STANDING COLUMN HEAT PUMP WITHOUT BLEED IN A COLD CLIMATE

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Abstract: Typical cold climate houses generally require one 160 m deep vertical closed-loop heat exchanger for ground-source heat pumps. The cost of such a ground heat exchanger is relatively high. The scope of this study was to determine if standing column heat pump systems without bleed are technically and economically feasible in cold climates. Two 150 mm diameter boreholes, 25% and 60% shallower respectively than conventional vertical wells for closed-loop heat exchangers have been designed and tested. The results show that, in the heating mode without bleed, the heat pump shuts-down after 8 to 29 hours of continuous operation depending on the well depth and whether the water is withdrawn from the top or bottom. To recover the initial temperature of the groundwater, the circulating pump has to run for at least 15 additional hours. On the other hand, system performance is high in mechanical cooling and dehumidification mode with both standing column wells. However, the system is unable to provide dehumidification and efficient air cooling in free cooling mode.

Key Words: ground-source heat pump, standing column, energy efficiency

1 INTRODUCTION

Electricity is still a relatively inexpensive energy source for residential space heating in Eastern Canada, while electrical baseboard heaters are easy to install, cheap and have a long technical life. However, increasing oil prices encourage many home owners to move from oil heating to electrical systems. Therefore, electrical utilities have to respond to future increasing power demand and energy consumption. This may represent hundreds of additional megawatts during winter peak power demand, while the cost of new fossil, nuclear or hydro-electric plants is relatively high. In this context, ground-source heat pump systems can contribute at reducing the coincident peak power demand. The scope of this study was to determine whether standing column groundwater heat pumps could represent technical and economical alternatives to geothermal systems with vertical closed-loop heat exchangers in cold climates. Standing columns are similar to open groundwater heat pump systems, but only one well is required for small-and medium-size residential applications. The groundwater is re-circulated from the bottom to the top of the column, or vice-versa, as well as through a water-to-air and/or water-to-water heat pump. During heat extraction in the winter, the column is cooled, and during heat rejection in the summer, it is heated. The performance of standing columns is most affected by such parameters as groundwater temperature, well depth and bleed. Bleed may be employed for purposes such as reducing the required well depth for a given heat transfer rate, improving energy efficiency by moderating fluid temperatures and increasing the efficiency of the heat pump, and preventing freezing in the well during heating operation. The bleed water can be diverted to a storm sewer, used for domestic water consumption, or otherwise disposed of. However, because standing column water systems use groundwater, they are regulated by national or local authorities and some may prohibit bleeding. Disposing off the bleed in cold climate homes is thus technically embarrassing and legally restricted. These were the main reasons to not consider the groundwater bleeding operation in this study.

2 BACKGROUND

A relatively small number of research studies on standing column with or without bleed have been published. Orio et al. (2006) described the configuration and the performance of a 700 kW standing column system in a public school located in Massachussetts (USA). The system used six 455-m deep wells and twenty 35 kW water-to-water heat pumps. After ten years, the standing column wells maintained the groundwater temperature at a 4.4°C minimum in the winter and a 26°C maximum in the summer. During the colder periods, a 10% bleed was activated at an entering groundwater temperature of 6°C, but no bleed was necessary during the summer peak cooling demand. Tan and Kush (1986) reported on a continuous 22-month field test without bleed of a standing column system located in New-York State (USA). The system included a 152.4 mm inner diameter, 189 m deep uncased well coupled to a 17.6 kW water-to-water heat pump. The entering water temperature to the heat pump ranged from 6.9°C in January to slightly over 15.6°C in July. The lower heat pump operation limit, set at a leaving water temperature of 3.3°C, was never reached and, consequently, no bleed was required. Mikler (1993) and Yuill and Mikler (1995) conducted experimental studies using a thermal well without bleed. In these cases, the water flows down inside a vertical pipe and flows up through the annular space between the pipe and the borehole wall. The 152.4 mm diameter and 325 m deep well was used in a 70 kW (cooling capacity) commercial system located at Pennsylvania State University (USA). Four 17.6 kW heat pumps operated at full capacity in both cooling (48 subsequent days) and heating (71 subsequent days) modes. These studies pointed out that the required drilled depth of a thermal well with concentric pipes is about 60% of the depth of a 38.1 mm U-tube heat exchanger, assuming that both are installed in the same geological formation. O'Neil et al. (2006) showed that standing column groundwater systems without bleed allow reductions between 25% and 65% in borehole depth compared to closed-loop systems. With bleed, reductions in the range of 40% to 78% can be achieved. Based on a simplified parametric study for economic analysis purposes, Deng (2004) also showed that standing column systems allow significant reductions in borehole depth, and concluded that, compared with single vertical closed-loop system without bleed, borehole depth reductions between 24.6% and 65.1% are possible.

