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Carbon dioxide evaporation process in direct expansion geothermal boreholes

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ABSTRACT

Ground Heat Exchangers (GHE) play an important role in the performance of Ground Source Heat Pumps (GSHP). The impact is even more significant in direct expansion GSHP (DX-GSHP) systems as the refrigerant used in the heat pump also acts as the heat transfer fluid for the GHE. In this study, several experiments were carried out to investigate the performance of GHEs in a carbon dioxide (CO_2) DX-GSHP. The evaporation of CO_2 in the GHE was studied under various mass flow rates and number of active boreholes. For this purpose, a transcritical CO_2 DX-GSHP test facility was built and fully equipped at CanmetENERGY-Varennes research laboratory. It was found that a partial two-phase flow regime along the GHE decreases the performance compared to the full two-phase flow and it has to be avoided for more efficient DX-GSHP systems.

INTRODUCTION

The global climate change and urge for using energy efficient systems call for the development and implementation of emerging eco-friendly technologies for heating and cooling applications. This new tendency has motivated the scientific community to adapt natural refrigerants such as carbon dioxide (CO_2) in DX-GSHP. The use of transcritical CO_2 in DX-GSHP offers several opportunities for the cost reduction of the ground loop and makes these systems a promising environmentally friendly and energy efficient alternative compared to other heating equipment. In addition, CO2 is inexpensive to produce and has a relatively high vapour density as well as latent heat of evaporation. This and its working pressures allows for less refrigerant with small specific volume to be cycled than conventional refrigerants, achieving the same heating/cooling capacity and size reduction of the GHE as well as other system components.

One of the main components in transcritical CO_2 DX-GSHP systems is the GHE, as it is the component where heat transfer between the GSHP system and the soil occurs. GHE heat transfer performance is the key factor influencing the operation performance of the entire system.

At present, a relatively few studies is reported on DX-GSHP. The available theoretical researches have mainly focused on numerical methods to simulate the GHE and study the effect of different parameters on the system performance (Ghazizade and Ameri, 2018; Yuefen, et al. 2017; Mastrullo 2014; Austin and Sumathy, 2011, Eslami Nejad, et al. 2014, and Eslami Nejad, et al. 2018). The modeling of transient behavior of GHE and the surrounding

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ground is somehow complex and only few transient models are available in the literature (Beauchamp, et al. 2013; Rousseau, et al. 2015; Eslami Nejad et al. 2015). Most of the experimental studies evaluated the whole system performance using typical refrigerants (Guo et al. 2012; Wang et al. 2009; Lenarduzzi and Bennet 1991 and Goulburn and Fearon 1978). Compared to other working refrigerants, CO_2 has been the least studied. Several studies were performed to establish some guides and improvements for the design of such systems (Mei and Baxter, 1990 and Wang, et al. 2013) while others focused on various GHE types (i.e, horizontal, vertical, spiral or inclined) in the heating and cooling mode (Johnson, 2002; Minea, 2003 and Goulburn 1983). Recently Badache, et al., 2018 experimentally investigated the overall system performance, phase change of CO_2 due to evaporation inside the ground heat exchanger and the effect of the number of boreholes on the system performance.

In the present work, several experiments were conducted to investigate the GHE performance using CO_2 as the working fluid. For this purpose, a transcritical CO_2 DX-GSHP test facility was built at CanmetENERGY-Varennes research laboratory. First, the profiles of the ground temperature and pressure drop through the boreholes are analysed. In the second step, the evaporation process taking place inside the heat exchanger and the related heat extraction performance were investigated for different number of active boreholes and the CO_2 mass flow rate per borehole.

