Applied Thermal Engineering 129 (2018) 165–178

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Energy and exergy investigation of a carbon dioxide direct-expansion geothermal heat pump

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HIGHLIGHTS

- Exergy-energy analysis of CO2 direct-expansion geothermal heat pump is developed.
- The effect of the refrigerant pressure drop in the heat exchangers is considered.
- Constant evaporator loop length and constant heating load are studied.
- The effect of the different parameters on evaporator loop length is investigated.

ARTICLE INFO

Article history:
Received 20 June 2017
Revised 10 September 2017
Accepted 4 October 2017
Available online 5 October 2017

Keywords:
Carbon dioxide
Geothermal heat pump
Transcritical cycle
Direct-expansion
Horizontal
Pressure drop

ABSTRACT

In this paper, a numerical simulation model has been extended for analyzing the energy and exergy of direct-expansion geothermal heat pumps (DX-GHP) in domestic hot water and heating applications. Carbon dioxide (CO_2) in transcritical cycle has been used as the refrigerant and the effects of the refrigerant pressure drop in the heat exchangers have been considered. The present numerical investigation gives the energy and exergy analysis under different operational conditions in two separate cases. In the first case, the ground heat exchanger loop length is considered to be constant and in the second case, the heating load is considered to be fix. With the aim of evaluation the system work performance, a detailed parametric investigation has been carried out on the effect of different parameters including the difference between soil temperature and the outlet temperature of the evaporator, the compressor speed, the temperature and the mass flow rate of inlet water to the gas cooler, the gas cooler length, the number of ground heat exchanger loops, and soil temperature. The results of this study include heating capacity, coefficient of performance (COP), exergy efficiency, ground heat exchanger loop length can be used for design and optimization of a DX-GHP.

1. Introduction

In recent years, because of environmental effects and technical advantages, chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants have attracted considerable attention to be replaced by natural alternative refrigerants such as carbon dioxide. Part of the noticeable features of carbon dioxide are zero ozone-layer depletion potential, very low direct-effect global warming potential, low cost, easy accessibility, non-flammability, non-toxicity properties, and compatibility with different common materials. Some scientists have recommended to use the carbon dioxide as an attractive source in applications such as air conditioning, heat pump and refrigeration due to the performance of the system in transcritical region [1–3]. For example, in the past several decades, many reseraches have been published on the performance of the systems using carbon dioxide as a natural refrigerant [4–14].

The tendency towards the development and use of more efficient refrigeration and air-conditioning equipment which are in agreement with the international laws for protecting the environment has resulted in the growth of technology in the geothermal heat pump systems. In order to develop these environment-friendly geothermal heat pump systems, the proper refrigerant for each application has to be chosen [15]. Due to temperature gradient available in the gas cooler, carbon dioxide can be used in domestic hot water and heating applications as a refrigerant in transcritical region. The application of the geothermal heat pumps, which include natural refrigerant with special capabilities, is a

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https://doi.org/10.1016/j.applthermaleng.2017.10.022
1359-4311/

Nomenclature

A	area (m^2)
C_p	specific heat (J/kg °C)
C	heat capacity rate (J/s °C)
$\dot{Ex}$	exergy destruction rate (kW)
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg/s)
N	compressor speed (rpm)
NTU	transfer units
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
s	entropy (kJ kg^{-1} K^{-1})
T	temperature
V	volume (m^3)
$\dot{W}$	work transfer rate (kW)

Acronyms

CO_2	carbon dioxide
COP	coefficient of performance
CPR	compressor pressure ratio
DX-GHP	direct-expansion geothermal heat pump
DX-CGHP	direct-expansion transcritical carbon dioxide geothermal heat pump
ELL	evaporator loop length
TEAG	thermal energy absorption from the ground
$\Delta T_{S,E}$	temperature difference between the soil and the evaporator outlet temperature

Greek symbols

ε	effectiveness of heat exchanger
ϵ	exergy efficiency
ψ	specific flow exergy (kJ kg^{-1})
η	efficiency
ρ	density (kg/m^3)

Subscripts

comp	compressor
dest	destruction
e	exit
exp	expansion
evap	evaporator
gc	gas cooler
i	inlet
isen	isentropic
k	boundary position
mech	mechanical
min	minimum
ref	refrigerant
s	swept
tot	total
vol	volumetric
W	water
0	dead state point
1,2,...,6	thermodynamic state points (Fig. 1b)

suitable option to be used in domestic hot water and heating applications.