3 OBJECTIVES

Typical Canadian cold climate houses (10.5 kW of nominal cooling capacity) generally require one 152 m deep, 152.4 mm diameter vertical well with one 31.75 mm inner diameter U-tube. The required specific drilling depth is consequently of 14.5 m per kW of nominal cooling capacity depending on the ground thermal properties and structure. The total cost of such vertical closed-loop, indirect ground-source heat exchangers, including the costs of drilling, U-tube, grout, brine, and filling and purge operations, could be as high as US$10,000 (2011). This cost is relatively high for small-and medium-size houses. Without subsidies, it may discourage consumers from installing ground-source heat pumps for heating and cooling their residences. The first motivation of this study was to determine whether the depths and, consequently, the costs of vertical uncased standing column wells without bleed could be reduced by 20% to 60% compared to those of typical vertical closed-loop heat exchangers in cold and very cold climates. In such climates, space heating is the dominant operating mode of geothermal heat pumps. In extreme cold weather conditions, the heat pumps may *continuously* operate for several hours or even days without, or few, *off* cycles. The groundwater temperature at the evaporator outlet will gradually fall under its freezing point. This temperature reduction occurs when the standing column well is not able to reheat the groundwater as the same rate as its simultaneous cooling within the heat pump. If the temperature of the water inside the evaporator drops below the freezing point, it may locally freeze and expand. It represents a very dangerous phenomenon that may mechanically destroy the evaporator and/or pipe network. To avoid this situation, the compressor suction pressure has to be set at a minimum pressure corresponding to the refrigerant evaporating temperature of 0°C. In this case, one of the most important issues is to determine how many hours are required for the groundwater entering the heat pump to reach the critical limit (about 4.6°C) without bleeding. It is also useful to determine how many hours are required to completely recover the initial groundwater temperature with the circulation pump running, but with the heat pump stopped. Another issue is to determine whether the compressor can re-start at full and/or partial capacity when the groundwater temperature at the inlet of the evaporator approaches the critical limit.

4 DESIGN CONSIDERATIONS

The complicated heat transfer mechanism in standing column wells and surroundings consists in convection, advection and conduction processes (Rees et al. 2004). In this study, it was assumed that the heat transfer by advection in boreholes without bleed can be neglected. In this case, *forced convection* at the borehole wall and casing becomes the dominant heat transfer mode. For a borehole with a 0.15 m inside diameter (d) and 0.63 kg/s groundwater flow rate, the Reynolds and Nusselt numbers, as well as the internal heat transfer coefficient have been calculated. By assuming an average groundwater ΔT within the heat pump evaporator of 2.2°C, the actual thermal power extracted in the heating mode has been also estimated, as well as the thermal power supplied by the heat pump in the heating mode and the coefficient of performance (COP), defined as the thermal power supplied divided by the electrical power input W_{input} (heat pump compressor only or compressor + groundwater and indoor water loop circulating pumps). The average wall temperature differences resulted of 1.6°C inside well #1 (61 m deep) and of 0.8°C within well #2 (122 m deep) (Table 1). Based on these assumptions and design parameters, standing column #1 (61 m deep) extracts 140 W, and the standing column #2 (122 m deep), 70 W of thermal power per meter of borehole length in the heating mode.

5 EXPERIMENTAL BENCH

Based on the simplified design, two standing column wells with a 61 m and 122 m depth respectively were drilled at a 30 m distance each one from another (Figure 1) (Minea 2008). Both wells are cased on the first 10 meters and the rest is uncased in a rock (granite) structure with relatively high thermal conductivity (2.8 W/mK). The groundwater is abundant, and moves slightly with hydrostatic levels close to the ground surface. The static groundwater table level is at depths varying between 1 m and 1.5 m, depending on the season. Both wells were caped because in the spring and fall, the groundwater is under pressure. The experimental standing column wells provide heat source/sink to a two-stage 10.5 kW water-to-water geothermal heat pump. The first stage provides 67% (7 kW) and the second, 100% of the nominal heating and cooling capacities. Groundwater is alternately withdrawn at the top of each well at depths of 5 meters, and at the bottom at depths of about 59.5 m and 120 m, respectively. When the water is withdrawn at the bottom, it is re-injected at the top sides of the wells, and vice-versa. A manual valve assembly with pipe by-passes switches the groundwater flow and direction from one well to another, and allows the system to be operated in the free cooling mode as well. Groundwater is filtered and filter F is periodically cleaned. The 0.35 kW groundwater circulation pump is located outside the wells at ground level. At the outlet of the heat pump, a three-way bleed valve can, if required, extract water from the loop when the inlet temperature drops under preset limits in the winter as well in the summer. The heat pump supplies hot water (in heating mode) and cold water (in cooling mode) to an indoor closed-loop. Indoor water loop pump circulates the hot or cold water through the air handler equipped with a fan coil and air blower. When the system is to be operated in the free cooling mode, the groundwater by-passes the heat pump and flows directly through the fan coil prior to returning to the wells. The standing column well simplified design described above has been validated for short periods of operation in both heating and cooling modes. However, the most important challenge of this study was to validate the design in extreme operating conditions in cold and very cold climates. One of these *extreme* conditions is the *continuous* operation in the heating and cooling modes over relatively long periods of time. The *question* was: are the standing column wells able to ensure safe and reliable operation of the heat pump?

