1. INTRODUCTION

Thermal modeling of the ground heat exchangers (GHX) at shallow depths has been of great interest to engineers over the last twenty five years. The need for the study and a better understanding of the thermal processes in the GHX stems from the quest for developing well proven and validated design procedures to optimally determine the loop length and other key parameters of the GHX. When present, the GHX forms the core of the space conditioning system comprising the set of heat pumps located in different zones, circulating pumps, piping, control equipment, etc.

Long term ground temperature drift

In the larger GHXs for the commercial buildings, there are multiple boreholes in close proximity of each other. Thermal interaction between the boreholes is inevitable though it is recommended that they are separated by at least 15ft (Kavanaugh and Rafferty, 1997). The recommended separation distance sometime may be compromised due to constraints on the area of open ground and the higher cost of piping and pumping. Whenever there is imbalance between the annual quantities of heat extracted and heat rejected, the thermal interaction effect between the adjacent boreholes becomes enhanced. The interaction results in slow long term temperature drift of the GHX leading to degraded performance in the season that generates higher aggregate annual load (heating or cooling). Though the performance deteriorates in the dominant season, drift in the temperature in favorable direction results in improved performance and lower energy consumption in the secondary season. However this is often not adequate to compensate the higher energy consumption during the dominant season. Further, the temperature drift could be serious enough to prevent even the heat pumps from operating as the return water temperature from the GHX may reach beyond the lock out settings during the peak load.

Present study

The models developed for loop design take into account the long term drift of ground temperature. However these are based on several simplifying assumptions and the boundary heat flow either from the atmosphere or from the depths below the GHX is ignored. It is hard to see how this assumption can be sustained when after years of operation the GHX has developed significant temperature gradients at its upper and lower boundaries. Obviously there is a possibility of this phenomenon being self limiting. Experimental observation of this phenomenon is feasible. The authors are not aware of any published study of a systematic investigation of experimentally observed ground temperature drift and its correlation with the load imbalance over extended period of time in clay formations in absence of groundwater flow.

The present study is designed to systematically observe this phenomenon. The GHX under study consists of 212 bore holes each 43.7 m (143.5 ft) deep drilled in tight clay/silt formations with little ground water flow on the University of North Dakota Campus at Grand Forks, ND. The separation distance between the boreholes is 3.65 m (12 ft). The horizontal boundary surfaces of the GHX are the interior earth interface (45.7 m i.e., 150 ft deep from the grade) at the lower boundary and the bottom of the thin (2.0 m) intervening layer of top soil below the open grade as the upper boundary. The clay has quite low hydraulic conductivity and as there is hardly any hydraulic gradient in the specific strata, ground water flow is insignificant. This is particularly advantageous for the study since the presence of groundwater flow leads to convective transfer of heat laterally and the study of the boundary...
heat flow in the GHX becomes complicated. For modeling purpose, the thermal reservoir around each borehole in the interior may be thought of as a parallelepiped and the vertical faces of this block are assumed to form adiabatic surfaces. For the exterior boreholes, the vertical faces inside the GHX are assumed to have adiabatic boundaries while the open side away from the GHX is considered to be stretched to the far field of undisturbed ground temperature.

Currently the ground temperature is monitored at three points at 7.3 m +/- 0.3 m depth (24 ft +/- 1 ft) depth from the surface. While the two points are points of symmetry in the adiabatic wall, one point is outside the field and at the same distance from the nearest borehole as the other symmetry points. The results from the two symmetry points identically located are meant to make the observations robust as they make a replicate set. Temperature observations from a single borehole may be subject to set-up errors e.g., deviations in marking of positions, angularity of drilling direction etc. Two independent observations are expected to compensate such errors and make validation of models more meaningful. Figure 1 gives the location of the monitoring holes in relation to the borehole field that is about 125 m X 38 m. The monitoring holes were drilled with auger drill and backfilled with bentonite chips. The GHX was commissioned in summer of 2004 and has already gone through one full seasonal cycle plus one cooling season. Ground temperature monitoring commenced from December 2nd, 2005 early in the second heating season of the GHX. The sensors are precision thermistors, and the data logger is programmed to capture the temperature data on hourly average basis. Ground temperature measurements are being complemented with concurrent recording of the exiting and entering fluid temperatures (EFT) and fluid flow rates to ascertain the heat extraction and rejection rates. An independent measure of the thermal conductivity of the soil is also being planned to validate the models. The necessary measurements required for meaningful validation of any model for GHXs have been summarized by Yavuzturk and Spitler (2001).