DESCRIPTION OF THE EXPERIMENTAL SETUP AND TEST PROCEDURE

Experimental setup

Figure 1(a) schematically shows the single-stage transcritical CO_2 DX-GSHP test bench in heating mode. The main components of this test facility include a semi hermetic compressor (one ton nominal refrigeration capacity), the GHE, and a water loop for heat rejection from the gas cooler. An oil system consisting of a separator, a reservoir and a pressure regulating valve ensures adequate compressor lubrication while minimizes the amount of oil circulating in the whole cycle including the borehole. The test facility is fully equipped with different measuring devices including the pressure and temperature sensors and flowmeters. The system operates in three pressure levels namely high, intermediate, and low. The refrigerant (CO_2) is compressed to the high-pressure level (supercritical pressure) at point 2 with a corresponding temperature rise. Then, the high pressure-high temperature gas enters the gas cooler to heat water. After internal heat exchanger (IHE), CO_2 is expanded to the intermiddiate-pressure level of the cycle (point 5). The two-phase CO_2 enters the separator and the vapor portion is bypassed around the boreholes, while the liquid portion flows toward the boreholes. Then, CO_2 with low vapor quality enters the boreholes, mixes with the the bypass vapor at the outlet of the boreholes, becomes superheated in IHE, and enters the compressor to complete the cycle. Note, for all tests, the pressure of the separator was set to 36.45 bars, corresponding to 1.7 ˚C.

The GHE consists of four 30-meter vertical boreholes with single cooper U-tube arranges in a square pattern with a uniform spacing of 6.25 m. The boreholes dimensions and the grout filling material are listed in Table 1. Insitu thermal properties of the soil obtained from a thermal response test are given in Table 2. One of the boreholes was equipped with temperature sensors in diferent levels to present the temperature profile of CO_2 in both two legs of the U-pipe. Figure 1 (b) shows the location of those temperature sensors on the borehole.

Table 1. Borehole dimensions

Borehole	r_b		cm	3.9
	U	ID		0.64
		OD		0.8
	D	ID		0.48
		OD		0.64
	$2D$			2.3
	k_{grout}		$W/m/K$	0.8
	k_{pipe}			400
	Length		m	30

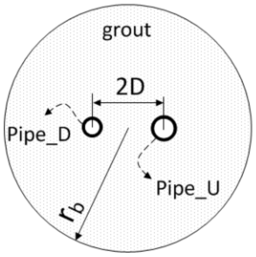


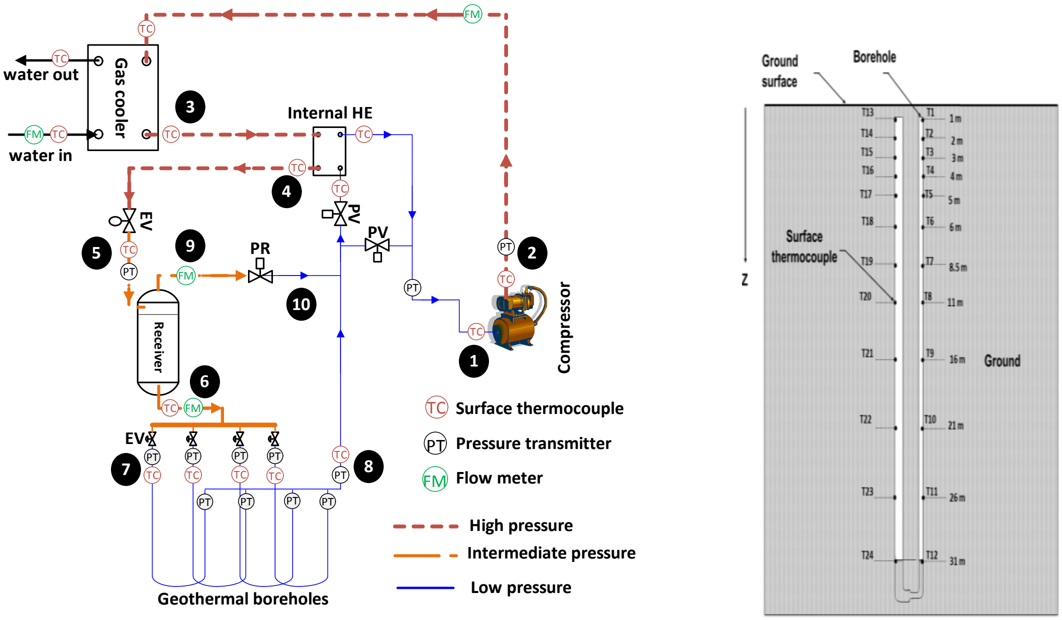
Table 2. Ground thermal properties

Ground	K_{ground}	$W/m/K$	2.65
	$(\rho c_p)_g$	$kJ/m^3/K$	2862
	UGT	°C	9.5

Test procedure

The system can be operated in two different modes; manual and automatic. The former is employed in the present work in which the opening position of the Expantion Valves (EVs) (installed before the inlet of the the boreholes) can be changed manually.

