EVALUATION OF A GROUND THERMAL ENERGY STORAGE SYSTEM FOR HEATING AND COOLING OF AN EXISTING DWELLING

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ABSTRACT

The modelling and analysis of a heat pump system for heating and cooling applications that utilizes surface ground as a thermal storage are described. The energy analysis is used to evaluate the performance of the system. The modelling efforts involve both simplified and comprehensive models. The simplified models of heating and cooling loads of a building, a heat pump unit, and heat transfer at the ground heat exchanger provide a relatively straightforward link to the comprehensive model of heat and moisture transfer in the ground, based on the finite element method. This combination of models facilitates a reasonably accurate and practical simulation tool for ground-coupled heat pump systems. The use of a horizontal ground heat exchanger (pipe) and the impact of heat deposition and extraction through it in the ground are studied. Parameters, such as length of pipe, depth of pipe and layout of pipe loop, are considered in order to achieve good thermal performance of the system and environmental sustainability of the ground. The design of a ground-coupled heat pump system for an existing residential dwelling in Ontario is used as a demonstration of the simulation tool.

INTRODUCTION

This paper considers the simulation of a ground-coupled heat pump (GCHP) system for heating and cooling of a residential dwelling. The system uses surface ground (not deeper than 2.0 m) as a thermal energy storage for storing thermal energy in the summer and for retrieving it in the winter. In addition to the renewable energy (such as, solar energy) received by the ground in the summer, the ground may also receive the heat rejected by the system during cooling operation. The link between a heat pump and the ground is a ground heat exchanger (GHE). There are two basic GHE configurations: vertical and horizontal.

Vertical GHE loops are made of co-axial pipes, coiled tubes or U-tubes placed in drilled vertical holes, and they are usually connected in a parallel arrangement. Horizontal GHE loops consist of straight or coiled tubes which are buried in trenches. They may be connected in series, in parallel or in a mixed arrangement.

The aim of a GHE design is to obtain a proper length of pipe which is capable of rejecting to and/or extracting from the ground the required amount of thermal energy. A challenging part of the design is to predict the thermal response of the soil surrounding the GHE since there are many parameters involved which can affect the performance of the GHE. Some examples are local climate, depth and layout of the GHE, system load characteristics, and soil transport properties which vary with soil type and depend highly nonlinearly on soil moisture content and temperature. Predicting GHE performance is not simple because the soil transport phenomena are very complex and require an advanced mathematical model for an accurate description of the coupled heat and moisture transport in soil. Moreover the variation of soil moisture content in the ground and the operation of a GCHP system by nature are both very dynamic. Due to these complexities, many of which are time-dependent, a steady-state modelling approach does not yield an optimum design.

Few models for sizing a GHE have been developed. Most models are based on line source theory (Bose et al., 1985) with simplifying assumptions—such as uniform and constant soil properties—which tend to oversize the GHE, thus increasing the cost of the system and making it less competitive with other conventional heating/cooling systems.

Another approach, which was proposed by Mei (1986), is based on an energy balance between the circulating fluid in the GHE and the surrounding soil. The soil domain along the GHE is divided into a number of elements and each element is further discretized into a mesh. The thermal interaction between the circulating fluid and the soil is calculated taking into account the heat transfer (with or without moisture transfer) in soil, soil thermal properties, the GHE arrangement and also the operation of the system. The temperature distribution in the soil domain can be calculated using any numerical scheme, e.g. finite difference or finite element methods. To reduce the computational time of the approach, Piechowski (1999) concentrates the computational effort on the heat and moisture diffusion equations at the locations with the largest temperature and moisture gradients, i.e. within a distance of 0.15 m from the pipe-soil interface. The remaining soil region involves only the heat diffusion equation. Although the approach offers a considerable reduction in simulation time, it is still very time demanding as it requires small simulation time steps, in the order of minutes. Thus it is not suitable for simulating the long-term performance of a large GCHP system.

To this end, a more rapid simulation approach is required without sacrificing excessively on accuracy. Such a tool would provide a balance between the above two approaches. A computer model, called GHEADS, has been utilized for such a purpose.