2. TEMPERATURE PENALTY AND BOUNDARY HEAT FLOW

This issue of thermal interaction and long term temperature drift is addressed by the loop designers by allowing additional loop length. Kavanaugh and Rafferty (1997) recommend a temperature correction that is to be applied to the undisturbed ground temperature, i.e. for a dominating winter season the ground temperature is reduced by the penalty amount, and for a dominating summer season the ground temperature is increased by the penalty amount. The penalty amount is computed using the line source heat solution, aggregating the heat that would have diffused out of the circular symmetric zone around the borehole in a ten year period, and assuming that this heat would correspond to the temperature change in a parallelepiped around the borehole. A complete detail of this methodology is found in the ASHRAE publication (Kavanaugh and Rafferty, 1997). A typical calculation detailed in the reference publication indicates that a temperature penalty of 1.66 °C (3 °F) on the undisturbed ground temperature of 16.7 °C (62 °F) led to an increased loop length by 12% for the specific parameter values i.e., undisturbed ground temperature, ground thermal properties etc. The actual increase in the loop length in a given situation depends on the difference between the undisturbed ground temperature and the target minimum or maximum EFT.

In the alternative design methodology based on the work of Swedish researchers, the long term temperature drift is directly accounted for in the numerical models used to compute the borehole temperature after continued heat rejection or extraction (Spitler, 2000). The borehole temperature is determined by following through the sequence of the series of stepped heat extracted and rejected into the ground, and applying the dimensionless thermal resistance parameter (g function). The dimensionless thermal resistance is obtained for a specific dimensionless time from a relationship that is predetermined through numerical simulation for a given borefield geometry and diameter to depth ratio. This time dependent dimensionless thermal resistance increases significantly over time pointing to the long term temperature drift for a continued resultant heat flux.

Kavanaugh and Rafferty (1997) have computed long-term change in the ground field temperature for a 10 by 10 vertical grid of boreholes with 100 ton nominal load under specified condition of the ground thermal properties and differing ratios of equivalent full load cooling and heating hours. This indicates that for a 1500 hour of full load heating and 500 hours of full load cooling, the ground temperature over 10 years may reduce by 2.44 °C (4.4 °F). One may presume that this would lead to the necessary temperature gradients to initiate heat flow from the ambient atmosphere through the top boundary surface. All the current models assume no heat flow in the GHX from the
boundary surfaces and consequently the design analysis stays focused on the EWT and whether the EWT exceeds the design limit of the heat pumps. This study would examine the long term impact of the imbalances and the extent of possible boundary heat flow that may alter the ground temperature profiles around the GHX in the time period that the facility remains functional.

**Land atmosphere heat transfer**

The GHXs for space conditioning are usually constructed under a layer of thin top soil. In this specific case, the depth of the top soil layer is 2 m (6.5 ft). The physical process that take place within this top layer, as well as inside the upper portions of the GHX are complex. From the ground surface, the heat budget includes radiation heat gain during the day, heat loss in the clear night, convective heat transfer from the air, effect of the precipitation (rain/snow), rain water run-off etc. Inside the top layer, percolation of the of the rain water, the seasonal freeze-thaw process (if present) are to be accounted for. Other things to be considered are the evapo-transpiration from the vegetative cover and the plant canopy, the ground water recharge, water transport in the root zone etc. Land surface models have been developed in the field of atmospheric sciences primarily for numerical weather simulation, and climate projections (Bonan, 1996). Other models to explain ground temperature variations in shallow depths have been developed by geophysicist and soil scientists (Schmidt et al., 2001). The authors are not aware of any study where the land surface models have been applied to model the heat transfer across the ground surface of a vertical GHX field.

