CHARACTERIZATION OF THE EFFECTS OF BOREHOLE LAYOUTS IN GEO-EXCHANGE

by

Ying Lam Law

Bachelor of Engineering, Ryerson University, Toronto, Canada, 2014

A thesis presented to

Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the Program of

Mechanical and Industrial Engineering

Toronto, Ontario, Canada, 2016

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

I understand that my thesis may be made electronically available to the public.

Abstract

CHARACTERIZATION OF THE EFFECTS OF BOREHOLE LAYOUTS IN GEO-EXCHANGE

Master of Applied Science, 2016

Ying Lam Law

Mechanical and Industrial Engineering

Ryerson University

In a ground-source heat pump (GSHP) system, when the heating and cooling loads are not balanced, the ground temperature may migrate up or down after a few years of operation. This change in ground temperature can lower system efficiency because of the ineffective heat transfer temperatures. The present work contributes to fundamental understanding of thermal imbalance in borehole design. Long term ground temperatures were simulated using finite element methods to imitate the performance of GSHP systems. Borehole field configurations are explored and different aspect ratios of borehole layouts were compared. In addition, an alternative borehole configuration was studied, which involves alternating the length of individual boreholes within a single system. The results of the studies expressed potential in alleviating the effects of thermal imbalance by changing borehole field layout and potential in reducing borehole separation distance by altering individual borehole lengths.

Acknowledgements

I would like to acknowledge my supervisor, Dr. Seth B. Dworkin, who provided me with the opportunity to pursue this degree. Dr. Dworkin provided me with many opportunities to attend conferences such as CSME 2014, ICCE 2014, and CSME 2016. I am thankful to have his guidance and support during this degree.

I would like to thank members of our research group, especially Hiep Nguyen and Adam Alaica, for providing suggestions to my research methods and emotional support throughout my graduate studies.

I would also like to acknowledge Mr. Lad Rak and Dr. Julie Wang of McClymont and Rak Engineers, for advising me during my internship. I would also like to thank NSERC, Ontario Centre of Excellence's Talent Edge Internship, Ontario Graduate Scholarship, Queen Elizabeth II Graduate Scholarship in Science and Technology (QEII-GSST), the Faculty of Engineering and Architectural Science at Ryerson, Centre of Urban Energy at Ryerson University, Enwave Energy Corporation, HydroOne, and Toronto Atmospheric Fund for financial support.

Dedication

To my parents, Ivy, Jeffery, and Geoffrey, for constantly bringing happiness into my life. This work would not be possible without your support and encouragement.

Table of Contents

List of Tables

List of Figures

Nomenclature & Abbreviations

BDF	Backward differentiation formula
c_A	cooling available, W
C_f	Heat flux adjustment factor, cooling
C_{fc}, C_{fh}	Correction factors that account for the amount of heat rejected or absorbed by the heat pumps
COP	Coefficient of performance
c_R	cooling required, W
F_{sc}	Short-circuit heat loss factor
GSHP	Ground source heat pump
h	Borehole depth, m
h_A	heating available, W
H_f	Heat flux adjustment factor, heating
HGSHP	Hybrid ground source heat pump
h_R	heating required, W
L_c	Required ground loop length for cooling, m
L_h	Required ground loop length for heating, m
PARDISO	Parallel direct sparse solver
PLF_m	Part-load factor during design month
q_{1c}	Building design cooling block load, W
q_{1h}	Building design heating block load, W
q_a	Net annual average heat transfer to the ground, W
q_b	Maximum heat flux at each borehole, W/m^2
q_C	maximum heat flux, cooling, W/m^2
$Q_{g,\ cooling}$	Heat released into ground, cooling mode, W
$Q_{g,\ heating}$	Heat extracted from ground, heating mode, W
q_H	maximum heat flux, heating, W/m^2

Q_{out}	Heat output by the heat pump, W
r	Borehole radius, m
R_b	Thermal resistance of bore, m.K/W
R_{ga}	Effective thermal resistance of the ground, annual pulse, m.K/W
R_{gd}	Effective thermal resistance of the ground, daily pulse, m.K/W
t_g	Undisturbed ground temperature, ^oC
t_p	Temperature penalty for interference of adjacent bores, ^oC
TSM	Thermal storage medium
t_{wi}	Liquid temperature at heat pump inlet, ^oC
t_{wo}	Liquid temperature at heat pump outlet, ^oC
W_{HP}	Work done by the heat pump, W
α	Affected soil distance, m

Chapter 1

Introduction

As global awareness for greenhouse gas emissions increases, so too does the demand for alternatives to reduce energy consumption. As such, it is essential to focus on reducing the energy consumption of large contributors of greenhouse gas emissions, such as residential space heating and cooling. Space heating and cooling consists of approximately 64% of total residential energy consumption followed by domestic hot water heating, appliances, and lighting at 17%, 14%, and 4% respectively [1]. Ground source heat pumps (GSHPs) are an environmentally friendly alternative to conventional heating and cooling systems because of their high efficiency and low greenhouse gas emissions [2]. Rather than direct energy consumption, such as the burning of fossil fuel, GSHPs use the ground as a stable heat transfer medium to transfer heat into or out of a building.

During the operation of a GSHP, the ground acts as a heat source and heat sink in heating and cooling modes, respectively [3]. An important aspect for a well-designed GSHP system is to balance the heat extraction and injection from and into the ground throughout the year. Long-term heat extraction of the ground (heating season), to heat the building, would cause the ground temperature to gradually decrease – lowering the heating efficiency of the system (*vice versa* for the cooling season). Ideally, when the heating and cooling demands of a building are balanced, the ground temperature fluctuates within a stable desirable range. However, when the heating and cooling demands are not balanced, the ground temperature may migrate up or down over time, and as a result, the ground may fail to accept/provide more heat from/to the building. This phenomenon is known as ground 'fouling' and many systems in the past have had to stop their operation due to the resulting low coefficient of performance (COP) [4]. To ensure that a design is feasible, it is important to model and project the changes in ground temperature over many years of operation.

This thesis is formatted in manuscript style and focuses on investigating ground temperature response of GSHPs. The performance effects of ground temperature changes are also closely studied through numerical modelling.

Chapter 1 of this thesis presents a thorough search of the literature on current GSHP technology, with summarizing and characterizing the body of knowledge as it relates to the subject.

Chapter 2 will describe the methodology used in the studies performed in this thesis. This chapter will focus on the methods used to calculate heat flux boundary conditions, build finite element model, and apply boundary conditions.

Chapter 3 will present a study that characterizes the effects of borehole configurations in geo-exchange. The study involves simulating the long-term performance of borehole fields with different aspect ratios for four buildings using finite element methods.

Chapter 4 will present a study that examines the effects of alternative borehole configurations in geo-exchange through finite element methods. In this study, borehole lengths and borehole separation distances were explored. Four centre boreholes in a 4x4 borehole field are shortened to various lengths, with the remaining borehole length recalculated, and the changes in ground temperature are studied. Borehole separation distances are also varied to determine its effects on ground temperature.

Chapter 5 summarizes the key findings from Chapter 3 and Chapter 4 and presents future work to further reduce knowledge gaps in geo-exchange.

1.1 Ground Source Heat Pump Systems

Ground source heat pumps (GSHP) use the ground as a stable medium for heat transfer. For example, in heating mode, the ground is used as a heat source. With the assistance of heat pumps, heat can be extracted from the ground to provide heating for buildings. Similarly, in cooling mode, the ground is used as a heat sink. The excess heat from the building is transferred to the ground through free cooling or with the aid of a heat pump. Components of a GSHP system include the distribution system, the heat pump and the heat exchanger. The heat exchanger can be of different configurations such as vertical, horizontal, and slinky. A figure of the three configurations is illustrated in Figure 1. Due to surface area space limitation, the vertical configuration is often selected for construction. The main focus of this review will be on the vertical configuration because it is where thermal imbalance often occurs.

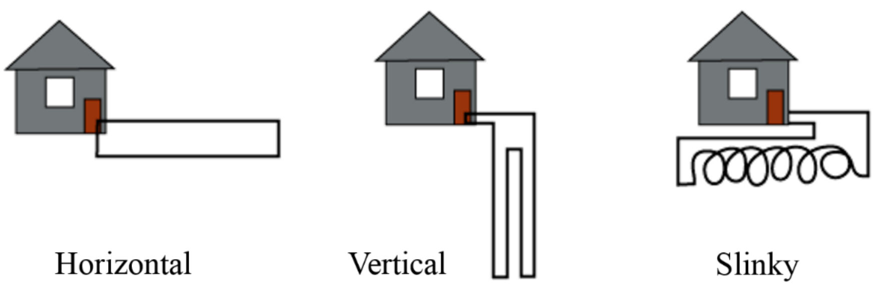

Figure 1: GSHP configurations (reproduced from [5])

1.1.1 Advantages of GSHPs

Compared to conventional heating and cooling systems, GSHPs are highly efficient and are more environmental friendly approach to space conditioning. GSHPs are dual purpose; they can be used for heating and cooling. GSHPs have generally higher coefficients of performances (2.5-5.0) than conventional systems [6]. This increase in COP results in a lower energy consumption than other systems such as fuel based boilers and air conditioners. These highly efficient heating and cooling systems, compared to conventional systems, can reduce carbon dioxide, sulphur dioxide and nitrogen dioxide released into the atmosphere because of the lowered gas and electricity consumption [7]. Table 1 summarizes the energy efficiency and CO_2 emissions of various heating systems. Because the combustion of fuels releases large amounts of GHGs, it can be observed in the table that the highest CO_2 emissions are from oil and gas fired boilers.

Green electricity can be used to further reduce CO_2 emissions. Green electricity is electricity generated from environmentally friendly sources such as hydro, wind and solar energy. The use of green electricity combined with a GSHP can potentially reduce the CO_2 emissions to zero and increase the energy efficiency to 300-400%.

Table 1: Energy efficiency and CO_2 emissions of heating systems (reproduced from [2])

System	Primary energy efficiency (%)	CO_2 emissions (kg CO_2/kWh heat)
Oil fired boiler	60-65	0.45-0.48
Gas fired boiler	70-80	0.26-0.31
Condensing gas boiler + low temperature system	100	0.21
Electrical heating	36	0.9
Conventional electricity + GSHP	120-160	0.27-0.2
Green electricity + GSHP	300-400	0.00

An additional advantage of using GSHP systems is that they can also increase the thermal comfort of building occupants [7]. With GSHP systems, one can achieve heating and cooling in multiple zones of the building at the same time. In most conventional methods, the entire building will experience heating or cooling based on the thermostat set points of the critical zone. On the contrary, using a GSHP system would allow building occupants to select whether they want heating or cooling in different zones. Heating or cooling at different zones of a building is useful in many residential and commercial applications where cooling is required in the kitchen and heating is required in bedrooms or offices. Simultaneous heating and cooling can be achieved by extracting excess heat from one zone (to achieve cooling) to provide heating for another zone.

1.1.2 Disadvantages of GSHPs

The inherent contributor that is preventing widespread adoption of GSHPs' environmental and thermal comfort benefits, is high upfront costs, which often make it a less appealing option. The high upfront cost is due to the cost of drilling and installing the heat exchanger.

Aside from the large upfront cost, the high cost of electricity also makes GSHP systems less appealing in heating dominant regions where the cost of natural gas is cheap. As a result, there is no economic benefit in installing a GSHP system to primarily operate in the heating mode when it is much cheaper to provide space heating by conventional means (*i.e.*, natural gas).

Another disadvantage of GSHPs is the potential thermal imbalance of heating and cooling loads. It is important to ensure that heating and cooling loads of a building are balanced prior to the design of a GSHP system. In the scenario where a building's heating and cooling loads are significantly imbalanced, this imbalance can change the ground temperature over time, causing the system to become less efficient (resulting in less desirable heat pump inlet temperatures). Further details on thermal imbalance will be discussed in section 1.3 and section 4.

1.2 Problem Statement and Motivation

As defined by the Brundtland Commission, sustainability is "Meeting the needs of the present generation without compromising the needs of future generations" [8]. Operating a GSHP could meet the space heating and cooling needs of the present generation without comprising the needs of future generations because of the reduction or elimination of GHG emissions. However, if the system was not adequately designed, the needs of future generations could be compromised through increased GHG emissions (poorer performance due to thermal imbalance). Improper designs can lead to an increase or decrease in ground temperature causing system failures. Increase in ground temperature can lead to an inefficient GSHP because of low COPs as a result of inadequate heat transfer temperatures [9]. In addition, the increase in ground temperature can lead to ecological problems of species in the soil [10]. This research seeks to fill the knowledge gap related to thermal imbalance. It is important to conduct studies to accurately model the ground temperature changes during the operation of a GSHP system. Doing so can lead to potential design solutions that can be used to alleviate the thermal imbalance problems.

1.3 Thermal Imbalance

In a GSHP system, the ground acts as a heat sink in the summer (space cooling) and a heat source in the winter (space heating). When a building's heating and cooling loads are balanced, the annual ground temperature change is negligible. However, if the heating and cooling loads are significantly imbalanced, the ground can gradually become colder or hotter over the system's operation life. This phenomenon is also known as ground fouling. Figure 2 shows an illustration of the ground temperature during the operation of a fictional GSHP. Seasonal fluctuations can be observed by the peaks and troughs on the plot. During the coldest days of the winter, the most heat is drawn out of the ground to provide heating for a building. This lowest ground temperature is depicted as the troughs in the curves. During the hottest days of the summer, the most heat is released into the ground to provide cooling for the building. This increase in ground temperature is depicted as the peaks in the curves.

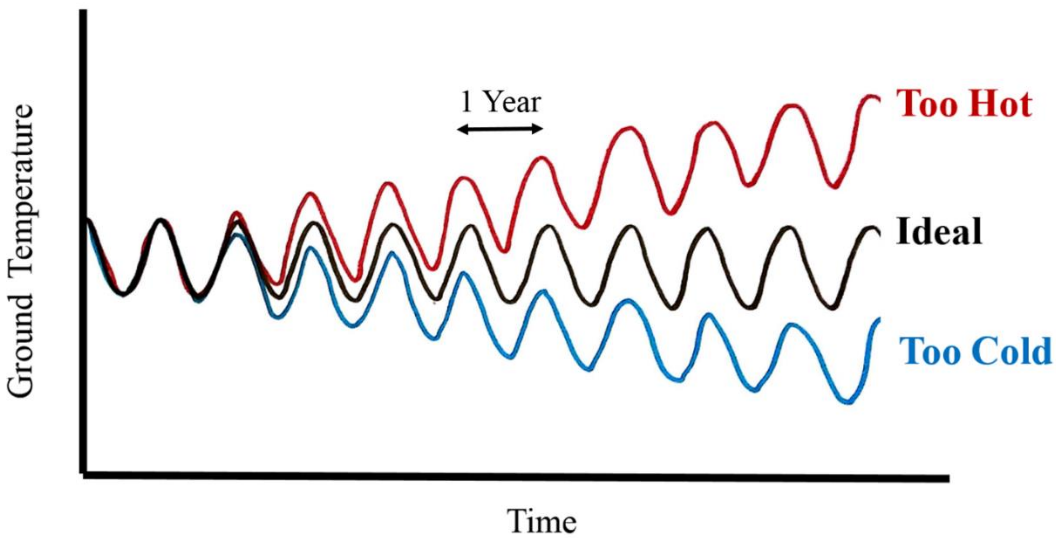

Figure 2: Ideal and fouling ground temperatures

In an ideal situation (illustrated by the black line), the seasonal fluctuations are well balanced and there is no overall change in the ground temperature during the long-term operation of the GSHP. GSHP systems do not have to be perfectly balanced to prevent ground fouling, slight imbalances will be alleviated by nature. However, when heating load is greater than cooling load, the ground can become too cold for the system to operate efficiently (illustrated by the blue line). In this situation, if the problem is not addressed, the ground can become too cold for heat transfer to occur between the ground heat exchanger (ground loop) and the ground (for space heating). Similarly, for space cooling, when cooling load is greater than heating load the ground can become too hot for the GSHP to operate (due to excessive long-term heat injection).

Studies have shown that during the operation of a GSHP, if the cooling loads are not fully compensated by the heating loads (or vice versa), changes can be observed in ground temperature [8] [10] [11]. In Zheng [11], the change in ground temperature was most significant in the region within 0.5 m of the borehole. It was also observed that the change in ground temperature occurs quickly in the first few years of operation and asymptotes after the first ten years [8] [10] [11].

In the present work, additional studies have been done with regards to thermal imbalance problems. Building functions, building location and borehole configurations were studied to observe the effects of them on the long term thermal imbalance of a building. The results of these studies can be found in the following subsections.

According to ASHRAE, to achieve a balanced system, the heat pump heating-to-cooling ratio has to be 1.6-1.8:1. For every hour of cooling, 1.6-1.8 hours of heating is required [12]. This ratio is not 1:1 because of the excess heat that is released into the system by the heat pump during heating mode. This ratio indicates that buildings that require 1.6 to 1.8 times more heating than cooling should result in thermally balanced ground.

It is important to evaluate the geographical location of the installation during the design phase. The ASHRAE heating-to-cooling ratio is an approximate guideline to implementing heat pump COPs. These values can be used in the thermal modelling of GSHPs.

1.3.1 Building Location

A building's heating and cooling loads are affected by its geographical location. Therefore, it is important to consider the building's geographical location during the design of GSHP systems in order to full understand the factors that affect this problem. Although outdoor temperature (ambient temperature) is a transient convective condition for the ground surface, its effects are limited to the first 15 m of soil [13]. As such, if thermal imbalance were to occur, the region of soil directly adjacent to GSHPs with vertical ground loops are not as affected by diurnal ambient temperature fluctuations on the surface. The effect of ambient air temperature in varying soil depths is illustrated in Figure 3. Any depth beneath the first 15m of soil is solely influenced by the GSHP system.

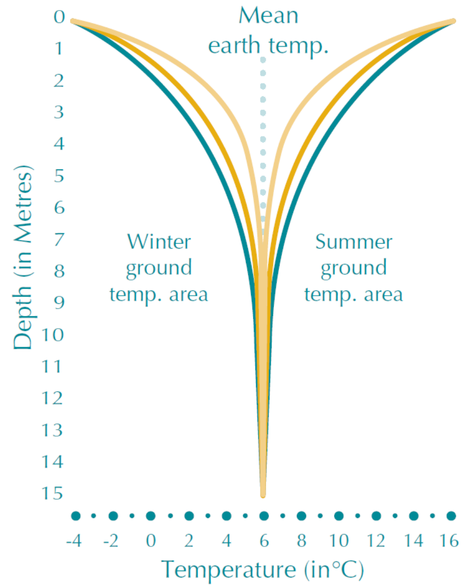

Figure 3: Air temperature effects on soil depths [12]

Although ambient air temperature does not affect the rate of heat transfer between ground-loop heat exchanger and the ground, compared to other parameters, it is important to note that weather patterns (seasonality) is a direct factor in thermal imbalance. In locations that have relatively balanced weather patterns (balanced summer and winter seasons), it is likely that operating a GSHP will not affect the ground temperature significantly. For most buildings, balanced weather results in balanced heating and cooling demands. For example, in locations such as the Yangtze River, in China, studies have shown that the balance of hot summers and cold winters allowed the ground to be relatively balanced [9]. However, in areas such as Hong Kong, space cooling is required in buildings throughout the year. As a result, during the operation of a GSHP system in Hong Kong, heat is constantly being rejected into the ground [14]. Because of the excess heat rejection, the ground temperature would increase throughout the operation of the GSHP if necessary precautions are not taken.

Conversely, in very cold climates (*i.e.*, Alaska), space heating is required in buildings for most of the year. There are two main concerns for operating GSHPs in cold climate regions [15]:

1) The soil temperature is too low to obtain high COPs,

2) Soil temperature cannot be maintained over time due to high load imbalances.

1.3.2 Building Function

The building function is the design use of the building. The amount of thermal imbalance experienced by a building can be affected by its function. For example, a building designed to be a fast food restaurant can expect to require cooling need throughout the year because of the large amount of heat release from kitchens. Studies were done to observe the effects of building functions on the change in ground temperature [16] [17]. In [16], three buildings were compared using the same weather patterns of northern China. Three buildings were analyzed: an office, an emporium, and a hotel. This study illustrates that although all three buildings were situated in the same geographical location (same weather patterns), the heating and cooling demands of each building were substantially different due to building function. The office's building loads were balanced, and load imbalance was inherent for the emporium and hotel. The emporium's and hotel's heating loads were greater than their respective cooling loads The results of the temperature drop at the borehole wall and overall temperature drop after a 15 year operation period, for the three buildings, is summarized in Figure 4. It can be noticed that the smallest drop in temperature occurs for the office building. However, it is interesting to note that the hotel's temperature drop is significantly greater than that of the emporium's even though the emporium has a greater load imbalance. The large increase in ground temperature for the hotel is contributed to by the long operating hours of the building as compared to the emporium.

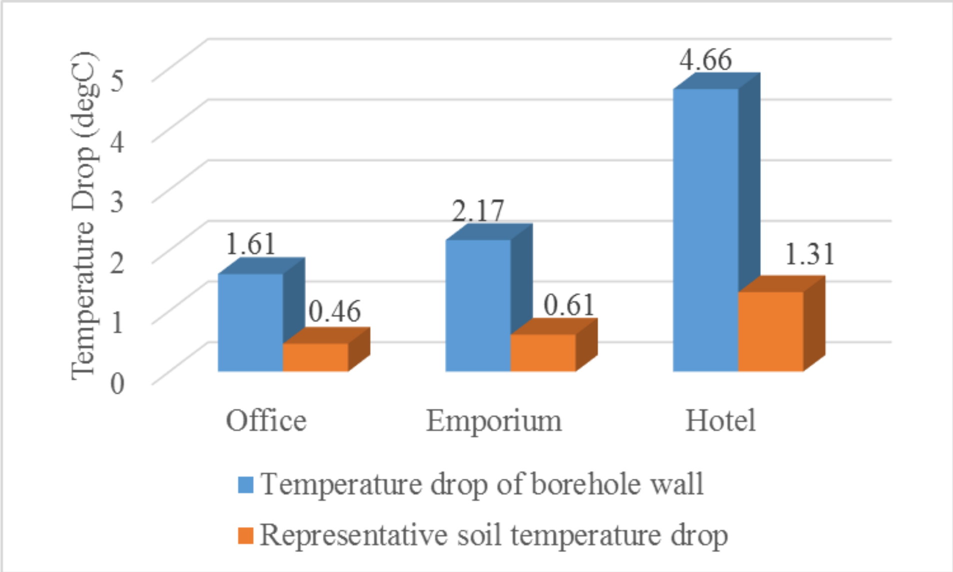

Figure 4: Temperature drop from office, emporium, and hotel (reproduced from [16])

This finding indicates that different building functions have a direct effect on the thermal imbalance of the ground. In modelling and analyses of GSHPs it is important to test the model using the correct building data. The direct effect of building loads on thermal imbalance also stresses the importance of accurate building energy simulations to obtain the correct building heating and cooling loads.

1.3.3 Borehole Configurations

Aside from the building function and location, it is important to assess the effects of borehole arrangements on the thermal imbalance problems. The ASHRAE handbook of design recommends that boreholes should be separated by a distance of 6 m when it is placed in a grid pattern [12]. However, it also indicated that this distance may be decreased when the boreholes are placed in a line or when the annual loads are well balanced [12].

Studies show that in an array of boreholes, the centre boreholes have the greatest temperature change compared to their surrounding boreholes [18]. To mitigate ground thermal imbalance, the centre boreholes can be removed to provide more space for surrounding boreholes to dissipate heat to and from, improving heat transfer [18]. The reduction of boreholes are compensated by increasing the workload for each of the remaining boreholes [18].

In [19], the effects of ground temperature during the operation of a single borehole (single line) and an array of boreholes was studied. The study was done by modelling a single borehole in an infinite field of soil, a line of boreholes and an array of boreholes in a grid. Each of these configurations were used to supply heating for a building. Zero, partial, and full compensation of heat were applied to each configuration to determine which configuration has the greatest change in ground temperature. A temperature of -5^{o}C was used as the minimum allowable temperature for the operation of the GSHP. Results indicate that for a single borehole in an infinite field of soil, no heat compensation is required to ensure that the GSHP continues to be operable. However, the line configuration requires at least partial compensation of heat and the grid configuration requires full compensation of heat.

The study in [19] indicates that there is a need to evaluate the grid configuration of boreholes to mitigate the effects of thermal imbalance. Studies in borehole configurations are important because large numbers of GSHP installations are in grid configurations due to space limitations.

1.4 Techniques to Mitigate the Effects of Thermal Imbalance

To alleviate the effects of ground thermal imbalance, several techniques have been developed. The remediation can be done through two methods: hybridized systems, intermittent operation and the increase of borehole spacing. The hybridized systems technique is best conceived during the design phase of the HVAC system. The purpose of these techniques is to ensure that the design is sustainable.

1.4.1 Hybridized Systems

When a GSHP system is designed, it is sized based on peak heating and cooling loads for a given building. However, peak heating and cooling loads only occurs for a short period of time during the winter and in the summer, respectively. As a result, it is common that GSHPs are overdesigned, resulting in high upfront costs, extending the payback period of the project [20].

To offset the imbalance in heating and cooling load demands, hybridized systems are designed to supply the excess demand (peak load) that cannot be met economically by the GSHP. Currently, in a hybrid GSHP system, the GSHP is designed to meet the base loads (usually "always-on" mode) and the heating/cooling auxiliary systems are used during peak loads. For buildings with unbalanced loads, to prevent thermal imbalance, the balanced portion would be met by the GSHP and the imbalanced portion would be met by the auxiliary system. Auxiliary systems include: a cooling tower and solar panel to provide additional cooling or heating for a building. In addition, a domestic hot water tank can be preheated using the building's heat rejection in cooling mode. In hybrid setting, the auxiliary system can restore thermal balance to the ground, by heating or cooling the ground directly, most efficiently in the shoulder seasons, to restore the ground temperature back to an equilibrium.

In [20], the authors proposed a shave factor to size GSHP systems. A shave factor is defined as the portion of the peak load met by the GSHP, ranging from 0.0 to 1.0. A shave factor of 0.60 indicates that 60% of peak load is met by the GSHP and the remaining 40% by an auxiliary system For example, for a building with a maximum load of 100 kW, applying a shave factor of 0.7 would indicate that 70 kW of the maximum load would be met by the GSHP with the remaining 30 kW to be met by a conventional system.

As mentioned, a well-designed hybrid system (*i.e.,* applying a shave factor) would alleviate/prevent thermal imbalance of the ground. Alternatively, while ground thermal imbalance can be alleviated by increasing the ground loop length (over design) or by increasing the distance between boreholes, these options are often not appealing due to extra costs and/or space limitations (lot size) [14].

1.4.1.1 Cooling Tower

In buildings where large amounts of cooling is required and little heating is needed, the ground can become thermally imbalanced due to excessive heat being injected into the ground over long periods of time. However, efforts have been made to address this problem of thermal imbalance. For example, cooling towers are used in extremely cooling dominant buildings to reduce the dependence on the GSHP for cooling. Using a cooling tower, as part of a hybrid system, can reduce the upfront cost of the GSHP and ensure that cooling demands can be met. These hybrid systems are designed to size the ground loop to the annual average cooling demand and to size the cooling tower to the difference between the peak loads and the annual average [14]. Alternatively, in some cases, cooling towers are used to pre-cool the ground during off-peak times to prevent thermal imbalance of the ground. The analysis in [14] indicates that using such hybrid systems can reduce the rate at which the ground temperature increases and relieve the drop in heat pump COP. The comparison between the change in ground temperature and COP is illustrated in Figure 5 and Figure 6. It can be observed from Figure 5 that the change in ground temperature is negligible in a hybrid GSHP system (HGSHP) compared to the change in ground temperature using a regular GSHP system.

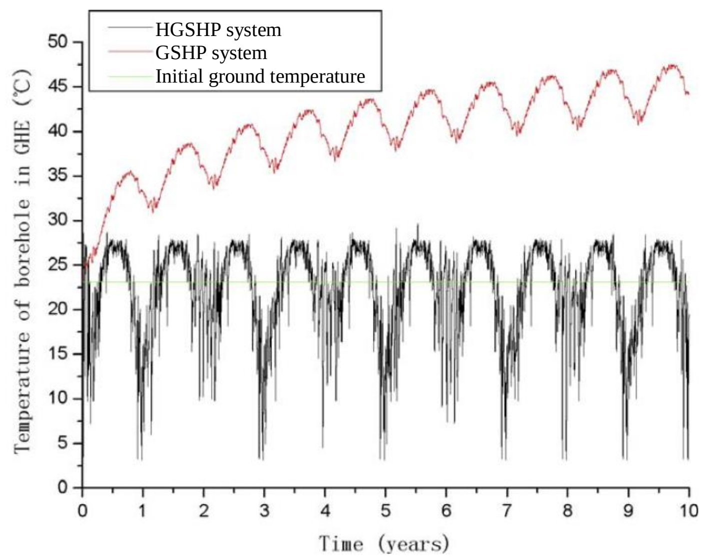

Figure 5: Ground temperature during 10 year operation of GSHP (reproduced from [14])

Because of the little change in ground temperature for the hybrid case, the COP of the heat pump also remains stable over the 10 years operation with seasonal fluctuations. However, the COP for the hybrid system is significantly higher than the COP for the regular GSHP system.