The objectives of this paper are (i) to design an optimum GCHP system for an existing dwelling in Ontario using GHEADS and (ii) to improve understanding of the need to carefully optimize such systems in terms of long-term performance, degradation of thermal and moisture conditions in the ground environment, as well as economic and environmental benefits.

BACKGROUND ON GHEADS

GHEADS (Ground-Heat-Exchanger Analysis, Design and Simulation) was developed by Tarnawski and Leong (1990) specifically for the computer simulation of GCHP systems containing horizontal ground heat exchangers.

Modelling Approach and Methodology

Details of all models used in GHEADS have been published elsewhere (Tarnawski and Leong, 1990, 1993; Leong et al., 1998) and will not be repeated here. But the following models are highlighted:

- A modified version of the Philip–de Vries (1957) model is used to describe coupled heat and moisture flow in soils. The finite element method is employed to attain a numerical solution of the set of nonlinear simultaneous governing equations.
- The moisture freezing/thawing process is modelled by an isothermal approach proposed by Hromadka et al. (1981). This model allows a relatively large simulation time step, on the order of hours, and relatively large spatial discretization while yielding good simulation results.
- Time advancement of the solution is made using the three-time-level scheme proposed by Goodrich (1980). The scheme provides the required stability, accuracy and quick convergence of solution, which permits a large simulation time step (hours or days). The simulation time step used in the present study is 12 hours.
- Energy and moisture balances at the ground surface are modelled according to Tarnawski (1982), which involve very complex processes, taking into account solar radiation, cloud cover, surface albedo, ambient air temperature and relative humidity, rainfall, snow cover, wind speed, and evapotranspiration. Such details provide a proper account of the renewable energy.
- The thermal and hydraulic properties of soils are evaluated by a special subroutine extracted from a computer package called TheHyProS (Tarnawski and Wagner, 1992, 1993).
- The log mean temperature difference (LMTD) method is employed to compute the GHE heat extraction from (or injection to) the ground.

The LMTD method is an iterative procedure. Through an energy balance, coupled with a heat pump performance model, a converged solution is attained of the entrance circulating fluid temperature to the heat pump and the GHE heat transfer. The advantage of using the LMTD method is two-fold:

- The variations of circulating fluid and soil temperatures along the GHE can be reasonably accounted for by the LMTD method, as long as the fluid and soil temperatures at the inlet and outlet of GHE, as well as the overall heat transfer coefficient, are properly determined.
- A 3-D ground domain along the GHE is reduced to solving only two 2-D ground domains, namely: one at the GHE inlet plane and another at the GHE outlet plane. The two 2-D domains can be used for a GHE of any length. This enables a significant reduction of computational time, as compared to a full 3-D case.

Lastly, a simple heating and cooling load model is used to compute the daily heating and cooling loads of a dwelling. Alternatively a file—which may be generated by a building simulation tool (e.g. ESP-r, EnergyPlus or TRNSYS)—containing daily heating and cooling loads of a dwelling throughout a year can be read by GHEADS.

GHEADS integrates all these models to perform simulations of GCHP systems for any dwelling located at any location provided that the local climatic data and soil information are available.

Ground Domains

As mentioned earlier, two 2-D ground domains are used in the simulation. The ground domains are of a rectangular shape. They cover from ground surface down to a 6-m depth, and their widths are half of the horizontal pipe spacing *H* of the GHE (see Figure 1). All boundaries are assumed to be adiabatic and impermeable to moisture, except the ground surface boundary at the position where energy and moisture balances are modelled. The two 2-D ground domains are discretized into triangular meshes using a computer code, called Gradmesh (Thompson et al., 1999). The finest mesh sizes of about 25 mm are used around the GHE and they expand radially from the GHE, with the coarsest meshes at the bottom of the ground domains. These mesh sizes are adequate enough to capture the highest temperature and moisture gradients around a GHE pipe (Piechowski, 1999).

SIMULATION OF A GCHP SYSTEM FOR AN EXISTING DWELLING

A two-storey old house located in Wasaga Beach, Ontario, with a total living floor area of 227 m^2 (2440 ft^2), including a finished basement, is considered in the present study. Presently, electric resistance heating is used, served through forced air and baseboard convection units. For cooling, two window-mounted air conditioners are used for the most commonly-used bedrooms.

