VŠB-Technická Univerzita Ostrava

Fakulta stavební

Katedra stavební mechaniky

Modelování zemního výměníku tepla

Vertical Ground Heat Exchanger Modeling

Student: Cristina Fernández Fernández

Vedoucí bakalářské práce: Ing. Petr Konečný, Ph.D.

Ostrava 2016

Prohlášení studenta / Student declaration

Prohlašuji, že jsem celou bakalářskou práci včetně příloh vypracovala samostatně pod vedením vedoucího bakalářské práce a uvedla jsem všechny použité podklady a literaturu.

I am declaring that I prepared the bachelor thesis including attachment by my self under the tutorship of the supervisor of the bachelor thesis and that references to all sources and literature is given.

V Ostravě
…………………………………

 podpis studentky /………………………………
signature

Prohlašuji, že (I declare that,)

byl jsem seznámen s tím, že na moji bakalářskou práci se plně vztahuje zákon č. 121/2000 Sb. – autorský zákon, zejména § 35 – užití díla v rámci občanských a náboženských obřadů, v rámci školních představení a užití díla školního a § 60 – školní dílo. (I was familiarized with the fact that my thesis is fully covered by law of the Czech Republic No. 121/2000 Sb. Intellectual Property Law, especially § 35 - use of civil works, within the religious ceremonies, during school presentations and use of school work and § 60-schoolwork.)

beru na vědomí, že Vysoká škola báňská – Technická univerzita Ostrava (dále jen VŠB-TUO) má právo nevýdělečně ke své vnitřní potřebě bakalářskou práci užít (§ 35 odst. 3). (I understand that the VSB - Technical University of Ostrava (hereinafter VSB - TUO) has the right to use thesis non-commercionally to its internal needs(§ 35 para. 3)

souhlasím s tím, že jeden výtisk bakalářské práce bude uložen v Ústřední knihovně VŠB-TUO k prezenčnímu nahlédnutí. Souhlasím s tím, že údaje o bakalářské práci budou zveřejněny v informačním systému VŠB-TUO. (I agree that a copy of the thesis will be deposited in the Central Library of VSB- TUO for on-site inspection. I agree that data on the thesis will be published in the information system of VŠB-TUO)

bylo sjednáno, že s VŠB-TUO, v případě zájmu z její strany, uzavřu licenční smlouvu s oprávněním užít dílo v rozsahu § 12 odst. 4 autorského zákona. (It was agreed that I will make a licensing agreement with permission to use the work within the scope of § 12 para. 4 of the Intellectual Property Law in case of the interest of VŠB-TUO.)

bylo sjednáno, že užít své dílo – bakalářskou práci nebo poskytnout licenci k jejímu využití mohu jen se souhlasem VŠB-TUO, která je oprávněna v takovém případě ode mne požadovat přiměřený příspěvek na úhradu nákladů, které byly VŠB-TUO na vytvoření díla vynaloženy (až do jejich skutečné výše). (It was agreed that the consent of the VŠB-TUO is required to use the work - Bachelor's thesis or to license its use to third party. In such a case VSB-TUO is entitled to demand an appropriate contribution to cover the costs that were VSB-TUO on the creation of the work expended (through to the full amount).

beru na vědomí, že odevzdáním své práce souhlasím se zveřejněním své práce podle zákona č. 111/1998 Sb., o vysokých školách a o změně a doplnění dalších zákonů (zákon o vysokých školách), ve znění pozdějších předpisů, bez ohledu na výsledek její obhajoby. (I understand that by submission of the work I agree to publish the work according to law No. 111/1998 Sb. about universities and on amendments and supplements to other acts (the Universities Act), as amended, regardless on the outcome of its defense.)

V Ostravě ………………………………

(In Ostrava)

Acknowledges

I am grateful to the University of Ostrava for giving me the oportunity of working in this Bachelor Final Thesis that deals with heat transfer and Ground Heat Exchangers (GHX).

I would like to do an especial mention to the tutor of this final thesis: Ing, Petr Konečný, Ph.D. for his patience and the time he expent in helping me to do this project. I would also like to do an especial mention to the Erasmus Coordinator Ing. Miroslav Rosmanit, Ph.D for helping me every time he could and letting me do this thesis.

TABLE OF CONTENTS

TABLE OF FIGURES

1. Introduction

Nowadays, heat transfer is a vital part of everybody's life. Heat transfer is all around us in such a way that its study plays a fundamental role in society.

For example, when cooking, heat is very important for the kitchen to work properly. Houses' heating is fundamental in regions with cold winters. Even in summer, when refrigeration systems work, there is an exchange of heat.

The problem is that as far as the need of heat transfer increases, the need of ideas of new devices to make it more efficient and less contaminant also increases.

In the same way, there is a need to find energy sources that are cheap and affordable for everyone. For these reason there are a lot of studies to reach the most efficient way of heat transfer for each conditions trying to be less contaminant as it is possible.

In order to study the behaviour of heat exchangers it is necessary to evaluate the working principle of the exchanger we are interested in to know if it is the best option for heating or not. This work consisting on evaluating the behaviour of the heat exchanger is absolutely fundamental to calculate the emissions and spends in it.

The search of a way to transfer heat trying to avoid environmental damage has increased the researches for a new heat transfer device. As a result, the GSHP (Ground Source Heat Pump) has been developed. Adding the cheap cost of this arrangement, the interest has increased. For this reason the investment in this kind of heat transferring has also became bigger.

In the same way, the operating principle study of the GHX (Ground Heat Exchanger) that works with the heat pump in this GSHP arrangements, involves many calculations. This project is related to these calculations.

The aim of this Bachelor Thesis is to focus on the selection of a suitable approximation for the GHX. This Ground Heat Exchanger is located in a building in Atlanta and has registered many measurements of heat rejected to the ground. All this data is referred to the date in which measurements were registered.

As far as there is a period in which there was not any data available, an approximation of the measured data will be carried out. In this project the study will consist on the calculation of this missing data based on the 'g-function' calculated many years before in Atlanta and the same calculation using the parameters file.

1.1. Heat Transfer Applications

Figure 1. Applications of Heat Transfer in industrial equipment. (Cengel, Y.A. and Menderes, A., 2015)

1.1.1. Heat Exchangers

A heat exchanger is a device designed to efficiently exchange heat from one matter to another.

Heat Exchangers can be classified as it is shown in Figure 2.

