

Improving ground heat exchangers for geothermal heat pump systems with a groundwater-filled borehole and a thermally enhanced double U-pipe



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ABSTRACT

Ground heat exchangers (GHEs) used for geothermal heating and cooling systems in North America, more specifically ground-coupled heat pump systems, are commonly made of a single U-pipe installed in a borehole backfilled with grout. This design can be improved to minimize the borehole thermal resistance and increase the system performance. A backfill free GHE with a double U-pipe made of thermally enhanced high-density polyethylene and allowing internal free convection of the groundwater inside the borehole was installed at INRS laboratories to verify this alternative design inspired by Scandinavian methods. A thermal response test was performed to evaluate the borehole thermal resistance. Analysis revealed, in best operating conditions, a borehole thermal resistance equal to 0.05 m K W^{-1} , which is 43 % lower than the thermal resistance inferred for a single U-pipe GHE installed at the same site with the conventional design method.

RÉSUMÉ

Les échangeurs de chaleur géothermique (ÉCG) utilisés pour les systèmes de chauffage et de climatisation en Amérique du Nord, plus précisément les systèmes de pompe à chaleur couplés au sol, sont couramment faits d'un tube en U simple installé dans un forage remblayé avec du coulis. Cette conception peut être améliorée en minimisant la résistance thermique du forage et augmentant ainsi la performance du système. Un ÉCG libre de matériaux de remplissage avec un double tube en U, fait de polyéthylène de haute densité amélioré sur le plan thermique, facilitant la convection naturelle de l'eau souterraine dans le forage a été installé aux laboratoires de l'INRS pour vérifier cette conception alternative, inspirée des méthodes scandinaves. Un test de réponse thermique a été réalisé pour évaluer la résistance thermique du forage. L'analyse indique, dans les meilleures conditions d'opération, une résistance thermique de forage égale à $0,05 \text{ m K W}^{-1}$, ce qui est 43 % inférieur à la résistance inférée pour un ÉCG ayant une conception conventionnelle avec un seul tube en U et installé sur le même site.

1. INTRODUCTION

Ground-coupled heat pump (GCHP) systems offer an energy-efficient heating and cooling alternative for buildings. GCHP can actually help achieve energy savings on the order of 60-70 % of the heating and 30-40 % of the cooling needs. The installation cost of such system is however important (Robert and Gosselin, 2014), especially when compared to other heating and cooling systems that do not require ground heat exchangers (GHEs). Care should be taken when designing geothermal systems to minimize GHE length and deliver cost-competitive GCHPs. Possible alternatives are to reduce the heating and cooling loads imposed to the ground loop with hybrid technologies, increase distances between GHE and decrease the borehole thermal resistance. Sizing methods, for example that described by Philippe et al. (2010), can yield a 10 to 30 % borehole length reduction with a significant decrease of the borehole thermal resistance. Conventional materials and pipe configuration used by the North American geothermal industry are indeed quite resistive and do not offer an optimal thermal performance. GHE are commonly made with a single U-pipe of high-density polyethylene (HDPE) standing in a borehole filled with a grout composed of silica sand, bentonite and water.

Efforts have been made to improve the grout thermal conductivity (Allan and Kavanaugh, 1999; Carlson, 2000; Borinaga-Treviño et al., 2013b, 2013a) or the pipe diameter and configuration (Raymond et al., 2015) to reduce the borehole thermal resistance, but often opting for boreholes filled with solids. In Scandinavia, GHE are commonly filled by groundwater only (Gustafsson and Westerlund, 2011; Gehlin et al., 2016). The idea is that natural convection due to vertical temperature differences in groundwater-filled boreholes can help enhance heat transfer (Spitler et al., 2016). This concept was combined with thermally enhanced pipe made of HDPE containing carbon type nanoparticles (Gosselin et al., 2017) to verify the applicability of Scandinavian GHE design in the St. Lawrence Lowlands, which is the largest geothermal market in Canada (Canadian GeoExchange Coalition, 2012). The objective of this project was, therefore, to evaluate the borehole thermal resistance reduction provided by a groundwater-filled borehole, which was actually improved by using a double thermally enhanced U-pipe. The enhanced GHE was installed at INRS geothermal pilot site, where a conventional GHE made with a single U-pipe and filled with grout had previously been installed and subject to a thermal response test (TRT; Ballard et al., 2016; Raymond et al., 2017). A new TRT was

made with the improved GHE (Ballard et al., 2019), such that resistances evaluated in the field were compared.