In order to size a heat pump unit, a heating and cooling load analysis is made using a program called HvacLoadExplorer (McQuiston et al., 2005), and the design heating and cooling loads are obtained as 14.3 and 13.3 kW, respectively. Based on the design loads and climatic data, a simple heating and cooling load model—which includes the effects of indoor-outdoor temperature difference, solar heat gain and wind speed for infiltration—is created for GHEADS to calculate daily load according to the daily climatic data. A commercially available water-to-air heat pump unit with nominal heating and cooling capacities of 13.6-kW and 17.6-kW, respectively, was selected. Its selection was based on heating capacity, because of much higher heating demand of the house. The performance data of the heat pump unit (such as heating and cooling capacities, COP, power consumption, water pressure drop at the water-to-refrigerant heat exchanger) were modelled as functions of entrance water temperature (EWT) for a given circulating fluid flow rate of 53 L/min (14 gpm) and entering air flow rate to the heat pump unit of 0.944 m^3/s (2000 cfm) at temperatures (EAT) of 21 and 24°C, respectively, for heating and cooling seasons. The heat pump unit is equipped with a single-speed scroll compressor and a thermostatic expansion valve for regulating refrigerant flow rate. When the heating or cooling capacity of the heat pump exceeds the heating or cooling load of the house, the GCHP system is operated under an ON/OFF condition.

In addition to the above, the following factors are considered:

- The circulating fluid used in the GHE is 20% (by weight) methanol antifreeze solution with a freezing point of about –12°C. The heat pump unit has a lockout freeze protection for the circulating fluid set at –9.4°C.
- Polyethylene pipe with a nominal size of 32 mm (1¼ in.) is used for the GHE. This size is selected to ensure turbulent flow in the pipe with low friction loss.
- The soil at the site is sand (bulk density of 1734 kg/m^3, porosity of 0.346, sand mass fraction of 0.852, silt mass fraction of 0.068, and clay mass fraction of 0.080).
- The Ottawa daily climatic data throughout a year is used due to its availability.

GHE Design

Two arrangements of horizontal GHEs are considered: (1) a single layer in a series and serpentine layout and (2) double layers in series and serpentine layouts, as shown in Figure 1.

The investigated depths of the single-layer GHE are 0.5, 1.0, 1.5 and 2.0 m (labelled Cases A, B, C and D, respectively). For double layers, the following combinations of pipe depths are considered: 0.5 and 1.0 m as Case AB, 0.5 and 1.5 m as Case AC, and 1.0 and 1.5 m as Case BC. For each case, GHE lengths ranging from 200 to 1000 m at 100-m increments are considered. In total, there are 63 simulations. All these simulations are with a horizontal pipe spacing of H = 0.5 m (see Figure 1). Among all these simulations, the best single-layer and double-layer cases are selected based on the highest overall thermal performance.

For the best single-layer and double-layer cases, a wider horizontal pipe spacing of H = 1.0 m is tested in order to investigate the effectiveness of doubling the horizontal pipe spacing. For a certain GHE length, the horizontal pipe spacing of H = 1.0 m requires twice as much ground surface area as needed with H = 0.5 m; but it is expected that the horizontal pipe spacing H = 1.0 m offers better performance because of the larger ground mass available for thermal energy storage.

Performance Evaluation

Energy analysis is used to perform a thermodynamic performance comparison in the present study. The energy consumption and coefficient of performance (COP) of the GCHP system can be written as

$$E_O = E_{HP} + E_{SUP} + E_{PUMP}, \quad (1)$$

the seasonal heating COP as

$$COP_H = \frac{Q_H}{(E_O)_H}, \quad (2)$$

the seasonal cooling COP as

$$COP_C = \frac{Q_C}{(E_O)_C}, \quad (3)$$

and the overall COP as

$$COP_O = \frac{Q_H + Q_C}{(E_O)_H + (E_O)_C}, \quad (4)$$

where E_{HP} is the total electrical energy supplied to the heat pump unit for fan and compressor operation, E_{SUP} is the electric energy required for supplementary heating or cooling purpose when the heat pump is unable to meet the demand, E_{PUMP} is the total electrical energy supplied to a motor which drives a pump for circulating the antifreeze solution through the GHE and the water-to-refrigerant heat exchanger. It is assumed that the efficiencies of the motor and pump are 90 and 70%, respectively. In the present study, Q_H and Q_C are the heating and cooling provided by the heat pump.