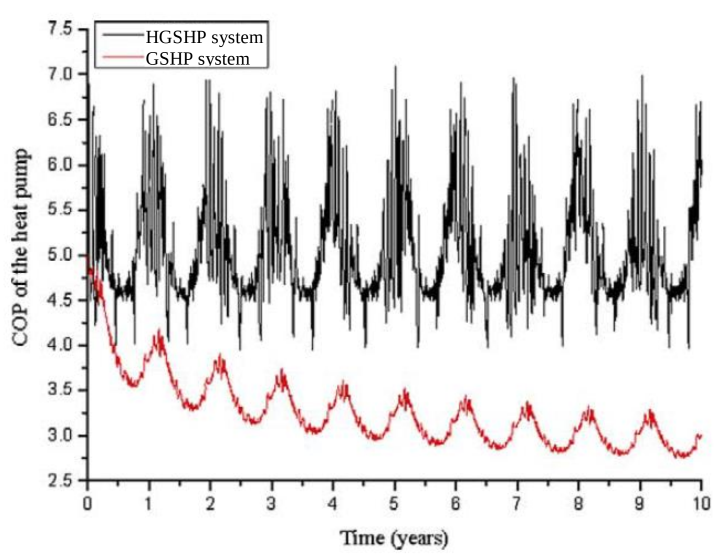

Figure 6: COP during 10 year operation of GSHP (reproduced from [14])

1.4.1.2 Solar Hybrid

Similarly to hybridization of GSHP with cooling towers in hot climate, in extremely heating dominant buildings, an alternative heat source is required in addition to the GSHP. For instance, solar collectors can be installed with the GSHP to provide additional heating for buildings. Doing so can allow smaller GSHP installations, reducing the high upfront cost of a GSHP system aside from reducing ground fouling problems. A study in [21] demonstrates that the use of solar assisted GSHP (SAGSHP) systems have benefits in maintaining system COP and ground temperature.

It was suggested in [15] that solar thermal collectors should be installed in heating dominant buildings in Alaska to reduce the usage of the GSHP. However, in locations where electricity rates are high, hybrid GSHPs may be unappealing as compared to fuel based furnaces due to the extra electricity consumption [15]. The hybridization of a solar collector and a GSHP can reduce the required ground loop length by 15% [22].

1.4.1.3 Domestic Hot Water

Aside from implementing additional technologies to hybridize GSHP systems, a waste heat recovery system can be used to mitigate ground thermal imbalance problems. For a cooling dominant building, the excess heat that is released into the ground can be used to preheat the water in the building. Hot water heating is 14% of energy consumption in a residential building [22]. The use of waste heat to heat water can be beneficial in an energy savings perspective aside from the ground thermal imbalance benefit. By using the excess heat to heat water, less heat is released into the ground, resulting in a more thermally balanced system.

1.4.2 Intermittent Operation

While hybridization is a method to alleviate ground thermal imbalance, it is best to be implemented during the design phase of the project prior to installation. However, in some cases, ground fouling problems may not be discovered until the system begins operation. Intermittent operation strategies can be applied to buildings that are currently operating.

Intermittent operation for ground temperature recovery can be done in two forms: short term and long term. Short term intermittent operation is done by operating a GSHP system for parts of the day and by stopping the operation for the other parts of the day to allow the ground temperature to recover. Long term intermittent operation is done by operating a GSHP system during the winter and summer months and turning the system off during changeover season (spring and fall) to allow the ground to recover back to its initial temperature.

In the study done by Meng *et al.* [16], described in section 1.3.2, it was found that the hotel had greater changes in ground temperature compared to the emporium although the emporium had a greater heating and cooling load imbalance. This difference in ground temperature change is because the emporium does not operate throughout the day and only operates during business hours. During the off hours, the HVAC system is turned off. At that time, the excess heat released by the building (to provide cooling demands) is allowed to dissipate freely to the surrounding soil. The ground is given time to recover until operation begins again the next day. A study in [10] was done to analyze the effectiveness of on-off ratios in a GSHP system that uses intermittent operation. The study uses on-off ratios to identify how long the system is operating and how long the system is off. An on-off ratio of 0 would represent a system that is only on and an on-off ratio of 2 would represent a 1:2 ratio of on and off times (8 hours on, 16 hours off). Analyzing on-off ratios of 0, 0.7, 1, 1.4, and 2, it was discovered that using an on-off ratio of 2 causes the temperature increase to reduce by 8.1^{o}C. With ratios of 0.7, 1, and 1.4, the temperature increase was reduced by 4.55^{o}C, 5.3^{o}C, and 6.3^{o}C, respectively. Applying short term intermittent operation periods are effective in reducing the change in ground temperature.

Long term intermittent operation can also be used to recover the ground temperature. For an operation of 137 days, the ground would need 80 days to recover to near its initial temperature [4]. Although there are mitigation techniques for the ground fouling problem, there is no systematic approach to determine how to size a hybrid GSHP system to minimize ground fouling. There is a knowledge gap in the understanding of the sizing of hybrid GSHPs in its relations to ground fouling. There is the need for further research in this field to determine how to hybridize a GSHP system with conventional systems. The methodology in [20] should be implemented in monitoring operating ground temperature to observe how adjusting the shave factor could potentially lead to more thermally balanced systems. These techniques should also be applied to the study of borehole configuration for the design of a sustainable GSHP system.

1.5 Author's contribution to published works

Below are four journal publications in the geo-exchange field that I contributed to.

- H. V. Nguyen, **Y. L. E. Law**, M. Alavy, P.R. Walsh, W. H. Leong, S. B. Dworkin (2013). An Analysis of the Factors affecting Hybrid Ground-Source Heat Pump Installation Potential in North America, *Applied Energy*, *125*, 28–38
    - In this publication, I assisted with the analysis performed in the studies.
- H. V. Nguyen, **Y. L. E. Law**, X. Zhou, P.R. Walsh, W. H. Leong, S. B. Dworkin (2016). A Techno-economic Analysis of Heat-Pump Entering Fluid Temperatures, and CO_2 Emissions for Hybrid Ground-Source Heat Pump Systems, *Geothermics,61*, 24–34
    - In this publication, I co-developed the algorithm used to calculate annual CO2 emissions in a GSHP system operation and assisted with the analyses performed in the studies.
- N. Kuzmic, **Y. L. E. Law**, S.B. Dworkin (2016). Numerical Heat Transfer Comparison Study of Hybrid and Non-hybrid Ground Source Heat Pump Systems, *Applied Energy*, *165*, 919–929
    - In this publication, I developed the algorithm to calculate borehole boundary conditions. The algorithm determined the hourly "On" and "Off" cycles of a

GSHP system based on a building's heating and cooling demands. Details of this algorithm can be found in Chapter 2.2 of this thesis.

- **Y. L. E. Law**, S. B. Dworkin (2016). Characterization of the Effects of Borehole Configuration and Interference with Long Term Ground Temperature Modelling of Ground Source Heat Pumps, *Applied Energy*, *179*, 1032-1047
    - I was the first author of this publication. Details of this publication can be found in Chapter 3 of this thesis.

Chapter 2

Research Methodology

2.1 Load Generation

In the present thesis, the long term ground temperature changes are highly dependent on the building's heating and cooling demands. The heating and cooling demands were based on building energy simulations of real buildings. Examples of hourly heating and cooling loads for a school are presented in Figure 7 and Figure 8, respectively. Hourly heating and cooling loads for other buildings studied in this thesis can be found in Appendix A.1.

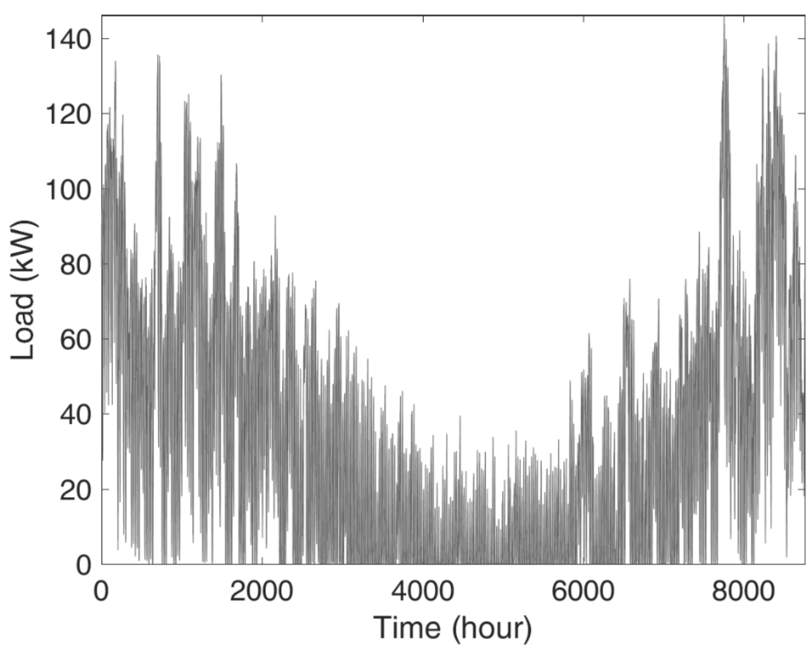

Figure 7: Heating load of school building

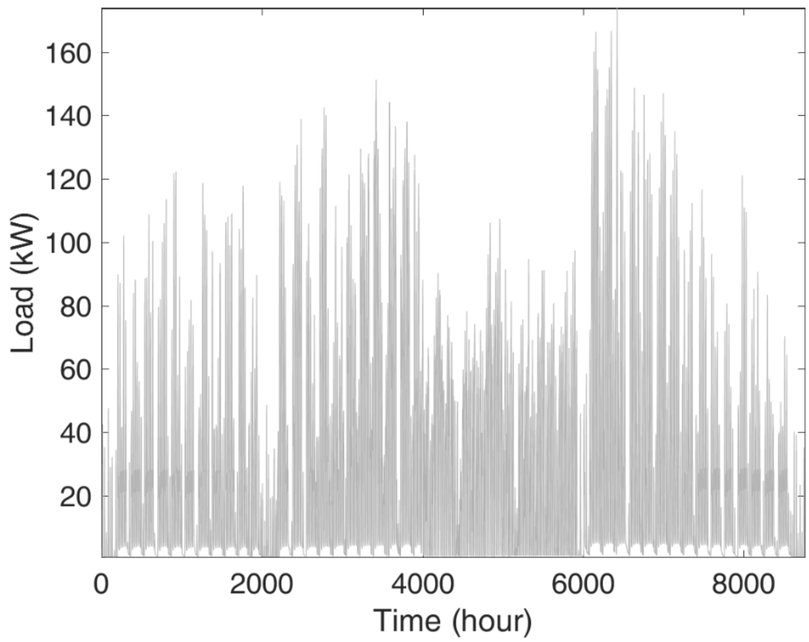

Figure 8: Cooling load of school building

In Figure 7, high heating demands can be observed in the winter months and low heating loads can be observed in the summer months. Low cooling demands can be observed in the winter months and high cooling demands can be observed in the summer months in Figure 8. Since the school building is an educational facility, the thermostat temperatures are higher than set point during summer months when the school year ends. This change in occupancy pattern can be observed by the drop in cooling load in the summer months of Figure 8.

Heating and cooling are assumed to be at the zone level, therefore heating and cooling loads can be present simultaneously at the same building. Assuming that a central distribution system is used and excess heat from one zone can be used to provide heat for another zone, the only demand that is required to be met by the GSHP system is the net heating and cooling load. Assuming that cooling load is positive and heating load is negative, the net demand is calculated by the sum of the two loads neglecting additional heat generated by the heat pump components. The loads are calculated hourly and summarized by Figure 9.

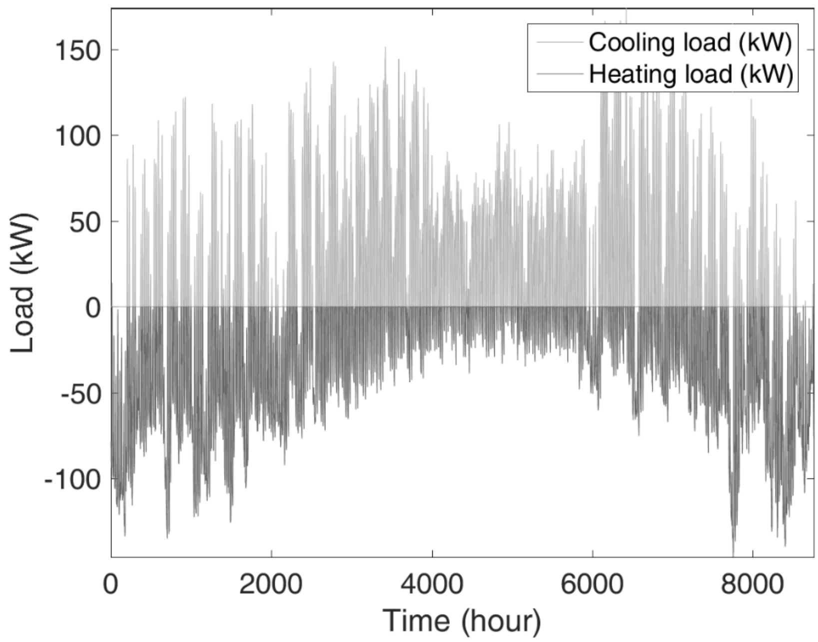

Figure 9: Net load of school building

2.2 Heat Flux Calculation

Heat flux boundary conditions need to be stipulated in order to simulate ground temperature response to geo-exchange. The heat flux boundary conditions are calculated based on the net demands calculated in the previous section. In the first step, the maximum heating and maximum cooling loads are determined. In this analysis, it was assumed that the GSHP system is sized to its full capacity. Based on Kavanaugh's equations (Eq. 1 & Eq. 2) for heating and cooling lengths, the maximum length of the two was determined to be the required ground loop length [23].

$$L_c = \frac{q_a R_{ga} + (C_{fc} w_{1c})(R_b + PLF_m + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \quad \text{(Eq. 1)}$$

$$L_h = \frac{q_a R_{ga} + (C_{fh} w_{1h})(R_b + PLF_m + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \quad \text{(Eq. 2)}$$

Where[1],

F_{sc}	= short-circuit heat loss factor
L_c	= required bore length for cooling (m)
L_h	= required bore length for heating (m)
PLF_m	= part-load factor during design month
q_a	= net annual average heat transfer to the ground (W)
q_{1c}	= building design cooling block load (W)
q_{1h}	= building design heating block load (W)
R_{ga}	= effective thermal resistance of the ground, annual pulse (m.K/W)
R_{gd}	= effective thermal resistance of the ground, daily pulse (m.K/W)
R_b	= thermal resistance of bore (m.K/W)
t_g	= undisturbed ground temperature (^oC)
t_p	= temperature penalty for interference of adjacent bores (^oC)
t_{wi}	= liquid temperature at heat pump inlet (^oC)
t_{wo}	= liquid temperature at heat pump outlet (^oC)
C_{fc}, C_{fh}	= correction factors that account for the amount of heat rejected or absorbed by the heat pumps

The maximum heating and cooling loads were divided by the required loop length and multiplied by 100 to determine the load for each 100 m length of piping. Then, the load was multiplied by 2 to determine the load for a 100 m borehole with a single U-tube (Eq. 3). To determine the maximum heat flux applied during the cooling and heating modes of the GSHP system, the loads are divided by the soil contact area of the borehole (Eq. 4). The soil contact area is defined as the outer area of the borehole cylinder plus the bottom circular area of the borehole (Eq. 5).

[1] The variable definitions for Eq. 1 and Eq. 2 are reproduced from [23]

$$\mathrm{Q_{g,heating}}\ (\mathrm{or\ Q_{g,cooling}}) = \frac{max\ load}{L_h\ (or\ L_c)} * 100\ m * 2\ pipes \qquad \text{(Eq. 3)}$$

$$q_b = \frac{Q_g}{Contact\ area} \qquad \text{(Eq. 4)}$$

$$Contact\ area = 2\pi rh + \pi r^2 \qquad \text{(Eq. 5)}$$

Upon determining the heat flux for the heating and cooling conditions, it is important to determine when the heating or cooling conditions are turned on. The process illustrated in Figure 10 depicts the procedure used to determine the “On” and “Off” conditions of the system. At each hour, the net demands of the building are evaluated. If the building requires net heating in the present hour, it was determined whether the amount of heating available is sufficient to meet the hourly demands. If the heating available is sufficient to provide heating for the building, the GSHP system can turn “Off” for that hour. Otherwise, the GSHP is turned “On” for the hour to meet the heating demand. The same process is repeated for each of the remaining hours and for cooling loads. At the end of the process, a series of “On” and “Off” conditions for heating and cooling are applied to each hour of the year.

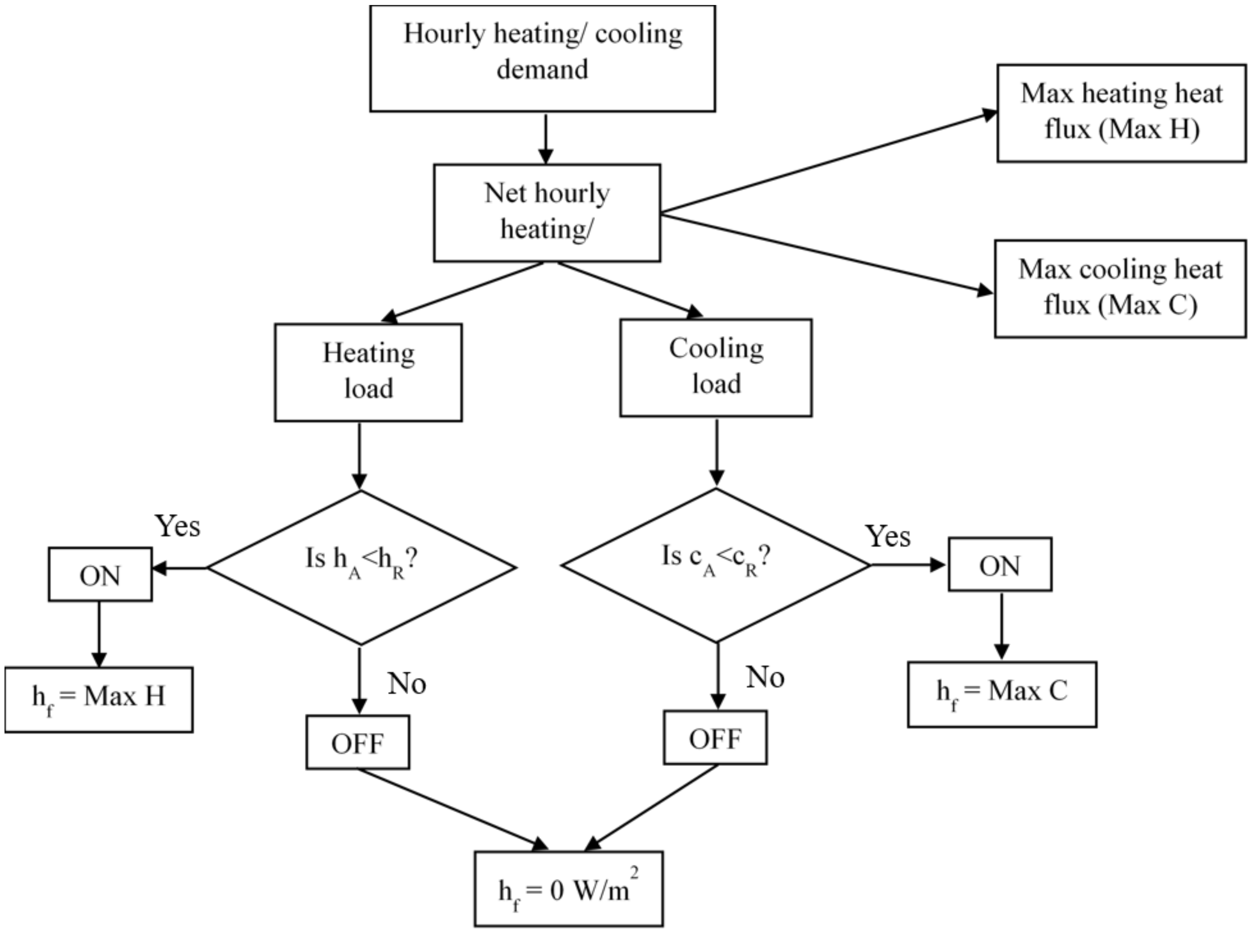

Figure 10: Hourly heat flux calculation

To determine the hourly heat flux conditions, the “On” and “Off” conditions are converted into hourly heat fluxes using conditions in Table 2. The maximum heating and cooling heat fluxes are applied to each hour according to the “On” and “Off” conditions applied in the previous step.

Table 2: Summary of heat flux conditions

Condition	Heating	Cooling	Heat Flux (W/m2)
1	ON	OFF	Max heating heat flux
2	OFF	ON	Max cooling heat flux
3	OFF	OFF	0

The hourly heat flux applied to the borehole walls for a school building is presented in Figure 11. Hourly heat flux conditions for other buildings studied in this thesis can be found in Appendix A.2.

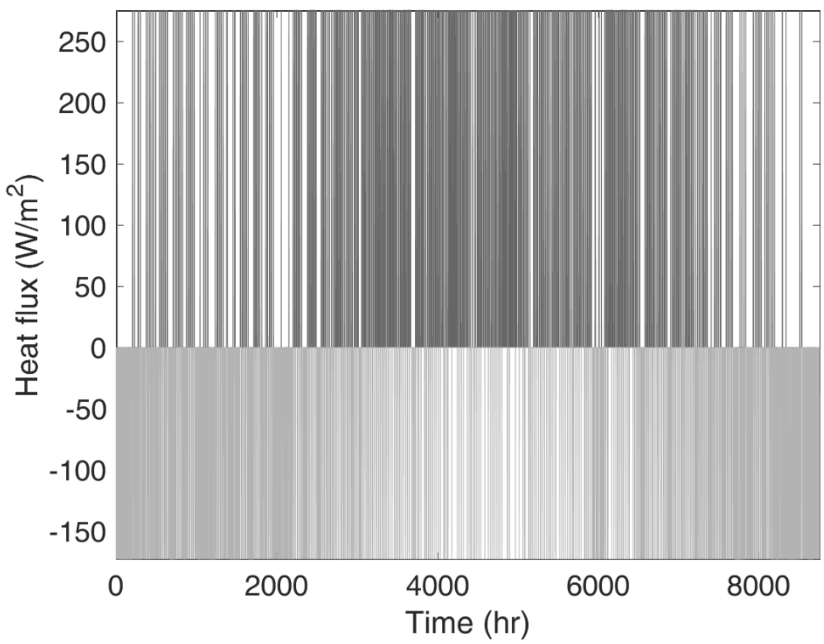

Figure 11: Hourly heat flux conditions for a school building

2.3 Finite-Element Model

2.3.1 Model Geometry

A finite-element model was created using COMSOL Multiphysics to simulate the changes in ground temperature during the operation of a GSHP [24]. A rectangular prism soil domain was created and four cylinders were subtracted out of the soil volume to model cylindrical boreholes as illustrated in Figure 12a. The void created by the subtraction is assumed to be hollow. Such voids allow heat applied by heat flux conditions to be transferred in one direction into the soil volume by conduction. Solid soil cylinders were modelled at y=0 m to y=50 m underneath the borehole geometry to simplify meshing procedures in 2.3.3. These solid cylinders are filled with soil with the same properties as the soil prism. It was assumed in this model that soil properties remain the same throughout the entire volume studied, and ground water movement was neglected. Boreholes are 0.0625 m in radius and 100 m in length. The specific geometry of the soil volume and boreholes used in Chapter 3 and 4 are described in the respective methodology sections. Since the borehole geometry is extremely fine, the figures in this section magnified borehole radius to 1 m from 0.0625 m for easy viewing, as illustrated in Figure 12b.

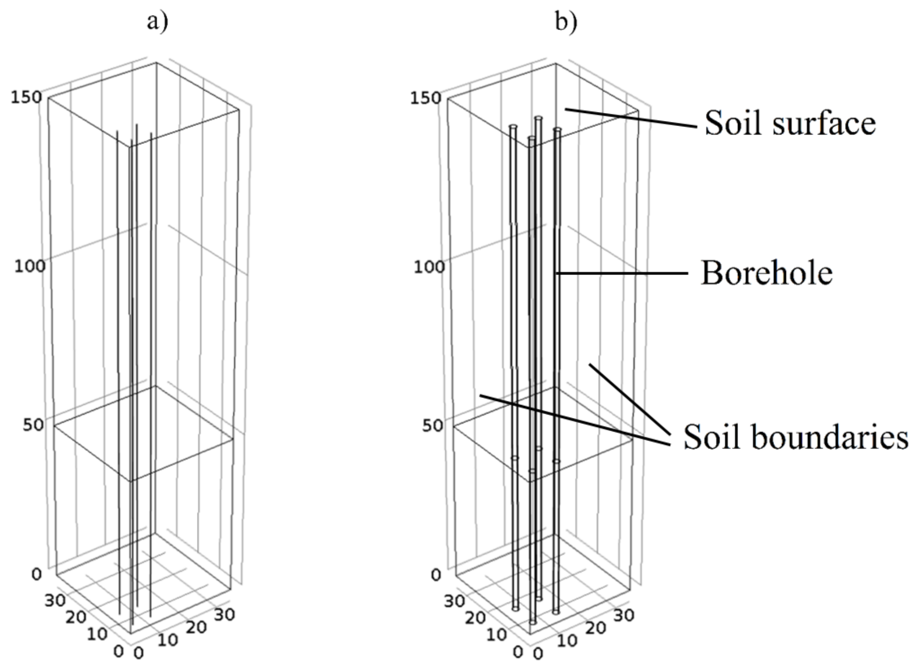

Figure 12: Outline Of Geometry With (A) Boreholes To Scale And (B) Boreholes Not To Scale

2.3.2 Boundary Conditions

Boundary conditions are applied to the borehole walls and soil volume faces prior to executing the simulation. Borehole heat flux conditions from section 2.2 were applied to the borehole wall using an hourly interpolation function. The surfaces that the conditions were applied to are illustrated in blue in Figure 13. At these boundaries, heat is released/extracted from the surrounding soil to provide heating and cooling for a building.

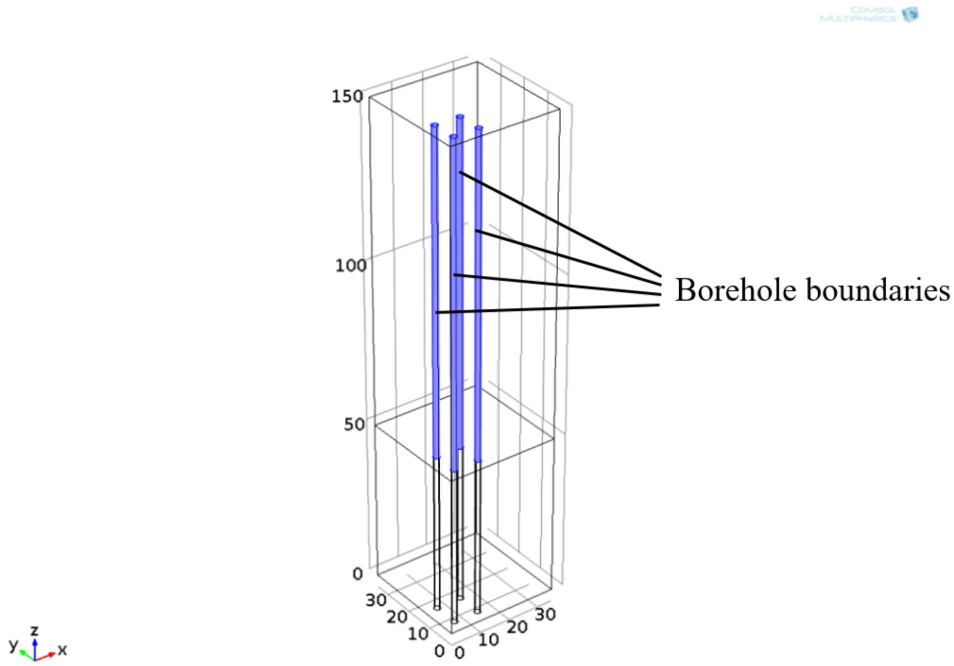

Figure 13: Borehole boundaries (borehole radius is not to scale)

A symmetry boundary condition was applied to the centre faces of the soil volume to mirror the simulation. By applying symmetry conditions, the performance of 16 boreholes can be simulated by modelling 4 boreholes, reducing computation time.