3. **RESULTS AND DISCUSSION**

The specific location of the temperature probe is a key issue for experimental observation of temperatures inside GHX. While the undisturbed earth in a given location would have a periodically varying temperature that is the same across the horizontal plane at a given depth and at a given time, the heat exchange process between the carrier fluid and the ground results in radial heat fluxes with respect to the boreholes. The temperature profile, in any horizontal plane is constantly changing, even if there is no flow of the carrier fluid. To be meaningful, the point of the probe should be at a characteristic point in the GHX. The vertical plane passing through midpoints between the adjacent boreholes is a plane of symmetry and is assumed as an adiabatic plane implying no flow of heat across it. A vertical line on the adiabatic plane passing through the midpoint is ideally suited for temperature monitoring purpose (schematically shown in Figure-1). Being the farthest point away from any borehole, the temperature swing on this line of observation inside the GHX should be minimal as the full thermal capacity of the thermal storage volume is available for damping the temperature response. Kavanaugh and Rafferty (1997) have used a parallelepiped model for calculation of the temperature penalty. This allows one to compare the results of the experimental observation with the model predictions. Further, since this point is at the adiabatic boundary in the parallelepiped, the results may be generalized. If the study is focused only on changes in ground temperature due to thermal storage effect, then the position of the probe should be halfway through the height of the boreholes (23 m or 75 ft in this case). At this depth, the effect of the atmospheric and surface forcing would be minimal. The three temperature probes used for the experimental investigation have been placed at a depth of 7.3m +/- 0.3m (nominally 24ft) depth also to observe the effect of the atmospheric forcing at the boundary. This also enables us to incorporate the results of the present study with the results of a study of seasonal ground temperature changes of undisturbed earth from a nearby site (Schmidt et al., 2001).

**Seasonal changes of ground temperature**

The department of Geology and Geological Engineering at the University of North Dakota has been active in ground temperature research and has studied long term trends of ground temperatures at several locations across the continental United States (Gosnold et al., 1997). The GHX under study is located at Grand Forks (47°55'N, 97°04'W, Elevation 252.3 m). Concurrently there has been an ongoing study initiated from 1980 onwards in which the ground temperatures at 19 different depths in the range of 0.01 -11.7 m have been recorded on daily average basis at a location in Fargo, ND (46°54'N, 96°48'W: Elevation 273 m) (Schmidt et al., 2001). The surface substrata of both the sites are quite similar as both the sites are located in a plain that formed once the floor of the glacial lake Agassiz, and currently is part of the Red River Valley. The regolith consists of clay, silt, fine sand, silty clay, pebbly loam etc in several layers. Since the study of ground temperature variation is limited to the depths of 7.7 m, the
geological units encountered by the probe boreholes could be limited to only two or three in both sites. In fact drilling of the probe holes in the Grand Forks location encountered only two layers in the depth of 7.2 m.