RESULTS AND DISCUSSION

Single-Layer Arrangement

Heating Season

Figure 2 shows the seasonal heating COP of the GCHP system with a single-layer GHE at various depths. The optimum pipe length is 600 m, except for Cases B and D where the optimum pipe lengths are about 500 m.

When properly sized, Case A (0.5-m depth) has the highest COP_H of 3.17 among all the cases considered. But if the pipe length is shorter than the optimum length, the COP_H of Case A decreases drastically, e.g. at a 200-m pipe length (not shown in Figure 2) the COP_H becomes 2.5 and the temperature of the antifreeze solution drops as low as –19°C in the winter. Of course, under real operation, the heat pump would shut down earlier due to its lockout freeze protection.

At the pipe length of 1000 m, all single-layer GHE cases converge to the same COP_H of 3.1, as one would expect for infinitely long pipe. The decline of COP_H when the pipe length is longer than the optimum is due to the increased power consumption for circulating the antifreeze solution. Essentially, the COP_H is independent of the GHE depth because the differences in COP_H among the single-layer GHE cases at any pipe length are negligibly small.

Cooling Season

Figure 3 shows the seasonal cooling COP of the GCHP system with a single-layer GHE at various depths. The optimum pipe length is again 600 m, except for Case A (0.5-m depth) whose highest COP_C is at a pipe length of about 900 m.

The system performance depends more strongly on the depth of GHE. A significant COP_C increase of 40.5% is observed at the optimum pipe length of 600 m for Case D with respect to Case A (see Table 1). However as the depth increases the increase of COP_C becomes less prominent, e.g. the COP_C increases by about 4.8% as the GHE depth changes from 1.5 to 2.0 m (see Table 1). Opposite to the heating operation, the best case for cooling is Case D (2.0-m depth) at the optimum pipe length. This is reasonable since deeper into the ground the temperature is cooler and more stable.

Overall Performance

The overall (yearly) performance of the GCHP system with a single-layer GHE is shown in Figure 4, and the COP_O values are relatively closer to the COP_H values than to the COP_C values. This is because the heating season is longer than the cooling season, and it requires much more energy consumption. The total heating and cooling loads for the house are 30.63 and 2.79 MWh, respectively. Also the energy consumption (e.g. of Case A) in the heating season is about 14 times more than that of the one in the cooling season.

The peak COP_O is again at the optimum pipe length of 600 m, and both Cases C and D have the same COP_O of 3.28, even though Case C has slightly more overall energy consumption than Case D (11.541 vs. 11.526 MWh, as indicated in Table 1). This difference is due to the fact that extra energy consumption of 15 kWh in Case C returns 55 kWh more for heating and cooling (see Table 1).

A similar situation is for the GHE length of 500 m, as shown in Figure 5. The overall energy consumption for the pipe length of 500 m appears to be the lowest, but the extra energy consumption for the GHE length of 600 m brings back more energy for heating and cooling. This is a reason why the thermal performance for a pipe length of 600 m is overall better than for a pipe length of 500 m.

In summary, the optimum pipe length for a single-layer GHE is 600 m, and it should be laid 1.5 m below the ground surface (Case C). For this design, two days in the winter required supplementary heating of 0.6 kW, for a total of 13 kWh; however, there is no requirement for supplementary cooling. The annual energy requirement is 11.54 MWh. The yearly temperature variation of the antifreeze solution ranges from –6.5 to 27.6°C, which seems to be environmentally acceptable. The required land area is 300 m^2 (for H = 0.5 m). Since the GHE at a 2.0-m depth does not offer much better overall performance than the GHE at 1.5-m depth, it is therefore not considered for the simulations of double-layer GHEs.

Double-Layer Arrangement

Heating Season

Figure 2 shows the seasonal heating COP of the GCHP system with a double-layer GHE at various depths. The optimum pipe length appears to be around 500 m, which is 100 m shorter than the optimum pipe length for the single-layer GHE.

Case AC has the highest COP_H, and it is also better than any cases of the single-layer GHE.

