Energy Conversion and Management 95 (2015) 120–130

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance of heat pumps with direct expansion in vertical ground heat exchangers in heating mode

Michele De Carli *, Stefano Fiorenzato, Angelo Zarrella

Department of Industrial Engineering, Applied Physics Section, University of Padova, Via Venezia 1, 35131, Italy

ARTICLE INFO

Article history:
Received 7 October 2014
Accepted 29 January 2015
Available online 26 February 2015

Keywords:
Ground source heat pumps
Direct expansion
Convective heat transfer coefficient
Borehole heat exchanger
Coefficient of performance

ABSTRACT

Ground source heat pump systems represent an interesting example of renewable energy technology for heating and cooling of buildings. The connection with the ground is usually done by means of a closed loop where a heat-carrier fluid (pure water or a solution of antifreeze and water) flows and, in heating mode, moves heat from ground to refrigerant fluid of heat pump. A new solution is the direct expansion heat pump. In this case, the heat-carrier fluid inside the ground loop is the same refrigerant fluid of heat pump.

This paper focuses on the energy performance of direct expansion ground source heat pump with borehole heat exchangers in heating mode, looking at residential building installations. For this purpose, the evaporating process of the refrigerant fluid inside vertical tubes is investigated in order to analyze the influence of the convective heat transfer coefficient on the global heat transfer with the surrounding ground. Then, an analytical model reported in literature for the design of common borehole heat exchangers has been modified for direct expansion systems. Finally, the direct expansion and common ground source heat pumps have been compared in terms of both total borehole length and thermal performance. Results indicate that the direct expansion system has higher energy performance and requires lower total borehole length compared to the common system. However, when the two systems are compared with the same mean fluid evaporating temperature, the overall length of the ground heat exchanger of the direct expansion heat pump is greater than that of the common system.

1. Introduction

High energy efficiency and decrease of emissions are essential objectives for the design of space conditioning systems. Ground source heat pumps are one of the most suitable solutions for this purpose, due to their high energy performance, named COP (i.e. Coefficient of Performance) [1–3]. In this case, soil is used as a "hot sink" or "cold sink", or rather, a thermal source where heat is absorbed or injected. The advantage is that the ground temperature is more constant and uniform than ambient air temperature [4]. The connection between the heat pump and soil is possible for example with closed loops, named Secondary Loop Ground Source Heat Pumps (SL-GSHPs). The design and sizing of these systems is always debated and several methods are widely discussed in literature.

Recently attention has been addressed to systems with a direct connection between the heat pump and the soil, namely Direct Expansion Ground Source Heat Pumps (DX-GSHPs). For these systems, the design of ground heat exchangers (GHEs) is delicate and difficult to analyze, due to the physical phase transition of the refrigerant fluid inside buried pipes. There are few experimental studies about DX-GSHP. Wang et al. [5] conducted experimental tests in heating mode with a direct expansion ground source heat pump which used R134a as refrigerant; the COP values of the heat pump and the entire system were found to be on average 3.55 and 3.28, respectively, when the evaporating temperature was 3.14 °C and condensing temperature was 53.4 °C. Wang et al. [6] analyzed a direct expansion ground source heat pump with R22 as refrigerant in heating mode and installed in China; they found an average COP of the heat pump equal to 3.12 and a heat-absorption rate per unit of GHE length of about 54.4 W/m. Fannou et al. [7] presented an experimental analysis of a direct expansion ground source heat pump with R22 as refrigerant installed in Montreal (Canada); their test measurements were conducted over a one-month in early spring and showed COP values between 2.7 and 3.44.

Beauchamp et al. [8] proposed a model to analyze the transient behavior of a vertical ground heat exchanger by an appropriate thermal resistances and capacities system. The U-tube is discretized in control volume and, for each element, mass and energy

* Corresponding author. Tel.: +39 049 827 6870; fax: +39 049 827 6896.
E-mail address: michele.decarli@unipd.it (M. De Carli).