Table 1: Design parameters and thermal power extraction in the heating mode

Parameter and equation (unit)	Symbol	Value
Groundwater flow rate (kg/s)	$\dot{m}_w$	0.63
Well inner diameter (m)	d	0.15
Groundwater dynamic viscosity (Pa.s)	μ	1400.10^{-6}
Groundwater density (kg/m^3)	ρ	1000
Groundwater specific heat (kJ/kgK)	$c_{p,w}$	4.18
Borehole interior cross flow section (m^2)	A	0.0182
Groundwater velocity (m/s)	v	0.0346
Reynolds number: $\mathrm{Re}_d = 4\dot{m}_w / \pi d \mu$	Re	3762
Groundwater thermal conductivity (W/mK)	k	0.57
Nusselt number: $Nu_d = 0.023\,\mathrm{Re}_d^{0.8}\,\mathrm{Pr}^{0.3}$ (Incropera and DeWitt 2002)	Nu	33.7
Convective heat transfer coefficient $h_{in} = Nu_d k / d$ (W/m^{2}K)	h_{in}	128
Heat transfer area: well #1 (61 m deep) (m^2)	A_1	28.73
Heat transfer area: well #2 (122 m deep) (m^2)	A_2	57.46
Wall temperature difference: well #1 (61 m deep) (°C)	$\Delta T_{wall,1}$	1.6
Wall temperature difference: well #2 (122 m deep) (°C)	$\Delta T_{wall,2}$	0.8
Groundwater average ΔT through the heat pump (°C)	ΔT_{hp}	2.2
Heat pump thermal power extraction from wells (W) $\dot{Q}_{extr,\mathrm{hp}} = \dot{m}_w c_{p,w} \Delta T_{\mathrm{hp}} = A_1 * h_{in} * \Delta T_{wall,1} = A_2 * h_{in} * \Delta T_{wall,2}$	$\dot{Q}_{extr,hp}$	5884
Thermal power supplied by the heat pump: $\dot{Q}_{\sup l} = \dot{Q}_{extr,hp} + W_C$ (W)		8544
System coefficient of performance: $COP = 1 + \dot{Q}_{extr,hp} / W_{input}$	COP	2.5 – 3.5
Specific thermal power extraction: well #1 (61 m deep) (W/m)	-	140
Specific thermal power extraction: well #2 (122 m deep) (W/m)	-	70

6 HEATING MODE

The maximum operating time of the heat pump in *continuous* heating mode was determined as a function of the well depth (61 m or 122 m) and the groundwater withdraw level (top or bottom) at the same flow rate (0.63 kg/s). The critical parameters surveyed were the temperatures of the groundwater entering and leaving the heat pump evaporator.

6.1 Continuous operation at full capacity

Tests in the continuous heat mode at full compressor capacity (2nd stage) were conducted with groundwater temperatures varying from 7°C to 9°C at the beginning of each cycle (Table 2). In all cases, with a groundwater flow rate of 0.63 kg/s and bottom or top extraction, the average temperatures at the end of cycles reached 4.6°C at the inlet and 2.6°C at the outlet of the heat pump evaporator. With these parameters, the evaporating temperature of refrigerant R-410A at the end of each cycle dropped to 0°C, a temperature corresponding to the compressor limit suction pressure (0.8 MPa). At this pressure the heat pump compressor shut down. With a 0.63 kg/s groundwater flow rate and *bottom* extraction, the heat pump operated continuously in the heating mode at full capacity for a maximum of 10 hours in the case of the 61 m well and about 24 hours in the case of the 122 m well (Figure 2a, b). In the case of top water extraction with the same 0.63 kg/s flow rate, the heat pump has continuously operated in the heating mode at full capacity for a maximum of 8 hours in the case of the 61 m well and about 29 hours in the case of the 122 m well (Figure 3a, b). To avoid the heat pump from stopping at the compressor low pressure limit, the well temperature can be returned to the far-field temperature by bleeding off some of the system flow, which can be extracted and discharged to some other well or watercourse.