In order to connect heat pump to the ground, the ground heat exchanger as an inseparable part of the system should be used in direct or indirect state. In direct connection state, known as DX-GHP, the evaporator is buried underground as ground heat exchanger and the refrigerant directly exchanges heat with the ground. In indirect connection state like the typical secondary-loop ground-coupled heat pump, an intermediary loop with secondary fluid is used as ground heat exchanger and the secondary fluid exchanges heat with the ground. It is clear that direct-expansion systems are more efficient and less costly in both primary and performance costs because the secondary heat transfer fluid heat exchanger and the circulation pump have been eliminated [16]. Therefore, because of environmental concerns, the interest in DX-GHPs using natural refrigerants (especially CO_2) has increased in recent years.

Generally, the simulation of DX-GHPs has been studied less than that of secondary-loop ground-coupled heat pump due to complexities in the modeling of two-phase flows in ground heat exchanger. Some available studies have investigated the performance of the entire system experimentally using common refrigerants [16–24]. Beauchamp et al. [25] have presented a nice numerical model for evaluating transient behavior of a vertical U-tube direct-expansion ground heat exchanger performance using R-22 refrigerant. They have ignored pressure and heat transfer coefficient changes of the two-phase fluid along the borehole. Also, they have calculated length of the boreholes in direct-expansion heat pump systems. Fannou et al. [26] have conducted a study on the heating capacity and the coefficient of performance (COP) of a vertical DX-GHP using the artificial neural network (ANN) method. Also, that study is focused on the execution of the best control strategies of a vertical DX-GHP operation. Further, Fannou et al. [27] have conducted a comparative study of the performance of vertical direct-expansion geothermal evaporator by replacing R22 with two refrigerants R410A and R407C. Results of that simulation showed that in specific conditions, each of R410A and R407C direct-expansion evaporator can have better performance than that of R22. Rousseaua et al. [28] have presented a new model and validated it with the experimental results of a vertical direct expansion geothermal heat exchanger using the refrigerant R22. They analyzed the effects of mass flow rate, the length and the angle of the borehole on the heat flux rate.

Very little research has investigated the DX-GHP using CO_2. Mastrullo et al. [29] have modelled a vertical U-pipe geothermal heat exchanger including CO_2 as secondary fluid using the thermosyphon principle. They assumed no thermal interaction between pipes. They have investigated the effect of two main parameters including fluid flow rate and borehole inlet temperature. The recent papers published by Eslami-Nejad et al. [30,31] have addressed the numerical modeling of the vertical DX-GHP using CO_2. In the first paper [30], they have concentrated on numerical simulation of a CO_2 vertical ground heat exchanger considering forced circulation. Their model considers the borehole wall temperature change as well as the thermal interaction between pipes and it calculates the fluid temperature, pressure and two-phase quality profiles. In the second paper [31], a theoretical model is extended to study quasi-transient performance of a CO_2 DX-GHP. Also, that model has evaluated variation of different system parameters such as total borehole length, number of boreholes. Austin and Sumathy research [32] is of the few papers that studied the entire system. They have expanded a numerical model for analyzing the thermodynamic performance of a CO_2 DX-GHP by the use of horizontal geothermal heat exchanger.

In most mentioned papers, CO_2 DX-GHP has been investigated vertically and very little of those has studied it horizontally. Also, so far exergy analysis has not been performed for CO_2 DX-GHP. Therefore, in this study, a numerical model has been studied to perform the energy and exergy analyze of a horizontal DX-GHP. In this model, the CO_2 in transcritical region has been used as the refrigerant. Furthermore, the pressure drop effects of the refrigerant in the heat exchangers have been considered. The presented numerical solution includes the energy and exergy analysis of