Again, similar to single-layer GHE cases, the differences of COP_H among the double-layer GHE cases at any pipe length are negligible. This also indicates that the COP_H is fairly independent of the depths of a double-layer GHE.

Cooling Season

Figure 3 shows the seasonal cooling COP of the GCHP system with a double-layer GHE at various depths. The optimum pipe lengths differ with depth (500 m for Case AB, 600 m for Case AC and 800 m for Case BC).

It appears that the advantage of having a deeper GHE is essential for cooling operation. For example, with the same pipe length of 600 m, both Cases AB and AC have significant COP_C improvement comparing to Case A.

Overall Performance

The overall (yearly) performance of the GCHP system with a double-layer GHE is shown in Figure 4. Again, the COP_O values are closer to the ones for COP_H than to the ones for COP_C due to the same reason explained before. The peak COP_O is at the optimum pipe length of 500 m, and Cases AC and BC both have the same COP_O of 3.28.

In summary, the optimum pipe length for a double-layer GHE is 500 m, and it should be laid at 1.0 and 1.5 m below the ground surface (Case BC). For this design, two days in the winter required supplementary heating of 0.8 kW, for a total of 17 kWh; however, there is no requirement for supplementary cooling. The annual energy requirement is 11.47 MWh. The yearly temperature variation of antifreeze solution ranges from –6.9 to 31.6°C, which also seems to be environmentally acceptable. The required land area is 125 m^2 (for H = 0.5 m).

Comparing single-layer and double-layer GHEs in Figures 2, 3, 4 and 5 and Tables 1 and 2, the advantages of double-layer over single-layer GHE can be seen.

Additional Simulations for H = 1.0 m

Two additional simulations are performed for Cases C and BC with a horizontal pipe spacing of H = 1.0 m (i.e., double the previous size).

The results are tabulated in Table 3. By increasing the horizontal pipe spacing the overall performance of both cases has marginally improved. But the improvement is slightly more significant for the single-layer GHE than for the double-layer GHE. In fact, although the case of a single-layer GHE has slightly better performance, it still requires about 62 kWh more energy to operate than the double-layer GHE, mainly due to the additional pumping power for the extra 100-m pipe. Moreover the case of a single-layer GHE requires 350 m^2 more land area.

Ground Environmental Assessment

In addition to the “best” thermal performance and cost effectiveness, the GHE design must also consider environmental aspects, such as preserving natural conditions of the ground by avoiding a drastic change of temperature and moisture conditions. A reference date of September 19 (the day before the start of heating season) is used for comparing the ground temperature and moisture content. Under natural conditions (i.e., without GCHP system), the average ground temperature and moisture content from the ground surface down to a 6.0-m depth are 13.9°C and 0.168 m^3 of H_2O/m^3 of soil, respectively.

If the temperature in the ground is much higher than would be the case for natural conditions, the soil moisture content may be greatly reduced. This effect may be harmful to biological life in the ground. Two additional simulations are performed for Cases C and BC with a horizontal pipe spacing of H = 0.5 m operating over a 10-year period, in order to verify the ground thermal and moisture sustainability.

By the end of the tenth year, on September 19, the average ground temperature and moisture content are 10.8°C and 0.200 m^3 of H_2O/m^3 of soil, respectively, for the case of a single-layer GHE. In fact, by the third year of GCHP operation, the conditions of the ground have already achieved that of the tenth year of GCHP operation. Comparing to the natural conditions, a thermal degradation of 3.1°C is apparent; however, there is no problem with soil moisture content. Since the temperature of 10.8°C is still well above the freezing temperature of water and there is no permafrost in the ground, the case of a single-layer GHE seems acceptable.

For the case of a double-layer GHE, the average ground temperature and moisture content by the end of the tenth year are 13.1°C and 0.200 m^3 of H_2O/m^3 of soil, respectively. In this case, the thermal degradation is only 0.8°C, which also seems acceptable. Also the ground moisture content remains similar to natural conditions.

Economic and Environmental Benefits

Since the house is currently electrically heated, the energy consumption for heating is 30.63 MWh. If the optimum GCHP system is in operation, the electrical energy consumption for heating would be 10.89 MWh (from Table 2 for Case BC), which yields a savings of 19.74 MWh. The current residential rate for electricity in Ontario is about \$0.12/kWh (including delivery, regulatory, debt retirement, loss factor adjustment, and tax charges). Therefore the monetary savings is \$2369/year in heating costs.