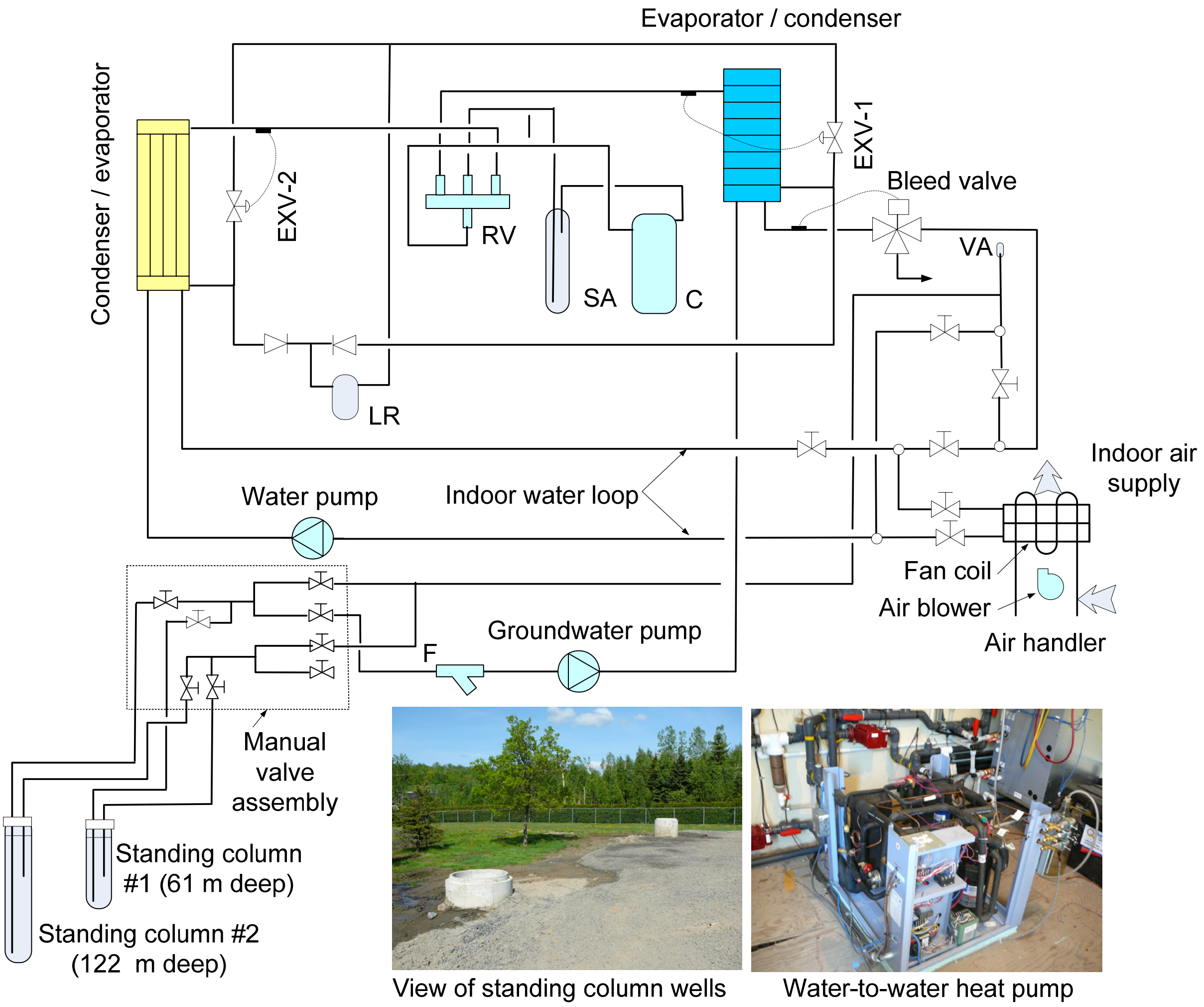
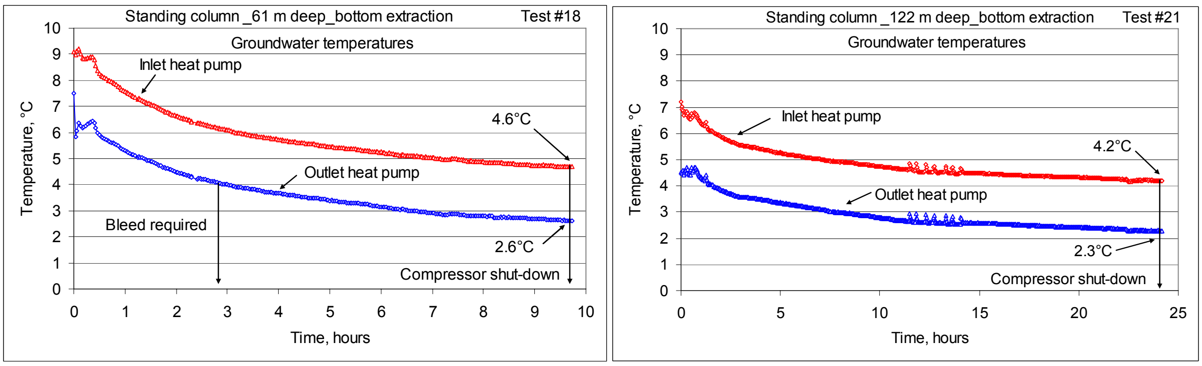


Figure 1: Experimental bench of the standing column system. C: compressor; EXV: expansion valve; F: filter; LR: liquid receiver; P: water circulating pump; SA: suction accumulator; VA: vent air

This will cause water inflow to the column from the surrounding rock formation, induce an additional flow of groundwater into the well, increase the heat exchange capacity and, finally, protect against approaching freezing conditions. The bleeding has to be initiated whenever the well water temperature drops below 4.6°C. This automatic operation may last for 30 minutes and divert approximately 10% of the groundwater flow from returning to the wells.

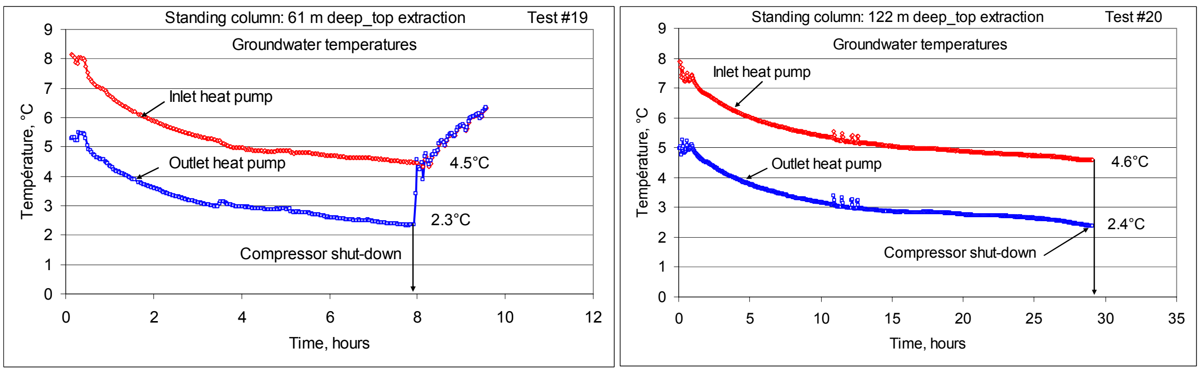
Table 2: Maximum operating time in the continuous heating mode at full compressor capacity