1.1.2. Types of heat exchangers

Heat exchangers can be classified attending to different characteristics:
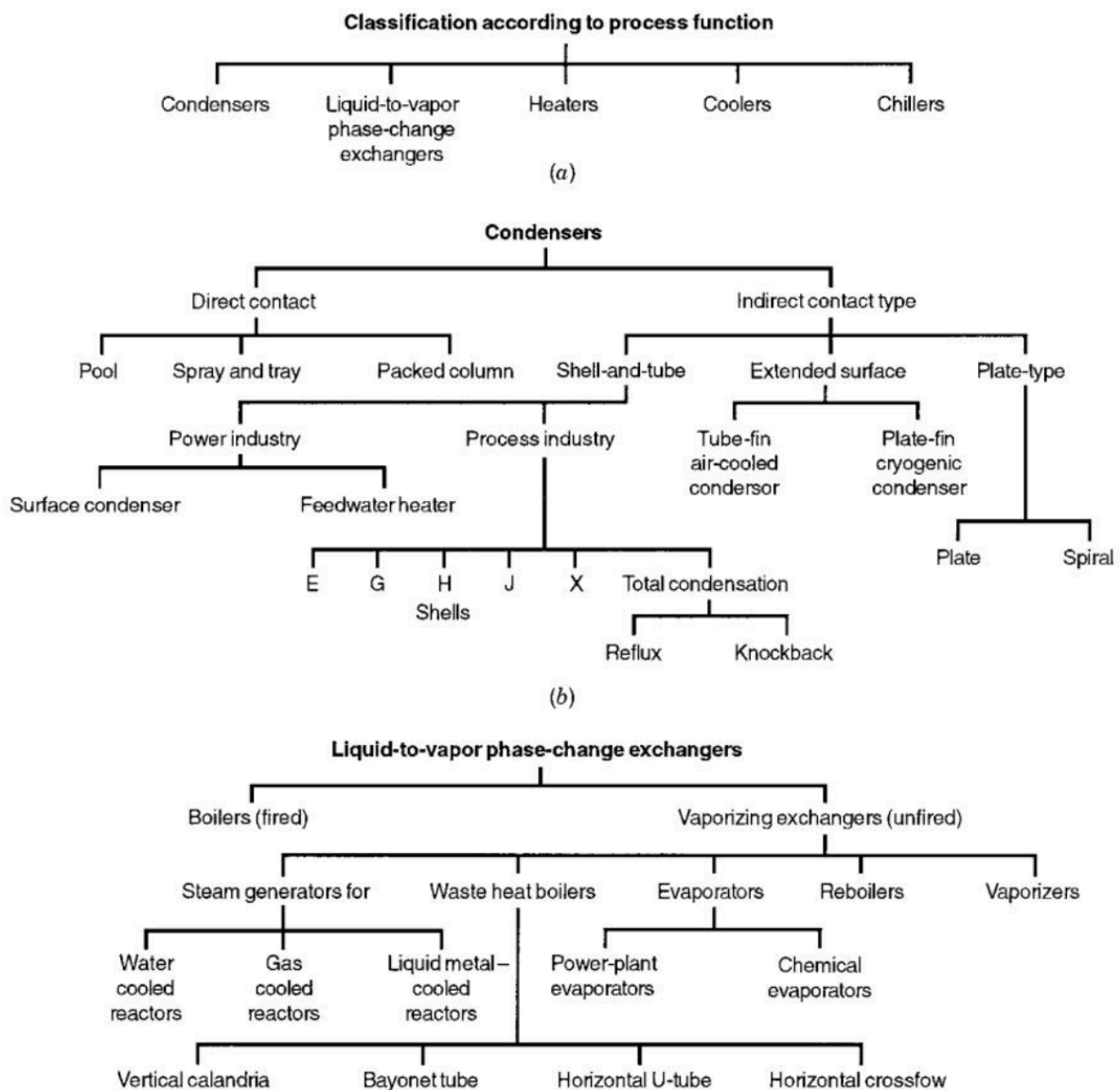
Figure 2. Classification of Heat Exchangers according to different variables. (Cengel, Y.A. and Menderes, A., 2015)

First of all, there is an initial classification that distinguishes between 'Direct-contact heat exchangers' and 'Indirect-contact heat exchangers'. After that, it is possible to make a differentiation inside indirect-contact ones. They can be 'Regenerative' if they accumulate heat or 'Recuperative' if material barriers separate the fluids.

Classification

➢ Direct-contact heat exchangers
➢ Indirect-contact heat exchangers
  • REGENERATIVE
  (There is a matrix of a material that accumulates heat)
  • RECUPERATIVE
  A barrier separates both fluids (typically tubes or plates)
    • Parallel arrangement
    • Cross flow arrangement
      – Counterflow
      – Cocurrentflow
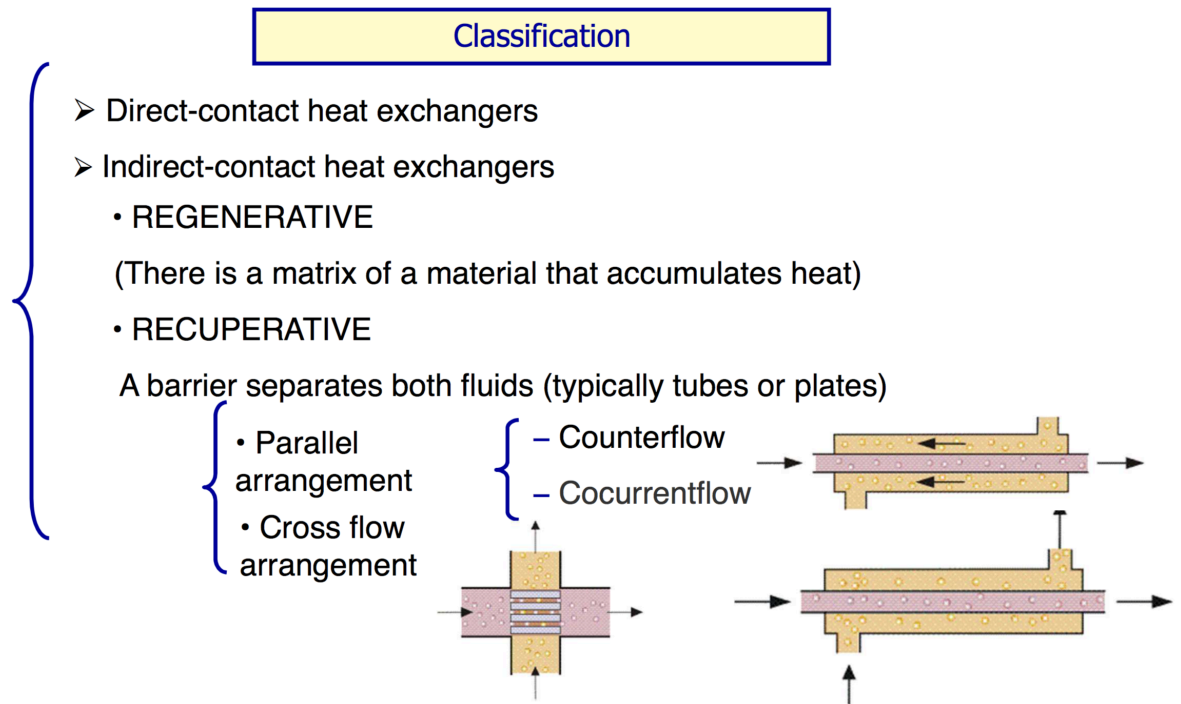
Figure 3. Classification of the Heat Exchangers depending on the arrangements. (Cengel, Y.A. and Menderes, A., 2015)

1.1.2.1. Direct-contact heat exchangers

Direct contact heat exchangers involve heat transfer between hot and cold streams of two phases in the absence of a separating wall. Example is shown in Figure 4.
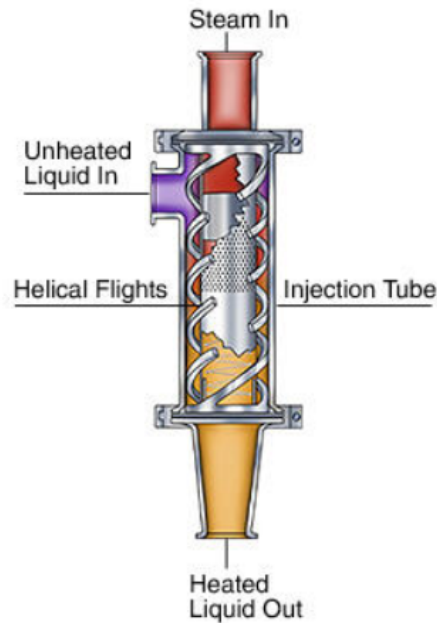
Figure 4. Example of a direct-contact heat exchanger. ('Energy Solutions Center', 2007)