The recorded temperature data in the interior of the GHX for two of the holes at the specified spots for little over first 100 days covering practically the entire official winter period (December-February of 2005/6) is presented in Figure-3. The 7.7 m ground temperature data for the Fargo location is shown in the same graph for the same Julian days in the years 2002/3 and 2003/4. It is quite evident that at the symmetry points on the square cylinder, the temperature shows a declining trend due to the ongoing heat extraction form the boreholes. In the absence of heat extraction, the undisturbed ground temperature at this depth should have trended upwards (as observed from the Fargo data points in Figure-2). If the thermal field developed by the atmospheric forcing is superimposed on the thermal field of the boreholes to produce the resultant field, clearly the engineered forcing has the dominant effect and has dominated over the atmospheric forcing. It is concluded that these points of observation are appropriate, and any long term trend of the annual mean temperature at these would be indicative of the long term temperature drift due to the operation of the thermal reservoir. The results of the Fargo data set (Scmidt et al., 2001) indicates that the mean annual temperature increase at 7.7 m is 1.04 +/- 0.03 degree C per decade. Since the present study is planned over a ten year period, it would be important to compensate the end result for the atmospheric forcing once the resultant trend is established.

In the course of drilling the originally planned number of holes, one hole (#4) with installed thermistor but with a much shorter depth of 4.87 m, has been obtained. This hole was planned to reach 7.6 m depth, but the borehole wall collapsed around the bottom as the drill string fell inside the hole. Temperature history from this hole is shown in Figure 3. In the same figure, the result from the undisturbed ground temperature for a comparable height from the Fargo data set is also shown for the identical period. Both the data set shows cooling trend in the reference period. However, as anticipated, the cooling trend is stronger in this shallower hole due to the combined effect of the engineered and atmospheric forcing.

The temperature difference history between sensed points in the shallow and the deep holes reveals that initially the point in the shallower hole was warmer than the points in the deeper holes indicating a downward heat flux (Figure 4). But towards the end of January, this gradient reverses and now heat flows upward. This should imply that even the sensing point in the deeper holes should indicate an accelerated cooling after this period.

**Undisturbed ground temperature**

In the development of models for GHX, it is necessary to determine the undisturbed ground temperature as this is the key input data to the design programs. For large GHXs the determination of the undisturbed ground temperature is carried out during the thermal response test of the ground. When the GHX has already been under operation for some time it is often problematic to find out this parameter as the temperature profile in the GHX has already been disturbed (Thornton et al., 1997). Yet the parameter is an important parameter in any GHX model. It is felt that the measurement of the ground temperature on the symmetry line outside the GHX (as shown in the Figure 1) away from the boundary can provide values of such parameter. The temperature history of the probe at Hole #2 that is located at about 1.85 m (6ft) from the symmetry line indicate that the temperature in this hole has remained virtually unchanged over the period of 100 days of winter. Following has been observed:

<table>
<thead>
<tr>
<th></th>
<th>At Grand Forks Hole #2</th>
<th>At Fargo 7.7 m (2003-04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum temperature, °C</td>
<td>10.55</td>
<td>8.2</td>
</tr>
<tr>
<td>Minimum temperature, °C</td>
<td>10.41</td>
<td>7.7</td>
</tr>
<tr>
<td>Average temperature, °C</td>
<td>10.50</td>
<td>7.9</td>
</tr>
<tr>
<td>Standard deviation, °C</td>
<td>0.031</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The above data indicates that the temperature at the depth of 7.5m in hole #2 may be a good candidate for determination of the undisturbed ground temperature. Future trend data may validate this hypothesis and once the thermal parameters of the soils are measured, the issue would be examined on sound theoretical basis. Gehlin and Nordell (2003) have compared different options for measurement of the undisturbed ground temperature in a GHX.
field. The methods described, however, are based on measurement of water temperatures in the U tubes and not on direct measurement of the temperature through probes placed in the ground.

4. CONCLUSION

This study reports only initial findings of first 100 days of observations that is to be continued for 10 years. The initial results have been quite insightful and would be of great value for validation of any model developed to theoretically study the long term temperature trend in the GHX.

5. ACKNOWLEDGEMENT

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Figure 1: Location of Holes in the borefield.
Figure 2 Ground temperature changes in the deeper holes

Figure 3 Ground temperature changes for a shallow hole
ACKNOWLEDGEMENT

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REFERENCES


Figure 4 Temperature difference between shallow and deep hole