Test	Well depth	Water withdrawn	Groundwater temperatures at the heat pump evaporator			Evaporating temperature	Operating time
-	-	-	Initial	Final		Final	-
-	-	-	Inlet	Inlet	Outlet	-	-
-	m	-	°C	°C	°C	°C	Hours
#19	61	Top	8.0	4.5	2.3	-0.3	7.93
#18	61	Bottom	9.0	4.7	2.6	0.0	9.73
#20	122	Top	7.5	4.6	2.4	-0.3	29.13
#21	122	Bottom	7.0	4.8	2.9	-0.2	24.2



(a) (b)

Figure 2: Groundwater temperatures entering and leaving the heat pump with *bottom* extraction. (a) 61 m deep well; (b) 122 m deep well



(a) (b)

Figure 3: Groundwater temperatures entering and leaving the heat pump with *top* extraction; (a) 61 m deep well; (b) 122 m deep well

During all tests, when the entire flow of groundwater extracted is circulated through the heat pump system and returned to the well, the average condensing temperatures of 47°C allowed the continuous supply of hot air to the house at around 40°C, which is an outstanding performance in the heating mode. The heat pump was operated with optimum parameters, i.e. compression ratio of 3.8, compressor superheating of 6.5°C and condenser liquid sub-cooling between 2 and 3.6°C (Table 3). Table 4 summarizes the system energy balance at full compressor capacity, including the electrical energy consumed by the heat pump compressor, the groundwater and distribution hot water circulation pumps, as well as the thermal energy extracted from the standing columns and supplied to the indoor air.

Table 3: Heat pump thermodynamic parameters in the *continuous* heating mode at *full* capacity

Test	Condensing temperature	Air supply temperature	Compression ratio	Compressor superheating	Condenser sub-cooling
	°C	°C	-	°C	°C
#19	47	40	3.7	6.6	2.9
#18	48	40	3.8	6.8	2.0
#20	47	39	3.7	6.6	3.4
#21	47	40	3.8	6.4	3.7

The coefficients of performance calculated only with the compressor energy consumption varied between 3.1 and 3.4. However, the coefficients of performance of the entire system, calculated with the energy consumptions of the compressor and groundwater and indoor water loop pumps, but excluding the indoor fan, were between 2.6 and 2.8, i.e. 17% to 20% less than the previous values. Optimization of the groundwater and indoor water loop design and selection may further improve the system overall performance.

Table 4: System energy balance in the *continuous* heating mode at *full* capacity

Test	Electrical input power and energy consumption			Thermal energy		Coefficient of performance (COP)	
-	Compressor	Ground water pump	Hot water pump	Extracted from well	Supply	COMPR only	COMPR + water pumps
-	kW (kWh)	kW (kWh)	kW (kWh)	kWh	kWh	-	
#19	2.45 (19.43)	0.35 (2.77)	0.2 (1.58)	44.2	63.5	3.27	2.67
#18	2.60 (25.3)	0.35 (3.40)	0.2 (1.94)	55.3	81.2	3.30	2.65
#20	2.50 (72.82)	0.35 (10.19)	0.2 (5.82)	175.5	247	3.38	2.78
#21	2.53 (61.22)	0.35 (8.47)	0.2 (4.84)	130	193	3.15	2.59

6.2 Intermittent operation at full capacity

The intermittent mode is the normal operating mode of heat pumps in residential applications. However, restarting the compressor a few minutes after it shuts down at its low pressure limit and/or at the request of the indoor thermostat could become a critical issue. That is firstly because of too low temperature of the heat source (groundwater) at the inlet of the heat pump evaporator. Without bleed, it can be as low as 5°C when the heat pump is called to restart. Figure 4a shows two (A and B) failed attempts to restart the compressor on its first stage after relatively long periods of time when the heat pump has not run and the groundwater has recovered its initial undisturbed temperature. Moreover, after about nine months of quasi-continuous operation, it was found that the compressor of the heat pump has never re-started at full capacity (2nd stage) (Figure 4b) even if the average groundwater temperature entering the evaporator was around 7.5°C (Figure 4c) and the water flow rate was 2.2 times higher compared to the previous tests. This was mainly due to the clogging of the evaporator interior heat transfer surface. It possibly altered the interior overall heat transfer coefficient. With lower heat transfer intensity, the refrigerant evaporating pressure quickly dropped under the protection limit during each restarting attempt of the compressor at its full capacity.

6.3 Operation at partial capacity

The unpredictable situation consisting in the inability to restart the heat pump at full capacity has lead to try operating the system at partial (67%) capacity, the second stage being disaffected. After having recovering the groundwater initial undisturbed temperature, the compressor shut down after about 10 hours of continuous operation. The subsequent groundwater thermal recovery period lasted approximately 15 hours with the circulating pump running (Figure 5a). Figure 5b shows all five successive heating cycles with the 61 m deep standing column well with *top* water extraction. Each of these cycles ended when the groundwater temperature at the outlet of the heat pump became low enough to attain the compressor suction pressure limit. As the first one, each subsequent cycle was followed by thermal recovery periods of about 15 hours allowing the initial groundwater temperature to be fully recovered.