Each test started by adjusting the water temperature, the water mass flow rate, and the opening of the EVs. For each test, the same opening was fixed for all EVs involved. The temperature variation along the borehole is then recorded during the system operation. Note that the temperature measurements along the borehole were not taken directly on the CO_2 but at the surface of both U-tube legs. Other data are also recorded from the test that enable the actual borehole extraction to be calculated and the actual pressure drop and enough information to yield any time dependent characteristics of the heat pump performance.



(a) (b)

Figure 1. (a) Simplified schematic of the CO_2-DX-GSHP test facility; and (b) Position of the thermocouples in the GHE.

RESULTS AND DISCUSSION

For investigating the GHE performance and the evaporation process taking place in the GHE, the profiles of the ground temperature and pressure drop through the boreholes are first analysed in this section.

Ground temperature measurement

The temperature distribution in the ground significantly affects the performance of the GHE. The profiles of the ground temperature for three days (April 20th, September 2nd, and October 24th) are presented in Figure 2. The profiles of the April 20th and September 2nd (black dash lines) present the ground temperature before conducting the first test (i.e. before operation of the CO_2-DX-GSHP), thus they represent the far field ground temperature. For each profile, two different regions are observed; the shallow zone (up to 8 meters) and the deep zone (down to 31 meters). It can be seen that for the shallow zone, the ground temperature depends greatly on the seasonal weather conditions. In the deep zone, the ground temperature profile stays almost constant for both days, which corresponds to the undisturbed ground temperature (UGT). At the lower zone, the influence of the seasonal climate changes on the ground temperature is negligible. Note that the UGT values are in accordance with the value determined by the thermal response test, which is about 9.5 °C.

After running a number of tests, the ground temperature is expected to be disturbed as shown in the temperature profile of October 24th (blue dashed lines). It corresponds to the ground temperature in the vicinity of the borehole when the system was not operating. In fact, the actual ground temperature at the proximity of an active borehole is different than the far field temperature even at the time that the system is off. As can be seen in Figure 2, the deep zone temperature value is 1.5 ºC less than that measured on April 20th and September 2nd.

An experimental estimates of soil temperature recovery after heat extraction test indicates that generally for the ground it took at least 8 hours for an adequate temperature recovery (i.e., to reach the profile in black). In consequence, a soil recovery time of 12 hours was scheduled before each test.

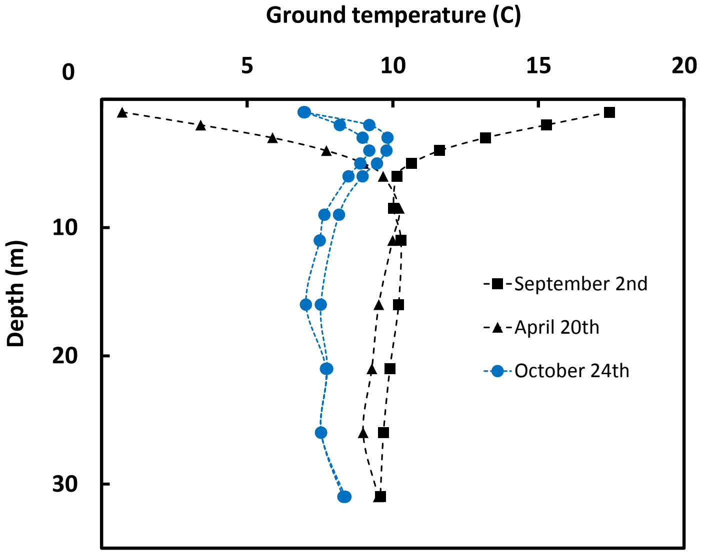


Figure 2. Measured ground temperature at different depths at Varennes for three days (April 20th, September 2nd, and October 24th).