1.1.2.2.   Indirect-contact heat exchangers

The difference with direct contact ones is that substances are separated by the walls. (Figure 5)
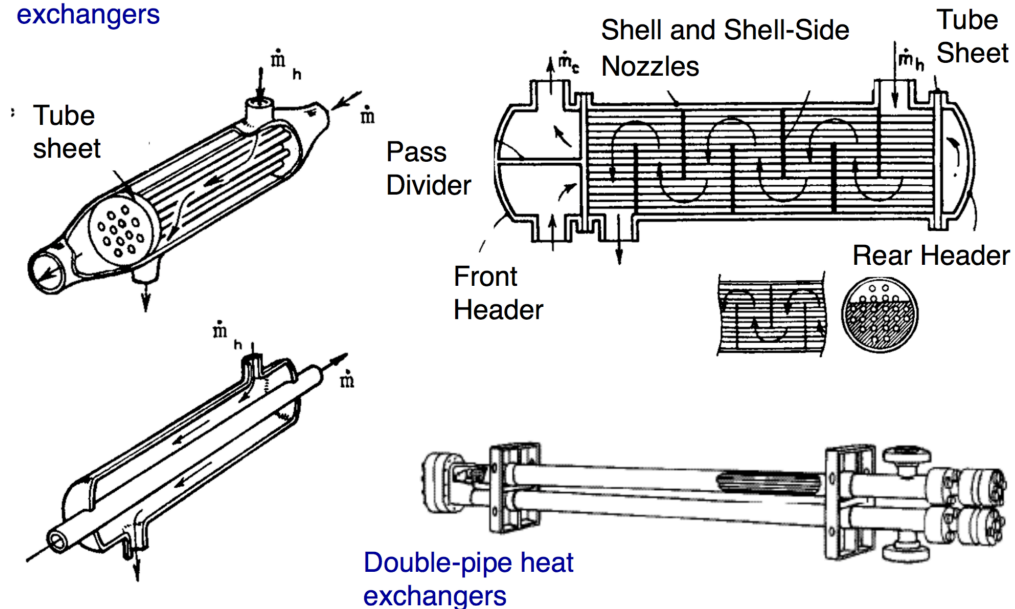
Figure 5. Examples of indirect-contact heat exchangers. (Cengel, Y.A. and Menderes, A., 2015)

1.2. GSHP (Ground Source Heat Pumps)

Ground Source Heat Pumps (GSHP) use grounds' temperature to heat and cool buildings.

Earth absorbs the 48% of the energy from the sun. Geothermal heating and cooling Systems take advantage of the heat stored in the ground in winter and the relative cool in the summer.
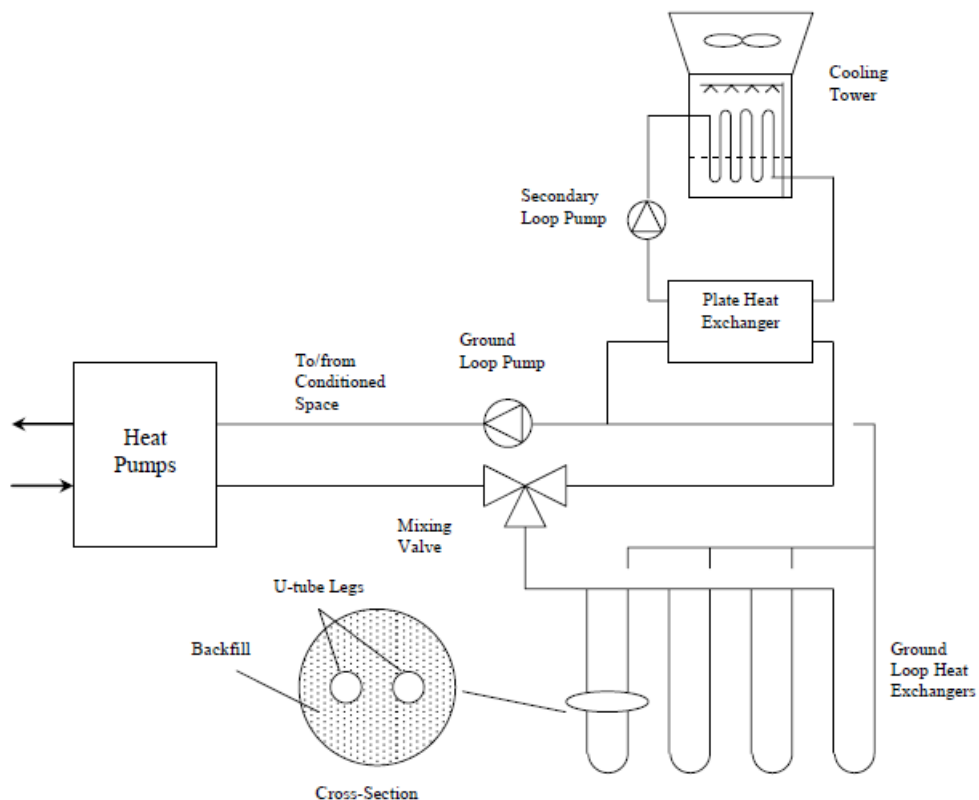
Figure 6. A schematic of a typical hybrid GSHP system using a closed-circuit cooling tower as a supplemental heat rejecter. (Xiaowei,X., 2007)

In winter, the fluid that circulates inside the GHX absorbs the ground's heat and carries it to the building.

In the summer, the system changes its working conditions and exchanges the building heat to the relative cool ground.
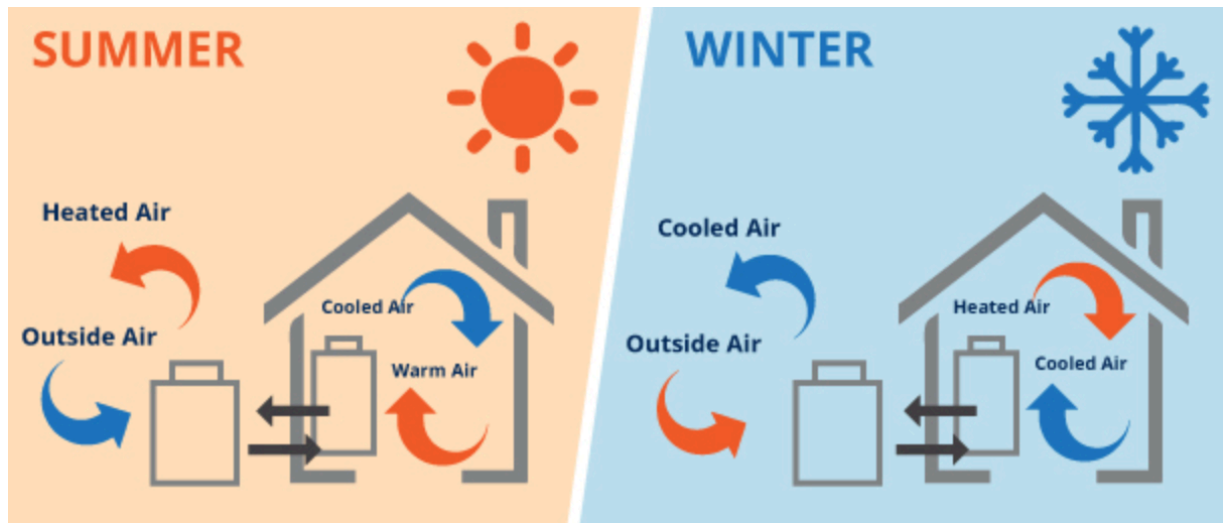
Figure 7. Operation of the GSHP depending on the season. (Green sepc, 2016)

1.2.1.Ground Loop Configurations

Ground loop configurations
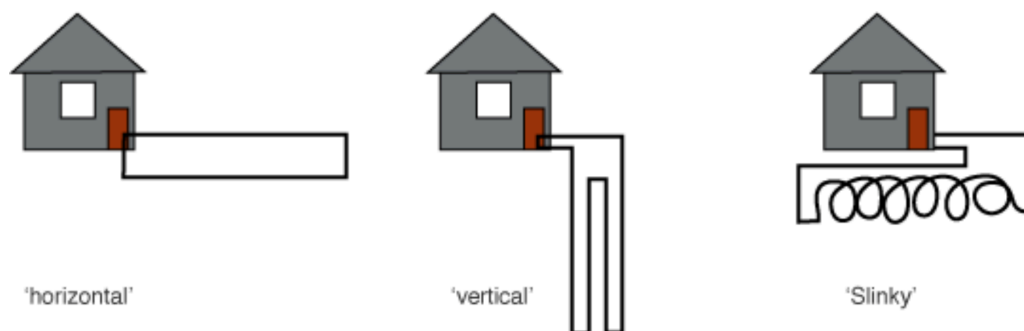
Figure 8. Ground Loop Configurations. (Green spec, 2016)

The most important ground loop configurations are closed loops but there are also open loops.