7 MECHANICAL COOLING MODE

The heat pump cooling mode was studied in order to determine whether the standing column wells could efficiently cool and dehumidify the indoor air while dissipating the recovered sensible and latent heat to the ground. Experimental variables (Table 5) include the depth of the standing column wells (61 m or 122 m) and the groundwater withdrawn level (top or bottom of wells). Results from two representative tests are shown in Figure 6a, b. The heat pump ran continuously during 116 hours (test #22 with 1.44 kg/s) and 102.83 hours (test #23 with 1.1 kg/s), respectively.

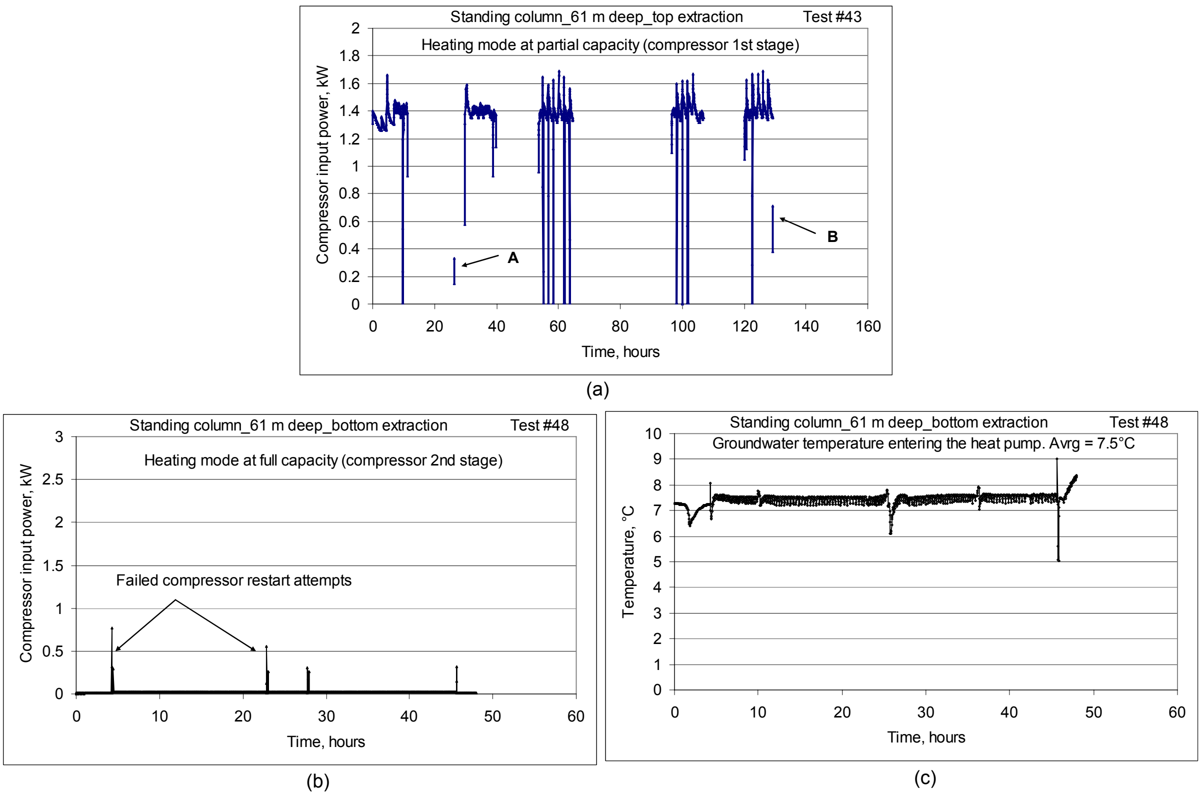
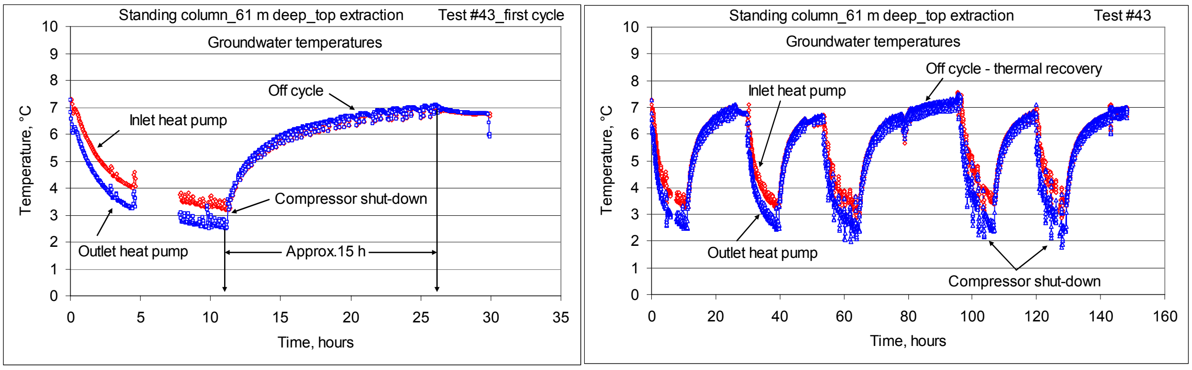