Pressure drop through the boreholes

Refrigerant pressure drop inside boreholes influences the performance of a GHE. Significant reduction in the pressure of the refrigerant results in an inconsistent evaporation temperature in a GHE. Therefore, to investigate the evaporation process inside a GHE, the pressure drop in a borehole needs to be measured. Thus, for different openings of the EVs (40%, 20% and 10%) the pressures at the inlet and the outlet of the boreholes were messured as presented in Figure 3. The tests were conducted with $\dot{m}_w$ = 0.27 kg/s and $T_{w,in}$ = 35 °C. It can be seen that when the opening of the EVs decreases from 40% to 10%, the pressure in the borehole decreases. It is also observed that the pressure drop, ΔP (difference between CO_2 inlet and outlet pressure) along the boreholes is relatively small. Table 3 illustrates ΔP values for different openings of the EVs. The maximum measured pressure drop was less than 80 kPa (at 40% opening). In other openings of the EVs, the measured pressure drop is less than 40 kPa. The pressure drop has negligible effects on the evaporating pressure and therefore the evaporation temperature along the borehole remains almost constant.

Table 3. Pressure drop through the boreholes

Number of Boreholes	EVs Opening	Pin (kPa)	ΔP (kPa)
3	40%	3422	≤80
3	20%	3245	≤40
3	10%	3116	≤40

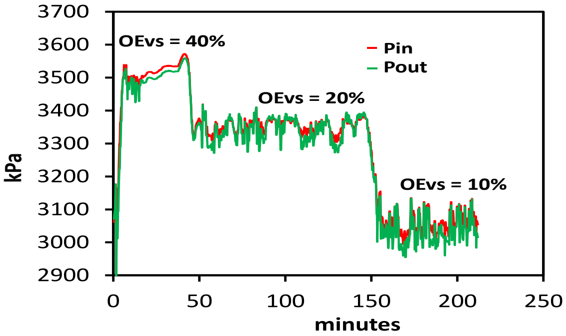


Figure 3. Inlet and outlet GHE pressure data

Phase change process in the GHE

The phase change process in the GHE was examined for the system working with different CO_2 mass flow rates ($\dot{m}_{CO2}$) and two different number of active boreholes (two and three boreholes).

Figure 4 illustrates temperature profile for three different CO_2 mass flow (1.46×10^{-3} kg/s, 2.21×10^{-3} kg/s and 2.58×10^{-3} kg/s) per borehole in a system operating with four active boreholes. Table 4 gives the tests conditions and the main results. For each mass flow rate, two temperature profiles are presented: one at the shutdown-period (recovered ground) and the other one during operation. As mentioned previously, the shutdown-period profile (black dash lines) illustrates the ground temperature at the vicinity of the borehole before it has been disturbed by the experiment. As the tests were conducted in different days of the year, the shallow ground temperatures are not identical. The blue solid lines present CO_2 temperature profile inside the borehole for a given mass flow rate. Arrows on the curves indicate the flow direction of CO_2 inside the pipe. In each profile, two regions can be distinguished: (a) two-phase region and (b) single-phase region. In the former region, CO_2 temperature remains constant due to the large amount of energy from the latent heat of vaporization, indicating that low pressure drop is maintained in the flow. The length of this region represents the length of complete evaporation, and it is equal to 10 m from the inlet of the first leg for case #1. However, it is equal to 40 m for the two other cases.

A comparison of cases #1 and #2 shows that the length of the two-phase region inside the borehole increased with the higher flow rate associated with large refrigerant quantities inside the GHE. This trend is not specific to CO_2 but general for all refrigerants. When comparing cases #2 and #3, however, the length of the two-phase region did not increase with higher flow rate (i.e, case #3). On the other hand, T_{evap} decreased due to the phase change process, compensating for the increase in the evaporation length. This result confirms our previous expectation meaning that the phase change process depends on both T_{evap} and CO_2 mass flow rate. Note that it was not possible to perform the tests with variable T_{evap} (without changing the mass flow rate) in order to highlight its effect on phase change process in the GHE.