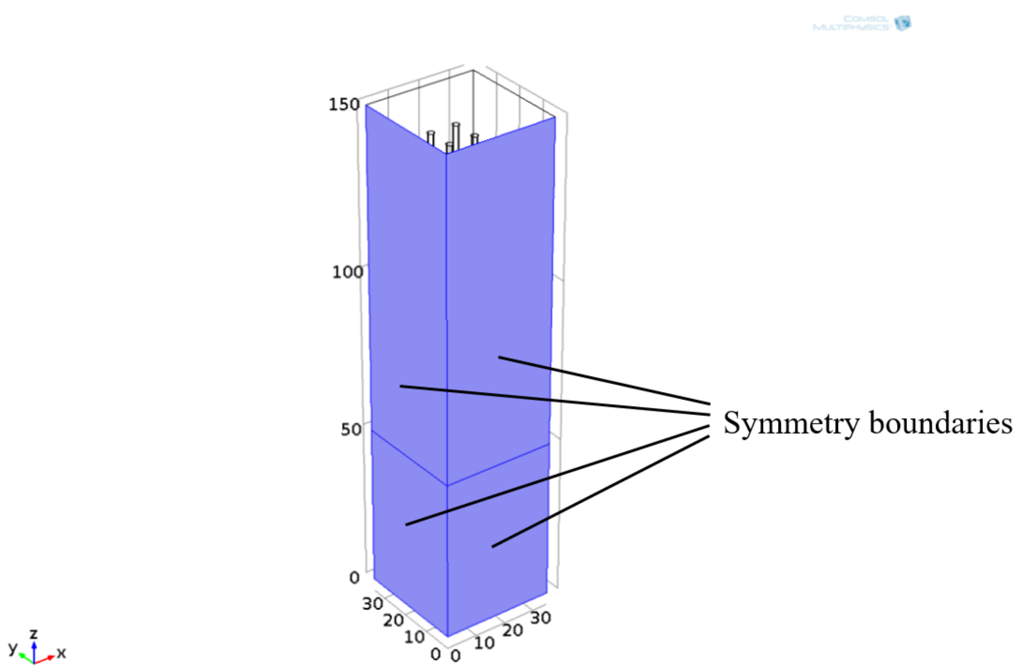

Figure 14: Symmetry boundaries (borehole radius is not to scale)

Open boundary conditions were applied to the outer surfaces of the soil volume. The open boundary depicts far field conditions where ground temperature remains at its initial temperature of 10^{o}C. The far field boundary was applied at 30 m away from the closest borehole. This distance was determined based on a domain size analysis that was done by increasing the domain size from 10 m to 30 m for a 2x2 borehole system. The temperatures at the same locations for the different domain sizes were considered. It was observed from the analysis that the maximum temperature difference between using 20 m and 30 m domain sizes were within 0.4% of each other, at a point adjacent to the borehole. Temperature differences between the two domain sizes at the same locations were less than 0.005% beyond 17.6 m away from the centre of the bore field. To ensure that the domain size was sufficient for a 16 borehole system, a 30 m domain size was used.

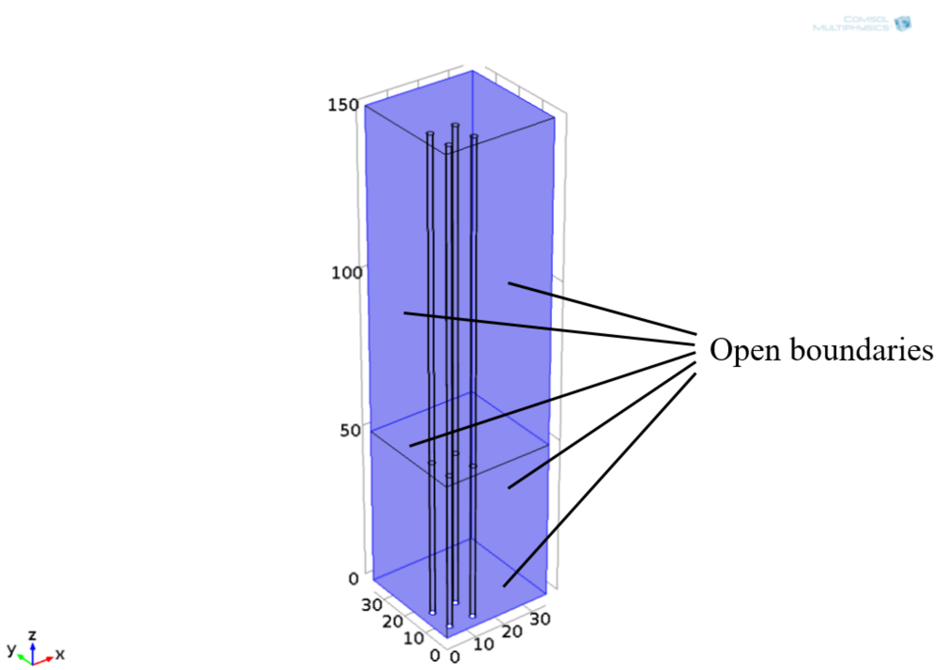

Figure 15: Open boundaries (borehole radius is not to scale)

2.3.3 Meshing

The meshing of the geometry involved a free triangular mesh on the top and bottom surfaces of the geometry. A swept meshing technique was used to create the remaining mapped meshes. The minimum element size chosen was 0.035 m to ensure that there is sufficient meshing at the borehole surfaces. Elements are small near the boreholes and increase in size as they approach the far field boundaries. The maximum element growth rate was limited to 1.5 to ensure that there are enough elements near the borehole walls. A triangular mesh was used on the top and bottom surfaces of the geometry rather than a quadrilateral mesh because the triangular mesh was able to create more elements near the borehole wall as illustrated by Figure 16. The swept mesh built on the remainder of the geometry is composed of quadrilateral shapes using an automatic sweep path. The source and destination faces of the sweep correspond to the top and bottom faces of the geometry, respectively. The sweep mesh also has a minimum element size of 0.035 m and maximum element growth rate of 1.5.

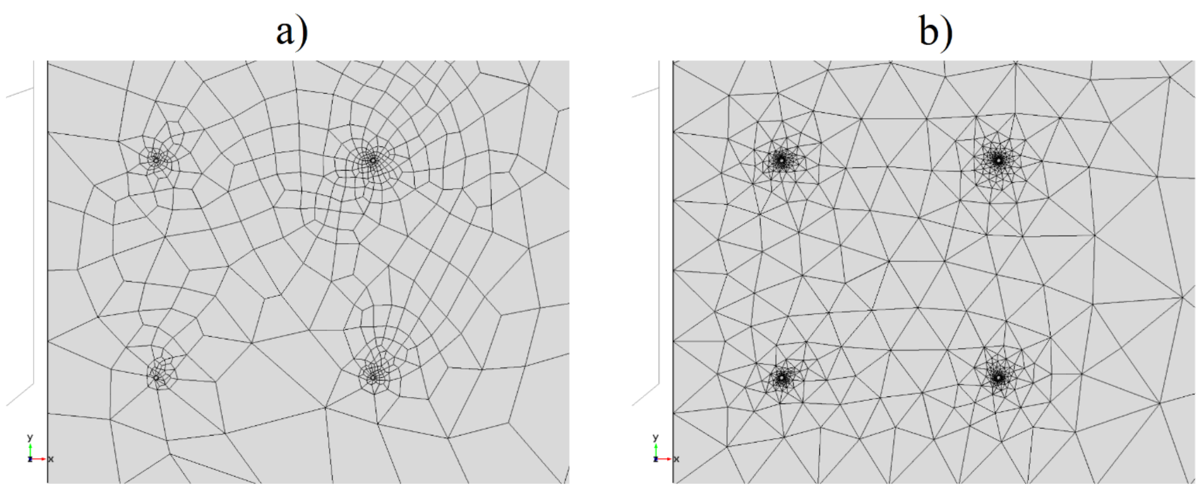

Figure 16: a) quadrilateral and b) triangular meshes

A mesh sensitivity analysis was conducted to determine the most appropriate mesh for the model created. The analysis involved varying the minimum element size from 0.005 m to 0.050 m. The results indicated that as minimum element size decreased, the difference in the temperatures interpolated from the same location decreased. This correlation can be observed from Figure 17. Using a criterion of $\Delta T < 0.01^{o}C$ as a threshold for maximum ground temperature change between element step sizes, the minimum element size was chosen to be 0.035 m.

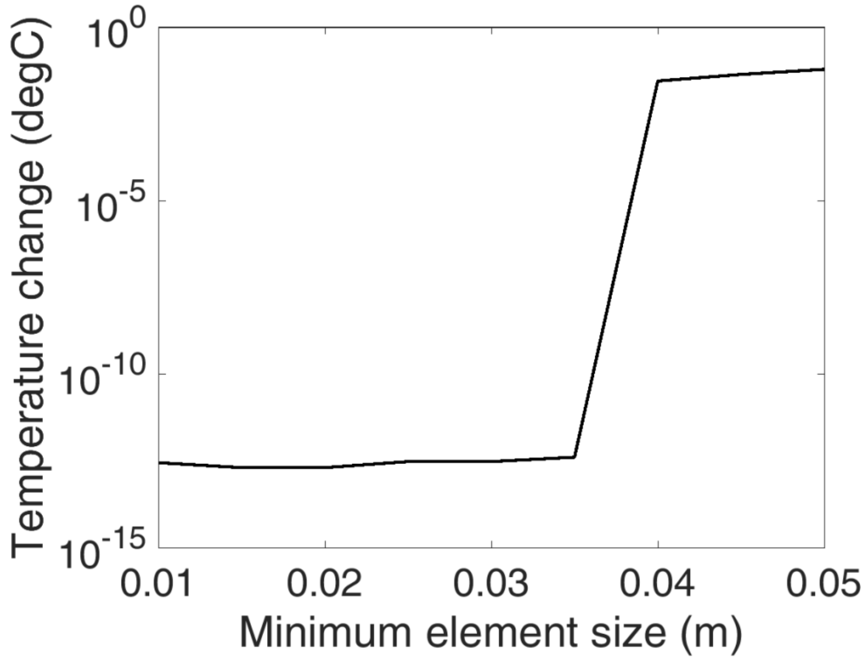

Figure 17: Mesh sensitivity analysis results

A sample meshed geometry can be found in Figure 18. The meshing method presented is general. Specific meshes used in the simulations vary depending on its geometry. The described mesh resulted in 12618 domain elements, 4288 boundary elements, and edge elements.

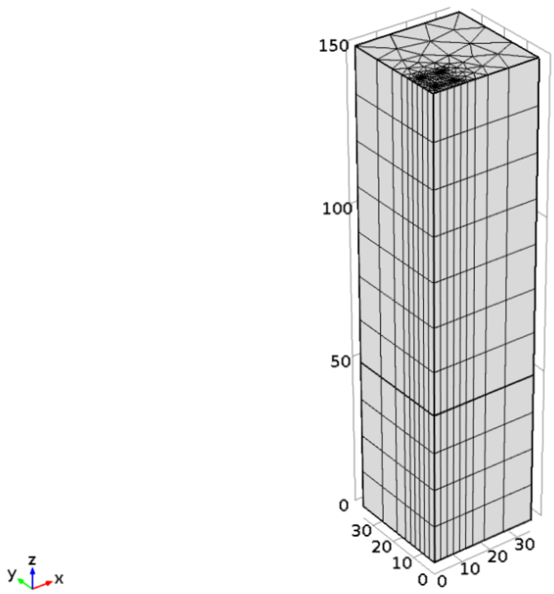

Figure 18: Meshed geometry

2.3.4 Simulation

A transient simulation method was used in this model. Five studies each with a four year simulation was created to reduce computation time. Each of the four year simulations consisted of hourly time-steps. At each hour, the boundary heat flux is updated according to the conditions calculated in section 2.2. The simulation uses a parallel direct sparse solver (PARDISO), which uses LU decompositions in its solutions [24]. The solver uses a backward differentiation formula (BDF) as its time-stepping method. For studies 2-5, the initial values were taken from the solution of the last time-step in the previous study. The simulation was continued for 175200 hours (20 years) and the analyses performed using these simulations can be found in Chapter 3 and 4 of this thesis.

Chapter 3

Characterization of the Effects of Borehole Configuration and Interference with Long Term Ground Temperature Modelling of Ground Source Heat Pumps

Corresponding Publication: Y.L.E., Law & S.B. Dworkin, "Characterization of the Effects of Borehole Configuration and Interference with Long Term Ground Temperature Modelling of Ground Source Heat Pumps" Applied Energy, 179 (2016) 1032-1047.

Abstract

Ground source heat pumps (GSHPs) are an environmentally friendly alternative to conventional heating and cooling systems because of their high efficiency and low greenhouse gas emissions. The ground acts as a heat sink/source for the excess/required heat inside a building for cooling and heating modes, respectively. However, imbalance in heating and cooling needs can change ground temperature over the operating duration. This increase/decrease in ground temperature lowers system efficiency and causes the ground to foul—failing to accept or provide more heat. In order to ensure that GSHPs can operate to their designed conditions, thermal modelling is required to simulate the ground temperature during system operation. In addition, the borehole field layout can have a major impact on ground temperature. In this study, four buildings were studied; a hospital, fast-food restaurant, residence, and school, each with varying borehole configurations. Boreholes were modeled in a soil volume using finite-element methods and heating and cooling fluxes were applied to the borehole walls to simulate the GSHP operation. 20 years of operation were modelled for each building for 2x2, 4x4, and 2x8 borehole configurations. Results indicate that the borehole separation distance of 6 m, recommended by ASHRAE, is not always sufficient to prevent borehole thermal interactions. Benefits of using a

2x8 configuration as opposed to a 4x4 configuration, which can be observed because of the larger perimeter it provides for heat to dissipate to surrounding soil, were quantified. This study indicates that it is important to carefully consider ground temperature during the operation of a GSHP. Borehole separation distances, layout, and hybridization should be considered to alleviate ground fouling problems.

3.1 Introduction

Ground source heat pumps (GSHPs) are an environmentally friendly alternative to conventional heating and cooling systems because of their high efficiency and low greenhouse gas emissions [2] [25]. GSHPs use the ground as a stable heat transfer medium to provide both heating and cooling for a building.

During the operation of a GSHP, the ground acts as a heat source and heat sink in heating and cooling modes, respectively [3]. An important aspect for a well-designed GSHP system is to balance the heat extraction and injection from and into the ground throughout the year. Long-term heat extraction of the ground (heating season), to heat the building, would cause the ground temperature to gradually decrease – lowering the heating efficiency of the system (vice versa for the cooling season). Ideally, when the heating and cooling demands of a building are well balanced, the ground temperature fluctuates within a stable, desirable range. However, when the heating and cooling demands are poorly balanced, the ground temperature may migrate up or down over time, and as a result, system performance diminishes, and in extreme cases the ground may fail to accept/provide more heat from/to the building. This phenomenon is referred to as ‘ground fouling’ and many systems in the past have had to stop their operation due to the resulting low coefficient of performance (COP) [4]. To ensure that a design is feasible, it is important to model and project the changes in ground temperature over many years of operation.

Furthermore, a deeper understanding of factors that can affect and mitigate ground fouling is sought.

GSHP systems are often designed to meet the full heating and cooling demands of buildings. When the building's heating and cooling loads are balanced, the system can operate for the designed duration. However, when there is a large imbalance of loads, the system could foul shortly after operation begins due to the change in ground temperature. This ground fouling can lead to system shut down, which causes economic loss, extended payback period, and occupant discomfort. Increasing ground temperature can lead to an inefficient GSHP because of low COPs as a result of inadequate heat transfer temperatures [9]. In addition, the increase in ground temperature can lead to ecological problems of species in the soil [10]. The study of ground temperature is important in GSHP designs.

Studies have shown that during the operation of a GSHP, if the cooling loads are not fully compensated by the heating loads (or vice versa), changes can be observed in ground temperature [10] [8] [11]. The change in ground temperature was most significant in the region within 0.5 m of the borehole [11]. It was also observed that the change in ground temperature occurs in the first few years of operation and asymptotes after the first ten years [10] [8] [11].

For most buildings, balanced weather results in balanced heating and cooling demands. For example, in locations such as the Yangtze River, in China, studies have shown that the balance of hot summers and cold winters allowed the ground to be relatively balanced [9]. Slight imbalances in ground temperature are recovered during spring and autumn seasons, when heating and cooling demands are low [26]. Other specialized buildings, such as restaurants or skating rinks with high cooling needs, or processing plants with high heating needs, may have severely unbalanced loads. Studies of regions with very hot/very cold climate indicate that ground temperature would increase/decrease throughout the operation of the GSHP if necessary precautions are not taken [14] [15]. There are two main concerns for operating GSHPs in cold climate regions: soil temperature is too low to obtain high COPs and soil temperature cannot be maintained over time due to high load imbalances [15]. An objective of the present study is to analyze the quantification of these imbalances so that engineers can better understand how to design accordingly.

According to ASHRAE, to achieve a balanced GSHP system, the heat pump heating-to-cooling ratio has to be 1.6-1.8:1; for every hour of cooling at full capacity, 1.6-1.8 hours of heating at full capacity is required [12]. There is a need to understand the severity and implications for buildings with load ratios outside this range.

Aside from the building function and location, it is important to assess the effects of borehole arrangements on the thermal imbalance problems. The ASHRAE handbook of design recommends that boreholes should be separated by a distance of 6 m when they are placed in a grid pattern [12]. It also indicated that this distance may be decreased when the boreholes are placed in a line or when the annual loads are well balanced [12]. However, no formalized method of determining such a spacing reduction currently exists in the literature.

Studies show that in an array of boreholes, the centre boreholes have the greatest temperature change compared to their surrounding boreholes [18]. To mitigate ground thermal imbalance, the centre boreholes can be removed to provide more space for surrounding boreholes to dissipate heat to and from, improving heat transfer [18]. This tactic may not always be possible due to space limitations. The present work seeks to quantify the ground temperature changes and to determine whether changing the arrangement of the boreholes can reduce the effect.

In [19], the effects of ground temperature during the operation of a single borehole (single line) and an array of boreholes was studied. The study was done by modelling a single borehole in an infinite field of soil, a line of boreholes, and an array of boreholes in a grid. Each of these configurations were used to supply heating for a building. Zero, partial, and full supply cooling loads of were applied to each configuration to determine which arrangement of boreholes has the greatest change in ground temperature. Results indicated that for a single borehole in an infinite field of soil, no heat balance is required to ensure that the GSHP continues to be operable. However, the line configuration requires at least partial balance of heating and cooling loads and the grid configuration requires full balance of loads. The study in [19] indicates that there is a need to evaluate the grid configuration of boreholes to mitigate the effects of thermal imbalance. Studies in borehole configurations are important because large numbers of GSHP installations are in grid configurations due to space limitations. A study in [27] indicated that there is interaction between boreholes, and separation distances between boreholes can be calculated to prevent thermal imbalance.

In [28] the authors used eQuest/DOE-2.2 to simulate ground temperature response to geo-exchange. The eQuest/DOE-2.2 program used complicated g-functions to simulate temperatures at the borehole wall [29]. The development of these g-functions are based on cylindrical models developed by Eskilson [28] [29]. The g-functions used the step responses of the boreholes to determine the temperature distribution of the borehole field. It was concluded that the use of g-functions was effective in reducing computation time for temperature distributions in a borehole field. The g-functions use the superposition of a single cylindrical model to predict the behaviour of a borehole field. The effects of groundwater filtration and surface convection were studied in [29] and were shown to have a negligible effect on modelling. G-functions are commonly adopted by ground heat exchanger programs, such as EED [30]. These works simplify multiple borehole simulations into a single borehole simulation through the use of a g-function. A master's thesis in 2013 [31], added to Eskilson's work by comparing the g-functions generated by Earth Energy Design (EED) with those generated using numerical models and COMSOL Multiphysics. The finite line source results were well-validated with the results from EED. Upon validation of the line source model results, the author built numerical models using COMSOL Multiphysics to create models involving borehole fields that were closer to reality than other methods [31]. Further examining the results of the study, the results of the numerical model were well validated against the results from EED.

A model in [32] used hourly heat fluxes and g-functions in an EnergyPlus program to simulate the temperature changes [33]. The results of this model were validated against the analytical solution and the results were within 2^{o}C error [32]. The study in [32] indicates that g-functions are highly accurate in determining the borehole wall temperature for multiple borehole simulation.

In [34], experimental results were validated against simulated results and ASHRAE design method results. The authors proposed the use of g-functions to simulate ground temperature response. The results indicated that using g-functions under-predicted required borehole length by 4% while the ASHRAE design method over-predicted the required borehole length by more than 100% [34]. This study indicates that the methods proposed by ASHRAE design guidelines may result in systems that are overdesigned, increasing the upfront cost of the system.

In [35], the authors demonstrated the importance of including a temperature penalty in the calculation of ground loop length. A temperature penalty is a factor that is applied to the ground loop length calculation that accounts for the increase/decrease in ground temperature over the system's operating duration. In a case where heating and cooling hours are 1500 and 500, respectively, the temperature penalty is -2.1^{o}C [35]. However, in an extremely cooling dominant case, the temperature penalty is +10.5^{o}C [35]. The change in ground temperature due to the thermal imbalance causes the required ground loop length to increase by 1.26 and 1.51 times, respectively in the two cases. This study proposed the quantification of the temperature variation by applying a temperature penalty.

In both studies, [34] and [35], g-functions were used to predict the ground temperatures by superimposing the g-function onto a single borehole simulation to model multiple boreholes. Although using the g-function can accurately determine the temperature penalty associated with each borehole configuration, the distribution of temperatures surrounding each borehole cannot be easily determined. Although studies have been done with regards to the thermal interactions of boreholes using g-functions and analytical methods, none involved 3D finite element modelling of the distribution of temperatures in the complete borehole field. The model proposed in the present work provides the temperature distribution surrounding each borehole so that the complete heat extraction/injection effects can be visualized.

The problem this research seeks to solve is that of thermal imbalance. To address this knowledge gap, it is important to conduct studies to accurately model the ground temperature changes during the operation of a GSHP system. Doing so can lead to potential design solutions that can be used to alleviate the thermal imbalance problems. The novel contribution of this chapter is that it simulates the heat transfer between the boreholes and their surrounding soil in a 3D finite element model. Present literature suggests the superimposing of a g-function to model the temperature penalty of various borehole configurations into a single borehole simulation. However, this method cannot model the temperature variation of different depths within the soil domain. Using this model, the temperature variation at any point in the soil domain can be determined and temperature distribution surrounding each borehole can be studied. The present study extended beyond temperature distributions in the ground and analyzed other aspects, such as the “on” and “off” cycles of the heat pump operation and the prediction of system life. The model present in this paper provides a useful tool for the geo-exchange industry, which can be used to simulate the temperature variations and distributions during the design phase of the system to ensure system efficiency. While not immediately integrable into the design process, the results of this study extend the fundamental understanding of a GSHP functionality and borehole design.

In this study, hourly building heating and cooling loads were processed to calculate hourly borehole heat fluxes. A model was created using COMSOL Multiphysics [24] to simulate the borehole field geometry. Hourly conditions were applied to the geometry and the simulation was performed for a 20 year time period. The analysis was repeated for 2x2, 4x4, and 2x8 configurations and comparative analyses were performed.

3.2 Methodology

The methodology used in this paper consists of a two-part process; i) performing building energy simulation, and using the predicted heating and cooling loads to calculate hourly heat flux using MATLAB [36], and ii) simulation of ground temperature using COMSOL Multiphysics finite element heat transfer methods [24]. In the first part, building loads are determined using building energy simulation data generated from eQuest [37] and processed using MATLAB to create an accurate set of transient heat flux boundary conditions. Afterwards, a model is created using COMSOL Multiphysics to simulate operating borehole exchangers in the ground. The loads generated in the first step are used as boundary conditions for the finite element model.

Using this methodology, some assumptions were made. It was assumed that there is negligible groundwater movement in the soil volume studied. In addition, soil properties and GSHP system COP were assumed to be constant throughout the study period regardless of the change in ground temperature.

3.2.1 Building Loads

The procedure used to process the building heating and cooling demands into finite element model boundary conditions was presented in section 2.1 and 2.2. Net hourly heating/cooling loads were calculated using the methods presented in 2.1. These net hourly heating/cooling loads were processed into hourly borehole wall heat flux conditions using the "On" and "Off" conditions applied using the method presented in 2.2.

Since the heat pump generates waste heat during its operation, it is important to properly account for this heat as it could contribute to or alleviate thermal imbalance. In the winter, the heat generated by the heat pump can help restore the ground temperature and in the summer, the heat generated contributes to greater heat removal requirements. This heat can be quantified using the heat pump's coefficient of performance (COP). In this study, a COP of 4 was used for heating and an infinite COP (free cooling) was applied for cooling mode because cooling can occur naturally from high to low temperature. Few installations exist that utilize passive cooling, however, this assumption is sufficient for the purpose of developing a model for ground temperature response.

Since the coefficient of performance of a heat pump is defined by the heat output divided by the compressor work, the net heat extracted (or injected) into the ground can be calculated by the difference (or sum) of heat output and heat released by the heat pump. This relationship was used to derive a factor that takes the COP into account for heat flux calculations (Eq. 1, Eq. 2).

$$H_f = \frac{COP_h - 1}{COP_h} \quad \text{(Eq. 1)}$$

$$C_f = \frac{COP_c + 1}{COP_c} \quad \text{(Eq. 2)}$$

Where H_f is the heat flux adjustment factor for heating, and C_f is the heat flux adjustment factor for cooling.

By multiplying heat flux conditions by H_f in heating mode and C_f in cooling mode, the net heat flux of a borehole can be estimated.

In this simulation, the heating COP is assumed to be 4.0 and free cooling is assumed. The heat flux calculated is based on the maximum required load for heating and cooling modes. The value of these heat fluxes are presented in detail in section 3.1. Consistent with [38], for every 1^{o}C drop in entering fluid temperature, the heating COP decreases by 0.06. Also, for every 1^{o}C increase in entering fluid temperature, the cooling COP decreases by 0.1. For simplicity, however, a constant COP was selected in this simulation. Although modelling a constant COP may cause errors in some of the computed values, the change is not expected to affect the qualitative trends present, and associated analysis. The increasing/decreasing trends of the overall ground temperature and the thermal interactions of borehole configurations are unaffected. The daily fluctuation of ground temperature will be affected by the hourly varying COP, however, the average daily ground temperature will remain the same.

Annual heating and cooling heat fluxes were repeated for 20 years to depict the heating and cooling operation of a GSHP system for a typical major maintenance cycle.

3.2.2 Finite Element Simulation

A 3D symmetrical model was created using COMSOL Multiphysics to simulate a series of boreholes in working conditions during a 20 year period. Soil properties from Table 4 were applied to the soil geometry. Uniform soil property was applied to the model. Studies in [39] found that using a single soil layer for modelling resulted in little difference in overall ground temperature change compared to multiple soil layers.

In the finite element simulation, it was assumed that the soil properties remain constant throughout the simulation time. The soil domain dimensions used in the simulations are summarized in Table 3. It was also assumed that negligible groundwater movement was present within the soil domain. The pipe geometry in the borehole was assumed to be a single U-tube. The borehole resistance associated with this geometry was handled in the determination of total piping length required for each building. The resulted heat flux was applied to the borehole wall of the model.

Table 3: Soil domain dimensions

Borehole configuration	Soil domain dimensions
2 x 2	40 m x 40 m x 150 m
4 x 4	70 m x 70 m x 150 m
2 x 8	70 m x 100 m x 150 m

Table 4: Soil properties

Property	Value	Unit
Thermal conductivity	1.63	W/(m.K)
Density	2050	kg/m^3
Heat capacity	1840	J/(kg.K)

In the multiple borehole model, a quarter of the boreholes were modelled in a rectangular prism of soil and mirror boundary conditions were used on two sides to effectively quadruple the domain. In the 2x2 model, a single borehole geometry was created and in the 4x4 model, four 100 m boreholes were created. Boreholes typically range between 20 m and 200 m in depth, with most modern installations targeted at 150 m or more [40] [41]. Symmetry boundary conditions were applied to the inner faces of the prism to model four times the number of boreholes modelled in the geometry as presented in Figure 19a. Hourly heat fluxes were applied to the borehole walls as presented in Figure 19b, using an exact time stepping technique in which hourly heat fluxes are exactly read from the tabulated values rather than interpolated. This method ensures that no random time-stepping is done and consistent results can be obtained in all trials. The simulation uses a parallel direct sparse solver (PARDISO) which uses LU decomposition in its solutions. The solver uses the backward differentiation formula (BDF) to calculate soil temperature at each time step [24]. An open boundary condition was applied to the exterior and bottom faces of the prism to approximate infinite domain size at initial temperature and zero heat flux beyond the boundary as presented in Figure 19c. Heat trasnfer through the top face of the geometry is neglected since ambiant conditions at most only affect the first 15 m of soil [13]. As such, if thermal imbalance were to occur, the region of soil directly adjacent to GSHPs with vertical ground loops are not affected by seasonal ambient temperature fluctuations on the surface. Any depth beneath the first 15 m of soil is solely considered to be influenced by the GSHP system and soil properties.