Figure 4: Failed attempts to restart the compressor; (a) at partial capacity (1st stage); (b) at full capacity (2nd stage); (c) groundwater temperature entering the heat pump. A, B: compressor failed attempts to restart at full capacity (compressor 2nd stage)



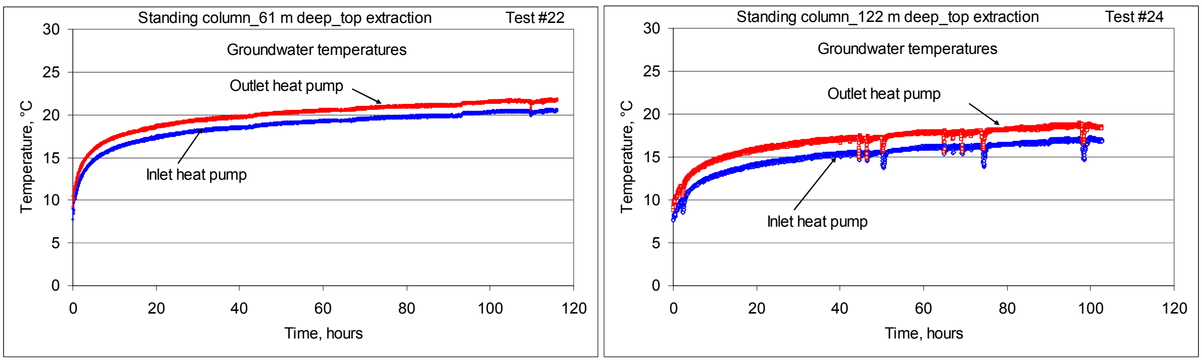
(a) (b)

Figure 5: Operating cycles of the 61 m standing column well at *partial compressor capacity (67%)*; (a) first cycle; (b) all five successive cycles

In this mode, the critical parameter was the groundwater temperature entering the heat pump. At the end of test #22, for example, with the heat pump continuously operating at full cooling capacity with the 61 m deep well, the groundwater enters the heat pump condenser at 18.7°C. This result indicates that a specific standing column well depth of 5.82 m per kW of nominal cooling capacity achieves excellent performance in the mechanical cooling mode.

Table 5: Experimental variables in the *mechanical cooling mode* at full compressor capacity

Test	Well depth	Water withdrawn	Water flow rate	Test duration
-	m	-	kg/s (gpm)	Hrs.
#22	61	Top	1.42 (22.5)	116
#23	61	Top	0.64 (10.2)	49.33
#24	122	Top	1.1 (17.4)	102.83



(a) (b)

Figure 6: *Mechanical cooling* mode: groundwater temperatures entering and leaving the heat pump condenser. Flow rates = 1.26 kg/s (20 gpm). (a) 61 m deep well (test #22); (b) 122 m deep well (test #24)

The compressor electrical input power was of 0.95 kW, 62% lower compared to conventional air cooling devices with the same capacity. Cooling water was supplied to the air handler fan coil at 6.8°C, and the indoor air was cooled from 21°C to about 12.7°C (Table 6). The electrical input powers of the groundwater and cooling water circulation pumps were constant at 0.35 kW and 0.204 kW, respectively. Table 7 details the heat pump main measured parameters in the cooling mode. Table 8 shows that the heat pump energy efficiency ratios

(EER), defined as the thermal energy extracted from the air, expressed in Btu (1 kWh = 3412 Btu), divided by the compressor energy consumption, expressed in kWh, reached values in the range of 21 to 28. However, considering also the electrical energy consumptions of both water circulation pumps, in addition to the compressor energy consumption, the EERs decrease by up to 39%. Design optimization of these pumps is recommended for each particular residential standing column heat pump application.

Table 6: *Mechanical cooling mode*: system measured parameters

Test	Compressor power input	Groundwater temperature at the end of cycle		Cooled water		Indoor air	
-	-	Heat pump inlet	Heat pump outlet	Inlet fan coil	Outlet fan coil	Inlet fan coil	Outlet fan coil
	kW	°C	°C	°C	°C	°C	°C
#22	0.94	18.7	20	6.8	8.7	21	12.7
#23	0.95	17.8	22	7.2	9.1	21.3	13.1
#24	0.86	15.2	17	7.2	9.2	22.2	13.5

Table 7 : *Mechanical cooling mode*: heat pump measured parameters

Test	Evaporating temperature	Condensing temperature	Compression ratio	Superheating	Sub-cooling
	°C	°C	-	°C	°C
#22	2.5	25	1.8	4.7	0.4
#23	2.7	26	1.8	4.9	0.2
#24	3.7	22	1.6	5.4	2.5

Table 8: *Mechanical cooling mode*: heat pump energy performance

Test	Electrical energy consumed			Thermal energy		Energy efficiency ratio (EER)	
-	Compressor	Groundwater pump	Cold water pump	Extracted from air	Rejected to groundwater	Compressor only	Compressor and water pumps
-	kWh	kWh	kWh	kWh (10^{-3}Btu)*	kWh	Btu/kWh	Btu/kWh
#22	115	49.4	23.7	780 (2 661)	895	23	14
#23	46.3	19.1	11.0	298 (1 017)	353	21	13.3
#24	87.2	39.8	16.2	727 (2 480)	814	28.4	17.3