http://dx.doi.org/10.1016/j.enconman.2015.01.080
0196-8904/

Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})
d_{bore}	borehole diameter (m)
d_{id}	pipe inner diameter (m)
d_{od}	pipe outer diameter (m)
d_{max}	diameter from borehole axis beyond which the undisturbed ground temperature is assumed (m)
f	friction factor
Fo	Fourier number
G	mass flow rate of fluid per cross-sectional area of flow (kg m^{-2} s^{-1})
GF	G-factor, used for determining soil thermal resistance
GHE	ground heat exchanger
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
$\dot{m}$	fluid mass flow rate (kg s^{-1})
n	number of boreholes
N	number of steps used for evaporating process
P	power (W)
Pr	Prandtl number
$\dot{Q}$	thermal power (W)
r	specific latent heat (J kg^{-1})
R	thermal resistance per unit length (m K W^{-1})
R_b	filling thermal resistance per unit length (m K W^{-1})
R_{ga}	thermal resistance of the ground related to annual impulse per unit length (m K W^{-1})
R_{gd}	thermal resistance of the ground related to daily impulse per unit length (m K W^{-1})
R_{gm}	thermal resistance of the ground related to monthly impulse per unit length (m K W^{-1})
Re	Reynolds number
s	thickness (m)
T	temperature (K)
T_{soil}	undisturbed soil temperature (K)
x	vapor quality

Greek symbols

α	convective heat transfer coefficient (W m^{-2} K^{-1})
ε	vapor volume fraction
φ_{LO}	two-phase multiplier (–)
η	efficiency (–)
ρ	density (kg m^{-3})
σ	surface tension (Pa m^{-2})
μ	dynamic viscosity (kg m^{-1} s^{-1})

Subscripts

c	critical point
$comp$	compression
eb	boiling point
el	electrical
ev	evaporating process
fr	friction
g	ground, system of ground heat exchangers
gr	gravity
hD	heating design condition
i	index corresponding to a generic state of the process, evaporation or superheating
L	liquid, phase fluid considered flows only with the own mass flow rate
LO	liquid phase flows with the total mass flow rate
$mech$	mechanical
mix	liquid–vapor mixture
ov	superheating process
p	pipe wall
R	refrigerant
SAT	saturation point
sys	system
V	vapor, phase fluid considered flows only with the own mass flow rate

balance equations were written; as a matter of fact, the model solves the transient problem using a purely implicit finite difference method. The results were temperature profiles, for both flowing refrigerant fluid and pipe wall, considering also the transient thermal interference between the pipes of the U-loop. The thermodynamic process, and hence, the convective heat transfer coefficient, as well as temperature and pressure losses were not evaluated because of the complexity of the two-phase flow related to this approach. Austin and Sumathy [9] presented a parametric study on the performance of a direct-expansion ground source heat pump using carbon dioxide and horizontal buried pipe. In their approach each component of the machine was modelled and the GHE was the evaporator of the heat pump; thermal resistances were used to simulate the heat exchange with the ground and, at the same time, the convective heat transfer coefficient and the pressure losses were estimated. Using that approach, it was possible to link the heat exchange and the thermodynamic process of the refrigerant but dynamic behavior and thermal interference between pipes were not taken into account. Eslami-Nejad et al. [10] developed a numerical model to evaluate the thermal performance of a carbon dioxide filled vertical ground heat exchanger consisting of a long copper U-tube; their study did not include the heat pump. According to their results, large amounts of energy were absorbed from the ground due to the high two-phase heat transfer coefficient of CO_2.

The drill's analysis has two main aspects that may be enforced in the model: the first one is an accurate characterization of the heat exchange with thermal behaviour and interference phenomena within the drills; the second one is the thermodynamic process of the refrigerant fluid, with the calculation of the fluid convective heat transfer coefficient, the pressure and the temperature trends for steady state conditions. The design of GHEs is usually similar for both the traditional systems (SL-GSHP) and the DX-GSHP: it is possible to follow and adapt the same approach to model soil and borehole, while the refrigerant has to be considered in a suitable way. The basic models use analytical solution of line source [11] and cylindrical source [12]. Using these approaches, Kavanaugh and Rafferty [13] proposed a design method of vertical GHEs (i.e. the well-known ASHRAE method), which considers the thermal interference between adjacent boreholes by means of a "ground penalty temperature". Eskilson [14] proposed dimensionless parameters, named *g-functions*, to describe the performance of boreholes in homogenous ground. Hellström and Sanner [15] presented another approach which combines analytical and numerical methods to calculate the borehole thermal resistance and uses the solution of cylindrical source given by Carslaw and Jaeger [12] to estimate thermal resistance between the borehole wall and the undisturbed ground. These models are valid when the long-term behavior is analyzed, i.e. in order to investigate the effect of the thermal drift of the ground or the interaction between boreholes [16]. When the short-time behavior (between 2 and 6 h) is considered, the previous approaches may give wrong results since the borehole thermal capacity is not modelled [17,18].