroundings.

Two heat pumps operate with heat transfer to and from a single-loop heat exchanger buried in the ground. The soil is modeled as a homogeneous solid with constant, uniform and isotropic properties. The thermal resistance of the wall of the buried pipe is assumed negligible relative to the thermal resistance posed by the solid around the pipe. This heat transfer model [16] is discussed further in conjunction with Fig. 6.

The two heat pumps are situated at the opposite ends of the loop. The high temperature heat pump (HT) rejects heat and is located at $x = 0$, where x is measured along the loop. The low temperature heat pump (LT) absorbs heat and is located at $x = L$. The objective of the work described in this paper is to identify the design (the flow configuration) such that the overall performance (q_H, q_L) is increased.

In the absence of the heat pumps, an auxiliary pump circulates fluid with the flow rate $\dot{m}_0$ in the clockwise sense shown in the figure. There are four ways to connect the pumps relative to one another. In Fig. 1 mixing occurs downstream of each heat pump. The LT pump draws its stream ($\dot{m}_L$) from the stream that comes from the outlet of the HT pump, namely $\dot{m}_a = \dot{m}_0 + \dot{m}_H + \dot{m}_L$. Right after this connection, the LT pump rejects its $\dot{m}_L$ stream to the loop, so that along the returning leg of the loop the flow rate is $\dot{m}_b = \dot{m}_a$.

In Fig. 2, the order in which the connections of the LT pump are made is reversed. First, the LT pump rejects its $\dot{m}_L$ stream (T_L) to the loop, and then it draws it back at a higher temperature, $T_{L,out}$. Mixing occurs downstream of HT, and upstream of LT. The flow rates in the long ducts of the loop are the same, $\dot{m}_a = \dot{m}_b = \dot{m}_0 + \dot{m}_H$.

The new feature of the design shown in Fig. 3 is that the background $\dot{m}_0$ is the only flow present in the two long stretches of the loop. The LT and HT pumps reject their streams ($\dot{m}_L$, $\dot{m}_H$) to the loop and extract them almost immediately, after the mixing with background flow with higher temperature $T_{L,end}$ and lower Temperature $T_{H,end}$.

The fourth possible way to connect the two heat pumps to the same loop is shown in Fig. 4. New relative to the other configurations is that the circulating fluid through the long legs of the loop contains the background flow $\dot{m}_0$ and the flow rate $\dot{m}_L$. The HT pump flow rate $\dot{m}_H$ enters the loop with T_H and then is extracted after the mixing with lower temperature $T_{H,end}$. Mixing occurs upstream of HT and downstream of LT.

The shape of the loop is not important as long as the ground volume affected by heat transfer with the loop has a thermal penetration distance that is much smaller than the loop length L. The two legs of the loop are in counterflow. They have the same length (L) because when placed in such a counterflow the two legs require a single trench in which to be buried, regardless of the shape of the counterflow, Fig. 5. If the two legs are independent (L_1, L_2) then the total trench length would be greater, $L_1 + L_2$, as shown in the lower part of Fig. 5.

In the design of Fig. 1, the HT pump adds fluid of temperature T_H and mass flow rate $\dot{m}_H$ to the loop. The LT pump adds cold fluid of temperature T_L and mass flow rate $\dot{m}_L$ to the same loop. The heat transfer from the loop to the ground is time dependent, in accord with the solutions for transient heat conduction from a buried cylinder in an infinite isothermal medium [17]. This process can be modeled as heat transfer from a cylinder to an isothermal conducting medium through a heat transfer coefficient h that decreases monotonically in time, Fig. 6. The loop has two long sections. On the warm side (a), the mass flow rate is $\dot{m}_a$ and the fluid changes from $T_{H,in}$ to $T_{L,out}$. On the cold side (b), the flow $\dot{m}_b$ is from $T_{L,in}$ to $T_{H,out}$. The objective of the analysis is the relationship between the heat rejected by one heat pump and the heat absorbed by the other,

$$q_H = \dot{m}_H c_P (T_H - T_{H,out}) \tag{1}$$

$$q_L = \dot{m}_L c_P (T_{L,out} - T_L) \tag{2}$$