* Btu: British thermal unit

8 FREE COOLING MODE

Free cooling mode consists in directly using the groundwater for cooling and dehumidifying the indoor air during the hot and humid seasons. The experimental variables considered in this study were the standing column depth (61 m and 122 m), the groundwater drawn level (top or bottom of the wells) and the groundwater flow rate (Table 9). The tests #2 (36.39 hours) and #3 (11.54 hours) were conducted with groundwater drawn at the *top* of the 62.5 m well with average flow rates of 1.1 kg/s. During a short period of time (about 1.6 hours) at the beginning of the free cooling cycles, the groundwater temperatures leaving the fan coil were lower than the dew point of the indoor air (12-13°C) and thus dehumidification of indoor air was provided. After this relatively short period of time, the groundwater temperatures at the fan coil outlet exceeded the indoor air dew point by at least 2°C to 4°C and, therefore, air dehumidification was no longer achieved. In the case of test #49, during which 1.03 kg/s of groundwater was drawn at the bottom of the 122 m standing column well for more than 97 hours (Table 9), the final average temperature of the groundwater leaving the fan coil was 12°C (Figure 7a and Table 10), approximately equal with the dew point of the indoor air. The indoor air was cooled down to 15°C, but not dehumidified (Figure 7b). These results prove that in cold climates, free cooling with standing column wells having a depth of 122 m or less isn't very efficient for both air dehumidification and cooling.

Table 9: *Free cooling mode*: experimental data

Test	Well depth	Water withdrawn	Groundwater flow rate	Test duration
-	m	-	kg/s	Hrs.
#2	61	Top	1.12	36.39
#3	61	Top	1.1	11.54
#49	122	Bottom	1.04	97.54

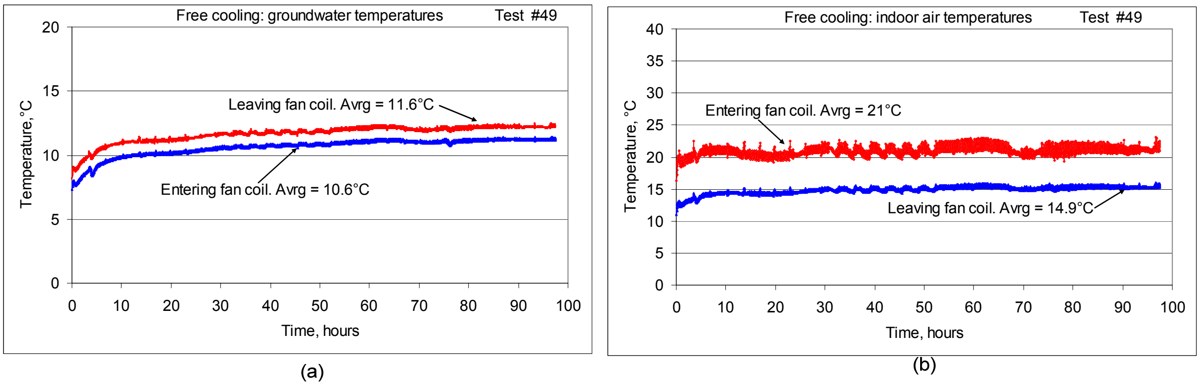


Figure 7: *Free cooling* mode. (a) groundwater temperatures; (b) indoor air temperatures (test #49)

Table 10: *Free cooling mode*: system measured parameters and performance

Test #	Groundwater temperature		Indoor air temperature	
-	Fan coil inlet	Fan coil outlet	Fan coil inlet	Fan coil outlet
	°C	°C	°C	°C
#2	15.3	16.3	25	19.4
#3	14.5	15.1	27.6	20
#49	11.6	12.6	21	14.9

9 CONCLUSIONS

Two 150 mm diameter boreholes, 25% and 60% shallower respectively than conventional vertical wells for residential closed-loop heat exchangers were designed, constructed and tested. The results show that it is possible to use standing column heat pumps for heating houses in cold climates with relatively high coefficients of performance, but only for limited periods of time. The continuous heating mode without bleed showed that both depths would not be sufficient to provide safe operation of the heat pump in cold climates. In the heating mode, the heat pump shuts down after 8 to 29 hours depending on the well depth and whether the water is withdrawn, from the top or from the bottom. To recover the initial undisturbed groundwater temperature, the circulating pump has to run for at least

15 additional hours at full flow rate. After the compressor stops at its suction pressure limit, restarting the heat pump is very difficult, sometimes impossible, because of too low temperature of the groundwater and, in certain cases, of possible clogging of the evaporator interior heat transfer surface. It is one of the most critical issues for this kind of geothermal systems. Because of these technical problems, even properly designed and installed standing column wells couldn't compete with the closed-loop and could not be applicable in cold climates. However, in the mechanical continuous cooling mode, both standing column systems have adequately operated. After more than 100 hours of continuous operation in this mode, the temperature of the groundwater leaving the heat pump stabilized at 22°C, while the global energy efficiency ratios varied between 13 and 17. Finally, in the free cooling mode, even if some air cooling could be provided, efficient dehumidification of the indoor air is practically not achievable at long term during hot and humid weathers.

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