Geothermics 57 (2015) 95–103

Contents lists available at ScienceDirect

Geothermics

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

Modeling and experimental validation of a transient direct expansion geothermal heat exchanger

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ARTICLE INFO

Article history:
Received 8 April 2014
Received in revised form 26 May 2015
Accepted 10 June 2015
Available online 30 June 2015

Keywords:
Direct expansion geothermal heat pump
Ground exchanger
Modeling
R22

ABSTRACT

Geothermal heat pump technology is currently one of the most interesting technologies used to heat buildings. There are two designs used in the industry: geothermal heat pump using a secondary ground loop and direct expansion (DX) ground source heat pump. The latter is less used, with one of the possibly reasons being that less research has carried out into the design of this sort of heat pump. In this paper, a model of a ground heat exchanger of a DX geothermal heat pump is presented in heating mode and a comparison with experimental results is presented. It is shown that the model is adequately validated by our experiment. After this validation, an analysis of the effect of the mass flow rate, the length and the angle of the borehole on the heat flux rate is presented. To conclude, an optimum configuration for the experiment is proposed.

1. Introduction

The last decade has seen a jump in interest in the geothermal heat pump (GHP). This may be explained by the fact that this technology can provide heating and cooling for a building at very low cost. There are two designs used in the industry, namely, the geothermal heat pump using a secondary ground loop and the direct expansion (DX) ground source heat pump. Both operate on the simple vapour compression refrigeration cycle (Beauchamp et al., 2013), with the main difference between them being that with the DX geothermal heat pump (Fig. 1), the ground heat exchanger is part of the refrigeration cycle. The energy and operational performances of the system are thus directly related to the working fluid behavior, the refrigerant, in relation with the ground heat transfer.

A review of the literature reveals the presence of several publications on geothermal secondary loop systems (Capozza et al., 2012; Esen and Inalli, 2009; Self et al., 2013), but a lack of scientific research and publications on direct expansion geothermal heat pump systems. One of the first studies of the DX heat pump was conducted by Smith (1956), who studied a geothermal DX horizontal heat pump and compared it to a secondary loop heat system. He proved that the size of the exchanger can be reduced, but also that the heat rejection or heat absorption needs to be controlled according to changes in ground temperature. One problem he encountered was in controlling the oil in the ground exchanger. Following this study, many other research endeavors also arrived at the same conclusion (Freund and Whitlow, 1959; Goulburn and Fearon, 1978, 1983).

More recently, a few works have been published on DX heat pumps. Wang et al. (2009) conducted an experimental study of a DX heat pump with the refrigerant R134a in heating mode. Their system consisted of three vertical 30 m deep boreholes examined over a period of 20 days in the winter. According to the results, on average, COP_{hp} and COP_{sys} were 3.55 and 2.28, respectively, and the average heating capacity obtained was 6.43 kW. They noted the problem of maldistribution of refrigerant flow between the boreholes. Wang et al. (2013) conducted an experimental study on a DX heat pump in heating mode, consisting of four vertical 20 m wells for which a copper coil system was developed to facilitate oil return. Fannou et al. (2014) analyzed an experiment with three vertical 30 m deep boreholes in heating mode like Wang et al., but with R22. They concluded that a dimensioning effort should be made to minimize pressure drop in the evaporator in order to find a compromise between low pressure drop, oil return and refrigerant charge. In 2011, Halozan (2011) presented a study on the commercialization of ground source heat pumps and the barriers facing the technology, in which he highlighted the lack of a

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http://dx.doi.org/10.1016/j.geothermics.2015.06.007
0375-6505/

Nomenclature

A	internal section of the pipe (m^2)
c_p	specific heat (J/kg K)
D_e	external diameter of the pipe (m)
D_i	internal diameter of the pipe (m)
D_b	extern diameter of the borehole (m)
f	friction factor
G	mass flux (kg/s m^2)
g	gravitational acceleration (m/s^2)
H_r	heat transfer coefficient between the pipe and the flow (W/m^2 K)
H_s	heat transfer coefficient, between the pipe and the grout (W/m^2 K)
H_p	heat transfer coefficient, between the grout and the ground (W/m^2 K)
h	specific enthalpy (J/kg)
h_{fg}	Enthalpy of phase changes (J/kg)
k	thermal conductivity (W/m K)
L	length of the pipe (m)
$\dot{m}$	mass flow rate (kg/s)
v	speed of the R22 (m/s)
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
R	Rayon (m)
T	temperature (K)
t	time (s)
x	quality of vapour (m)
z	depth

Greek letters

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
θ	angle of the pipe compared to the horizontal
σ	surface tension (N/m)
τ	shear stress (Pa)

Subscripts

c	grout
f	liquid phase
g	gas phase
m	mixture of liquid and gas of R22
p	pipe
s	ground
i	at the entry of the evaporator

design method as one of the major problems facing DX technology.