Assuming a fixed annual interest rate of 2%, the payback periods calculated using a present worth–annual payment analysis are 4.5, 6.8 and 9.3 years for the initial costs of \$10,000, \$15,000 and \$20,000, respectively.

A typical GCHP system can be in service for at least 20 years. After the payback period, the \$2369/year in savings is available to the system owner. This economic analysis is done without cooling because it is difficult to compare a central system to two window-mounted air conditioners. However because of its high efficiency one would expect a shorter payback period if cooling is included in the analysis.

The environmental benefit is another important factor to consider. If natural gas (heating value of 10.42 kWh/m^3 and total cost of \$0.48/m^3) is to be used for heating, the following two scenarios can be analyzed:

1. If a natural gas furnace with an efficiency factor of 0.9 (including the effects of rated full-load efficiency, part-load performance, and oversizing) is installed to heat the house, the annual amount and cost of natural gas are about 3270 m^3 and \$1570, which is still about \$260 more than operating the GCHP system.
2. If the electricity for the GCHP system is generated using natural gas and delivered with an overall efficiency of 35%, the annual amount of natural gas is 2990 m^3, which is still about 280 m^3 less than the amount required by a natural gas furnace.

These two scenarios together show the economic and environmental benefits of operating the GCHP system, i.e. an annual savings of \$260 and an annual reduction in greenhouse gas emission by 8.6%, as compared to operating a natural gas furnace for heating.

CONCLUSIONS

A useful simulation tool for simulating a GCHP system with a horizontal GHE has been briefly presented. The design of an optimum GHE using such tool for an existing dwelling in Wasaga Beach, Ontario, has been presented as an example to demonstrate the capabilities of the simulation tool.

There are many factors to be considered when one wants to optimize the design of a GHE. The optimum design of the GHE in the present study may only be applicable to the existing dwelling, because it is specific to the site characteristics (such as soil type and climatic conditions) and system operating parameters (such as magnitude and frequency of heating and/or cooling operation). The optimum GCHP system designed for the existing dwelling appears to have both economic and environmental benefits. Its payback period is also relatively short compared to its serviceable life.

Some long-term research needs are apparent. The simulation tool, GHEADS, requires further enhancement to include exergy analysis and to couple to a building simulation tool, such as ESP-r, EnergyPlus or TRNSYS, for more accurate evaluation of building thermal loads. The inclusion of exergy methods will allow process inefficiencies in a GCHP system to be better pinpointed than does an energy analysis, and efficiencies to be more rationally evaluated.

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REFERENCES

Bose, J.E., Parker, J.D and McQuiston, F.C. (1985), *Design/Data Manual for Closed-Loop Ground-Coupled Heat Pump System*, ASHRAE, Inc., Atlanta, GA, ISBN 0-910110-41-7.

Goodrich, L.E. (1980), 'Three-Time-Level Methods for the Numerical Solution of Freezing Problems', *Cold Regions Sci. and Tech.*, 3, 237-242.

Hromadka, II, T.V., Guymon, G.L. and Berg, R.L. (1981), 'Some Approaches to Modelling Phase Change in Freezing Soils', *Cold Regions Sci. and Tech.*, 4, 137-145.

Leong, W.H., Tarnawski, V.R. and Aittomäki, A. (1998), 'Effect of Soil Type and Moisture Content on Ground Heat Pump Performance', *Int. J. Refrig.*, 21, 595-606.

McQuiston, F.C., Parker, J.D. and Spitler, J.D. (2005), *Heating, Ventilating, and Air Conditioning: Analysis and Design*, 6th ed., Wiley, New York.

Mei, V.C. (1986), *Horizontal Ground-Coupled Heat Exchanger, Theoretical and Experimental Analysis*, Technical Report ORNL/CON-193, Oak Ridge National Laboratory.

Philip, J.R. and de Vries, D.A. (1957), 'Moisture Movement in Porous Materials under Temperature Gradients', *Trans. Amer. Geophys. Union*, 38, 222-232.