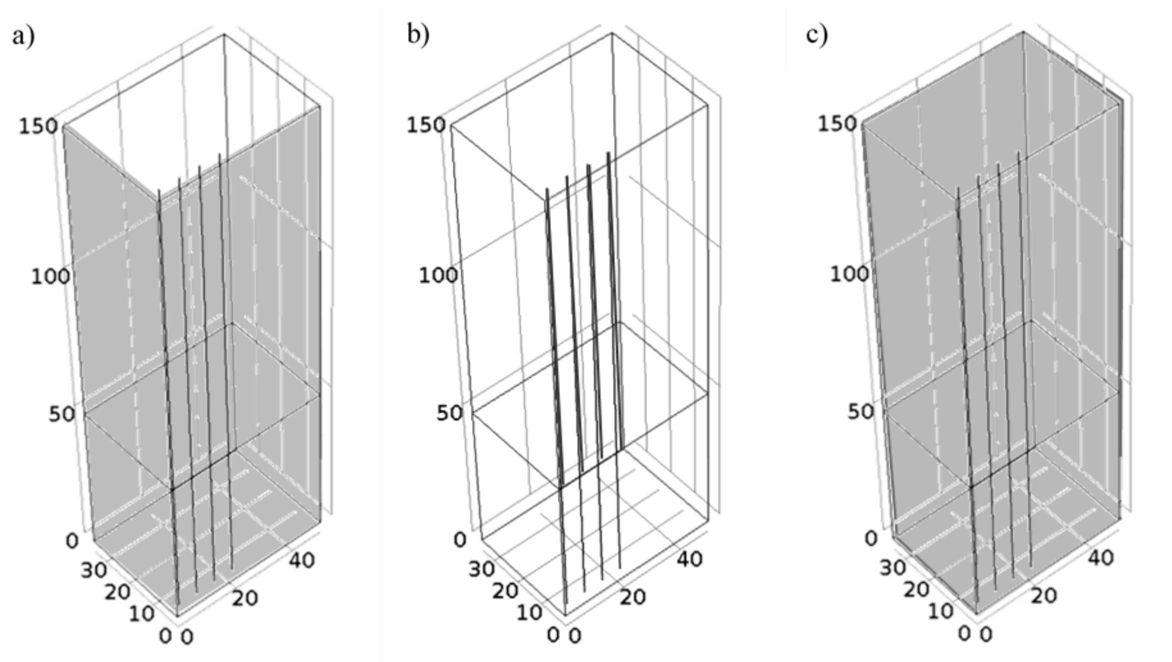

Figure 19: Boundary conditions for (a) symmetry boundary, (b) heat flux boundary, and (c) open boundary

3.3 Model Validation

Using the same validation procedure as in Kuzmic et al., [42] the finite element model was validated against analytical and experimental results. Finite element models were created using the same parameters and boundary conditions as in [42].

3.3.1 Validation against Analytical Results

The finite element model was validated against the analytical results presented in [42]. The analytical results were generated using a finite line-source model. The model parameters are outlined in Table 5. The geometry was created using finite element methods with the computational domain shown in Figure 20a. A 150 m borehole with radius of 0.01 m was modelled within a 4.34 m radius soil volume. A boundary temperature of 0^oC was applied to the top and bottom boundaries of the soil volume. Zero gradient conditions were applied to the inner and outer soil boundaries. A heat flux of 1592 W/m^2 was applied to the borehole wall. A summary of the conditions applied are presented in Figure 20b.

Table 5: Parameters for analytical validation (reproduced from [42])

Parameter	Value
Borehole height (H)	150 m
Radial soil domain (r_∞)	4.34 m
Underneath soil domain (L_b)	11.25 m
Soil conductivity (k_{soil})	2.4 W m^{-1}K^{-1}
Soil density·soil specific heat	3.9 x 10^6 J m^{-3} kg^{-1}
Heat transfer rate (q_1)	100 W m^{-1}

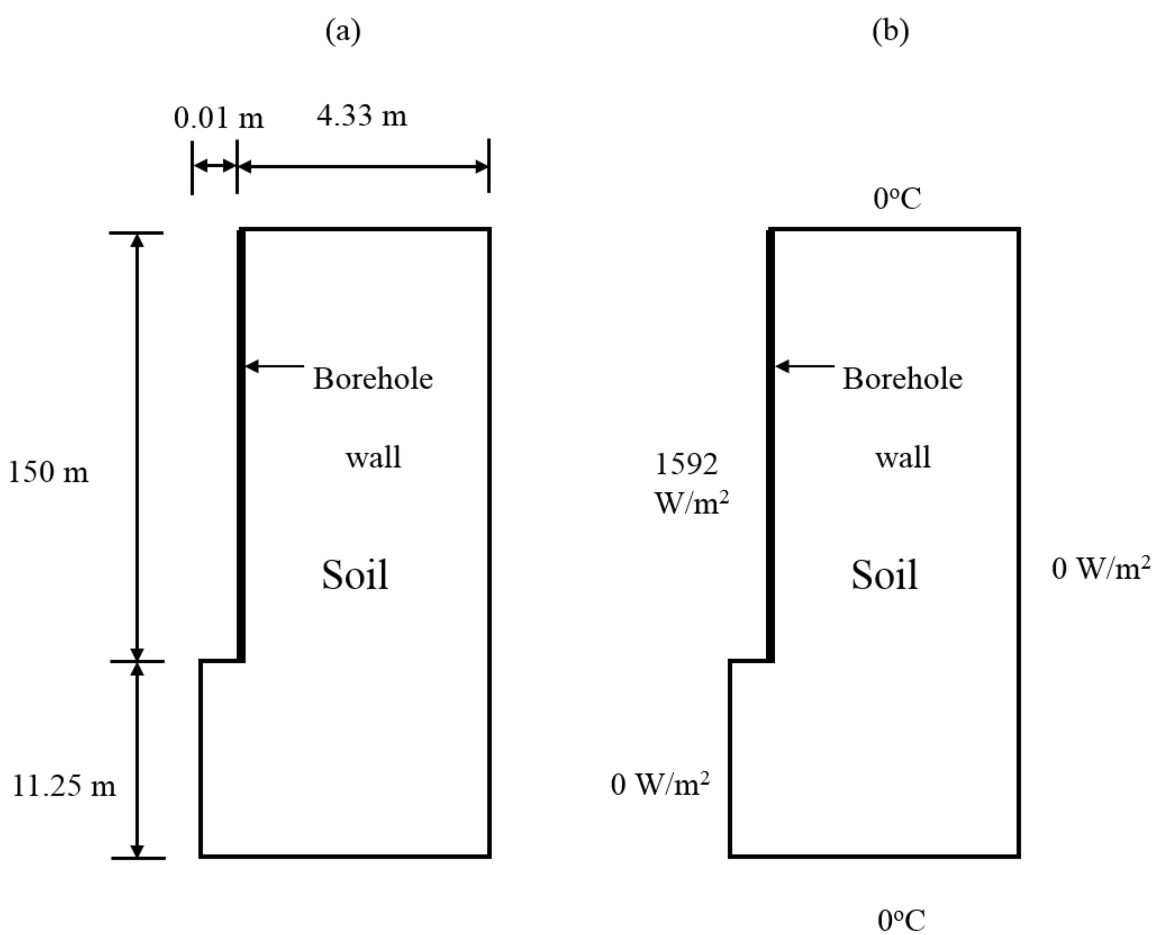

Figure 20: Analytical validation model (a) geometry and (b) boundary conditions

A 100 hour simulation was conducted and the results of the finite element model for temperature as a function of radius at 75 m are illustrated in Figure 21. It can be observed in the figure that the finite element model produced results that were in line with those obtained from the analytical model. The finite element results are within 0.08°C of the analytical results.

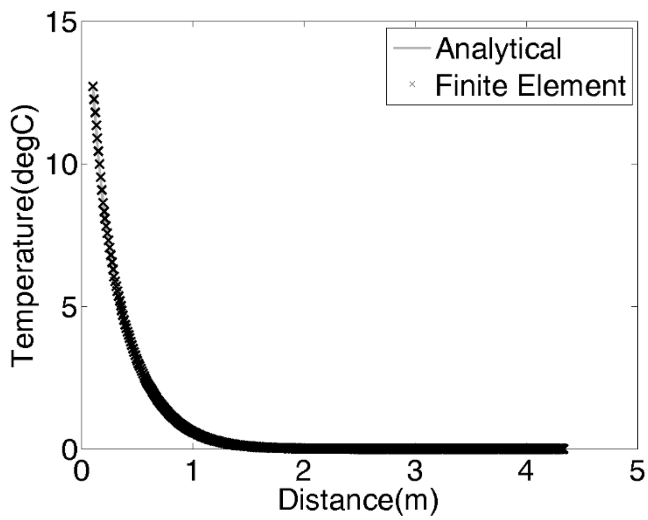

Figure 21: Analytical validation results

3.3.2 Validation against Experimental Results

The finite element results were validated against experimental results presented by [43]. In the experiment in [43], an aluminum pipe was set up inside a wooden box filled with sand to imitate the operation of a borehole ground heat exchanger. Borehole and soil temperatures were recorded and published in [43]. In this section, a finite element model was created according to the parameters provided in [43] and the analysis was performed. The results of the simulation are compared to the experimental results.

A layout of the boundary conditions and geometry are outlined in Table 6 and Figure 22, respectively. The geometry of the finite element model built to generate results for the experimental validation is illustrated in Figure 22a. The geometry depicts an 18.3 m deep borehole inside a 37.5 m radius of soil. The boundary conditions used in the model are summarized in Figure 22b. Soil and grout properties from Table 6 were applied to the geometry. An average of pipe inlet and outlet temperatures from [43] were applied as a temperature boundary to the interface between the pipe and the grout. A temperature boundary was used rather than a heat flux boundary, so as to be consistent with the conditions of the experimental data. A zero gradient was applied to all other boundaries. The thermal storage of the circulating water and grout are taken into account because the initial temperature of the borehole is set to 22^{o}C. Although the thermal storage of the circulating water is not modeled, the thermal storage of the grout is considered. The model handles the grout as a resistive layer around the circulating fluid.

Table 6: Parameters for experimental validation

Parameter	Value
Grout conductivity	0.73 W $m^{-1}K^{-1}$
Grout density·grout specific heat	3.9 x 10^6 J m^{-3} kg^{-1}
Soil conductivity	2.82 W $m^{-1}K^{-1}$
Soil density·soil specific heat	2.9 x 10^6 J m^{-3} kg^{-1}
Soil radius	37.5 m
Grout radius	0.063 m
Pipe radius	0.01 m
Borehole depth	18.3 m
Soil beneath borehole	5.5 m

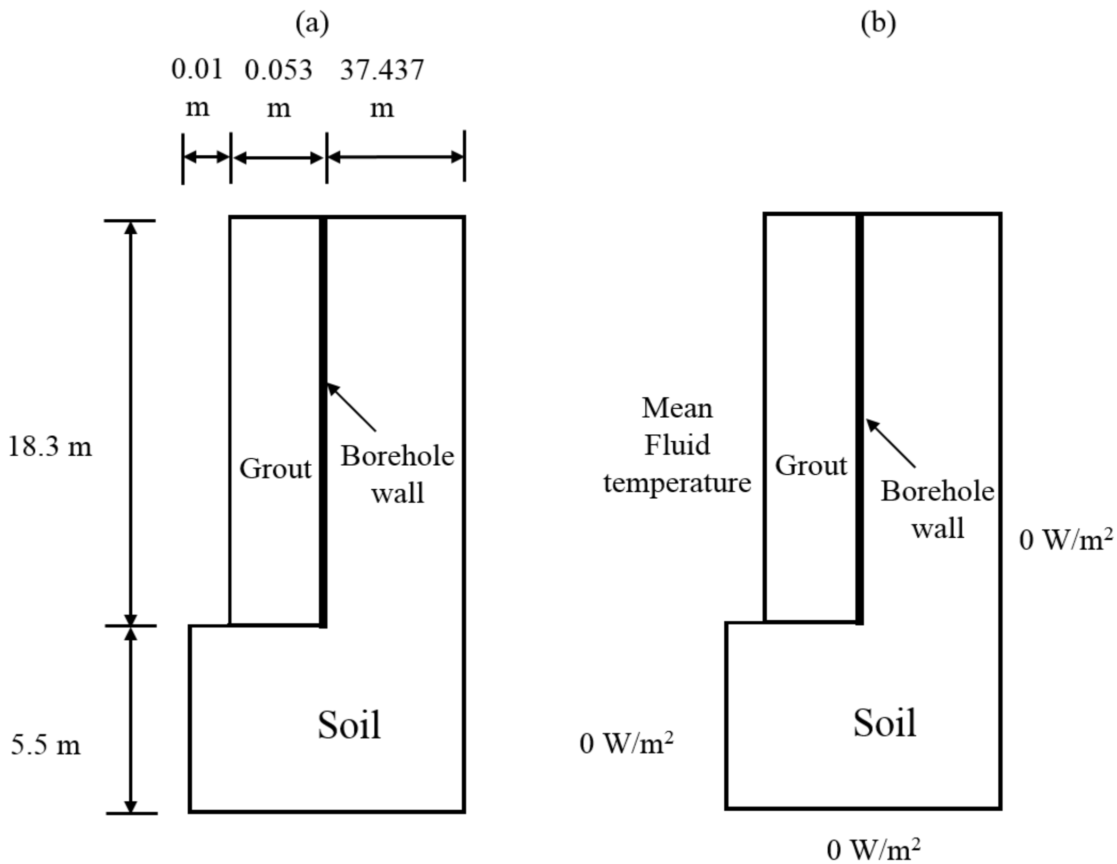

Figure 22: Experimental validation model (a) geometry and (b) boundary conditions

The simulation was conducted for a one-thousand minute study period at time steps of one minute. The results of the finite element simulation are summarized in Figure 23. Figure 23 compares results from the finite element simulation with results from the experimental data for three data points: 24 m, 44 m, and 65 m away from the centre of the borehole. The finite element simulation results are within 1.5% of the experimental data. The greatest difference can be found at points that are closest to the centre of the borehole. As the distance away from the borehole increases, the temperature difference between the experimental data and model predictions decreases. It can be concluded that the finite element model is well validated by the experimental data.

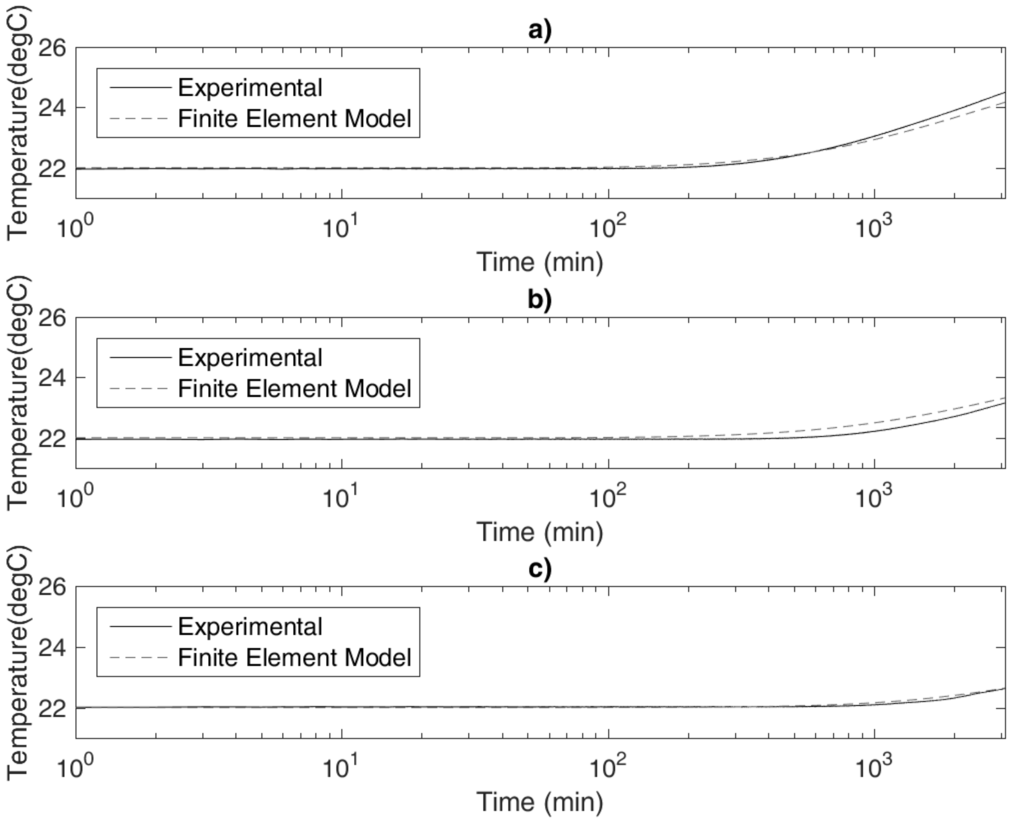

Figure 23: Experimental validation results for a point (a) 24 m, (b) 44 m, and (c) 65 m away from the centre of the pipe

3.4 Results

3.4.1 Hourly Heat Flux

Four buildings were considered in this study: a hospital, fast-food restaurant, residence, and school. Each of the four buildings are real, and either had a GSHP installed or considered [20] [44]. The annual building loads of the four buildings are illustrated in Figure 24. In Figure 24, the cooling and heating requirements of the buildings can be clearly seen. The cooling requirements are illustrated in light gray and the heating requirements are illustrated as negative cooling load in dark gray. It can be observed from the figures that the hospital is slightly heating dominated (Figure 24a), the fast-food restaurant is extremely cooling dominated (Figure 24b), the residence is heating dominated (Figure 24c), and the school is slightly cooling dominated

(Figure 24d). The heating and cooling balance is relatively even in the hospital and in the school. Of the 8760 hours in a year, only a few hours require heating in the fast-food restaurant because of the large amount of excess heat emitted from the kitchen.

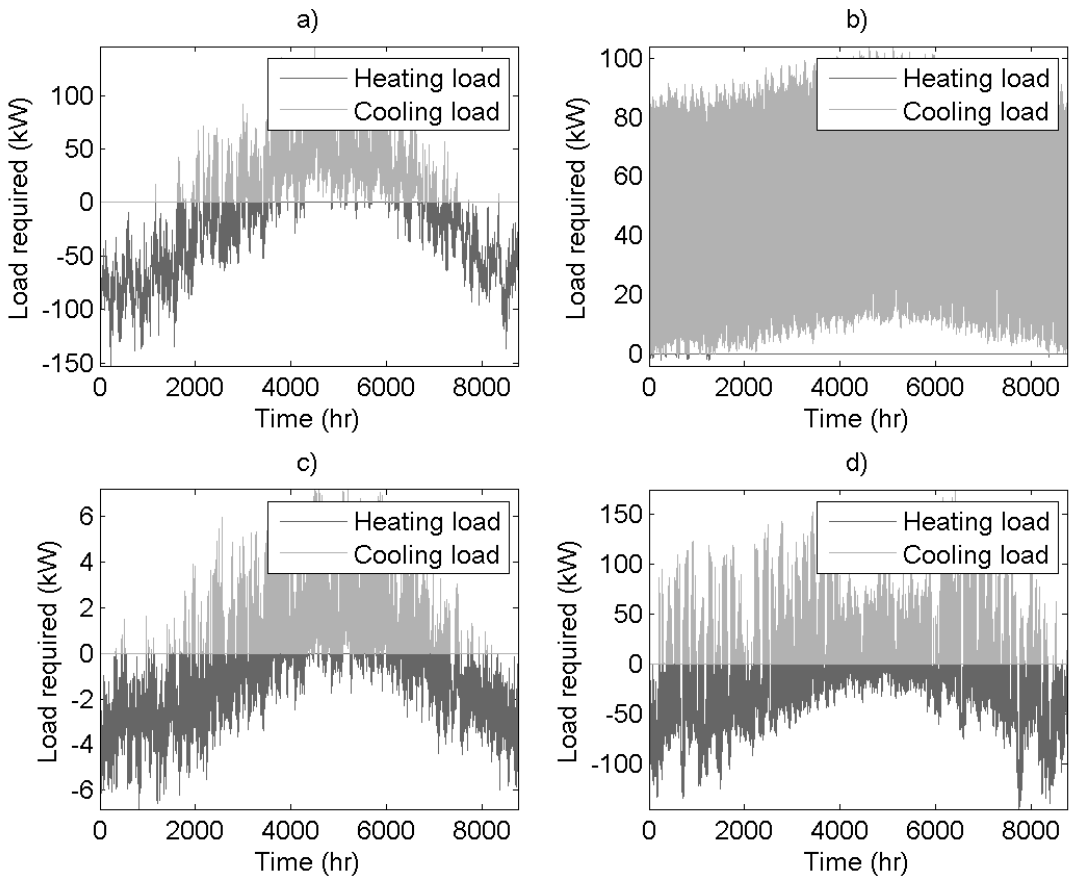

Figure 24: Building loads for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school

The hourly building loads were read into the algorithm described in the previous section and the hourly boundary heat fluxes were calculated for each 100 m of borehole. One year's hourly heat fluxes were calculated and are presented in Figure 25. Since the fast-food restaurant requires cooling throughout the year, only hours 2200 to 2400 were presented in Figure 25b to show the on and off cycles of the heat pump. When the heat pump is on, the heat flux of 161.44 W/m^2 is applied to the borehole boundary. When the heat pump is off, a zero heat flux is applied to the boundary. The positive heat fluxes in dark gray denote heat that is moved into the ground and negative heat fluxes in light gray denote heat that is extracted from the ground. A summary of the total heating and cooling hours and heat fluxes is shown in Table 7. Large thermal imbalances can be observed in the fast-food restaurant and a slight imbalance of heating and cooling hours can be observed in the three remaining buildings.

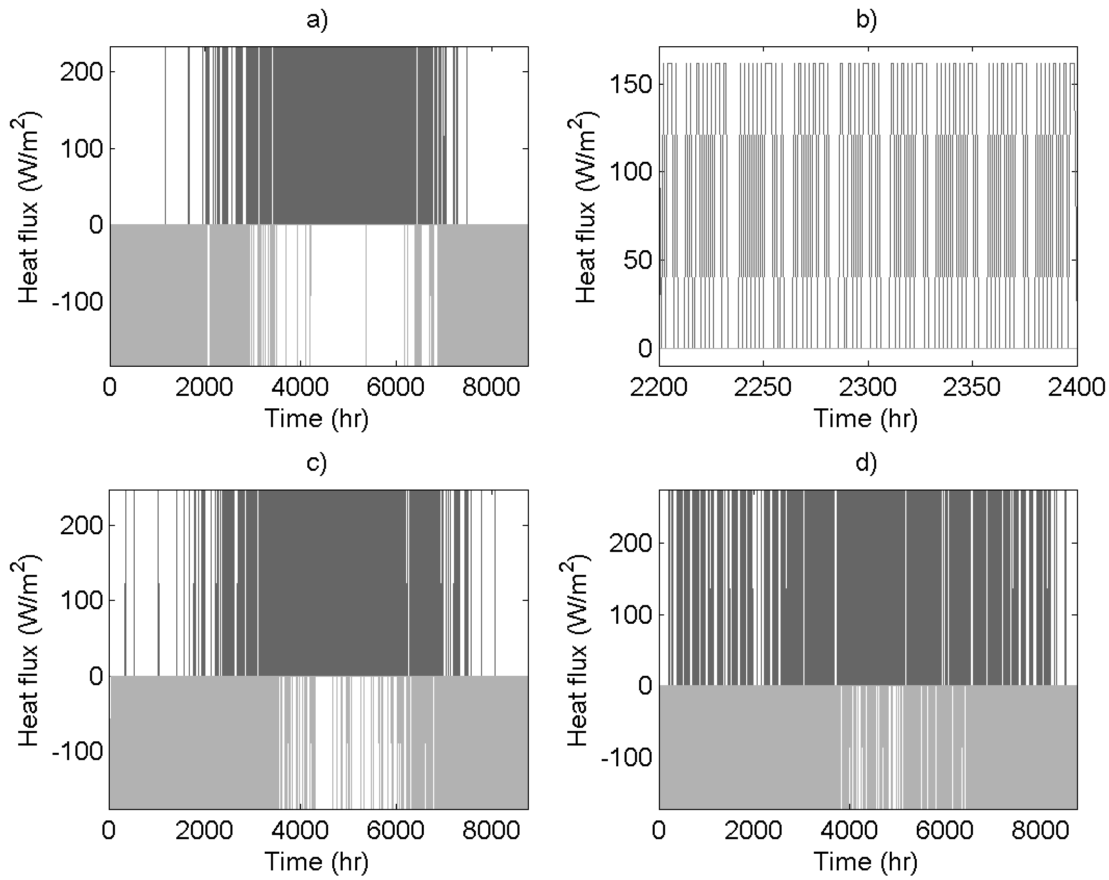

Figure 25: Hourly borehole boundary heat flux for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings (W/m^2)

Table 7: Summary of heating/cooling heat fluxes and system on/off times for a hospital, fast-food restaurant, residence, and school

Building	Heating heat flux (W/m^2)	Cooling heat flux (W/m^2)	Cooling (hrs)	Heating (hrs)	System off (hrs)	Heating hr to cooling hr ratio
Hospital	233.55	-183.60	1201	1588	5971	1.322
Fast-food restaurant	161.44	-4.82	4571	10	4179	0.002
Residence	247.87	-176.83	1066	1858	5836	1.743
School	275.19	-172.64	1169	1699	5892	1.453

3.4.2 2x2 Configuration

By modelling one borehole with symmetry conditions, a 2x2 borehole configuration was created. Heat flux boundary conditions depicted in Figure 25 were applied. After a 20 year simulation, the ground temperature at 3 points were studied. The location of the three points can be found in Figure 26. Point A is located in the centre of the 4 boreholes. Point C is located 5 m away from the corner borehole at a 45 degree angle. Point B is located at the same *x*-axis location as point C and located at $y = 0$ on the *y*-axis. The three points are chosen to study the effects of far field temperature (point C), four borehole interaction (point A), and two borehole interaction (point B). Boundary conditions were applied to the geometry and the simulation was performed for the four buildings.

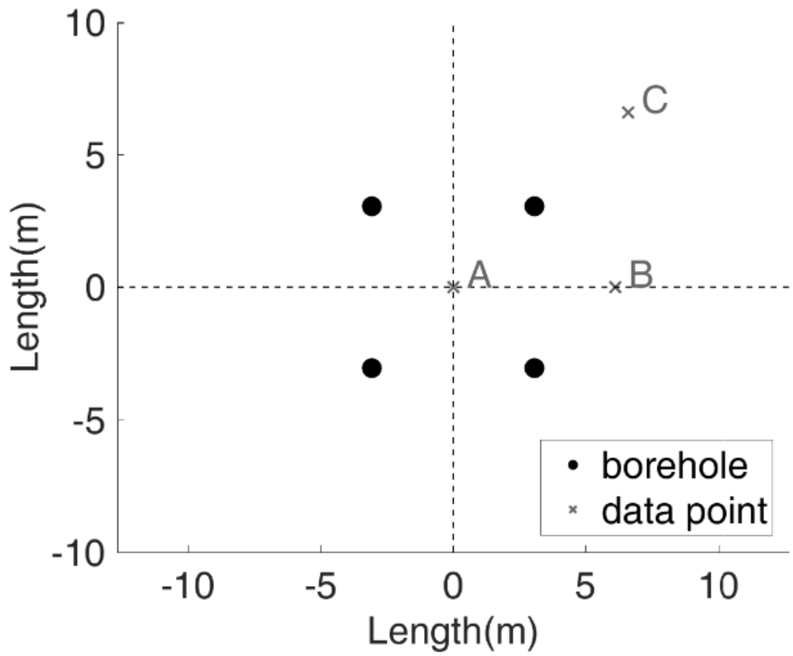

Figure 26: 2x2 borehole layout

The results of the simulations are summarized in Figure 27. Annual fluctuations can be seen for each case due to seasonal changes. The highest ground temperatures occur in the peak summer months when large amounts of excess heat was released into the ground to provide cooling for the building. The lowest ground temperatures occur in the peak winter months when large amounts of heat was extracted out of the ground to provide heating for the building.

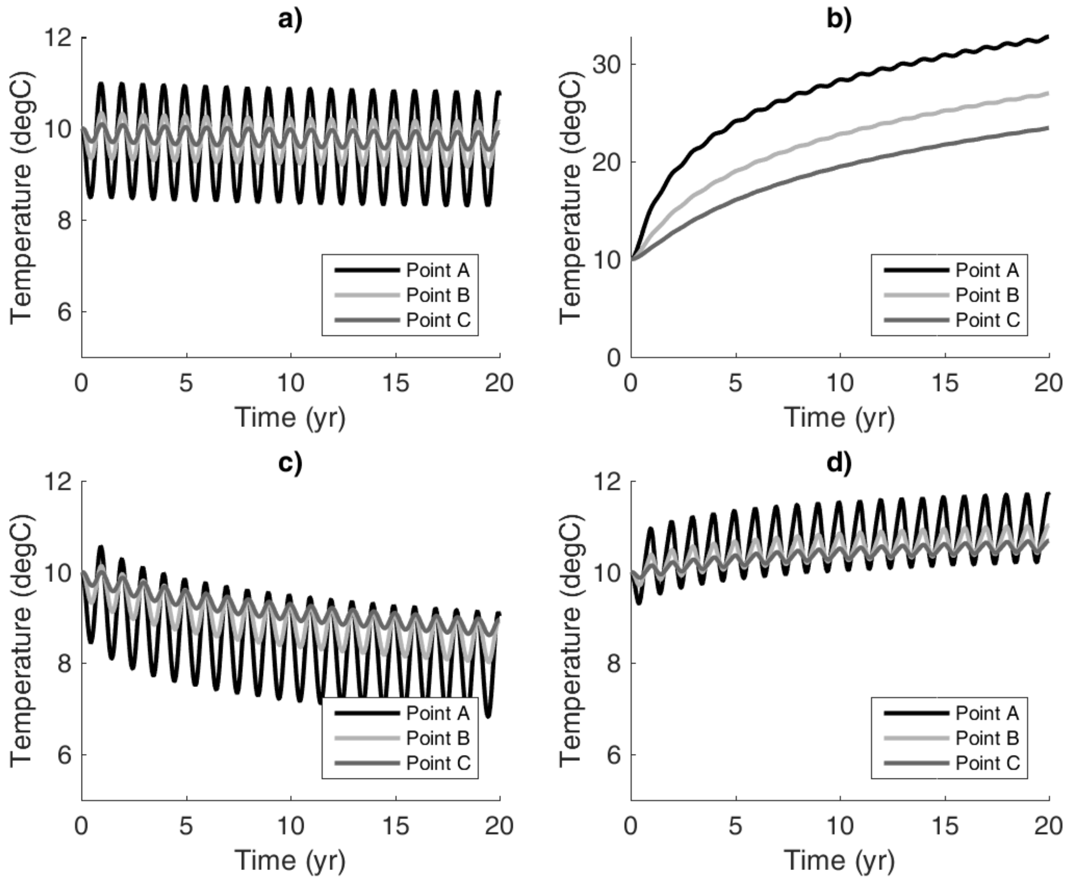

Figure 27: Ground temperature at points A, B, and C for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 2x2 borehole configuration. A different scale is used for (b) to depict the full predicted temperature range

The (im)balance in heating and cooling load can be clearly perceived in Figure 27. For the fast-food restaurant, the large imbalance in loads causes a large increase in ground temperature. Heat accumulation can be observed in the centre of the four boreholes (point A). After a 20 year operation period, the temperature at point A hikes to a maximum of 32^{o}C from the initial temperature of 10^{o}C. This large change in ground temperature indicates that the efficiency of the system will gradually decrease within the 20 years. The actual system would become inoperable before the 20 year mark as efficiency would decline beyond tolerable values, or functionality would cease. For the fast food restaurant, it is clear that an alternative HVAC technology should be employed, or an alternative method of dissipating heat from the ground would be needed.