Closed Loops are divided into:

- **Horizontal Loops:**

  Piping is installed in horizontal trenches. The depth varies according to the design characteristics.

- **Vertical Loops:**

  It is the configuration commonly used. The advantage is that it needs less space. Vertical loops consist in a pipe inserted into vertical boreholes.

- **Slinky Coils:**

  Slinky coils are flattened coils of piping spread out and laid either horizontally or vertically. Their facility to focus the area of heat transfer into small volume reduces the length of the trenches and hence the quantity of land needed.

1.2.2. Thermal Modeling

Thermal Modeling is critical design in any installation of a Ground Source Heat Pump. The sizing of the ground loop is a key to the successful operation of the heat pump. Before sizing the ground loop correctly it is necessary to understand the qualities of the ground to be used as well as the expected heating loads and cooling loads of the building and these will be affected by the design of the building, its orientation to the sun, the activities in the building and the ventilation strategies. These are complex issues, which need to be analyzed in a thermal model to ensure that the system will meet the temperatures required in the building throughout the seasons of the year in a well-balanced and sustainable way.

All building simulation programs employ some means of representing the local climate conditions relative to building models because of this. (Crawley,D., Hand,J. ,and Lawrie,L.,1999)

1.2.3. Advantages and disadvantages of GSHP

1.2.3.1. Advantages of Ground Source Heat Pumps

1. Heat pumps are much cheaper to run than direct electric heating, oil boilers and can be cheaper than running gas boilers. Because heat pumps can be fully automated they demand much less work than biomass boilers.

2. Heat pumps save carbon emissions.

3. Heat pumps save space. There are no fuel storage requirements.

4. Heat pumps are safe. There is no combustion involved and no emission of potentially dangerous gases. No flues are required.

5. Heat pumps require less maintenance than combustion based heating systems.

6. A well-designed ground source heat pump system will increase the sale value of a property.

7. Heat pumps can provide cooling in summer, as well as heating in winter.

8. The planning authorities like ground source systems as they are safe, silent, invisible heating systems with low environmental impact.

1.2.3.2. Disadvantages of Ground Source Heat Pumps

1. GSHPs are more expensive to install than air source heat pumps because of the need to install a ground heat exchanger.

2. Problems arise with ground source heat pumps if the installation is poorly designed or not matched to the heating needs of the building. The design and installation of an effective ground source system depends on the ground.

3. Greater benefits can be achieved by moving to a full Interseasonal Heat Transfer system.

1.3.   Numerical modeling of GHX

This Bachelor Thesis mainly focuses on managing with Numerical Methods to find a Numerical Approximation Model for a GHX in a building in Atlanta.

For this project realization it is necessary to work with Excel (Microsoft Excel, 2010) and Matlab (Matlab R2015a, 2015) programming to achieve this goal.

Excel is one of the most useful programs when dealing with thousands of problems. For that reason, as Numerical Method consists on working with a lot of numbers, Excel will be a tool that will make this task easier because of its accuracy and its high speed for working.

One of the main advantages of Excel is that is generally easy to work with it. In this case, computing with Excel results a little bit heavier than it is used to be because of the 'Macros'. (Microsoft Excel Macros, 2010)

These tools called 'Macros' will be one of the keys in this Numerical Method Calculations. As it was previously explained, Numerical Methods consist in working with lots of data and doing approximations to determine the behavior of any variable.

The objective of a 'Macro' is to automatize an action that takes place many times. To create a 'Macro' it is necessary to program a code. In the code of the Excel Files needed to do this Project, the code was previously programmed. So, the 'Macros' were given to use them for making calculations for the GHX easier.

'GLHEPro' for Windows is used as an aid in the design of vertical borehole-type ground loop heat exchangers used in geothermal heat pump systems. (GLHEPro 4.1 for Windows, User's Guide ,2014).

GLHEPro for Windows performs three different tasks:

- First, it allows users to perform a simulation of their ground loop heat exchanger to determine monthly peak and average entering fluid temperatures to the heat pump from the borehole(s), the power consumed by the heat pump and the heat extraction rate per unit length of borehole.

- Second, GLHEPro for Windows can determine the required depth of the borehole(s) that will meet a user-specified minimum and maximum temperature entering the heat pump. This can be done with or without a supplementary heating/cooling unit.

- Third, GLHEPro can output parameter files for either the HVACSIM+ or EnergyPlus simulation programs. These parameter files contain the inputs necessary for simulating a ground heat exchanger on an hourly or sub-hourly time step.

1.4. ASHRAE Headquarter GHX System

This project has as reference the data measured in ASHRAE building in Atlanta. (Figure 10) (P. Konečný, L.E. Southard, Spitler, C., 2014)

It is divided into 2 floors. The first floor contains 25 VRF indoor units. The second floor contains 13 GSHP and is the object of this study. (Figure 9) (Cullin, J. R., J. D. Spitler, C. Montagud, F. Ruiz-Calvo, S.J. Rees, S. S. Naicker, P. Konečný, L.E. Southard, L. E., 2015) & (Claesson, J. And Javed, S., 2011)

Thousands of data had been measured and registered. The way of accessing these data for carrying out the computations is using the Excel File given as an input by the Thesis Supervisor, called *'Wheather_Data_Atlanta'* (Annex 1).

2nd Level Floor Plan
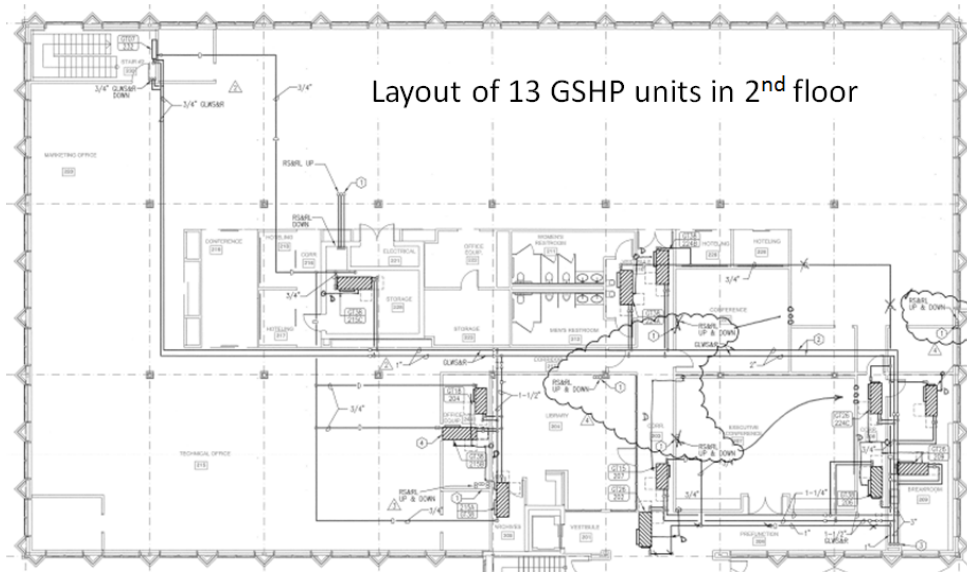
Figure 9. Second Level Floor Plan. (P. Konečný, L.E. Southard, Spitler, C., 2014)

Figure 10. ASHRAE HQ Building at Atlanta, GA. (P. Konečný, L.E. Southard, Spitler, C., 2014)

2. Objectives

The work will be aimed at the numerical modelling of the vertical Ground Heat Exchanger. Ground Heat Exchanger (GHX) serves to extract heat from, and rejects heat to the soil on a seasonal basis. It is frequently part of Ground Heat Pumps Systems.