Piechowski, M. (1999), 'Heat and Mass Transfer Model of a Ground Heat Exchanger: Theoretical Development', *Int. J. Energy Res.*, 23, 571-588.

Tarnawski, V.R. (1982), *An Analysis of Heat and Moisture Movement in Soils in the Vicinity of Ground Heat Collectors for Use in Heat Pump Systems*, Acta Polytechnica Scandinavica, Mechanical Engineering Series No. 82, Helsinki.

Tarnawski, V.R. and Leong, W.H. (1990), *Computer Simulation of Ground Coupled Heat Pump Systems*, Technical Report, National Research Council, Ottawa.

Tarnawski, V.R. and Leong, W.H. (1993), 'Computer Analysis, Design and Simulation of Horizontal Ground Heat Exchangers', Int. J. Energy Res., 17, 467-477.

Tarnawski, V.R. and Wagner, B. (1992), 'A New Computerized Approach to Estimating the Thermal Properties of Unfrozen Soils', *Canadian Geotech. J.*, 29, 714–720.

Tarnawski, V.R. and Wagner, B. (1993), 'Modeling the Thermal Conductivity of Frozen Soils', *Cold Regions Sci. and Tech.*, 22, 19-31.

Thompson, J.F., Soni, B.K. and Weatherill, N.P. (1999), *Handbook of Grid Generation*, Boca Raton: CRC Press, A.16-A.17.

Table 1
Energy (MWh) and performance data for a single-layer GHE of 600 m at various depths.

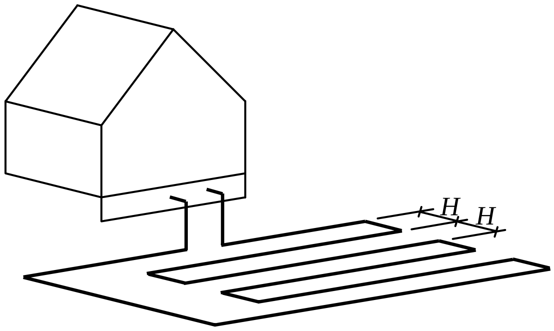
Case (depth)	Q_H	Q_C	$(E_O)_H$	$(E_O)_C$	E_O	COP_H	COP_C	COP_O
A (0.5 m)	34.72	3.08	10.96	0.761	11.72	3.17	4.05	3.23
B (1.0 m)	34.73	3.11	10.99	0.647	11.64	3.16	4.81	3.25
C (1.5 m)	34.72	3.13	10.97	0.571	11.54	3.17	5.43	3.28
D (2.0 m)	34.66	3.13	10.97	0.556	11.53	3.16	5.69	3.28

Table 2
Energy (MWh) and performance data for a double-layer GHE of 500 m at various depths.

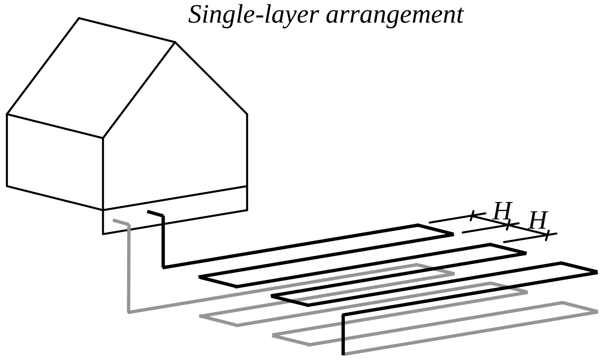
Case (depths)	Q_H	Q_C	$(E_O)_H$	$(E_O)_C$	E_O	COP_H	COP_C	COP_O
AB (0.5/1.0 m)	34.59	3.11	10.91	0.628	11.54	3.17	4.94	3.27
AC (0.5/1.5 m)	34.59	3.11	10.89	0.593	11.48	3.18	5.20	3.28
BC (1.0/1.5 m)	34.56	3.11	10.89	0.584	11.47	3.18	5.31	3.28

Table 3
Energy (MWh) and performance data for a doubling of the horizontal pipe spacing (i.e. H = 1.0 m).