2. MATERIALS AND METHODS

The conventional GHE previously installed at INRS pilot site has a diameter of 114 mm (4.5 in) and a depth of 154 m (505 ft; Figure 1). The single U-pipe made of regular HDPE has a nominal diameter of 32 mm (1.25 in), a surface to dimension ratio (SDR) equal to 11 and a thermal conductivity of $0.4 \text{ W m}^{-1} \text{ K}^{-1}$. The borehole is filled with thermally enhanced grout made of silica sand, bentonite and water having a thermal conductivity of $1.7 \text{ W m}^{-1} \text{ K}^{-1}$. The enhanced GHE have a diameter of 152 mm (6 in) and a depth of 164.6 m (540 ft; Figure 2). The double U-pipe placed with no backfill material and made of thermally enhanced HDPE have the same diameter and SDR, but a thermal conductivity of $0.7 \text{ W m}^{-1} \text{ K}^{-1}$. Upon installation, drillers had a doubt that the double U-pipe would reach the bottom of the hole but it was easily sunk until the base of the borehole under the weight of water inside the pipe. Groundwater inside the annular space between the open borehole wall and the pipe stabilized at a level of 2.45 m below the ground surface.

Both boreholes are located 20 m from each other and intercepted a similar stratigraphy (Figures 1 and 2). Backfill material was found down to a depth of 2 m, followed by 8 m of till and clay and then shale, constituting the host rock. This last geological unit is the Les Fonds Formation of the Sainte-Rosalie Group in the St. Lawrence Lowland sedimentary basin (Globensky, 1987). The undisturbed subsurface temperature was measured with a submersible probe over the depth of the new borehole before conducting the TRT, which revealed an average value equal to $7.8 \text{ }^\circ\text{C}$.

A TRT was performed with water circulation in the double U-pipe, starting near the end of December 2017 (Ballard et al., 2019). The flow rate and the water temperature at the inlet and outlet of the GHE during the test were recorded every minute with an accuracy of 0.3 % and $0.03 \text{ }^\circ\text{C}$, respectively. The heat injection rate was calculated from the flow and temperature data. Two sequences of heat injection, each followed by a monitoring of the thermal recovery, were achieved (Table 1). In fact, three sequences of heat injection were attempted but monitoring problems creating data gaps occurred during one of the sequences such that it was discarded for analysis. During the first successful round of heat injection, the flow rate was varied but a similar heat injection rate was maintained. The heat injection rate was increased by about 10 W m^{-1} during the second round of heat injection. Minor heat extraction occurred during both recovery periods as the test was conducted during winter and the surface piping was exposed to cold atmospheric temperature, although isolated. The total duration of the test with useful data was 434 h.

Similar to the previous test conducted at the site, the inlet and outlet water temperature were averaged to evaluate the mean water temperature increments with the p -linear average (Marcotte and Pasquier, 2008). This fitting parameter was assumed to tend toward -1 to take into account the asymmetric temperature distribution along the

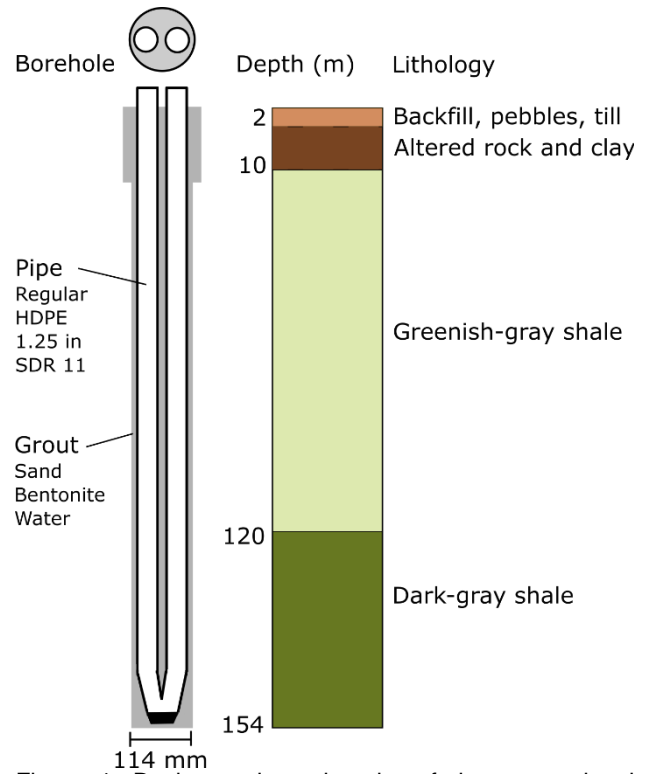


Figure 1. Design and stratigraphy of the conventional ground heat exchanger installed at INRS pilot site.