From the four cases, it can be observed that the ground temperature at point C experiences the least change compared to points A and B. The greatest heat reduction/accumulation can be observed in point A for the four cases. However, the hospital case experiences the least change in ground temperature compared to the other cases. This observation confirms that the borehole separation distance of 6 m may be sufficient in some cases in a 2x2 installation to prevent borehole interactions as the loads are relatively balanced.

In Figure 28, the annual average ground temperature for the four buildings are plotted. This figure illustrates the overall trend in ground temperature changes in each building over 20 years. The average is calculated by the mean of the 8760 hours of each year from the first hour on January 1st to the last hour of December 31st. Changes in ground temperature are fast in the beginning and gradually slow down as time passes. A jump in the data can be seen in the first year because only a partial winter was experienced in the data set. As with Figure 27, the smallest change in ground temperature is found at point C and the largest change occurs at point A. From Figure 28, the effects of borehole interactions can also be observed. Point B's temperature is predominantly affected by the temperature of the two boreholes on the left whereas point A's temperature is affected by the temperature of all four boreholes. It is interesting to note that the curve formed by point B is almost at the halfway point between point A and point C. This observation indicates that although the boreholes are not immediately adjacent to the points, the point still experiences effects from it. Although point C is only adjacent to one borehole, its overall change in ground temperature is 50% of the change in point

A (which is surrounded by four boreholes), because of the interactions with the other nearby boreholes.

A key difference between this model and those in literature is that the present model presents the temperature variation at different points on the soil domain. The effects of having 4, 2 and 1 surrounding boreholes are studied for points A, B, and C. In previous studies, temperature penalties are determined using a g-function and applied to a single borehole model to depict the effects of borehole geometries [21, 22]. However, in those models, only the temperature at the borehole wall can be determined.

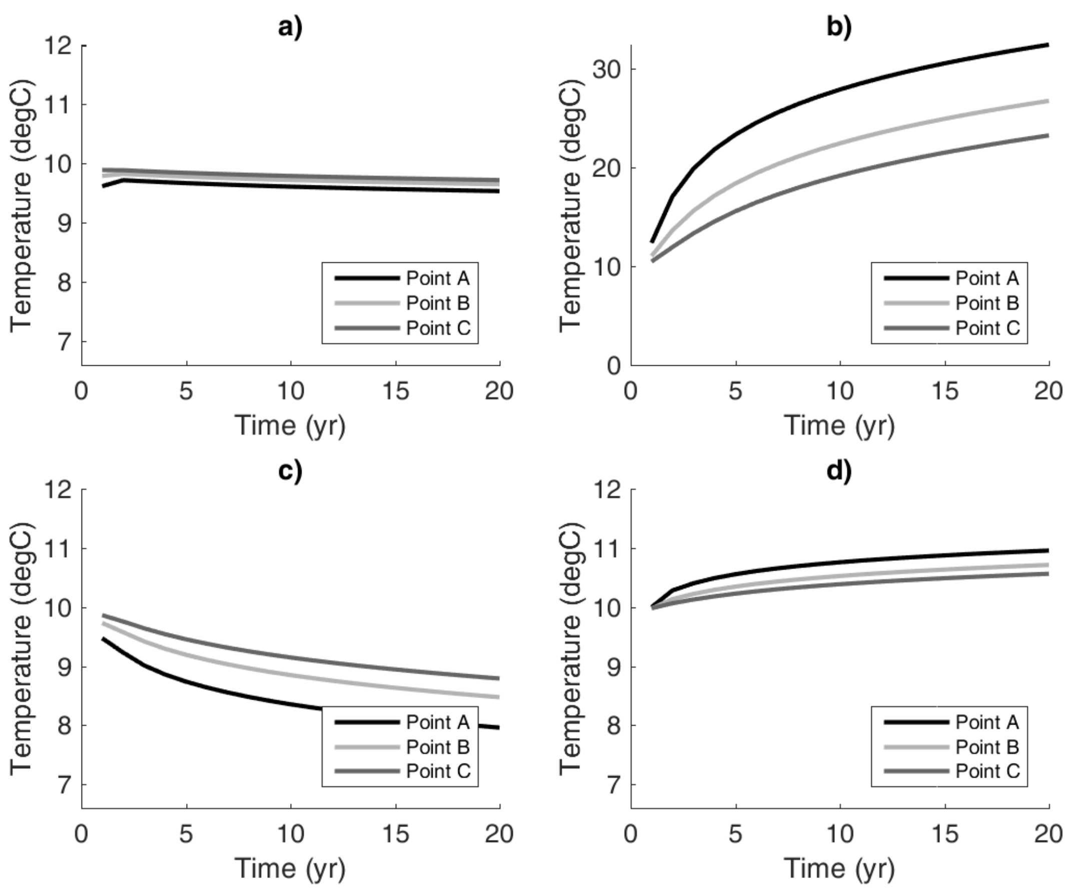

Figure 28: Average ground temperature at points A, B, and C for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 2x2 borehole configuration

Figure 29 summarizes the ground temperature of the four buildings at point A. Large increases in ground temperature can be observed in the fast-food restaurant. Of the four buildings, the hospital ground temperature remains relatively steady over the 20 years. The residence is slightly heating dominant and the school is slightly cooling dominant, and the ground temperature can be seen to be changing by less than about 2°C for these cases, indicating GSHP suitability.

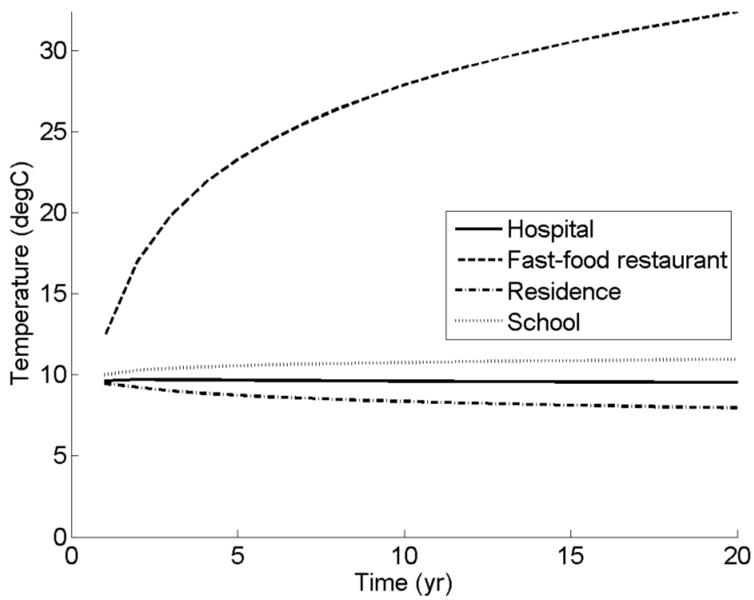

Figure 29: Point A temperature for a hospital, fast-food restaurant, residence, and school building for 2x2 borehole configuration

In Figure 30, the maximum and minimum ground temperatures for 20 years were studied for the four buildings. The maximum and minimum curves show the opposite character. As expected, the maximum ground temperature occurs in peak summer when a large amount of excess heat is transferred into the ground to achieve cooling for a building. This temperature occurs at the soil volume adjacent to the borehole walls. During this time, the minimum temperature is the far field temperature. Similarly, during peak winter when large amounts of heat are extracted from the ground, ground temperature is at its minimum. At this time, the maximum ground temperature is the far field temperature. This phenomenon can be observed in Figure 30a, c, and d where the maximum and minimum ground temperatures remain steady between 30°C and -10°C. However, in Figure 30b, the heating and cooling load imbalance is large; ground temperatures around the boreholes are greater than the far field temperature even in peak winter.

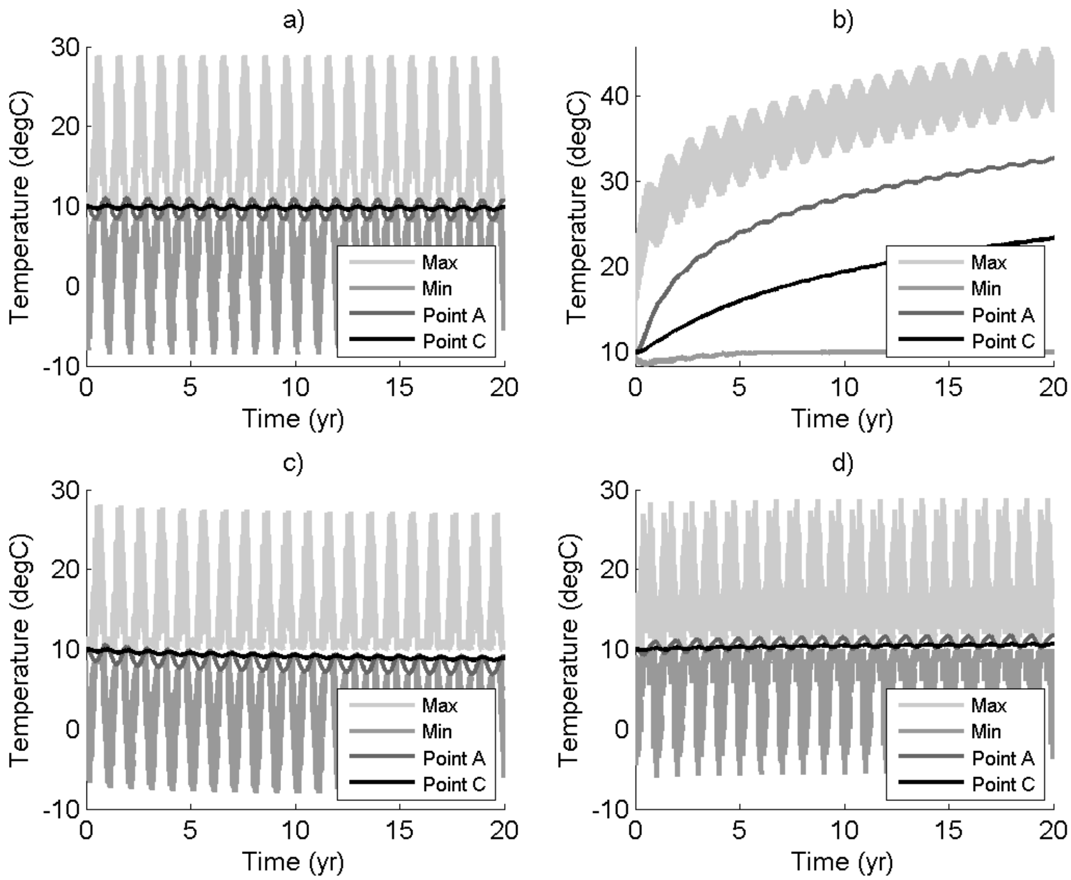

Figure 30: Maximum, minimum, point A, and point C ground temperature for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 2x2 borehole configuration

3.4.3 4x4 Configuration

A 4x4 borehole configuration was generated by modelling four boreholes with two symmetrical soil surfaces. Points A, B, C, D, E, F, and G were studied because they were representative of the geometry as illustrated in Figure 31. Boundary conditions were applied as they were in the 2x2 borehole configuration. A 20 year simulation was performed for the geometry and the results for points A, B, and G were plotted in Figure 32. Points D, E, F and G were not plotted in the figure because they showed similar behaviour to other points. In particular, points D, F, and G show similar behaviour to point B, and point E shows similar behaviour as point C.

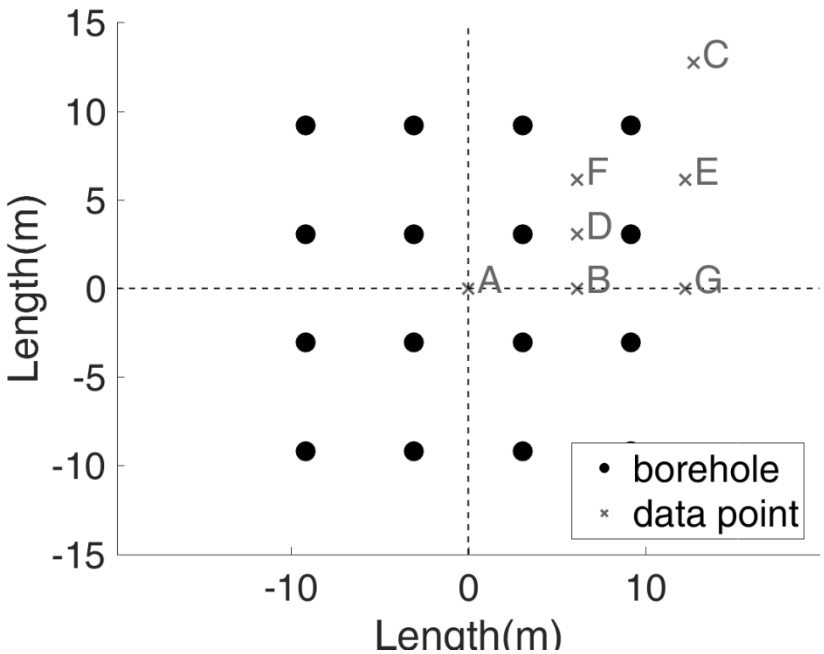

Figure 31: 4x4 borehole layout

In Figure 32, the reduction/accumulation of heat can be observed from the four buildings. Since the fluid temperature is approximately 35^{o}C during cooling mode, any ground temperature above 35^{o}C will not allow heat transfer from the borehole to the soil thus fouling the system. It can be observed in Figure 32b that the system will begin to foul within the first five years after the beginning of operation as point A approaches 35^{o}C. The system life of less than five years indicates that the system is not appropriately designed. A potential solution to avoid system fouling is to space boreholes further apart or to hybridize the system with a device such as a cooling tower.

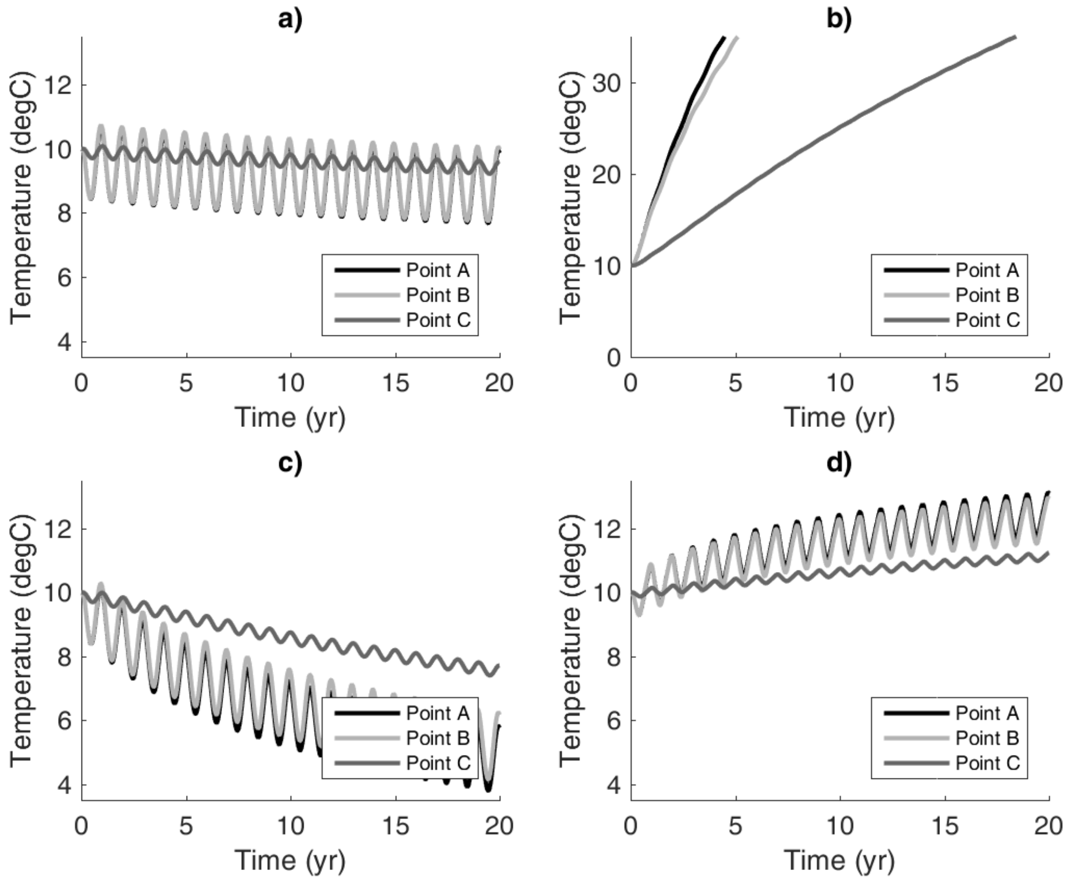

Figure 32: Ground temperature at points A, B, and C for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 4x4 borehole configuration

Figure 33 illustrates the annual averages of ground temperatures over 20 years for points A, B, and C. It can be observed from this figure that temperatures at point A and point B are very similar. Ground temperature at point C increases/decreases gradually due to the effects of the surrounding boreholes. However, the change in ground temperature at that point is small.

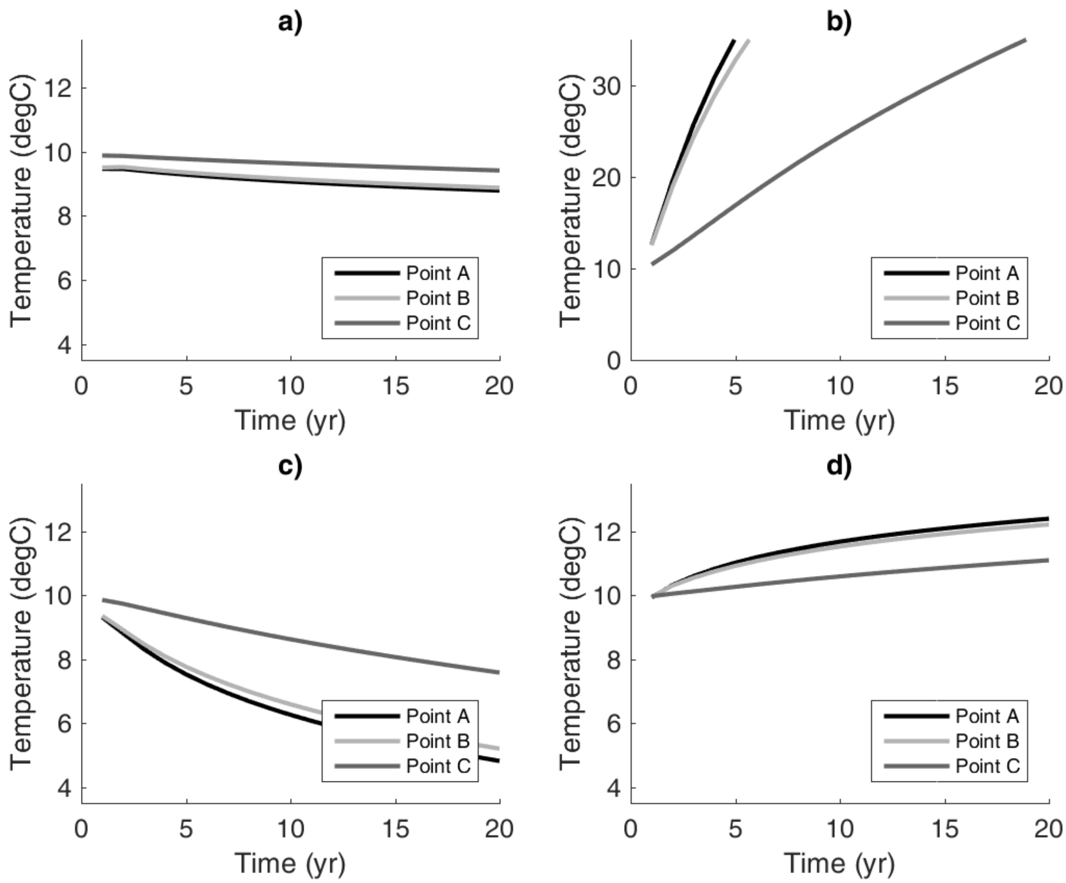

Figure 33: Average ground temperature at points A, B, and C for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 4x4 borehole configuration

For the 4x4 borehole configuration, the maximum and minimum ground temperature in the entire soil volume was also studied. The plots are located in Figure 34. In Figure 34a and d, the ground temperature for the hospital and the school change by a small value and the maximum and minimum ground temperatures remain approximately constant. The residence experiences a decrease in overall ground temperature. At the same time, the maximum and minimum ground temperature also decreases. For the fast-food restaurant, the borehole wall temperatures reach a maximum of 50^{o}C after a 4.5 year operation period. Due to the large increase in ground temperature, the system is fouled, hence, results beyond 4.5 years (perhaps earlier) are not realistic to model.

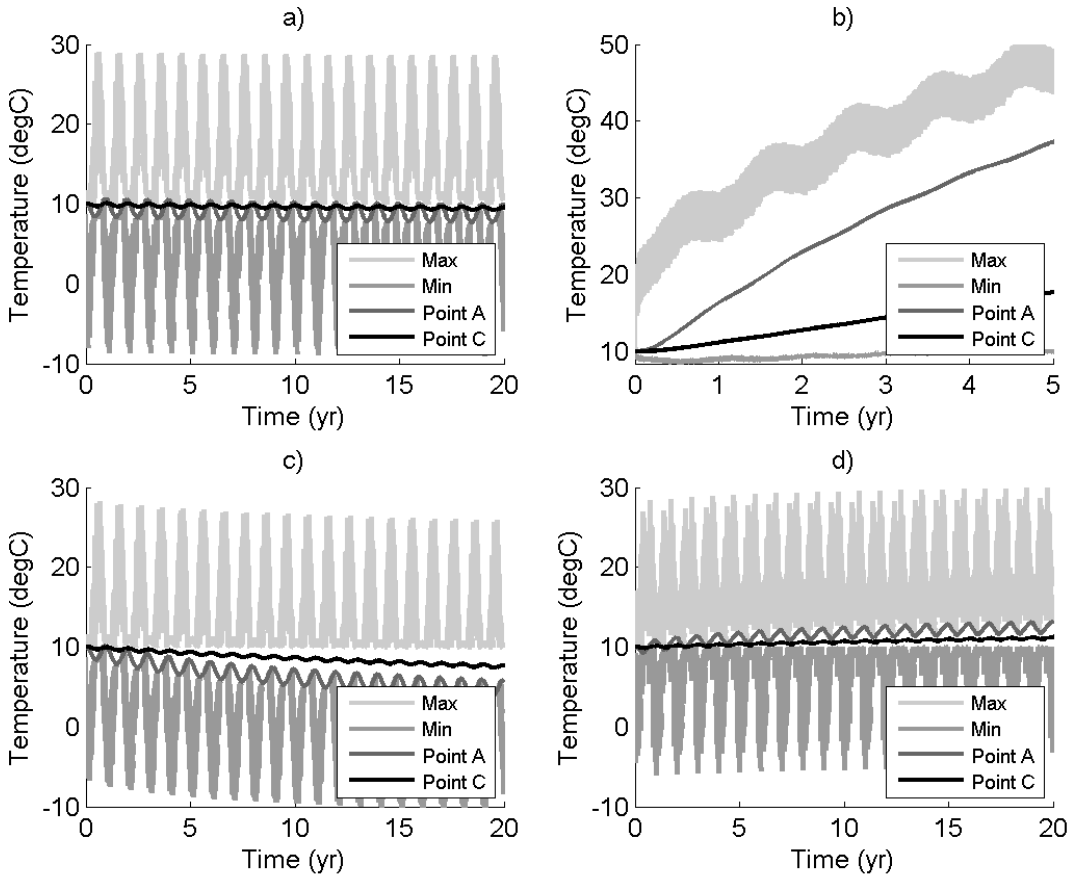

Figure 34: Maximum, minimum, point A, and point C ground temperature for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 4x4 borehole configuration

3.4.4 2x8 Configuration

The same analysis for the 4x4 borehole configuration was repeated for the 2x8 borehole configuration to compare the effects of borehole layout. The purpose of this analysis is to quantify the potential benefit in ground thermal imbalance in changing the configuration of a borehole field. In this analysis, the boreholes were placed in a 2x8 field as illustrated in Figure 35. Temperatures at points A, B, C, D, E, F, G, H, I, and J were extracted for analysis. Points D to J showed similarities to points A and B, respectively, and thus were omitted from the figures.

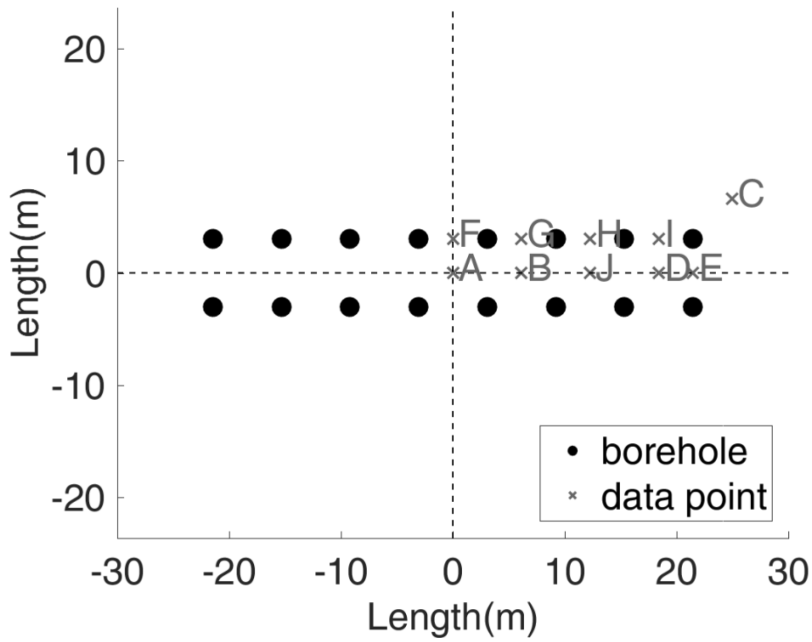

Figure 35: 2x8 borehole layout

The annual averages for ground temperature were calculated and presented in Figure 36. From Figure 36, it can be observed that ground temperature at points A and B are similar. Ground temperature changes quickly in the beginning and slowly at the end of the simulation. At 6.5 years, the ground temperature at point A for the fast-food restaurant climbed to 35^{o}C. At 6.5 years, the end of system life is reached since any further increase in ground temperature will not allow heat transfer from the borehole to the surrounding soil. Maximum and minimum ground temperatures show similar trends as Figure 34.