The main objectives of this project are:

- Selection of a suitable approximation of missing GHX data based on the correlation of existing data with its corresponding temperatures.

- Evaluate quality of GHX model.

- Comparison of the data obtained with the Finite Element Analysis.

3. Problem to be solved

The thesis will focus on the selection of a suitable approximation for the GHX. This Ground Heat Exchanger is located in a building in Atlanta and has registered many measurements of heat rejected to the ground.

All this data is referred to the date in which measurements were registered. The problem is that there is a big number of data that is missing from measurements. In order to study the working behaviour of this GHX it is necessary to do an approximation of missing data based on correlation of existing data with its corresponding temperatures.

In this project the study will consist on the calculation of this missing data based on the 'g-function' calculated many years before in Atlanta. It will be also calculated using the parameters file. Thus, two numerical models will be calculated: 'XLS' and 'PAR'.

The calculus that are going to be compared with the Finite Element Analysis (FEA) (Cagigal Bedia, M.E., 2016) are the ones for 1 borehole in the x-axis and 1 borehole in the y-axis using 1kwh. On the other hand, it will be done a calculation of the 12 boreholes' temperature using the 'par-file' and the 'g-function'. After comparing both results, it will be done error estimation.

The flow rate is constant. It is necessary to obtain the Heat Rejected as a function of Temperature and the Heat Rejected as a function of Radiation. Taking into account if the data refers to weekdays or weekends.

The main part of this project consists on calculating the data that is missing by the data that is known and making a numerical model with the 'g-function' and parameters file to compare it with FEA model, and making conclusions.

4. Methodology of calculation

This project was done by following many steps by means of numerical model computation and Matlab Programming. For an easy understanding of the whole procedure, the partial results are presented in this part.

4.1. Project step by step

4.1.1. Third Degree Polynomial Calculation

The first step of this work consisted in managing with several data from the file *'Weather-data-Atlanta'*, from Annex 1. This File contains the main variables measured in Atlanta and also the time in which the values were registered. In this case the time is indicated by the day the measurements were carried out (day-month-year).

It is important to make a reference to the most relevant variables of this file because of its use during the calculus. Thus, the values that will be taken into account throughout the whole calculation process will be the following:

- Average Temperature in [°C], represented by *'temp_avg °C'* in this file.
- Heat Rejected by the GHE in [KWh], represented by *'qrej kWh'* in this file.
- Average Radiation in [KWh], represented by *'radia_gh_avg'* in this file.

Once the selection of the most important variables was done, a new Excel File was created. In this Excel File *'Plots_Days'*, from Annex 2, are represented the previous variables related with the dates in which the measurements were taken.

	A	B	C	D	E	F	G	H
1	year	month	day	temp_{avg}	radia_{gh,avg}	dayofweek	q_{rej,estim}	q{rej}
2	2010	3	5	4.95	232.0833333	6	-90.64	-19.32
3	2010	3	6	4.9375	232.875	7	-28.14	-6.12
4	2010	3	7	6.1375	237.875	1	-12.34	-20.71
5	2010	3	8	10.65416667	243.4166667	2	31.39	-23.53
6	2010	3	9	12.2625	204.4166667	3	69.17	123.56
7	2010	3	10	10.09583333	65.91666667	4	18.74	79.36
8	2010	3	11	15.14166667	105.75	5	143.11	60.26
9	2010	3	12	14.0875	68.79166667	6	114.97	70.05
10	2010	3	14	8.7375	98.375	1	9.28	-52.24
11	2010	3	15	9.570833333	127.2083333	2	7.04	-97.39

Table 1. Fragment with most important variables represented in 'Plots_Days'. (Annex 2)

All the data is represented in the sheet 1 called *'Alldata'*. The other sheets represent the data divided in *'Weekdays'* and *'Weekend'*. This division is taken into account because at the weekend the building is closed and there is no need to have the Heat Exchanger working in the same way that on a weekday. To complete the information, is important to take into account the 'National Days' in the USA because in those days the Working Conditions for the Ground Heat Exchanger are the same.

The main purpose is to obtain two third degree polynomial equations. The main objective is to calculate the values that are not measured in the model by the use of these third degree equations.

To achieve this objective the process consists on calculating the coefficients of these equations. This is possible by plotting the Temperature versus the Heat Rejected in a graphic and doing the same with respect to the Radiation.

First of all it is necessary to plot the Temperature versus the Heat Rejected by the GHX.

A dispersion diagram will be chosen because it is the easiest way to represent points that are very far from each other and do not follow a linear or quadratic relationship. After this, by selecting the data with the right mouse button, the polynomial of third degree must be chosen. The last step is to represent the tendency line and R^2 on the same plot.

This tendency line is the third degree polynomial we were looking for. Once we get the tendency line for the Temperature we will repeat the process to obtain the Radiation third degree polynomial. All data is represented in the sheet 1 of File *'Plots_Days'* (Annex 2) as it is shown in Figure 11 and Figure 12.
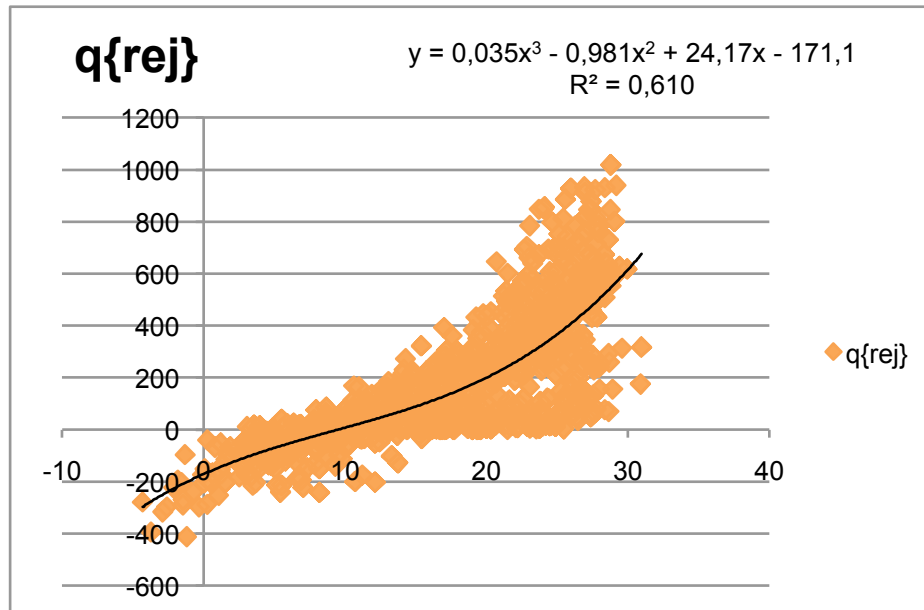
Figure 11.Heat Rejected (y-axis) vs. Temperature (x-axis) for all data points. (Annex 2)
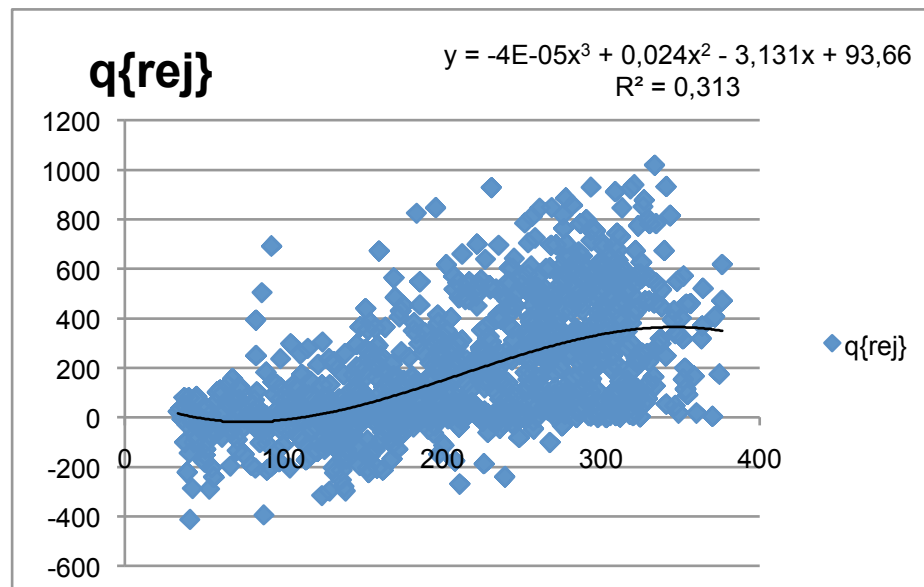
Figure 12. Heat Rejected (y-axis) vs. Radiation (x-axis) for all data points. (Annex 2)