The single-phase region starts from the last point of the two-phase region and finishes at the end of the second leg. The temperature variation of CO_2 is more significant in case #1 due to the relatively low specific heat of single-phase CO_2. In this case, single-phase CO_2 fills the major part of the GHE. The CO_2 temperature increases from -2.5 °C to reach the UTG, which is the maximum temperature that can be reached, then, it decreases in the second leg due to the negative thermal interaction with the first leg as well as the cold soil temperature at the shallow depth. The borehole is less efficient in this case (case#1). The superheating, observed for the case #1 is 1 °C higher than that of case #2.

As it can be seen in table 4, the borehole extraction rate in case #3 shows a slight difference compared to case #2, while it is 43% higher than that of the case #1 in which the major part of the GHE is filled by single-phase CO_2. This means that a partial two-phase flow rather than a full two-phase flow regime along the U-tube length leads to lower borehole performance and it has to be avoided for more efficient DX-GSHP systems.

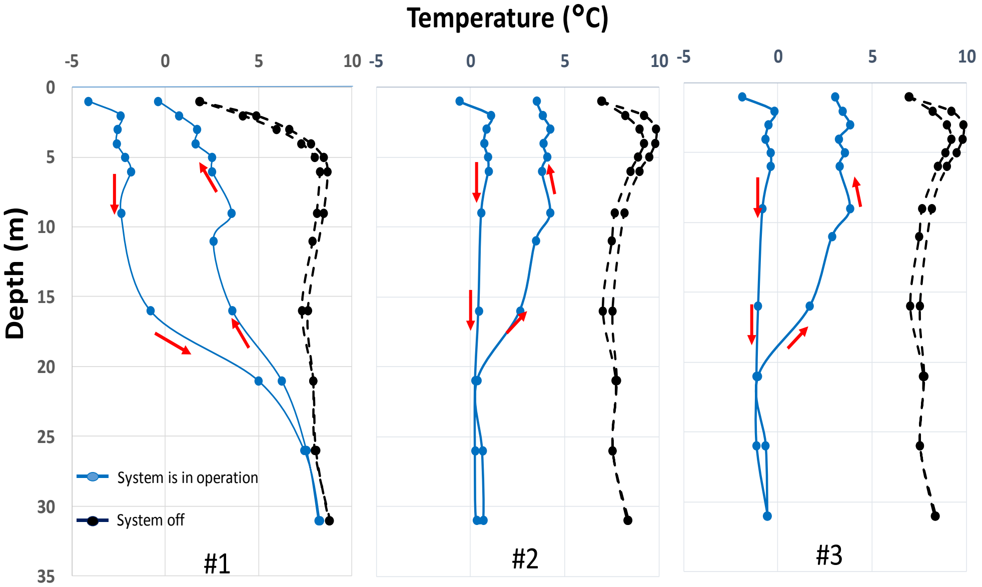


Figure 4. Pipe wall temperature variation along the borehole for different mass flow rates

Table 4. Tests conditions and results

Case Number	Number of Boreholes	Tw, in (°C)	CO_2 Gas bypass flow (kg/s)×10^3	CO_2 total liquid flow (kg/s)×10^3	CO_2 liquid flow/bor (kg/s)×10^3	T_{evap} (°C)	Operation period (hours)	$Q_{GHE/bor}$ (kW)
1	4	35	11.90	5.86	1.46	-2.55	15	0.3
2	4	35	11.10	8.78	2.21	0.50	12	0.57
3	4	30	7.53	10.33	2.58	-1.2	2.5	0.59

Figure 5a and 5b presents the change of CO_2 fluid temperature profile for two different number of active boreholes. The water mass flow rate to the gas cooler was set to 0.25 kg/s during all the tests. Table 5 illustrates the main test conditions and results. Here again the solid lines show the pipe wall temperature profile representing the CO_2 flow temperature along the U-tube in three cases. Black dash lines represent the ground temperature profile before starting the system. As shown in this figure, the temperature profiles show clearly the evaporation length, two-phase region with constant temperature (CO_2 quality < 1) and single-phase region.