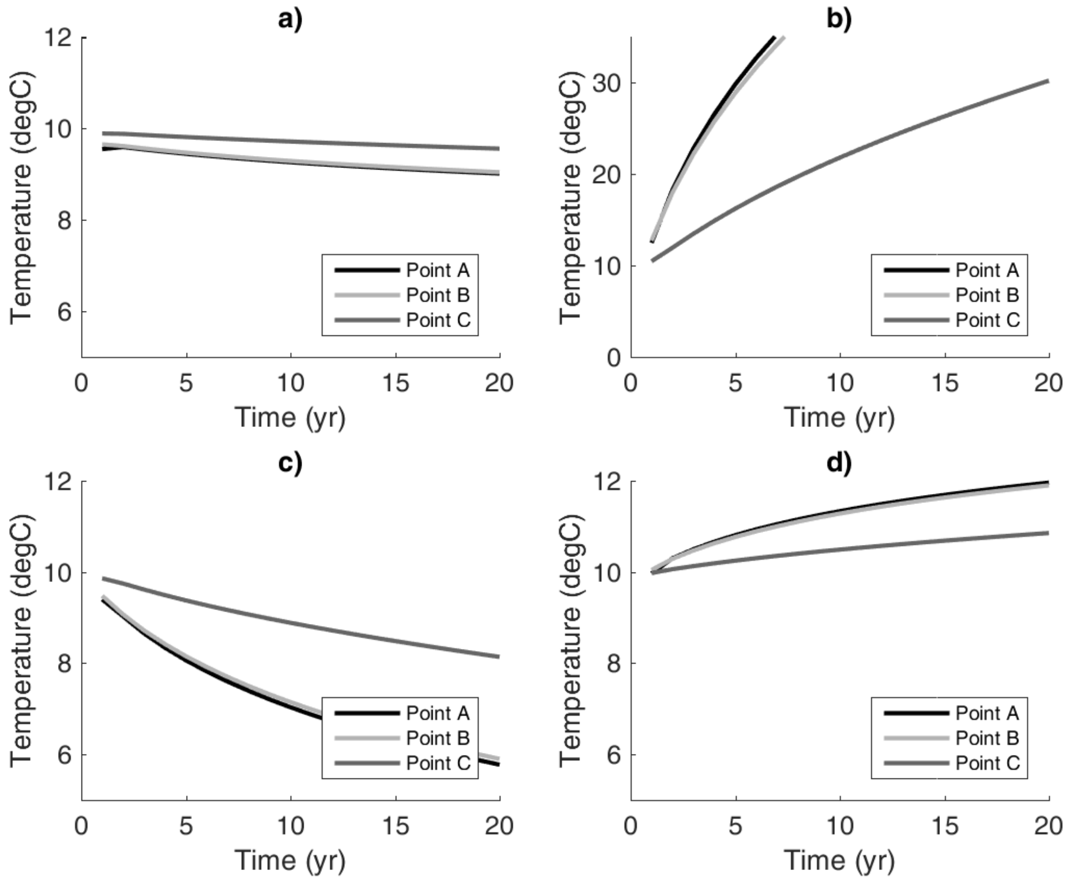

Figure 36: Average ground temperature at points A, B, and C for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 2x8 borehole configuration

3.4.5 Geometry Comparisons

In this section, the three borehole geometries were compared. For the purposes of comparison, the 2x2 configuration represents four sets of four boreholes that are far apart, where each set is a 2x2 configuration. As such, each configuration being compared contains a total of 16 boreholes. The borehole configurations are not necessarily intended to meet the full demands of the 4 buildings presented in the simulations, but rather provide information on temperature variations in a ground volume, that would also be representative of an extended domain. The location of maximum heat reduction/accumulation was studied in each case. This location is point A in all configurations. The temperatures are plotted in Figure 37. The results of the four buildings vary depending on the heating/cooling load imbalance. Using four 2x2 systems separated at a large distance apart only achieves a 0.5^{o}C temperature reduction for the hospital (Figure 37a) after 20 years compared to using a 2x8 system. The benefits of using a 2x8 system over a 4x4 system is also only 0.2^{o}C.

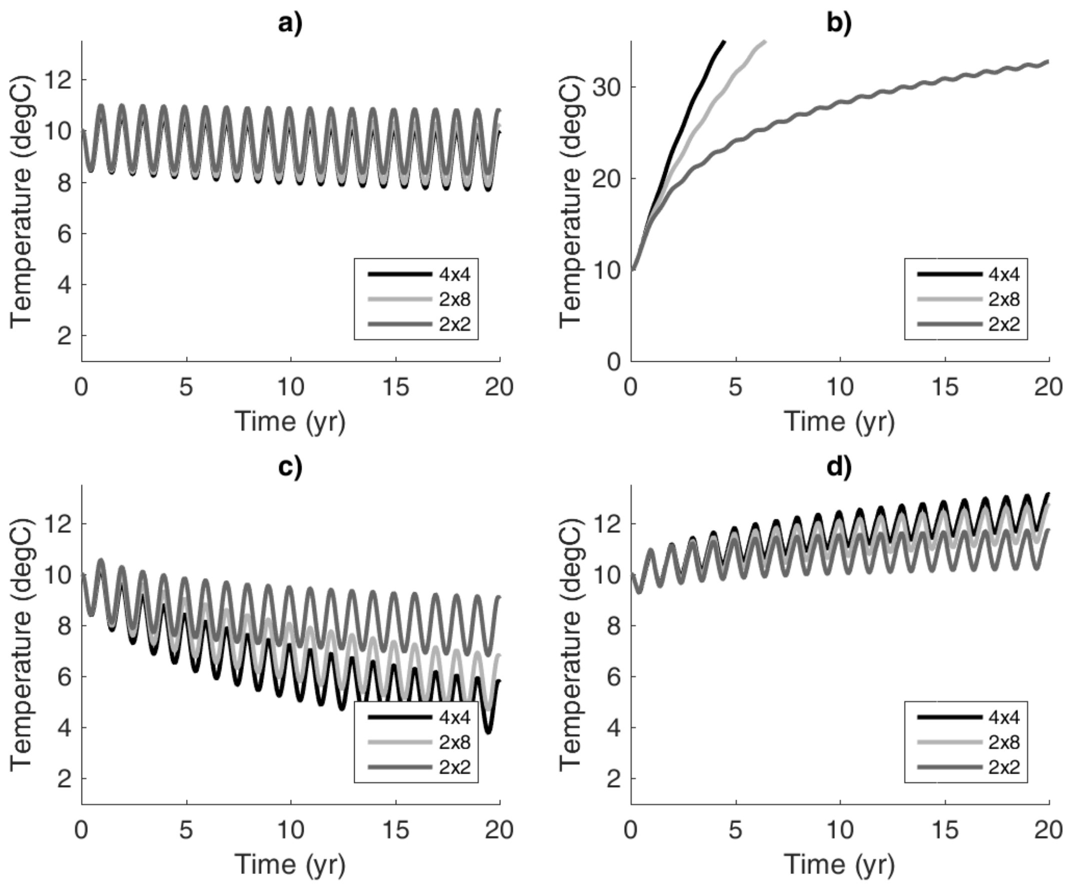

Figure 37: Ground temperature at centre point for (a) hospital, (b) fast-food restaurant, (c) residence, and (d) school buildings for 2x2, 4x4, and 2x8 configurations.

However, different results can be observed in Figure 37c for the residence. When four separate 2x2 systems are installed with a large distance apart, the average ground temperature after 20 years is 8.8^{o}C (1.2^{o}C drop from initial ground temperature). However, when 2x8 and 4x4 systems are used, the ground temperatures after 20 years are 5.8^{o}C (4.2^{o}C drop) and 4.8^{o}C (5.2^{o}C drop), respectively. The excess temperature drop can lead to a significant COP reduction in the heating season. By installing a 2x8 system rather than a 4x4 system, a 1^{o}C temperature drop in the ground can be prevented. These results indicate that if space permits, it is more beneficial to install four 2x2 borehole systems separated at a large distance apart, rather than one 4x4 system. In addition, the methodology presented here demonstrates the ability to quantify the benefits of different potential borehole configurations.

In the extremely cooling dominant case of the fast-food restaurant, the ground temperature climbed quickly to 35^{o}C. As illustrated in Figure 37b, the only design that lasts through the entire 20 year operating period is the separate 2x2 installations, albeit with significant ground temperature increase. However, due to space limitations in the property size, this design may not be feasible. In the 2x8 system, the system life is approximately 6.5 years and the system life is 4.5 years in the 4x4 system. This result indicates that by simply changing the configuration of the boreholes, the system life can be extended. For this particular building, it would be expected that the system COP will be very low near the end of the system life. A 2x8 configuration is more favorable in terms of design for thermal balance because there is a greater perimeter in the geometry, which provides more space for heat to dissipate to surrounding soil. These results are all under the assumption that borehole lengths are the same, 100m, for each borehole.

Table 8 summarizes the maximum and minimum temperatures at point A for the four buildings for the three borehole configurations. Year 20 temperatures for the fast-food restaurant were neglected because the ground temperature in inadequate for effective heat transfer. The hospital and school experience the least temperature change in all three borehole configurations. As illustrated in Table 7, the heating to cooling hour ratio for the four buildings are 1.322, 0.002, 1.743, and 1.453 for the hospital, fast-food restaurant, residence, and school, respectively. According to ASHRAE, a 1.6-1.8 cooling to heating ratio should be used to ensure that the system is balanced. However, in the four buildings studied, the least change in ground temperature occurred in the hospital and school (heating hour to cooling hour ratio of 1.322 and 1.453). The residence building with heating to cooling ratio of 1.743 *did not* result in the minimum change in ground temperature. Discrepancies between these results and the ASHRAE standards may be due to the different system off hours for each building, or to a now improved understanding of the system heat flow. Buildings with large numbers of "system off" hours allow more time for the ground to recover to its initial temperature. This observation iterates the importance to study building loads closely and assess each building separately whenever possible rather than using rules-of-thumb.

These results also indicate that the greatest ground thermal imbalance occurs in the fast-food restaurant if a system designed for the full load capacity was installed. Potential methods to mitigate the imbalance include hybridizing the GSHP system so that a smaller load demand is required from the GSHP, thereby reducing the ground temperature changes.

Table 8: Summary of maximum, minimum, and temperature and point A for a hospital, fast-food restaurant, residence, and school

Building	End of Year 1 point A (^oC)	End of Year 20 point A (^oC)	Year 1 Maximum (^oC)	Year 20 Maximum (^oC)	Year 1 Minimum (^oC)	Year 20 Minimum (^oC)
2x2 configuration						
Hospital	10.91	10.71	11.00	10.80	8.49	8.30
Fast-food restaurant	15.30	32.71	15.30	32.71	10.00	32.22
Residence	10.46	9.03	10.56	9.11	8.45	6.82
School	10.92	11.69	10.96	11.73	9.31	10.21
4x4 configuration						
Hospital	10.59	9.87	10.65	9.93	8.43	7.68
Fast-food restaurant	16.27	--	16.27	--	10.00	--
Residence	10.09	5.76	10.18	5.87	8.38	3.79
School	10.84	13.10	10.86	13.14	9.29	11.73
2x8 configuration						
Hospital	10.75	10.13	10.82	10.20	8.47	7.84
Fast-food restaurant	15.77	--	15.77	--	10.00	--
Residence	10.28	6.76	10.37	6.86	8.43	4.70
School	10.87	12.67	10.91	12.71	9.30	11.25

The study of ground temperature variation is important because of its relationship with GSHP system performance. In a heating dominant scenario, an increase in ground temperature can lead to an inefficient GSHP system because of the resulting low COPs due to inadequate heat transfer temperatures [5].

This model can be used to study the long term temperature variation of GSHP systems. Real building energy demand data can be imported into the model to calculate the borehole boundary conditions. Then, the boundary conditions can be imported in the finite-element model to simulate the long term operation of the GSHP. The industry can use the results of the model to determine whether their design is suitable and optimal for their design operating duration. By studying the temperature variations prior to building the system, inefficient GSHPs system designs can be avoided.

3.5 Conclusions

In GSHP designs, it is important to closely study the temperature of the soil surrounding the boreholes. Present literature suggests the superimposing of a g-function to model the temperature penalty of various borehole configurations into a single borehole simulation. However, this method cannot model the temperature variation at different depths within the soil domain. The model proposed in the present work provides the temperature distribution surrounding each borehole so that the complete heat extraction/injection effects can be visualized for various configurations. The model studied the effects of borehole interaction in a 3D manner. In this study, a 20-year analysis was performed for 2x2, 4x4, and 2x8 configurations for a hospital, fast-food restaurant, residence, and school. In the 2x2 configuration, it was observed that the borehole separation distance of 6 m recommended by ASHRAE was not always sufficient to prevent borehole interaction. As a result, heat accumulation/reduction occurred in the centre of the domain.

In all three configurations, temperature increased quickly in the first few years, then the rate of increase slowed. The greatest change in ground temperature occurred in the fast-food restaurant where the building is extremely cooling dominant. The large imbalance of heating and cooling loads in this case caused ground temperature to increase quickly to 35^{o}C within the first 4.5 and 6.5 years for 2x8 and 4x4 configurations, respectively. From the present study, it can be concluded that the 2x8 configuration, with its greater perimeter, is more beneficial than the 4x4 configuration because it has a lower temperature change over 20 years. This small change in ground temperature is because the 2x8 configuration has a greater perimeter for heat to dissipate to surrounding soil.

This study demonstrated that without balanced loads, the ground fouls before reaching the end of the system life, causing system shut down and economic loss. In addition, the importance of accurate energy simulations, modelling, and design should also be noted. To fulfill the knowledge gap that this study presents, further study is needed to examine borehole separation distances and the potential of hybridization for more feasible systems for extreme heating/cooling cases. In addition, lengths of individual boreholes in a field should also be studied to determine potential benefits in its variation.

Chapter 4

A Study of Alternative Borehole Configurations in Geo-Exchange

Corresponding Manuscript: Y.L.E., Law & S.B. Dworkin, "A Study of Alternative Borehole Configurations in Geo-Exchange", *In preparation*.

Abstract

As global awareness for sustainable energy systems arises, there is a need to study alternative heating and cooling methods. Ground-source heat pumps (GSHPs) provide heating and cooling for buildings with low greenhouse gas emissions. The ground acts as a heat sink and heat source in cooling and heating modes respectively. In heating mode, the ground provides heat for the building's heating demands. In cooling mode, heat is injected into the ground from the building to provide the building's cooling demands. When heating and cooling loads are balanced, the ground temperature remains steady over time. However, when heating and cooling loads differ significantly, ground temperature can slowly migrate up or down in the long term. Extreme cases of thermal imbalance can cause large changes in ground temperature, diminishing the GSHP system's performance, and eventually causing the ground to foul. Ground fouling occurs when the ground fails to accept or provide more heat for a building. It is important to study ground temperature changes during the operation of a GSHP to ensure that system performance is maintained throughout the design lifetime of the system.

Borehole configurations can play a major role in ground temperature changes. Previously, a study in Chapter 3 was performed and the results have shown that by varying the aspect ratio of borehole configurations, ground temperature changes can be slightly alleviated. However, no study has been done to see the effect of operating a GSHP system with boreholes of varying

length. In this study, a 4x4 borehole configuration was studied. The four centre boreholes in the 16 borehole system were shortened and the length of the remaining boreholes was recalculated so that the total required ground loop length can be met. This recalculation ensures that system capacity can be met by the GSHP system.

In this chapter, a 20 year operation was simulated for a school building model with centre borehole lengths of: 100 m, 80 m, and 50 m to study the benefits of shortening the centre boreholes. In addition, borehole separation distance was adjusted for each of the models from 6 m to 4 m and 3 m to study the effects of reducing borehole spacing.

The results demonstrate that by adjusting the length of the centre boreholes, separation can be reduced. This study illustrates the importance of considering long-term ground temperature changes during the design phase of the system.

4.1 Introduction

Ground-source heat pump (GSHP) systems use the ground as a stable heat transfer medium to provide heating and cooling for a building. Heat is extracted/released into the ground during heating and cooling modes, respectively. Because the ground, approximately 10 m beneath the surface, remains at approximately the same temperature throughout seasonal fluctuations, it is a stable medium for heat transfer. When the heating and cooling demands of a building are balanced, ground temperature remains steady over time. However, when heating and cooling demands of a building are greatly imbalanced, ground temperature can slowly climb or decline. Increase (or decrease) in ground temperatures can cause a degradation in system performance because of the inefficient heat transfer temperatures. Many systems in the past had to stop operation because of low system efficiencies, making them uneconomic to operate.

Borehole configurations can play a major role in ground temperature changes. Borehole performance is immediately affected by neighbouring boreholes [27]. Borehole systems with small separation distances experience more thermal interference from neighbouring boreholes than systems with greater separation distances [27]. The increase in separation distance can also increase the percentage of temperature restoration due to the reduction in borehole thermal interference [45]. Comparing three systems with borehole separation distances of 4 m, 5 m, and 6 m, respectively, the system with 6 m separation distance produces a greater percentage of temperature restoration [45]. In addition, the temperature distribution of the borehole field can also be affected by borehole separation distances. When studying the temperatures at the centre, side, and corner of the borehole field, the greatest change in temperature can be found in the centre of the configuration. However, when borehole separation distances are increased, the difference between the temperatures at these locations are reduced [45].

While borehole separation is important in the design of geo-exchange, studies have shown that borehole separation distance is not the only factor that contributes to thermal imbalance. The study described in Chapter 3 have showed that by varying the aspect ratio of borehole configurations, ground temperature changes can be slightly alleviated [17] .The increase in borehole field perimeter was able to slightly lower the changes in ground temperature due to the larger area available for heat to dissipate to the surrounding soil. The decrease in ground temperature change can allow the system to operate efficiently for a longer period of time.

In an array of boreholes, the centre boreholes of the configuration are most affected by thermal imbalance due to neighbouring borehole interactions. These boreholes are the least effective because of the poor heat transfer temperatures in the surrounding soil. A method to alleviate ground temperature change is to remove inner boreholes [18]. In this method, the least effective boreholes (inner boreholes) were removed from the borehole field to prevent thermal accumulation in the centre of the borehole fields. The results in [18] showed that the cavity created by the removal of inner boreholes contributed to better heat transfer, resulting in smaller changes in ground temperature. This method moves the location of thermal accumulation away from the centre of the borehole field.

Another method to alleviate the effects of thermal imbalance is to alter borehole configurations in the axial direction. Examples of this method include the installation of inclined boreholes [46]. During the construction phase of GSHP system, instead of drilling boreholes vertically into the soil, boreholes can be drilled diagonally. These boreholes are known as inclined boreholes. Inclined boreholes are boreholes that are angled away from the centre of the borehole field a few meters away from the ground surface. A dip angle was defined as the angle at which the borehole is oriented away from the vertical direction. A reduction in temperate changes was observed by changing the dip angle of the boreholes [46]. In addition, borehole length savings were also achieved [46]. The inclination of boreholes pose a beneficial design in geo-exchange because their installation does no incur a greater cost in construction.

While most simulation methods use the superposition of g-functions to determine the temperature distribution in a borehole field, these studies neglect axial effects. Axial effects are important in the simulation of boreholes especially in short borehole systems with unbalanced loads [47]. A study in [47] compared finite and infinite line-source models for the same borehole system. The infinite line-source model predicts a single temperature for the entire length of borehole, however, the finite line-source model predicts a gradient of temperatures approaching the infinite line-source temperature as the depth of the borehole increase. In the prediction of percentage borehole freezing, the discrepancy between the infinite and finite line-source models were 48%, outlining the importance of axial effects [47]. Due to the discrepancies in the results of the two models, axial effects are important, especially in shallow boreholes.

Studies have indicated the importance of studying borehole separation distances, borehole configurations, and axial effects, there is a need to combine the effects of all three aspects in a borehole field. Borehole designs typically consist of various borehole field layouts of uniform length boreholes. However, no study has been done to see the effect of operating a GSHP system with boreholes of varying length.

In this study, a 4x4 borehole configuration was studied. The four centre boreholes in the 16 borehole system were shortened and the length of the remaining boreholes was recalculated to maintain system capacity. A finite-element model was created to demonstrate the operation of a 16 borehole system with varying borehole lengths. Heat flux boundary conditions were calculated and applied to the borehole wall surfaces to imitate the extraction and release of heat into the ground from the borehole wall. The simulation was computed for a 20-year operating duration at hourly time-steps. Ten cases were simulated, each with different combinations of centre borehole length and borehole separation distance.

4.2 Methodology

This study consists of finite element modelling of alternative borehole configurations. The alternative borehole arrangement is illustrated in Figure 38. The centre four boreholes (depicted in grey) are shortened and the remaining boreholes (depicted in black) are extended relative to a base case. The borehole lengths used in this study are summarized in Table 9. For example, in the ‘80’ configuration, the four centre boreholes are each 80 m in length and the remaining boreholes are each 106.67 m.

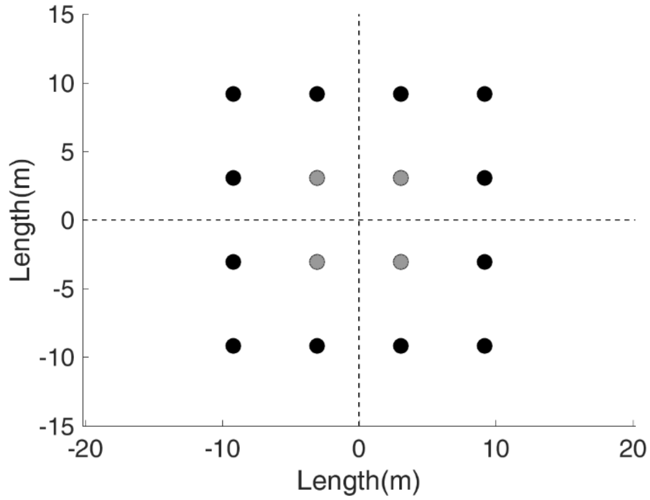

Figure 38: Alternative borehole arrangement layout

Table 9: Borehole lengths summary

Borehole configuration	Inner borehole length (m)	Outer borehole length (m)
100	100	100
80	80	106.67
50	50	116.67

First, hourly heating and cooling demands of a building was processed to obtain hourly borehole wall heat fluxes. Then, a finite element geometry as illustrated in Figure 38 was created in COMSOL Multiphysics [24]. Hourly heat fluxes were applied to the borehole walls to simulate a borehole providing heating and cooling for a building. The operation of the system was simulated for a 20 year period with hourly time steps. The results of the simulation are presented in the following sections.

4.2.1 Model Set Up

The method employed to determine the hourly heat flux is the same as the one used in [17] and outlined in Chapter 3. The variation in COP during the operation of the GSHP was not considered in this study. Hourly heating and cooling demands were processed into hourly heat fluxes using MATLAB [36]. Positive heat flux represents the release of heat into the borehole field and negative heat flux represents the extraction of heat from the borehole field. The hourly heat flux was calculated by determining the hourly “on” and “off” cycles of the heat pump. For every hour that the heat pump is turned “on”, the maximum heating or cooling capacity is provided. For every hour that heating or cooling is not required, the system turns “off”. Residual heating or cooling from the previous hour can be used to supply the building with heating or cooling when the system is “off”. For example, if 10 kWh of heating is the capacity of the heat pump and the heating demand of the building for the first two hours are 5 kWh each, the GSHP can turn “on” for the first hour and be “off” for the second hour. The same approach as in [17] and Chapter 3 was taken to calculate the hourly heat flux, upon determining the “on” and “off” cycles of the heat pump.

4.2.2 Test Case and Simulation Properties

The test case used in this analysis is a school building with slightly unbalanced heating and cooling loads. The net heating and cooling demands of this building can be found in Figure 39. The heating and cooling demands of the school building exhibits an interesting pattern in which the cooling demands drop significantly in the summer months when the occupancy of the school is low. The heating hour to cooling hour ratio of the building is 1.453.

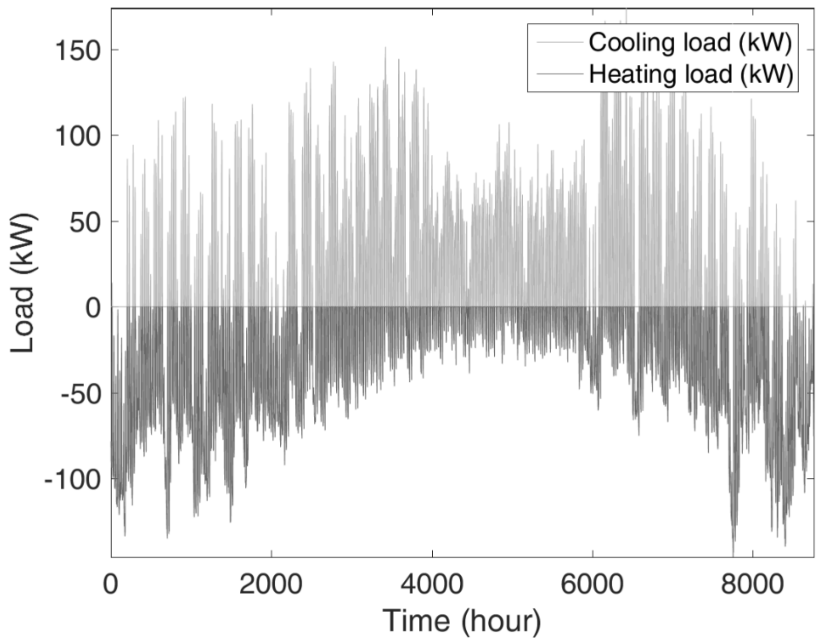

Figure 39: Net heating and cooling demands of a school building.

Using the same calculation method as outlined in [17] and Chapter 3, the hourly heat fluxes were determined based on the hourly heating and cooling demands. The GSHP system was sized to its maximum heating and cooling capacities. At each hour, it was determined whether the system was "ON" for heating, "ON" for cooling or "OFF" for both. It was assumed turning the system "ON" would supply a building with its maximum capacity.

The heating and cooling systems' "ON" and "OFF" conditions were determined for each of the 8760 hours of the year and hourly heat fluxes are calculated based on these conditions. The hourly heat fluxes for the school building are presented in Figure 40. Lines in dark gray represent positive heat flux where heat is transferred into the ground. Lines in light gray represent negative heat fluxes where heat is extracted from the ground. "ON" and "OFF" cycles of the system can be observed in Figure 40 by the occasional spacing between hours.

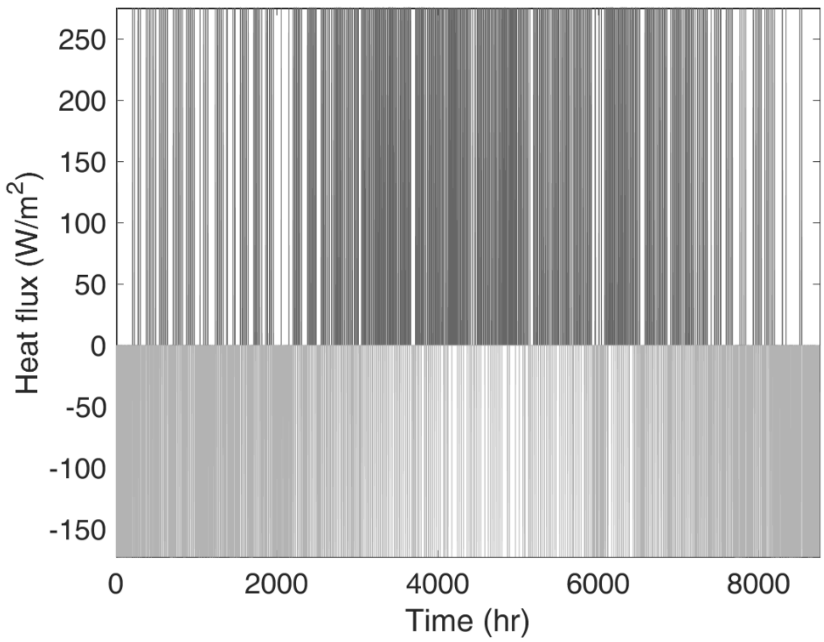

Figure 40: Hourly heat flux of school building

The simulation was conducted on COMSOL Multiphysics [24] for a 20 year period at hourly time steps. At each hour, the boundary heat flux condition at the borehole walls are updated with the hourly heat fluxes calculated in the previous step. A quarter of the simulation domain was created to model 4 operating boreholes. Symmetry conditions were applied to two faces to mirror conditions. Using the symmetry conditions, a 16 borehole system can be simulated by only modelling 4 boreholes. This simplification of geometry allowed a reduction in computation time. Open boundary conditions were applied to the remaining faces to model far-field conditions.

The simulation was repeated for 9 different cases of borehole configurations. The configurations are selected based on combinations of different borehole spacing and centre borehole length as presented in Table 10. For example, case 2 is a 16 borehole installation in a 4x4 configuration. The inner 4 boreholes in the system are 80 m in length and the remaining 12 are 106.67 m in length. The 3 m borehole spacing indicates that the boreholes are spaced 3 m apart from each other.

Table 10: Borehole configurations

Case	Borehole spacing (m)	Centre borehole length (m)
1	3	100
2	3	80
3	3	50
4	4	100
5	4	80
6	4	50
7	6	100
8	6	80
9	6	50
10	5	50

4.3 Results

4.3.1 Borehole Wall Temperature

In this simulation the temperature at a point near the borehole wall is studied. This temperature is extracted from a point 1 cm away from the borehole wall (point A). The location of 1 cm was chosen because it is very close to the borehole wall, and therefore can represent borehole wall temperature. A parallel line 1 cm away from the borehole wall was drawn along each borehole and the average temperatures of those lines were calculated. The yearly average temperature of the boreholes were calculated and summarized in Figure 41-43.

In Figure 41, three cases are presented. The three cases have centre borehole lengths of 100 m and vary in separation distance (3 m, 4 m, or 6 m). Figure 42 and Figure 43 are similar for centre borehole lengths of 80 m and 50 m, respectively. From the figures, it is evident that the borehole wall temperatures are highest in the case with the 3 m separation distance and lowest in the case with the 6 m separation distance.