The process must be repeated to represent the weekdays and the weekends because of the different behavior of the GHX depending on the day of the week. It is necessary to take into account the *'day_of_week'* (Annex 3) because it represents the position of the day whose data we are managing. In this case, as we are working with the American week model,'7' is Saturday and '1' represents Sunday.

Thus the graphics are obtained (Figure 13 and Figure 14) for the weekdays and the graphics (Figure 15 and Figure 16) for the weekend.

q{rej}

$$y = 0,022x^3 - 0,337x^2 + 21,38x - 194,2$$
$$R^2 = 0,835$$
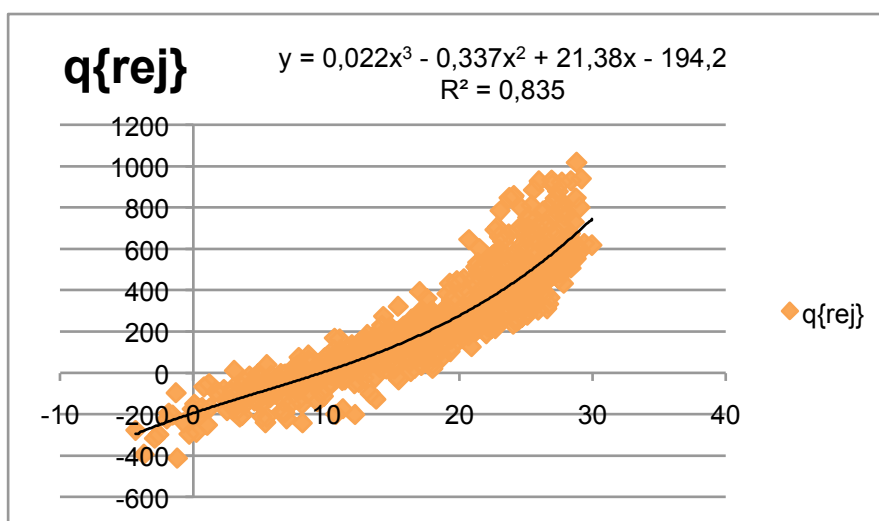
Figure 13. Heat Rejected (y-axis) vs. Temperature (x-axis) for weekdays. It is also represented the third degree equation calculated and R2. (Annex 2)

q{rej}

$$y = -5E{-}05x^3 + 0,033x^2 - 3,960x + 102,7$$
$$R^2 = 0,476$$
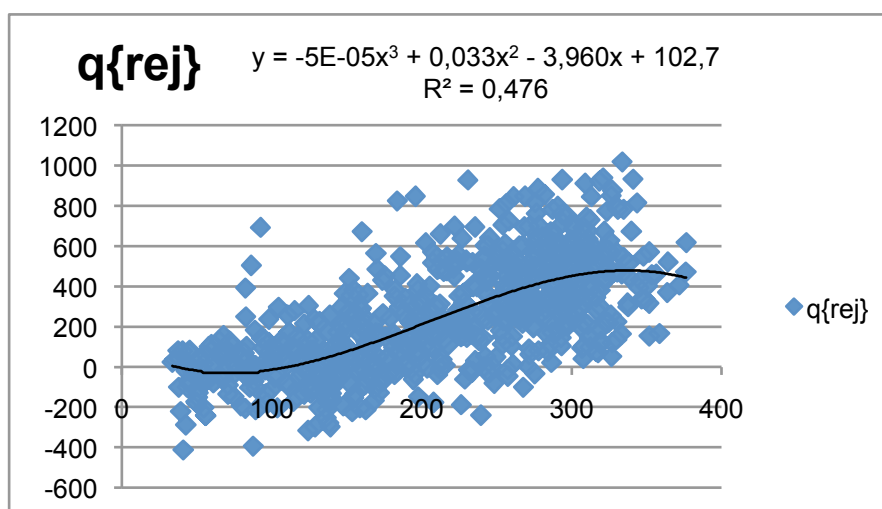
Figure 14. Heat Rejected (y-axis) vs. Radiation (x-axis) for weekdays. It is also represented the third degree equation calculated and R2. (Annex 2)
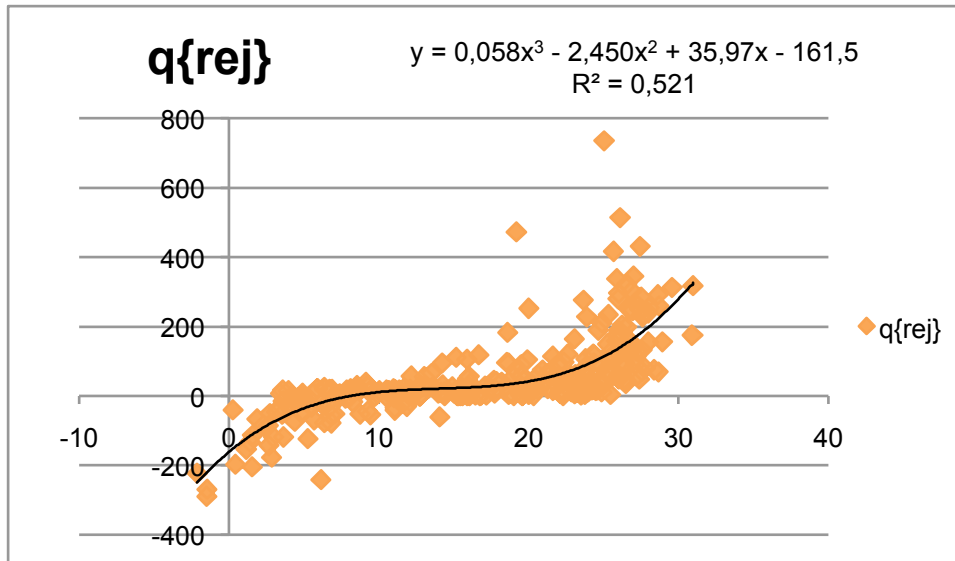
Figure 15. Heat Rejected (y-axis) vs. Temperature (x-axis) for weekends. It is also represented the third degree equation calculated and R2. (Annex 2)
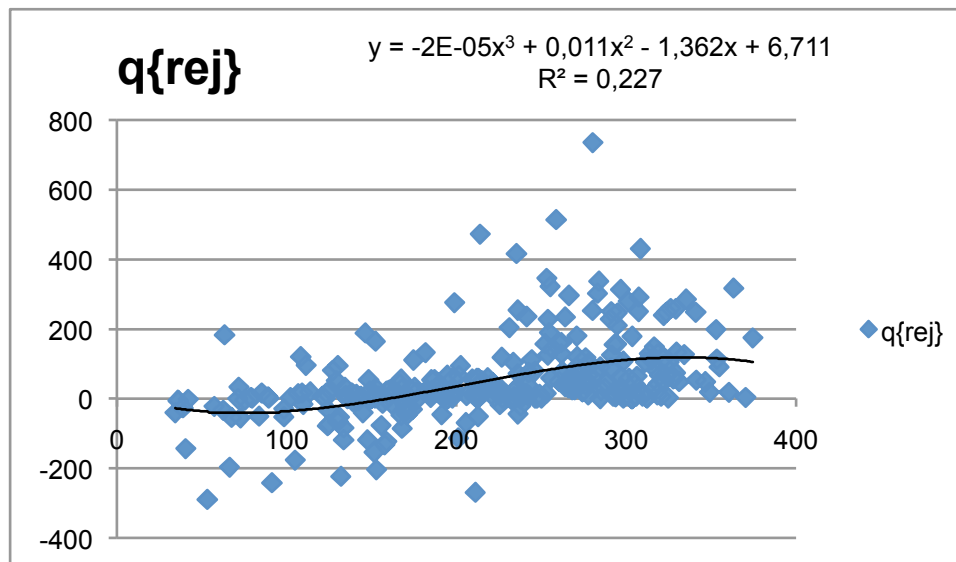
Figure 16. Heat Rejected (y-axis) vs. Radiation (x-axis) for weekends. It is also represented the third degree equation calculated and R2. (Annex 2)