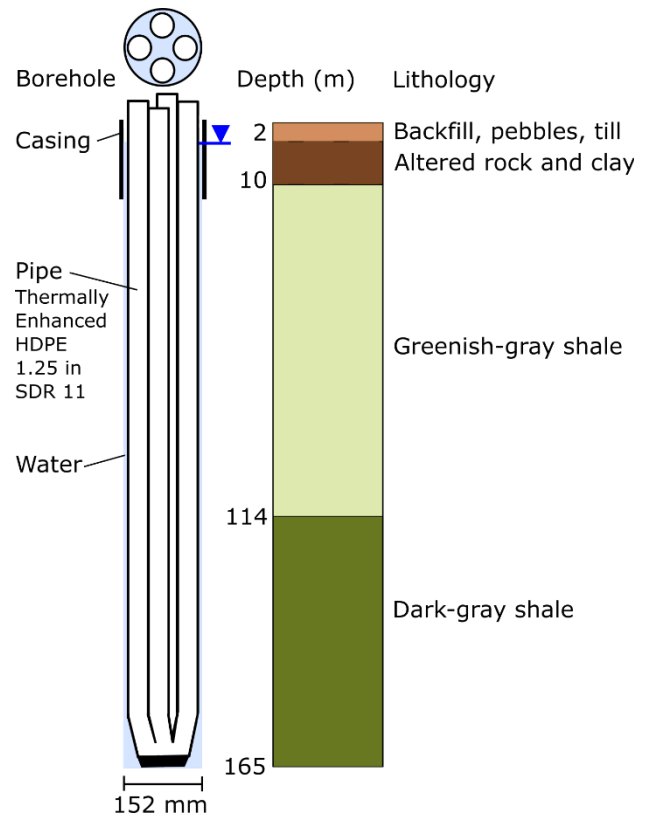


Figure 2. Design and stratigraphy of the enhanced ground heat exchanger installed at INRS pilot site.

Table 1. Average water flow and heat injection rates during the thermal response test conducted on the enhanced ground heat exchanger at INRS pilot site.

Period	End time (h)	Flow rate ($10^{-4} \text{ m}^3 \text{ s}^{-1}$)	Heat injection rate (W m^{-1})
1a	63.0	4.10	27.3
1b	108.2	2.05	28.4
1c	323.5	1.00	-0.30
2a	383.2	2.84	38.5
2b	434.1	2.84	-0.40

GHE pipes. Observed temperature increments were reproduced with the infinite line source equation taking into account variable heat injection rates with the superposition principle (Raymond et al., 2011). A non-linear solver was used to minimize the sum of squared residuals between observed and calculated temperature (Lasdon et al., 1978), automatically adjusting the subsurface thermal conductivity and the borehole thermal resistance. The subsurface thermal conductivity was assumed constant during the test duration, while three different borehole thermal resistances were considered; two for the first heat injection period with the two different flow rates and one for the second heat injection period. These four unknowns were adjusted all together in a single optimization sequence, which differs from previous analysis where optimization was made one parameter at a time (Ballard et al., 2019). The subsurface heat capacity, a parameter needed to compute the GHE temperature, was assumed equal to $2.3 \text{ MJ m}^{-3} \text{ K}^{-1}$ according to the description of geological materials intercepted while drilling and available literature (Waples and Waples, 2004a; 2004b).

3. RESULTS

Fifty data points were correlated to the observed temperature and the sum of squared residuals was minimized to $0.04 \text{ }^\circ\text{C}^2$ in the single optimization considering the whole test sequence (Figure 3). The analysis conducted for the enhanced GHE revealed a subsurface thermal conductivity equal to $1.74 \text{ W m}^{-1} \text{ K}^{-1}$, which compares to $1.75 \text{ W m}^{-1} \text{ K}^{-1}$ for the test achieved on the previous GHE (Raymond et al., 2017). Borehole thermal resistances equal to 0.050, 0.093 and 0.063 m K W^{-1} were found for the enhanced GHE considering each period of heat injection given in Table 1, namely 1a, 1b and 2a. This compares to a borehole thermal resistance of 0.088 m K W^{-1} inferred for the conventional GHE at the same site (Raymond et al., 2017).

The borehole thermal resistance of the groundwater-filled GHE with a double U-pipe appears to vary according to both the heat injection rate and the pipe flow rate (Figure 4). Counterintuitively, the change of resistance with the increasing flow rate seems more important and better correlated than that associated to the change of heat injection rate. With a doubled flow rate, the borehole thermal resistance decreased by 46 %.