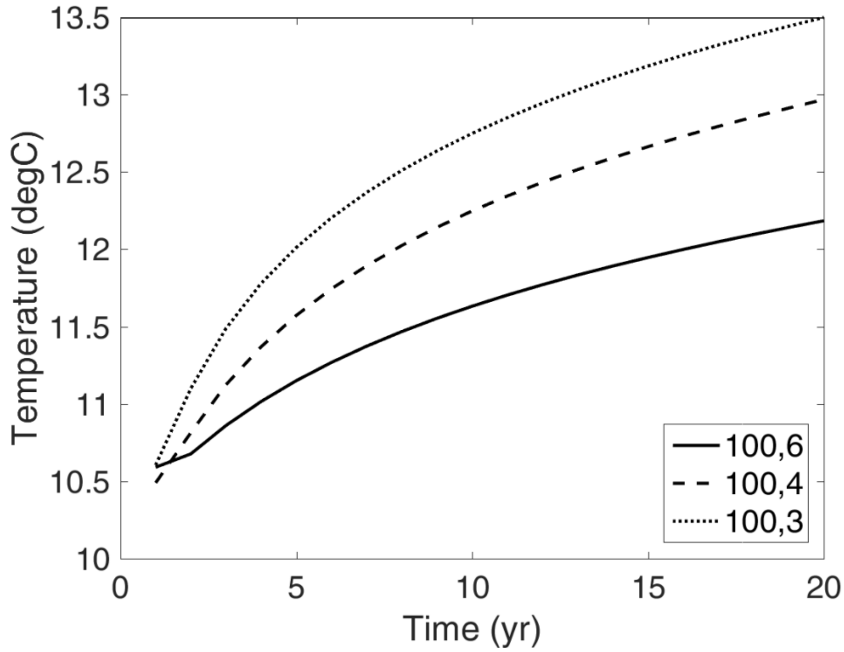

Figure 41: Average temperature at point A for 100 m centre borehole length configurations

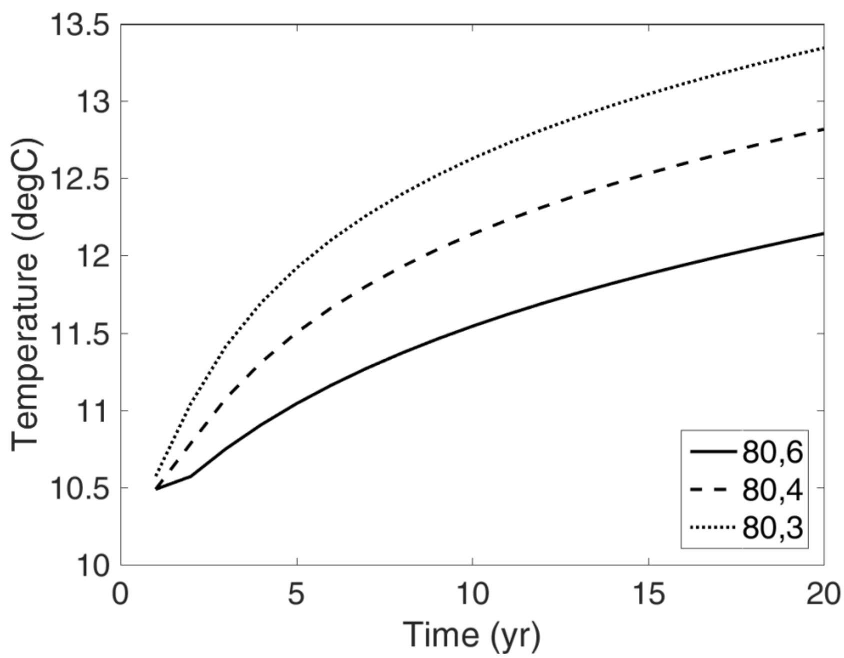

Figure 42: Average temperature at point A for 80 m centre borehole length configurations

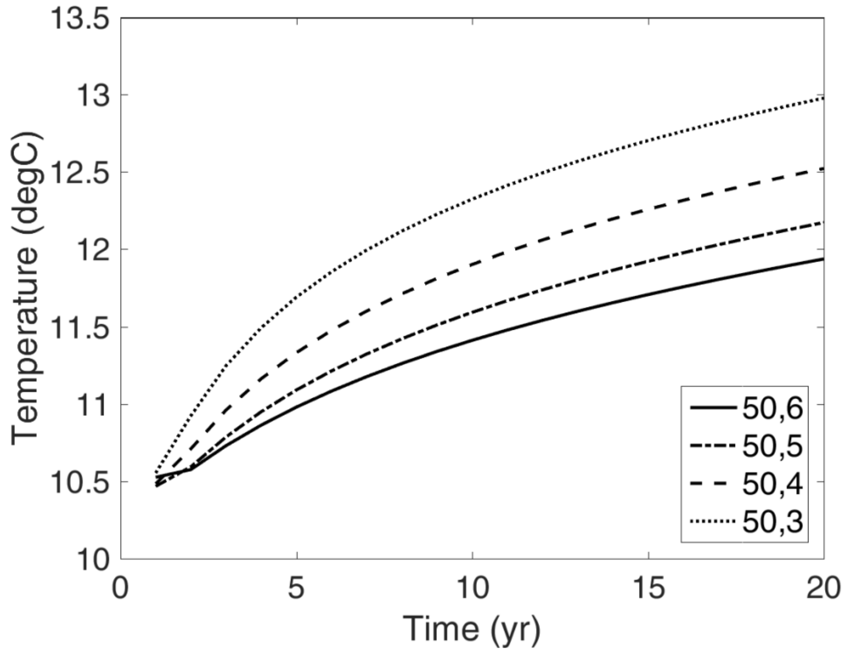

Figure 43: Average temperature at point A for 50 m centre borehole length configurations

In Figure 43, it is interesting to note that the temperature difference between the 3 m and 4 m separation distance is significantly greater than the temperature difference between the 5 m and 6 m cases. The rate of increase in ground temperature is higher when separation distance is small and is lower when the separation distance is greater.

The effects of varying borehole lengths were also studied. The results are presented in Figure 44 for the cases with 4 m borehole separation distances. The plots for 3 m and 6 m separation distances are not presented in this analysis because of their similarities with Figure 44. In Figure 44, the average temperatures at point A were studied for three borehole configurations. It can be observed from the figure that the "50" configuration has a smaller increase in temperature compared to the "80" and "100" configurations over the 20 year study period. Thermal benefits in using the "50" configuration can be observed. Using the same amount of drilling and piping, over 20 years, the "50" configuration on average has a 0.5^{o}C lower temperature than the "100" configuration.

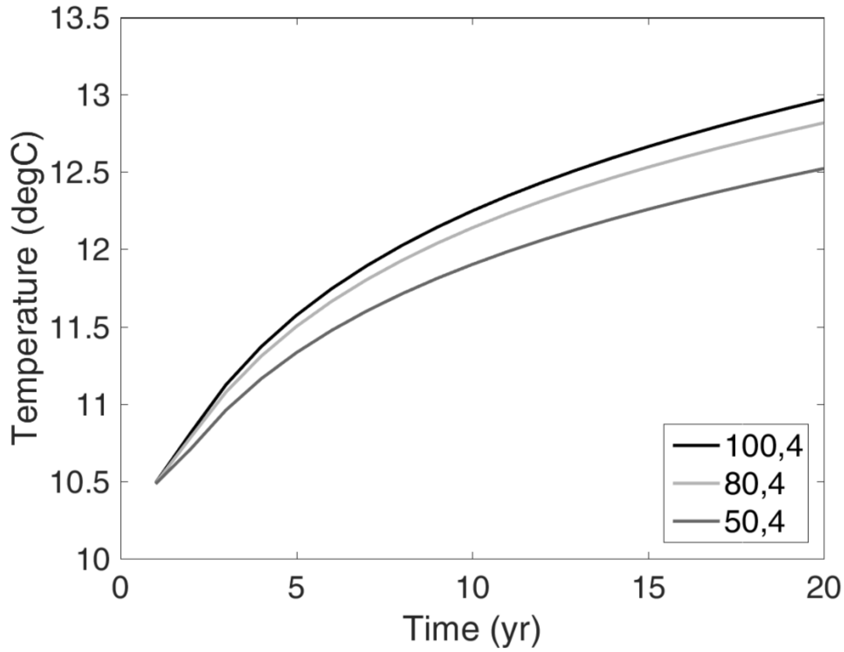

Figure 44: Average temperature at point A at 4 m separation distance

4.3.2 Affected Soil Radius

In the previous section, the results indicated that there was thermal benefits in using an uneven distribution of borehole lengths. The "50" configuration with centre boreholes of 50 m and exterior boreholes of 116 m in length demonstrated benefits over the "100" configuration with all borehole 100 m in length. However, it is also useful to study how well heat is dissipated to surrounding soil.

In this section, a parameter α is defined as the affected distance at which the ground temperature is changed by greater than 0.01%. The maximum value of α in year 20 was summarized in Figure 45. It can be observed from Figure 45 that the value of α is not greatly affected by the changes in borehole configurations. For example, the 6 m line in Figure 45 shows an affected distances ranging from 6.2 m to 6.39 m, a mere 0.19 m difference.

In Figure 46, similar information is presented in a different format. The effects of varying borehole separation distances can be observed in the figure. As borehole separation distance increase, the value of α decreases. This study indicates that the affected soil distance in a borehole field is independent of borehole depths but rather dependent on borehole separation distance.

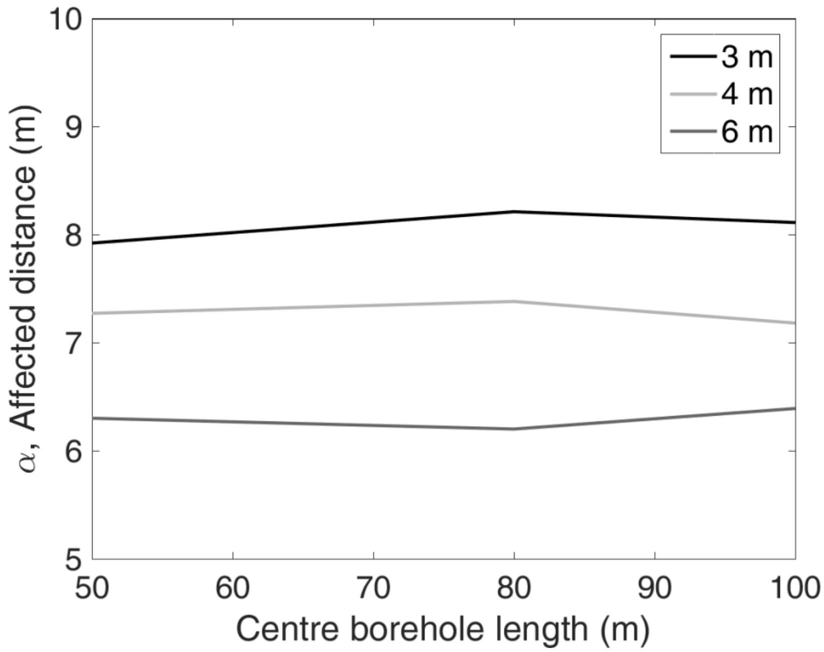

Figure 45: Affected soil distance from corner borehole for varying centre borehole length

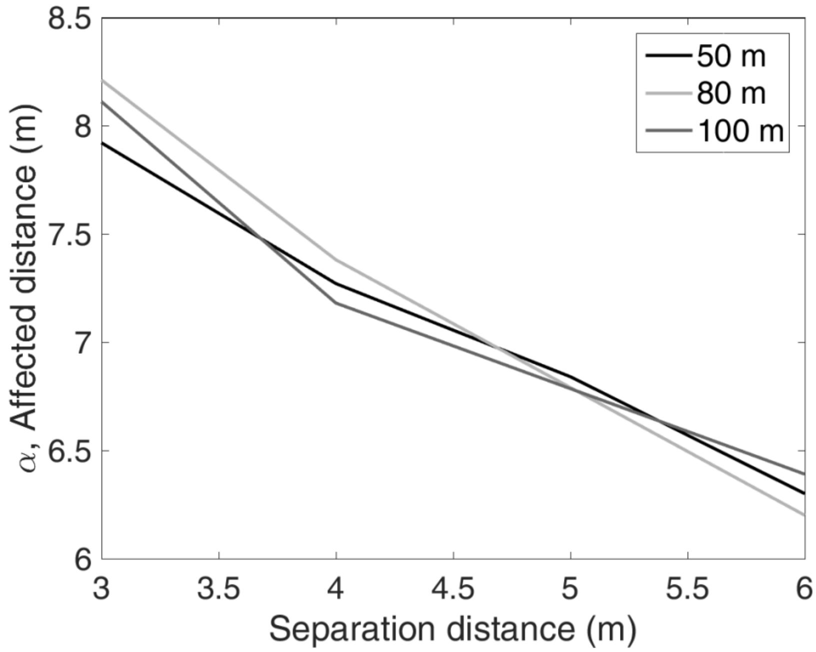

Figure 46: Affected soil distance from corner borehole for varying separation distance

4.3.3 Alternative Designs

In hopes of developing ways to alleviate the effects of thermal imbalance, the ground temperature changes in all 10 configurations indicated in Table 10 were compared. Annual average temperatures were calculated for 20 years for each system and summarized in Figure 47. Based on the results in this figure, it can be noticed that ground temperature increases with decreasing separation distance. As separation distance decreases, the ground volume available for heat dissipation is decreased, resulting in an increase in temperature. In addition, an increase in ground temperature can also be correlated with the increase in centre borehole length. Although in all cases, ground temperature increases as time increases, the overlapping/shadowing lines may lead to potential alternative designs.

Several potential designs can be considered based on the results presented in Figure 47. If a GSHP system were originally designed with a uniform borehole field (100 m boreholes) with separation distance of 6 m (line labeled 100, 6 in figure), alternative configurations can be determined using lines adjacent to the proposed design line in Figure 47. For example, a “50, 6” design can be used to lower the ground temperature increase since it resulted in the smallest temperature change after 20 years.

Alternatively, based on the simulation results, a “50, 5” design can be proposed. It can be observed that the behaviour of his line is very similar to the original “100, 6” design. However, this new design will decrease borehole spacing, allowing the system to be installed in a smaller space. This finding can provide potential designs for buildings that have property sizes that are determined to be insufficient for installation of GSHP systems.

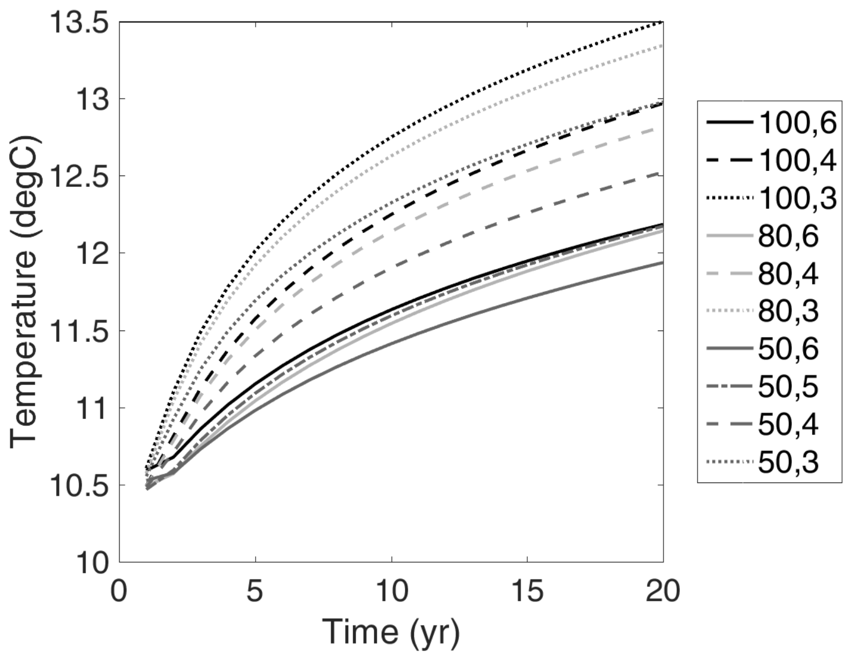

Figure 47: Summary of all simulation results

Table 11 summarizes the average increases borehole temperature after 20 years of operation. Similar trends can be observed as in Figure 47. However, it is interesting to note that the temperature of the bolded pairs in Table 11 are in similar locations. One can predict the behaviour of the “100, 5” configuration to be similar to the “50, 4” configuration. This table can potentially be used in future designs to predict centre borehole length and borehole separation distance pairs (indicated in bold in black and gray) that behave similarly after 20 years of system operation. However, more buildings should be simulated using the same methodology to confirm the results of the study in this chapter.

Table 11: Average year 20 borehole wall temperature increase

	Borehole Separation Distance				
Centre Borehole Length		3 m	4 m	5 m	6 m
	50 m	**+2.98℃**	+2.52℃	**+2.17℃**	+1.94℃
	80 m	+3.34℃	+2.82℃	--	+2.14℃
	100 m	+3.50℃	**+2.97℃**	--	**+2.18℃**

4.4 Conclusions

Although studies have previously been done to characterize the effects of borehole geometry in terms of borehole field arrangements and borehole separation distance, little research had been done to explore the effects of alternating the length of boreholes. To fill the knowledge gap in the study of borehole lengths, a series of simulations were performed in this chapter.

This chapter simulated the operation of a 4x4 configuration borehole field with varying borehole lengths and borehole separation distance. Ten cases were studied and an increase in ground temperature near the borehole wall can be observed with the decrease of borehole separation distance. In addition, an increase in ground temperature near the borehole wall can also be observed with the increase of inner borehole depth. It was observed from the present results that alternative designs can be used to achieve the same ground temperature change with uniform borehole lengths. Specifically, it was found that the configuration with inner borehole length of 50 m at a separation distance of 5 m behaved similarly as the configuration with inner borehole length of 100 m at a separation distance of 6 m. This result indicates that borehole separation distance can be reduced by alternating the borehole lengths of a system. This reduction can allow GSHP systems to be installed in smaller spaces, which is beneficial to locations where property prices are high, or properties are dense.

This study demonstrated the importance of the study of alternative borehole configurations. Alternative borehole configurations can be used to reduce the effects of ground thermal imbalance. To fulfill the knowledge gap present in this study, further study should be performed on the effects of alternating borehole lengths in other borehole field arrangements.

Chapter 5

Summary and Recommendations

5.1 Summary[2]

In this thesis, the thermal performance of boreholes with varying configurations were compared. Finite element simulations were conducted to model the operation of borehole fields and temperature distributions throughout a 20 year period. Chapters 3 and 4 focused on different aspects of varying borehole configurations to seek potential methods in reducing the effects of thermally imbalanced systems. In Chapter 3, borehole field aspect ratios were compared. The arrangement of borehole field layouts were varied and the temperature distributions after 20 years were studied. In Chapter 4, borehole depths for interior boreholes were shortened and the remaining boreholes were extended to maintain the required system capacity. The soil effective length and temperature near the borehole wall were studied.

In Chapter 3, a 20-year analysis was performed for 2x2, 4x4, and 2x8 configurations for a hospital, fast-food restaurant, residence, and school. In the 2x2 configuration, it was observed that the borehole separation distance of 6 m recommended by ASHRAE was not always sufficient to prevent borehole interaction. As a result, heat accumulation/reduction occurred in the centre of the domain.

In all three configurations, temperature increased quickly in the first few years, then the rate of increase slowed. The greatest change in ground temperature occurred in the fast-food restaurant, which the building is extremely cooling dominant. The large imbalance of heating and cooling

[2] For the manuscript style thesis, the content in this section is adapted from Chapters 3 and 4

loads in this case caused ground temperature to increase quickly to 35^{o}C within the first 4.5 and 6.5 years for the 2x8 and 4x4 configurations, respectively. From this study, it can be concluded that the 2x8 configuration, with its greater perimeter, is more beneficial than the 4x4 configuration because it has a lower temperature change over 20 years. In the cases studied in this chapter, the decrease in ground temperature change using the 2x8 configuration were 0.16 ^{o}C to 2^{o}C compared to the 4x4 configuration. In the case of the fast-food restaurant, the decrease in ground temperature change also has potential to extend its system operation life by 2 years. This small change in ground temperature is because the 2x8 configuration has a greater perimeter for heat to dissipate to surrounding soil.

This study also confirmed the importance of load balance. Without balanced loads, the ground fouls before reaching the end of the system life, causing system shut down and economic loss. In addition, the importance of accurate energy simulations, modelling, and design should also be noted.

The study in Chapter 4 considered the operation of a 4x4 configuration borehole field with varying borehole lengths and borehole separation distance. Ten cases were studied and an increase in ground temperature were observed with the decrease of borehole separation distance. In addition, an increase in ground temperature can also be observed with the increase of inner borehole depth. It was observed from the results that alternative designs can be used to achieve the same ground temperature change as designs with uniform borehole lengths. Specifically, it was found that the configuration with inner borehole length of 50 m at a separation distance of 5 m behaved similarly to the configuration with inner borehole length of 100 m at a separation distance of 6 m. This result indicates that borehole separation distance can be reduced by alternating the borehole lengths of a system. This reduction can allow GSHP systems to be installed in smaller spaces, beneficial to locations where property prices or density is high.

5.2 Recommendations

To fill the knowledge gap present in the studies in this thesis, further research should be conducted. Research topics should extend into the study of borehole field arrangements combined with varying borehole lengths to examine the effects of combining the benefits of both studies presented in this thesis. Unique borehole field arrangements with varying borehole lengths should be explored to determine how best thermal imbalance can be alleviated.

G-functions should also be further explored in terms of varying borehole length designs. G-functions are thermal response factors that are developed to simplify the thermal behaviour of boreholes arrays into a single function. The temperature of borehole arrays can be determined by superimposing the respective g-function onto a line-source simulation. The addition of g-functions for varying borehole lengths can simplify the simulation procedure by superimposing the g-function onto a single borehole system. By creating g-functions for borehole configurations with varying borehole lengths, one can easily examine the thermal performance of GSHPs during the design process.

To develop models that are more representative of an operating GSHP system, refined details should be added to the model presented in this thesis. These details include the modelling of fluid flow inside the pipes enclosed by grout and additional soil properties. Attention should be paid to the modelling of the soil volume including its porosity. To more accurately predict ground temperature changes, temperature-dependent properties should be time-dependent. For example, soil moisture content, density, conductivity, and heat capacity are all properties that vary with temperature.

Research should also extend into the study of thermal storage media (TSM) to explore potential methods of using thermal imbalance to offset heating/cooling demands, therefore reducing electricity consumption. A thermal storage medium is an inexpensive material with high heat capacity that can be placed around boreholes to reduce temperature deterioration in surrounding soil. Because of the high heat capacity property of TSMs, the change in TSM temperature will be small, also decreasing the change in soil temperature. Further study should be conducted in TSM to assess its potential in alleviating thermal imbalance effects.

Appendix A

A.1 Building Loads[3]