The results of the calculations are the following equations:

- Weekdays
    - *Temperature equation*
        $$y = 0.0224x^3 - 0.3371x^2 + 21.38x - 194.26$$
    - *Radiation equation:*
        $$y = -5\text{E-}05x^3 + 0.0334x^2 - 3.9603x + 102.75$$

- Weekends
    - *Temperature equation*
        $$y = 0.058x^3 - 2.4506x^2 + 35.974x - 161.59$$
    - *Radiation equation*
        $$y = -2\text{E-}05x^3 + 0.0112x^2 - 1.3628x + 6.711$$

4.1.2. Heat Rejected depending on Temperature and Radiation

After the previous file calculations, another Excel File has to be done. In this case the objective of the File is to obtain the Heat Rejected with respect to Temperature and the Heat Rejected with respect to Radiation.

To do this the next steps must be followed.

1st. Represent all the data from the variables in File *'Plots_Days'(Annex 2):*

- Average Temperature in [°C], represented by 'temp_avg °C' in this file.
- Heat Rejected by the GHE in [KWh], represented by 'qrej kWh' in this file.
- Average Radiation in [KWh], represented by 'radia_gh_avg' in this file.

	A	B	C	D	E	F	G	H
1	year	month	day	day of week	national day	temp_avg °C	radia_gh_avg	qrej kWh
2	2008	1	1	3	1	4.7875	135.125	0
3	2008	1	2	4		-2.8875	135.833333	0
4	2008	1	3	5		-3.20416667	136.541667	0
5	2008	1	4	6		-1.25	142.541667	0
6	2008	1	5	7		4.22916667	139.583333	0
7	2008	1	6	1		9.77916667	135.875	0
8	2008	1	7	2		11.4791667	131.708333	0
9	2008	1	8	3		14.15	81	0
10	2008	1	9	4		16.2458333	42.6666667	0
11	2008	1	10	5		18.2041667	58.625	0

Table 2. Part of the table with the most important variables represented in 'Qrej_Temperature_Radiation'. There is a column included that represents if there is a National Day or not. (Annex 3)

2nd. In the first two orange columns, the values of the Heat Rejected estimation are represented. In the first one, the estimation is done by calculating all the data as if they were weekdays. In the second one, the estimation is for all the data considering weekend's behavior. To do these calculations it is necessary to introduce the value of the third degree equation calculated in the previous file. In this case, in the x-axis the temperatures are substituted. These values are represented in 'Qrej_est_T_week' and 'Qrej_est_weekend'.

3rd. In order to continue with the calculations, the next orange columns represent the effect of the Temperature in the Heat Rejected but taking into account if the data is obtained by the measurements in the GHX or not. If there is data for a determined date, it will be shown in the column, if there is not, the data will be the estimation calculated in the previous columns. By means of using the 'IF CONDITION' this data will be generated. This data will be introduced in two new columns, 'Qrej_T_week' and 'Qrej_T_weekend'. Each one represents the previous calculation but taking into account the difference between weekdays and weekends. Values are represented in Table 3.

I	J	K	L
Qrej_est_T_week	Qrej_est_T_weekend	Qrej_T_week	Qrej_T_weekend
-97.17167712	-39.16825552	-97.1716771	-39.16825552
-259.3446535	-287.2935344	-259.344654	-287.2935344
-266.9628567	-303.9242052	-266.962857	-303.9242052
-221.5554688	-210.4998438	-221.555469	-210.4998438
-108.1753507	-48.89377392	-108.175351	-48.89377392
3.52953262	10.09144628	3.52953262	10.09144628
40.62727432	16.17508559	40.6272743	16.17508559
104.2345189	21.09944725	104.234519	21.09944725
160.1509225	24.74536539	160.150922	24.74536539
218.3656383	31.07537877	218.365638	31.07537877

Table 3. Fragment of the table representing Heat Rejected with respect to Temperature for weekdays and weekends taking into account the model measurements and the estimations. (Annex 3)

4th. It is the same procedure that was done in the second step with the difference that represents Radiation instead of Temperature effect. The results will be shown in 2 blue columns called, 'Qrej_est_R_week' and 'Qrej_est_R_weekend'.

5th. This step consists in the same procedure that was followed in the third one. Calculations are done in the same way but with respect to Radiation instead of Temperature, in this case. The values are represented in table 4 as the 4th step.

M	N	O	P
Qrej_est_r_week	Qrej_est_r_weekend	Qrej_r_week	Qrej_r_weekend
300.8180196	-22.2828891	300.8180196	-22.2828891
306.3734109	-21.87867546	306.3734109	-21.87867546
311.9827638	-21.47140123	311.9827638	-21.47140123
361.6766529	-17.90475686	361.6766529	-17.90475686
336.6858992	-19.68874578	336.6858992	-19.68874578
306.701878	-21.85480246	306.701878	-21.85480246
274.775912	-24.18827714	274.775912	-24.18827714
27.67515	-40.82082	27.67515	-40.82082
-1.536340741	-32.59900148	-1.53634074	-32.59900148
-4.55605498	-38.71912926	-4.55605498	-38.71912926

Table 4. Fragment of the table representing Heat Rejected with respect to Temperature for weekdays and weekends taking into account the model measurements and the estimations. (Annex 3)

6th. To obtain the final results, it will be used and 'IF CONDITION' to obtain the data of Heat Rejected related to Temperature and Radiation taking into account if the value is measured in a weekday or weekend. The 'If Condition' used in this calculation as well as the other calculations carried about in this file are shown in Annex 3 which contains 'Qrej_Temperature_Radiation' File. (Annex 3)
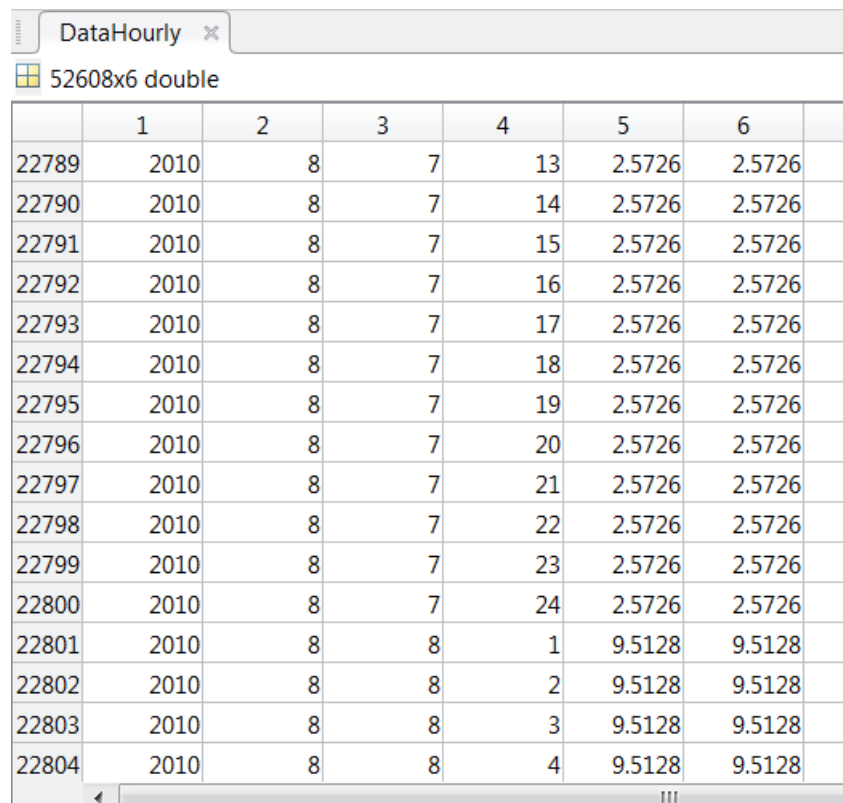
4.1.3. Heat Rejected values represented per hour.