Firstly, systems with three and two active boreholes show different CO_2 fluid temperature variation (single and two phase regions) along the borehole and different length for complete evaporation. Since the system with two active boreholes carries through a lower T_{evap} (-2.55 °C), higher mass flow rate (3.31×10^{-3} kg/s) of liquid CO_2 per borehole, this creates a larger temperature difference between the CO_2 and the ground. Consequently, it results in a longer length for complete evaporation (50 m) and higher $Q_{GHE/bor}$ compared to the case with three active boreholes. It means that employing more boreholes decreases the heat extracted per unit borehole due to lower CO_2 mass flow rate.

Secondly, in both profiles, the temperature increase in the single-phase region is marginal as the temperature of the surrounding material (grout) decreases due to the cold soil temperature at the shallow depth.

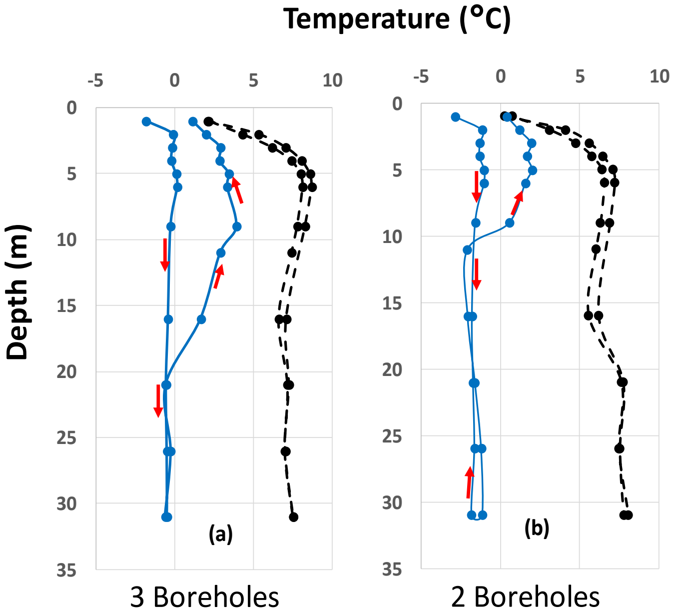


Figure 5. Pipe wall temperature variation for different number of active boreholes.

Table 5. Main test conditions and results

Number of Boreholes	CO_2 Gas bypass flow (kg/s)×10^3	CO_2 total liquid flow (kg/s)×10^3	CO_2 liquid flow/bor (kg/s)×10^3	T_{evap} (°C)	Operation period (hours)	$Q_{GHE/bor}$ (kW)
2	10.40	6.61	3.31	-2.55	15	0.66
3	10.70	8.64	2.88	-0.50	36	0.57

CONCLUSION

In this work, an experimental investigation was performed to analyze the evaporartion process of CO_2 in the GHE as well as its heat extraction performance for different CO_2 mass flow rates per borehole and number of active boreholes of the system. For this purpose, pressure drop through the boreholes and the ground temperature profiles (before and after running the tests) were first monitored and analyzed.

Results show that the evaporation process was completed in the first leg of the U-tube with insufficient CO_2 mass flow rate per borehole. Therefore, the single-phase CO_2 fills the major part of the GHE. Furthermore, single-phase CO_2 temperature at the first leg of the U-tube increases to reach the ground temperature in some cases and it decreases in the second leg due to the thermal interaction with the first leg as well as the cold soil temperature at the shallow depth. It is concluded that a partial two-phase flow rather than a full two-phase flow regime along the U-tube length leads to lower borehole heat extraction rate and it has to be avoided for more efficient DX-GSHP systems design.

It is also shown that employing more boreholes decreases the heat extracted per unit borehole due to lower CO_2 mass flow rate. Nevertheless, increasing the number of GHEs over a certain limit may have a negative impact even on the system performance due to the borehole performance reduction as described in case with insufficient CO_2 mass flow rate.

ACKNOWLEDGMENTS

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NOMENCLATURE

$\dot{m}$ = mass flow rate (kg/s)
Q = Specific heat load (W/m)
T = Temperature of the medium (°C)
P = Pressure
x = Vapour mass fraction quality
ΔP = Pressure drop through the boreholes (kPa)
OEV= Expansion valve opening

Subscripts

in = inlet
out = outlet
bor = Borehole
evap = *Evaporating*
w = *Water*

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