Case (depths)	Pipe Length	Q_H	Q_C	$(E_O)_H$	$(E_O)_C$	E_O	COP_H	COP_C	COP_O
C (1.5 m)	600 m	34.84	3.12	10.87	0.635	11.50	3.21	4.93	3.30
BC (1.0/1.5 m)	500 m	34.59	3.11	10.83	0.613	11.44	3.20	5.04	3.29



Single-layer arrangement



Double-layer arrangement

Figure 1. Horizontal GHE arrangements.

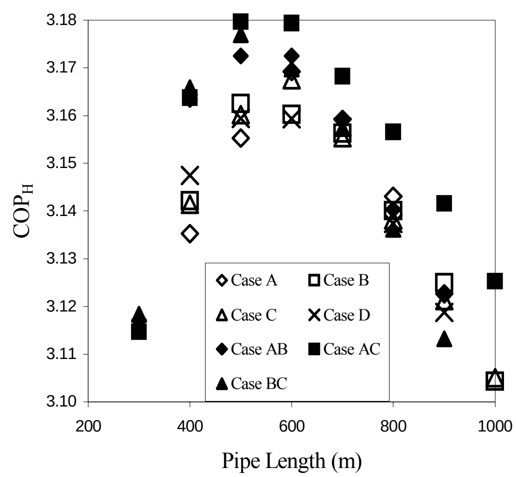


Figure 2. Variation of seasonal heating COP of the GCHP system with pipe length for a GHE at various depths.

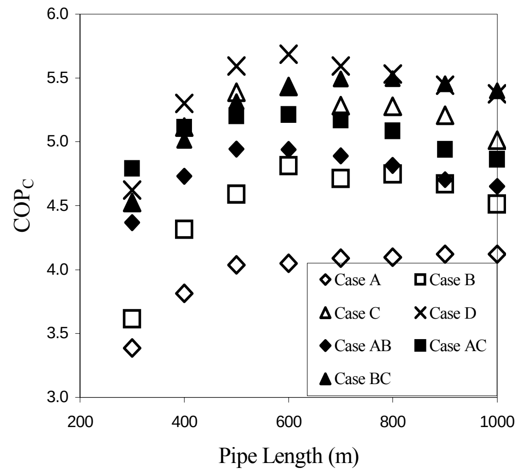


Figure 3. Variation of seasonal cooling COP of a GCHP system with pipe length for a GHE at various depths .

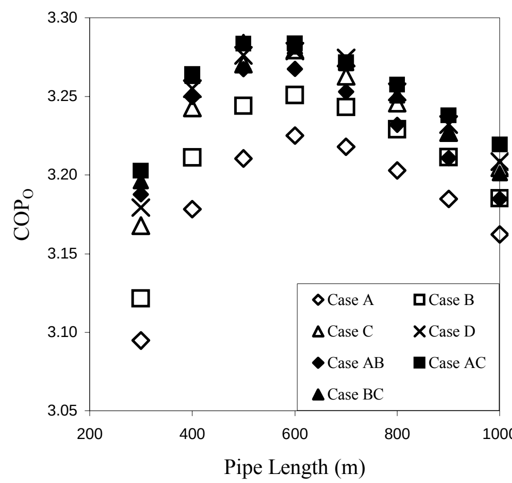


Figure 4. Variation of overall COP of GCHP system with pipe length for a GHE at various depths.

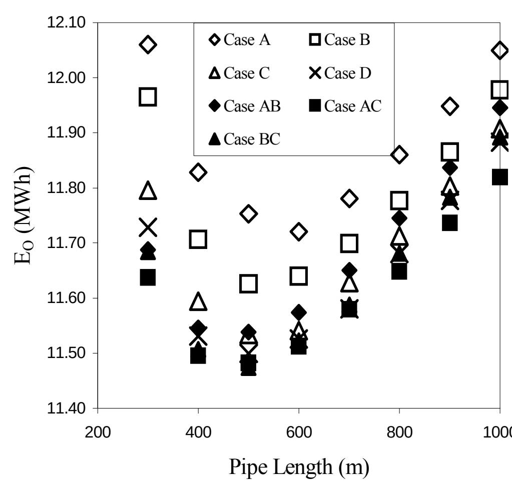


Figure 5. Variation of total energy consumption of GCHP system with pipe length for a GHE at various depths.