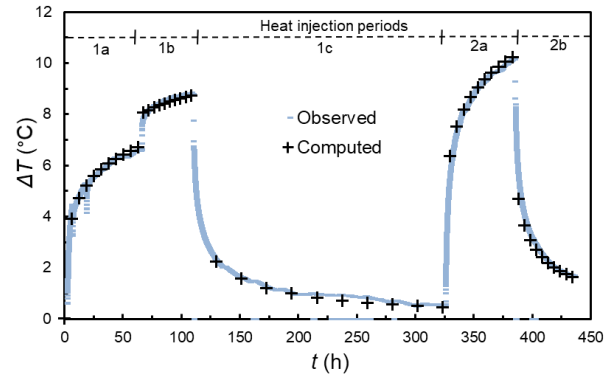


Figure 3. Observed water temperature (p -linear average) recorded during the thermal response test conducted with the enhanced ground heat exchanger at INRS pilot site matched to computed water temperature for analysis using the infinite line source equation.

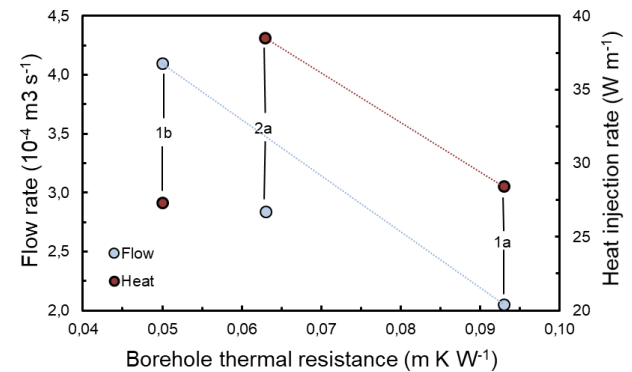


Figure 4. Borehole thermal resistance inferred from the enhanced ground heat exchanger at INRS pilot site correlated with flow rate and heat injection rate. Dotted lines connect points that can be compared together, which have a similar heat injection rate (1a; 1b) and a variation in flow rate or similar flow rate and variation in heat injection rate (1a; 2a).

4. DISCUSSION

The GHE installed at INRS geothermal test site has a unique design. It combines for the first time a groundwater-filled borehole and a thermally enhanced pipe, with double connections in that case. This GHE design inspired by Scandinavian methods was shown to have a borehole thermal resistance that can be 43 % smaller to 6 % higher than that of a single U-pipe GHE filled with grout and tested on the same site. The thermal resistance of groundwater-filled borehole is known to change with the heat injection rate (Gustafsson and Westerlund, 2011; 2010). At a constant flow rate imposed to the GHE pipe, the higher is the heat injection rate, the more natural convection can occur in the groundwater filling the borehole, which can result in a lower borehole thermal resistance (Spitler et al., 2016). The variation of the borehole thermal resistance with respect to the rate of water flowing in the GHE pipe requires more attention. A low flow rate can increase the

thermal interference between pipe legs and therefore increase the internal borehole thermal resistance (Lamarche et al., 2018). In our study, the flow rate was shown to have a major impact on the borehole thermal resistance, which was lower (0.05 m K W^{-1}) for the highest flow rate considered ($4.1 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$), although the heat injection rate was at its minimum (27.3 W m^{-1}). Further evaluation of the internal borehole thermal resistance and an assessment of free convection taking place inside the groundwater filling the borehole are needed to go beyond the pragmatic field testing approach described in this manuscript and carefully explain the inferred resistances.

5. CONCLUSIONS

The enhanced GHE tested during this study can offer several advantages. Not only it can have a low borehole thermal resistance when the water flow rate of the GHE pipe is appropriate, but it also avoids grouting material and manipulations. The decrease of the borehole thermal resistance can help minimize the required borehole length to reduce the cost of drilling, while avoiding grouting can further help reduce cost because less material is put inside the GHE. Grout is used in GHEs to ensure thermal contact when the ground is not saturated and to prevent surface water infiltration as well as vertical groundwater flow along the borehole in the presence of multiple aquifers. Therefore, care should be taken to ensure efficient heat transfer and protect groundwater resources when choosing not to grout GHEs. At 2.45 m below the surface, the water table at INRS test site is relatively shallow and significant loss in thermal contact is not expected considering that the borehole had a depth of 164.6 m. Aquifer potential was not expected at the site. Minor groundwater flow has been inferred in fractured horizons of the shale unit that is considered an aquitard (Koubikana Pambou et al., 2019), such that if vertical groundwater flow occurs along the borehole, there should be no threat to groundwater resources. This study clearly shows significant advantages associated to the enhanced GHE to consider this alternative design for geothermal heat pump systems.

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