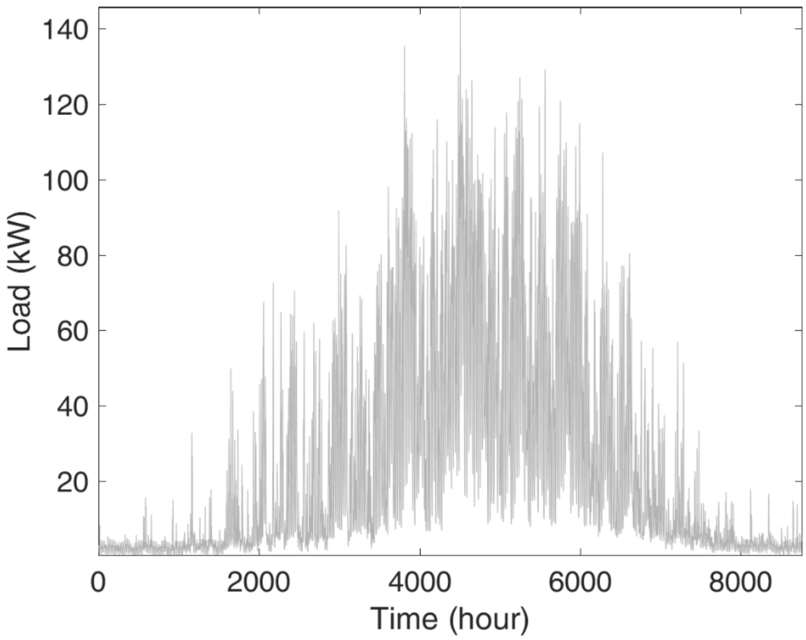

Figure 48: Cooling demands for a hospital building

[3] Building load data courtesy of CleanEnergy™ Developments

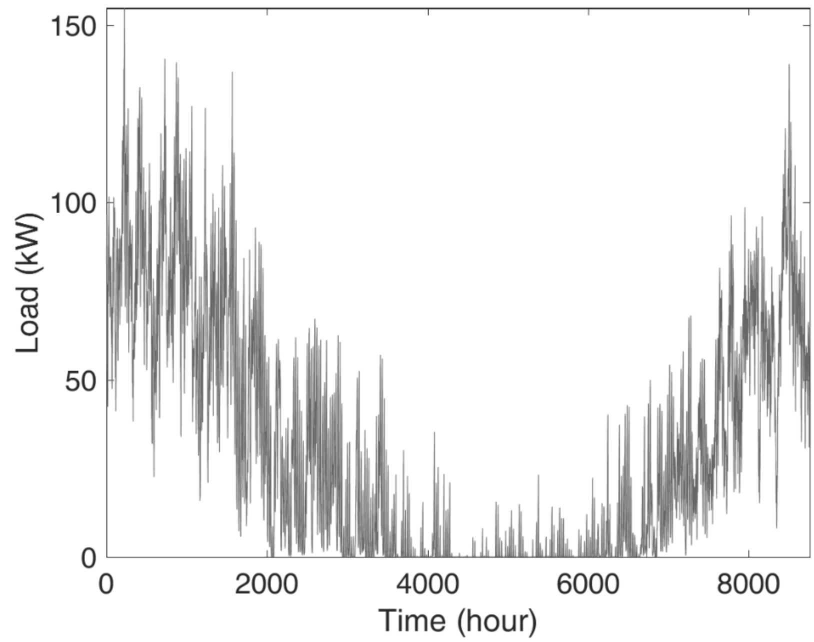

Figure 49: Heating demands for a hospital building

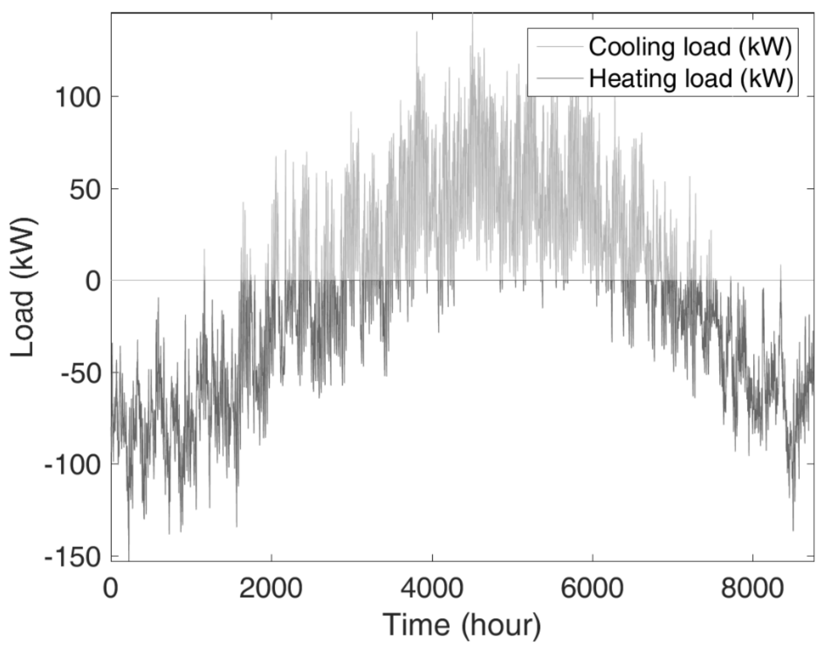

Figure 50: Net demands for a hospital building

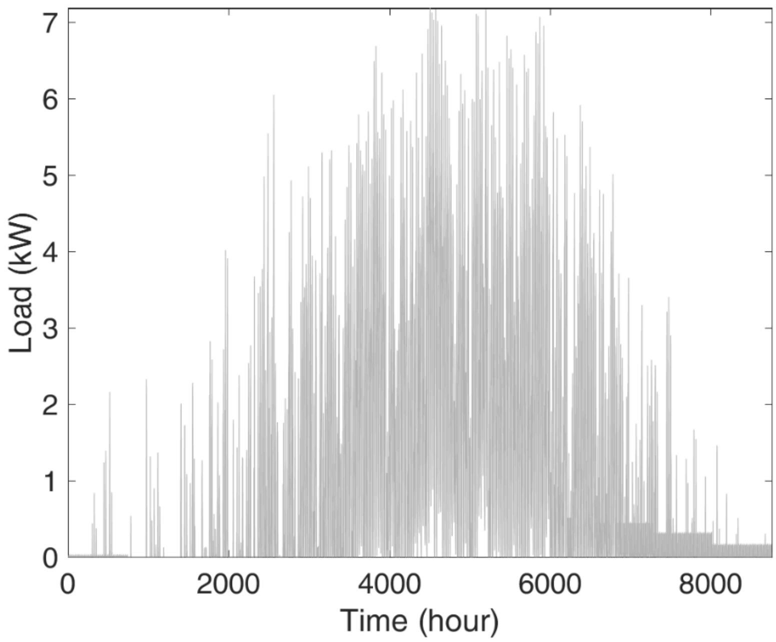

Figure 51: Cooling demands for a residence

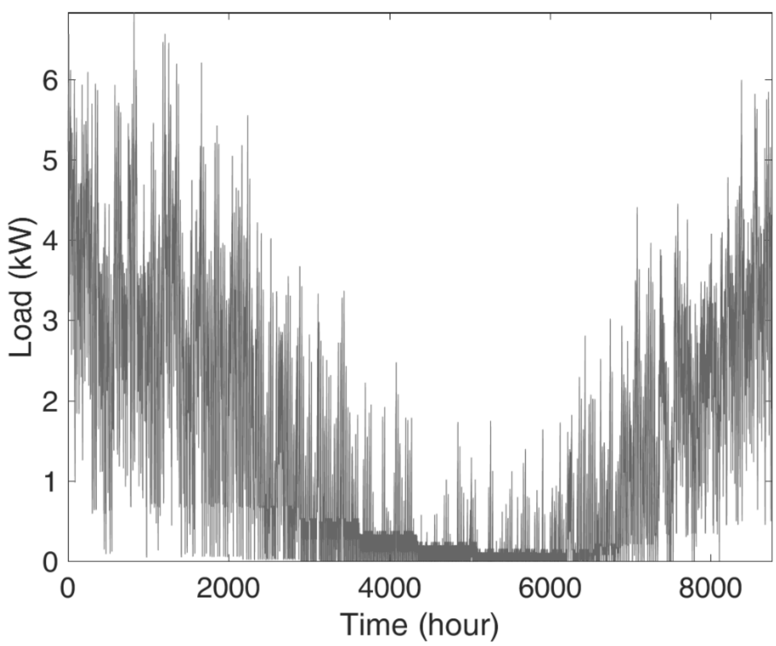

Figure 52: Heating demands for a residence

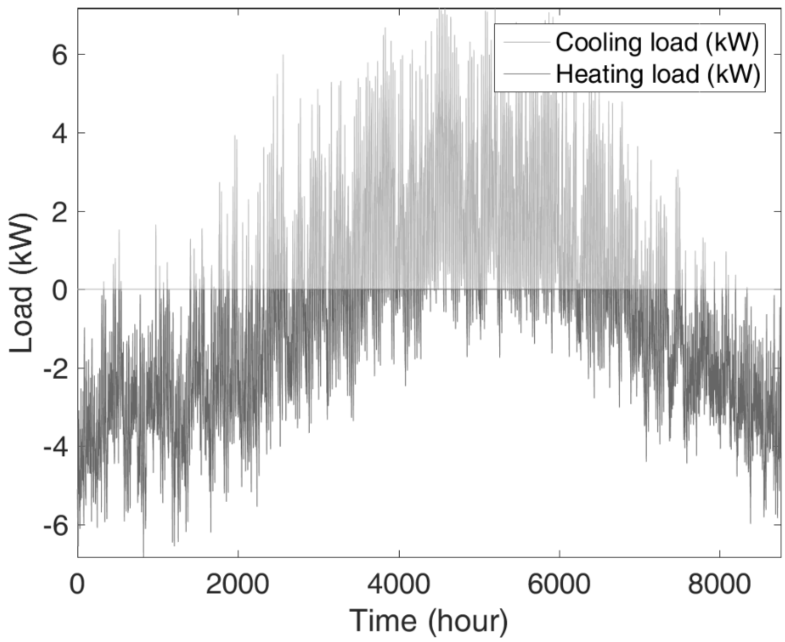

Figure 53: Net demands for a residence

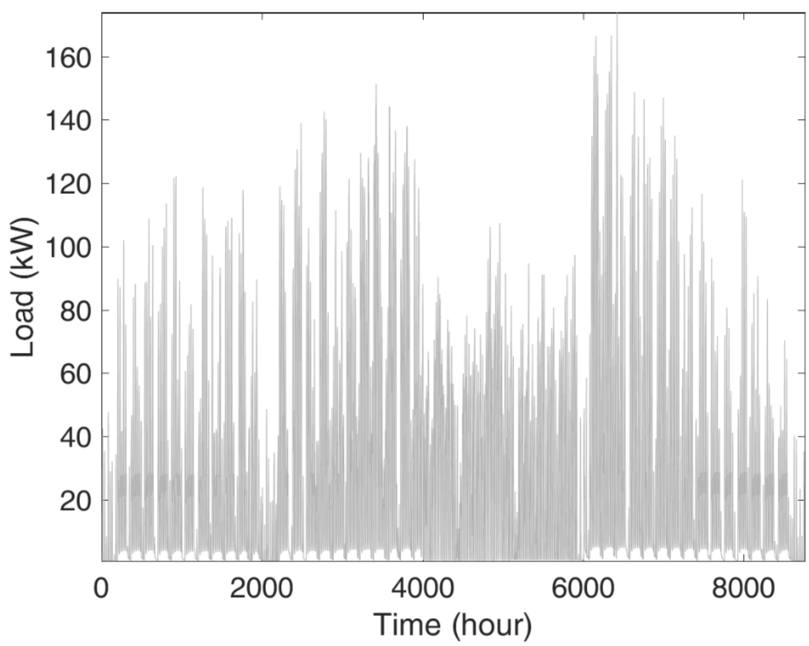

Figure 54: Cooling demands for a school building

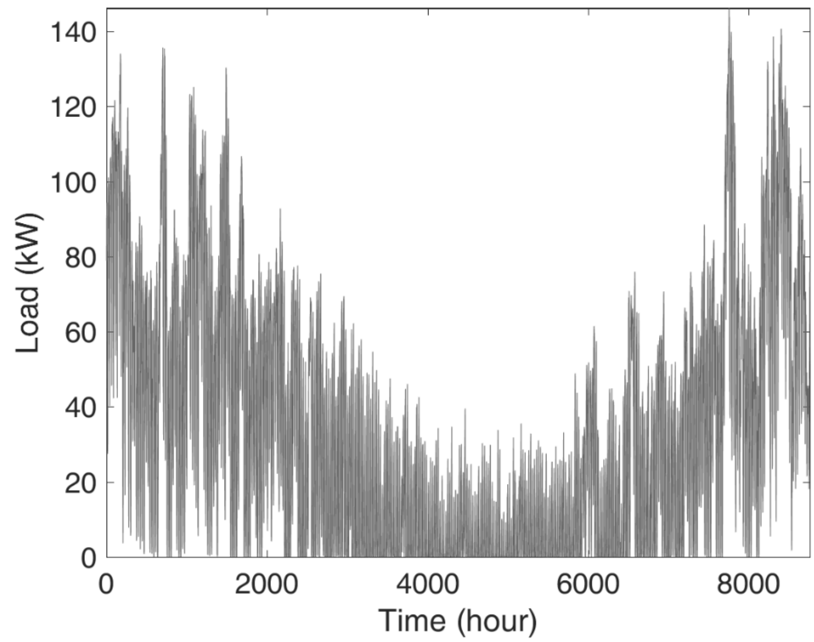

Figure 55: Heating demands for a school building

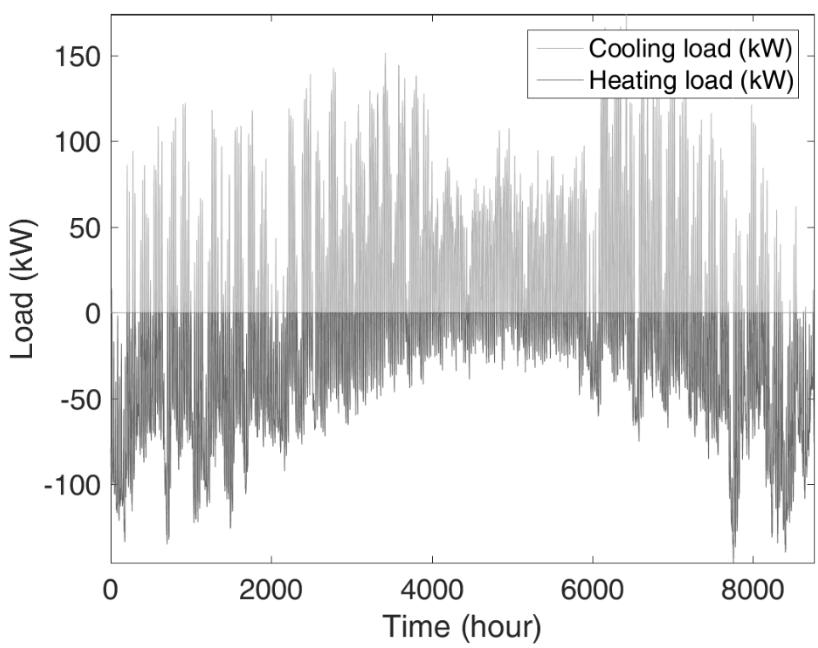

Figure 56: Net demands for a school building

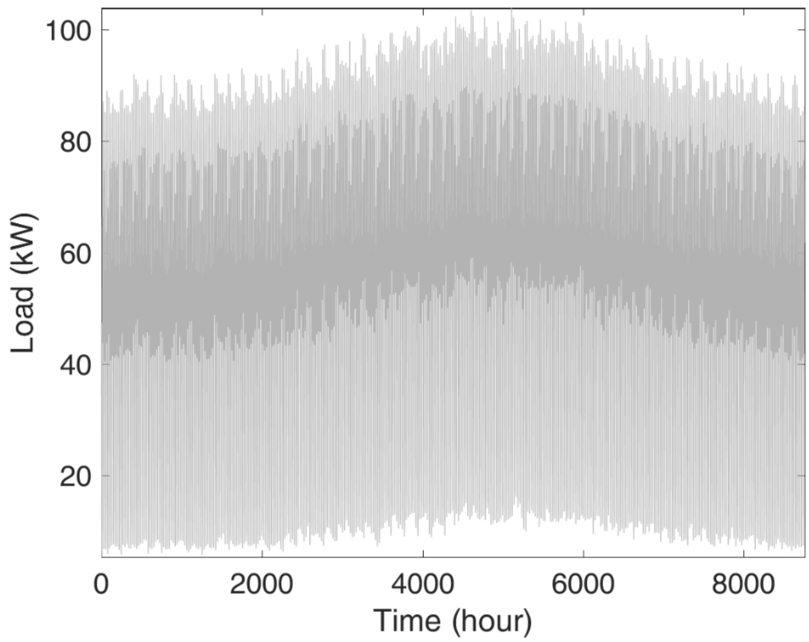

Figure 57: Cooling demands for a fast-food restaurant

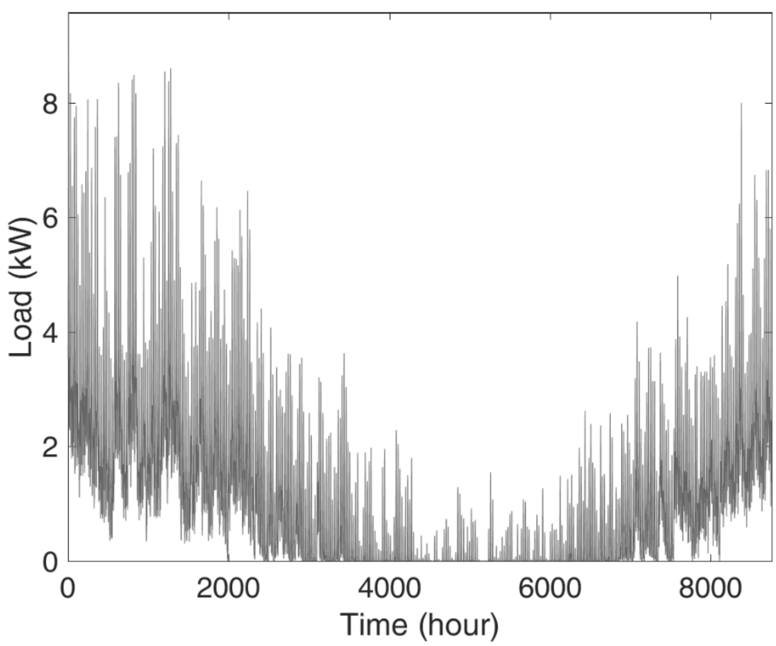

Figure 58: Heating demands for a fast-food restaurant

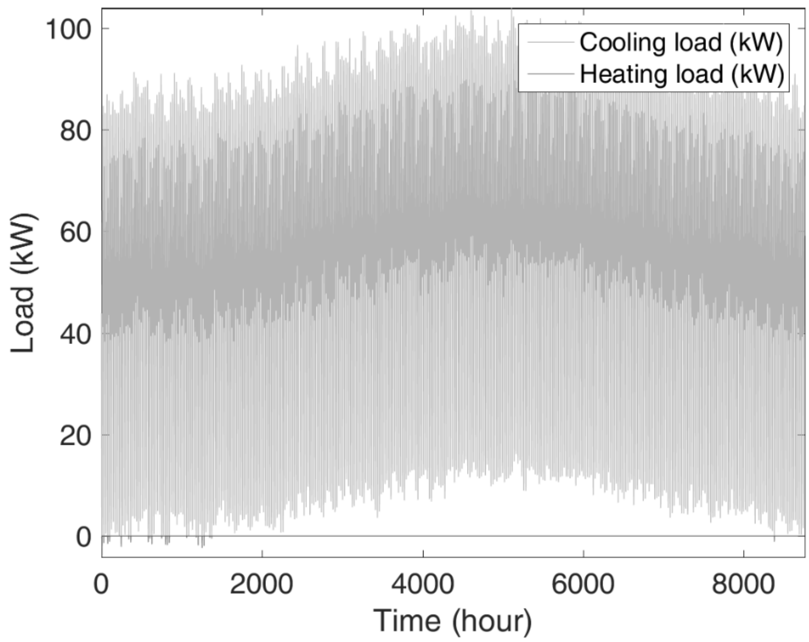

Figure 59: Net demands for a fast-food restaurant

A.2 Hourly Heat Flux Conditions

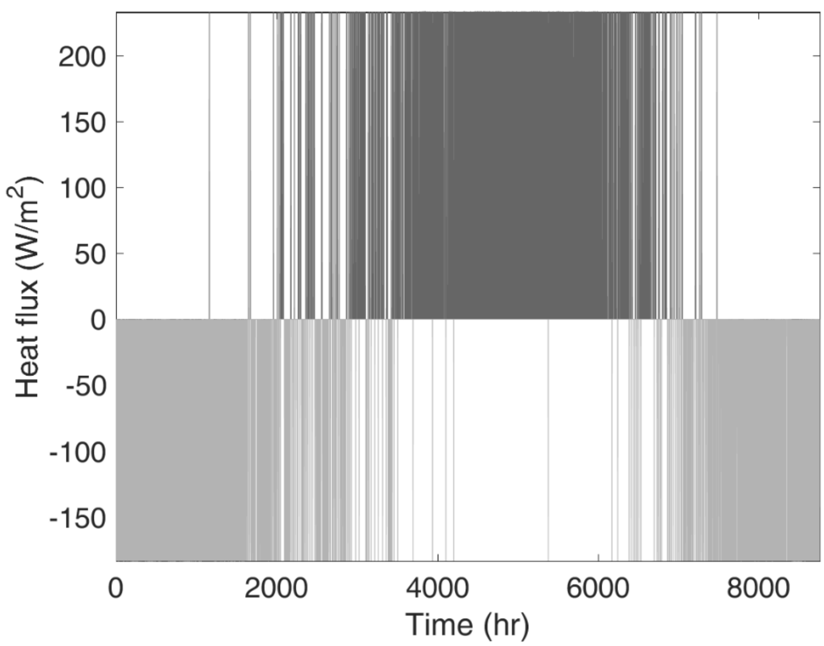

Figure 60: Hourly heat flux conditions for a hospital

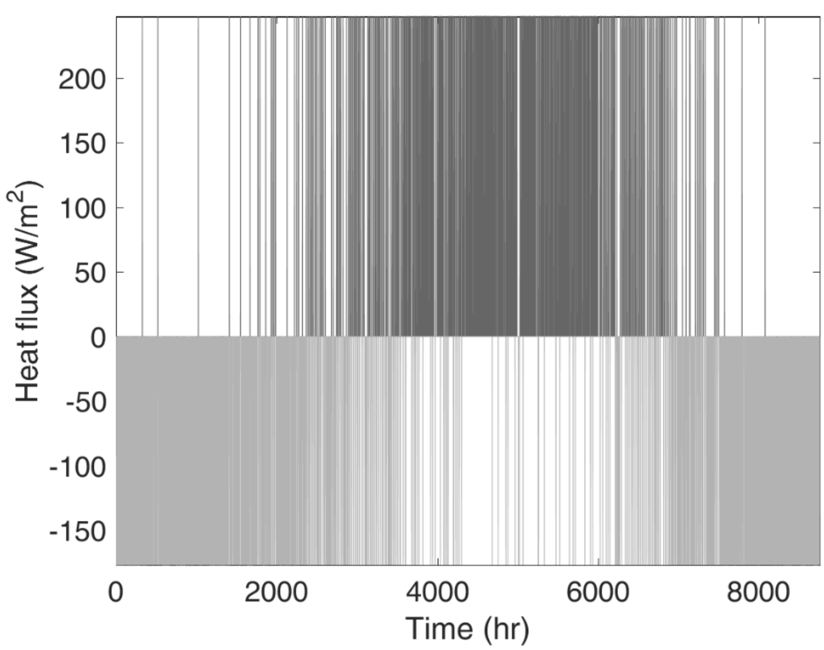

Figure 61: Hourly heat flux conditions for a residence

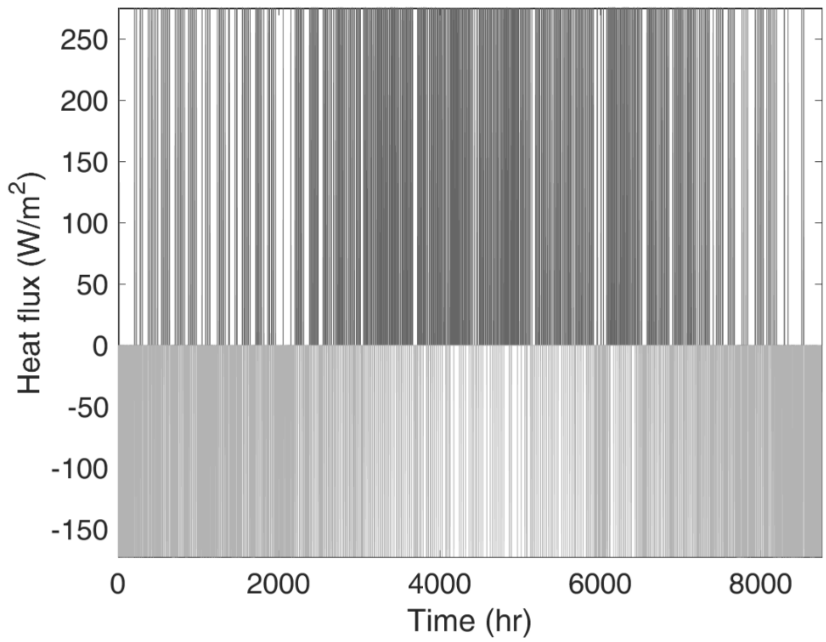

Figure 62: Hourly heat flux conditions for a school building

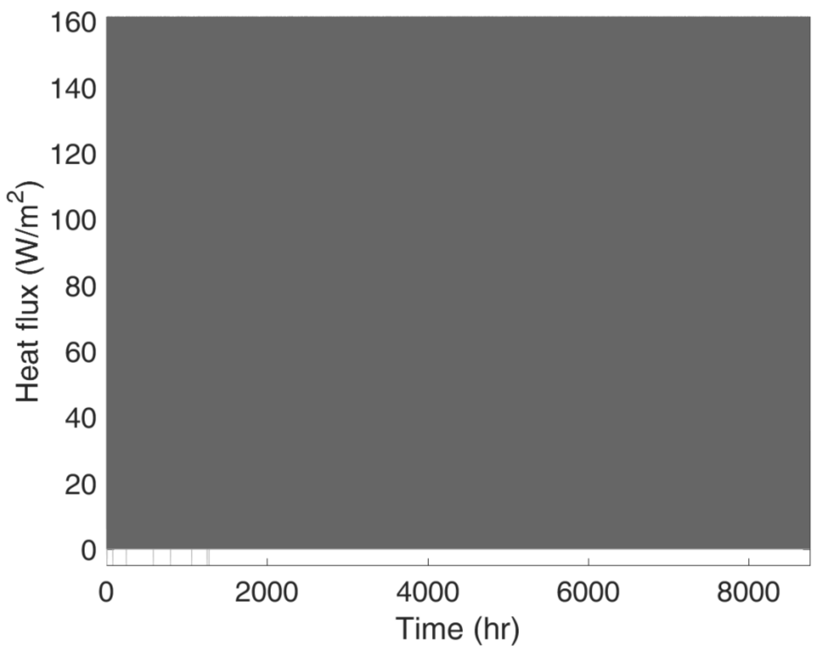

Figure 63: Hourly heat flux conditions for a fast-food restaurant

References

[1] Natural Resources Canada, "Energy Efficiency Trends in Canada, 1990 to 2009," 2012. [Online]. Available: http://oee.nrcan.gc.ca/publications/statistics/trends11/chapter3.cfm.

[2] A. Omer, "Ground-source heat pumps systems and applications," *Renewable and Sustainable Energy Reviews,* vol. 12, no. 2, pp. 344-371, 2008.

[3] G. Florides and S. Kalogirou, "Ground heat exchangers -- A review of systems, models and applications," *Renewable Energy,* vol. 32, no. 15, pp. 2461-2478, 2007.

[4] S. Hu, W. Song, Y. Zhang, D. Pan and T. Meng, "Study of Cold/Hot Stacking Problem Based on Balance Storage of Gound Source Heat Pump," vol. 3, pp. 671-675, 2010.

[5] Greenspec, "Ground Loop Configrations," [Online]. Available: http://www.greenspec.co.uk/building-design/ground-source-heat-pumps.

[6] IEA Heat Pump Centre, "Heat Pump Performance," [Online]. Available: http://www.heatpumpcentre.org/en/aboutheatpumps/heatpumpperformance/Sidor/default.aspx.

[7] Toronto and Region Conservation Authority, "Closing the loop: a survey of owners, operators and suppliers of urban geoexchange systems in the Greater Toronto Area," [Online]. Available: http://www.sustainabletechnologies.ca/wp/wp-content/uploads/2015/03/GeoexchangeSurvey_ES_Feb2015.pdf.

[8] L. Rybach and W. Eugster, "Sustainability aspects of geothermal heat pump operation.

with experience from Switzerland," *Geothermics*, vol. 39, no. 4, pp. 365-369, 2010.

[9] S. Li, W. Yang and X. Zhang, "Soil temperature distribution around a U-tube heat exchanger in a multi-function ground source heat pump system," *Applied Thermal Engineering*, vol. 29, no. 17-18, pp. 3679-3686, 2009.

[10] C. Wu, C. Hui, W. Wang, X. Li and W. Fu, "Characteristics of ground temperature and system performance for the intermittent operation of GSHP system," *Environment, Energy and Sustainable Development*, pp. 123-127, 2014.

[11] X. Zheng, "Long-term effects of ground source heat pumps on underground temperature," in *COMSOL Conference*, Boston, 2013.

[12] ASHRAE, 2011 ASHRAE Handbook-HVAC Systems and Equipment SI Edition, Atlanta: ASHRAE, 2011.

[13] RETScreen International, "Clean energy project analysis: Ground-source heat pump project analysis," Canada: Ministers of Natural Resource Canada, 2005.

[14] Y. Man, H. Yang and J. Wang, "Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like Hong Kong," *Applied Energy*, vol. 87, no. 9, pp. 2826-2833, 2010.

[15] Alaska Center for Energy and Power and Cold Climate Housing Research Center, "Ground-Source Heat Pumps in Cold Climates," 2011. [Online]. Available: http://www.cchrc.org/sites/default/files/docs/Ground-Source-Heat-Pumps-in-Cold-Climates.pdf.

[16] T. Meng, Y. Di, L. Liu, F. Ma and Y. Zhao, "Research of ground heat balance of ground source heat pump," in *2009 International Conference on Energy and Environmental Technology*, Guilin, 2009.

[17] Y.L.E. Law and S.B. Dworkin, "Characterization of the effects of borehole configuration and interference with long term ground temperature modelling of ground source heat pumps," *Applied Energy*, vol. 179, pp. 1032-1047, 2016.

[18] P. Bayer, M. dePaly and M. Beck, "Strategic optimization of borehole heat exchanger field for seasonal geothermal heating and cooling," *Applied Energy*, vol. 136, pp. 445-453, 2014.

[19] S. Lazzari, A. Priarone and E. Zanchini, "Long-term performance of BHE (borehole heat exchanger) fields with negligible groundwater movement," *Energy*, vol. 35, no. 12, pp. 4966-4974, 2010.

[20] M. Alavy, H.V. Nguyen, W.H. Leong and S.B. Dworkin, "A Methodology and Computerized Approach for Optimizing Hybrid Ground Source Heat Pump System Design.," *Renewable Energy*, vol. 57, pp. 404-412, 2013.

[21] E. Wang, A. Fung, C. Qi and W. Leong, "Build-up and long-term performance prediction of a hybrid solar ground source heat pump system for office building in cold climate," in *eSim 2012: The Canadian Conference on Building Simulation*, Halifax, 2012.

[22] Z. Qi, Q. Gao, Y. Liu, Y. Yan and J. Spitler, "Status and development of hybrid energy systems from hybrid ground source heat pump in China and other countries.," *Renewable*

And Sustainable Energy Reviews, vol. 29, pp. 37-51, 2014.

[23] S. Kavanaugh and K. Rafferty, Ground-source heat pumps: design of geothermal systems for commercial and instutional buildings, ASHRAE, 1997.

[24] COMSOL Inc., "COMSOL Multiphysics," 2016. [Online]. Available: http://www.comsol.com.

[25] O. Ozyurt and D. Ekinci, "Experimental study of vertical ground-source heat pump performance evalulation for cold climate in Turkey," *Applied Energy,* vol. 88, pp. 1257-1265, 2011.

[26] C. Montagud, J. Coberan and F. Ruiz-Calvo, "Experimental and modeling analysis of a ground source heat pump system," *Applied Energy,* vol. 109, pp. 328-336, 2013.

[27] S. Koohi-Fayegh and M. Rosen, "Examination of thermal interaction of multiple vertical ground heat exchangers," *Applied Energy,* vol. 97, pp. 962-969, 2012.

[28] X. Liu and G. Hellstrom, "Enhancements of an integrated simulation tool for ground-source heat pump system design and energy analysis," in *Estock 2006*, NJ: Pomona, 2006.

[29] P. Eskilson, *Thermal analysis of heat extraction boreholes*, Lund University, 1987.

[30] G. Hellstrom, B. Sanner, M. Klugescheid, T. Gonka and S. Martensson, "Experiences with the borehole heat exchanger software EED," in *Megastock Conference 1997*, Japan: Sapporo, 1997.

[31] J. Perez, *Understanding numerically generated g-functions: A study case for a 6x6*

borehole field, KTH Industrial Engineering and Management, 2013.

[32] D. Fisher, A. Murugappan, S. Padhmanabhan and S. Rees, "Implementation and validation of ground source heat pump system models in an integrated building and system simulation environment," *HVAC&R Research*, vol. 12, no. 3a, pp. 693-710, 2006.

[33] Energy+ Inc., "Energy +," 2016. [Online]. Available: http://www.energyplus.ca.

[34] J. Cullin, C. Montagud, F. Ruiz-Calvo and J. Spitler, "Experimental Validation of Ground Heat Exchanger Design Methodologies Using Real, Monitored Data," *ASHRAE Transactions*, vol. 120, pp. 357-369, 2006.

[35] M. Bernier, A. Chahla and P. Pinel, "Long-term ground temperature changes in geo-exchange systems," *ASHRAE Transactions*, vol. 114, no. 2, pp. 342-350, 2008.

[36] MathWorks Inc., "MATLAB," 2016. [Online]. Available: http://www.mathworks.com.

[37] eQUEST, "eQUEST," DOE2.com, 2016. [Online]. Available: http://doe2.com/equest.

[38] J. Spitler, "GLHPRO: a design tool for commercial building ground loop heat exchangers," in *Fourth international heat pumps in cold climates conference*, Alymer, Quebec, 2000.

[39] C. Lee, "Effects of multiple ground layers on thermal response test analysis and ground-source heat pump simulation," *Applied Energy*, vol. 88, pp. 4405-4410, 2011.

[40] H. Yang, P. Cui and Z. Fang, "Vertical-borehole ground-coupled heat pumps: a review of models and systems," *Applied Energy*, vol. 87, pp. 16-27, 2010.

[41] M. Aydin and A. Sisman, "Experimental and computational investigation of multi U-tube

boreholes," *Applied Energy,* vol. 145, pp. 163-171, 2015.

[42] N. Kuzmic, Y.L.E. Law and S.B. Dworkin, "Numerical heat transfer comparison study of hybrid and non-hybrid ground source heat pump systems," *Applied Energy,* vol. 165, pp. 919-929, 2016.

[43] R. Beier, M. Smith and J. Spitler, "Reference data sets for vertical borehole ground heat exchanger models and thermal response test analysis," *Geothermics,* vol. 40, no. 1, pp. 79-85, 2011.

[44] H.V. Nguyen, Y.L.E. Law, M. Alavy, P. Walsh, W.H. Leong and S.B. Dworkin, "An analysis of the factors affecting hybrid ground-source heat pump installation potential in North America," *Applied Energy,* vol. 125, pp. 28-38, 2014.

[45] Y. Yuan, X. Cao, J. Wang and L. Sun, "Thermal interaction of multiple ground heat exchangers under different intermittent ratio and separation distance," *Applied Thermal Engineering,* vol. 108, pp. 227-286, 2016.

[46] D. Marcotte and P. Pasquier, "The effect of borehole inclination on fluid and ground temperature for GLHE systems," *Geothermics,* vol. 38, pp. 392-398, 2009.

[47] D. Marcotte, P. Pasquier, F. Sheriff and M. Bernier, "The importance of axial effects for borehole design of geothermal heat-pump systems," *Renewable Energy,* vol. 35, pp. 763-770, 2010.