The proposed modeling and analysis of this DX heat pump therefore aims to fill this gap. The modeling and analysis of a direct expansion geothermal heat pump begins with the modeling of different components: ground heat exchanger, compressor, thermostatic expansion valve, reversing valve, pipe, and water-refrigerant exchanger, and the coupling of these components to form a closed loop corresponding to the heat pump.

The first step of the research, the modeling of the ground heat exchanger in evaporator mode, is presented in this paper.

We present a model of the ground exchanger operating like an evaporator in 1 dimension (Fig. 2). The model represents the phase change of the refrigerant, here Chlorodifluoromethane R22, with governing continuity, momentum and energy equations, and with heat exchange between the pipe and the grout and between the grout and the ground.

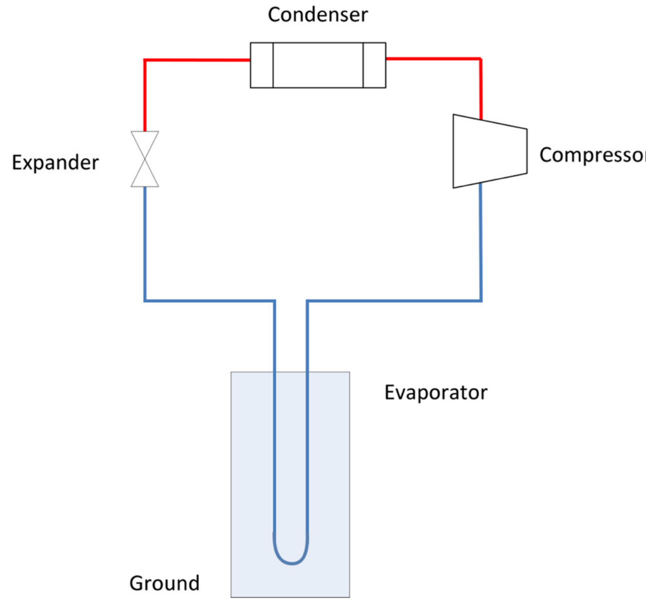

Fig. 1. Direct expansion heat pump.

To take the effect of the tube between them into account, two flows are created, one for the ascending flow, and one for the descending flow.

2. Theory

In this study, the equations of governing continuity, momentum and energy and heat exchange between the flow and the pipe, the pipe and the grout, and finally, the grout and the ground, are solved, Fig. 3.

The model is devised into four domains:

- The flow of R22, ascending and descending, in one dimension (z);
- The pipe, ascending and descending, in one dimension (z);
- The grout, in one dimension (z);

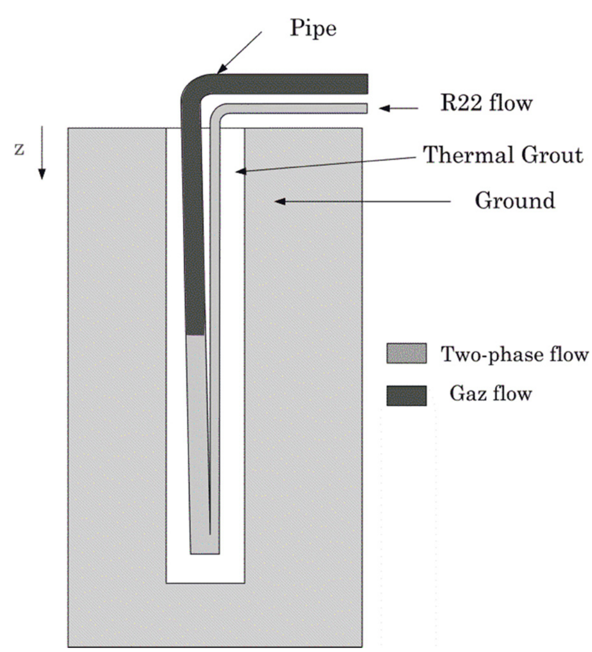

Fig. 2. Ground heat exchanger.