After this process two values are obtained: 'Qrej_T' (Heat Rejected with respect to Temperature) and 'Qrej_R' (Heat Rejected with respect to Radiation).

This data is measured per day. These data are needed in hours to fulfill the next calculations and introduce it in the Excel Simulations Program.

In order to change the data in an easy way, Matlab programming is required.

There must be a program that, given an input with the days and the Heat Rejected each day, displays an output with the same values but in hours. So, the input will be the values obtained in the Annex 3.

This is a helpful procedure because if the values are plotted in the Matlab Table 5, it will be easy to copy them and paste after in an Excel File.

DataHourly					
52608x6 double					
	1	2	3	4	5	6
22789	2010	8	7	13	2.5726	2.5726
22790	2010	8	7	14	2.5726	2.5726
22791	2010	8	7	15	2.5726	2.5726
22792	2010	8	7	16	2.5726	2.5726
22793	2010	8	7	17	2.5726	2.5726
22794	2010	8	7	18	2.5726	2.5726
22795	2010	8	7	19	2.5726	2.5726
22796	2010	8	7	20	2.5726	2.5726
22797	2010	8	7	21	2.5726	2.5726
22798	2010	8	7	22	2.5726	2.5726
22799	2010	8	7	23	2.5726	2.5726
22800	2010	8	7	24	2.5726	2.5726
22801	2010	8	8	1	9.5128	9.5128
22802	2010	8	8	2	9.5128	9.5128
22803	2010	8	8	3	9.5128	9.5128
22804	2010	8	8	4	9.5128	9.5128

Table 5. Fragment of the Matlab programmed output table. (Annex 4)

4.1.4. Simulations in Excel.

Now, the values of Heat Rejected are obtained in hours and it is easier to work with them with the simulations. In this part of the procedure 3 main simulations will be required.

1st simulation: 'Simulation1' file. (Annex 6)

It will consist in the program that evaluates 1 Borehole (number of boreholes is introduced in Table 6). The input parameters are shown in the sheet 'Inputparameters' of the file 'Simulation1'. The selected simulation parameters for this first simulation (744 hours) are in Table 7. The Ground Heat Exchanger Parameters appear in Table 8.

Borehole Coordinate Parameters		
Boreholes in X	1	-
Boreholes in Y	1	-
X Spacing	7.62	m
Y Spacing	7.62	m

Table 6. Borehole Coordinate Parameters. (Annex 6)

	A	B	C	D
1	Simulation Parameters			
2	Simulation Starting Year	2008	Unitless	
3	Simulation Starting Month	1	in a range of 1-12	
4	Simulation Starting Day	1	in a range of 1-31	
5	Simulation Stopping Year	2008	Unitless	
6	Simulation Stopping Month	1	in a range of 1-12	
7	Simulation Stopping Day	31	in a range of 1-31	
8	Repeat First Year ?	○ YES	◉ NO	

Table 7. Simulation Parameters for 1 month. (Annex 6)
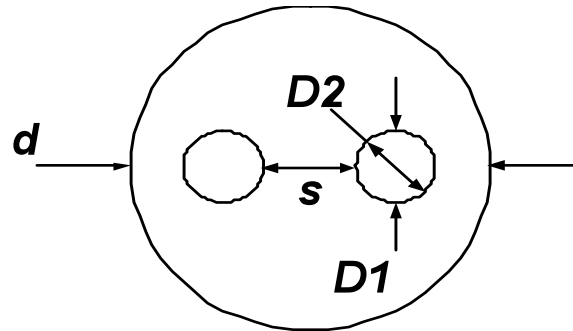
Figure 17. GHE with its corresponding parameters. (Annex 6)

Ground Heat Exchanger Parameters		
Lower limit for mass flow rate of ground heat exchanger	0.2	kg/s
Undisturbed Ground Temperature	20.24	°C
Grout Thermal Conductivity	1.70	W/m•K
Ground Thermal Conductivity	3.25	W/m•K
	0.3895	W/m•K
Grout Volumetric Capacity	3901	kJ/K•m^3
Ground Volumetric Capacity	2160	kJ/K•m^3
Fluid Type	0. Pure Water	---
Weight Concentration of Antifreeze Solution	0	%
Fluid Volumetric Capacity	4173	kJ/K•m^3
Pipe Inside Diameter (D1)	34.49	mm
Pipe Outside Diameter (D2)	42.16	mm
Convection Coefficient	1596	W/m^2•K
U-tube Shank Spacing (s)	19.6	mm
Borehole Diameter (d)	126	mm
Start of Active Borehole Depth	0	m
Active Borehole Depth	121.9	m

Table 8. Parameters file '1620-Test1'. (Annex 6)

There are two options to do the simulation. The first simulation is computed by the import parameter file generated by GLHEPRO. The other option consists on making the simulation by computing g-function from the code.

For the first simulation the file generated '1620-test1' is used to get the values. It is a test file with all the parameters needed. (Figure 18) (Annex 5)

Figure 18. Parameters file '1620' for the study of 1 borehole. (Annex 5)
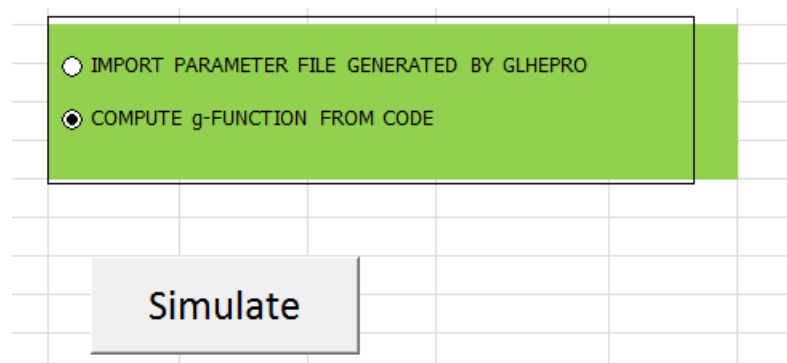

Figure 19. Options for Simulation. (Annex 6)

2nd simulation: 'Simulation2' file. (Annex 6)

It will consist in the program that measures all the data obtained with the Matlab programming tools using Heat Rejected as a function of the Temperature. The selected simulation parameters for this first simulation are in Table 10. The Ground Heat Exchanger Parameters appear in Table 8.

Borehole Coordinate Parameters		
Boreholes in X	2	-
Boreholes in Y	6	-
X Spacing	7.62	m
Y Spacing	7.62	m

Table 9. Borehole Coordinate Parameters (12 boreholes). (Annex 6)

	A	B	C
1	Simulation Parameters		
2	Simulation Starting Year	2008	Unitless
3	Simulation Starting Month	1	in a range of 1-12
4	Simulation Starting Day	1	in a range of 1-31
5	Simulation Stopping Year	2014	Unitless
6	Simulation Stopping Month	1	in a range of 1-12
7	Simulation Stopping Day	2	in a range of 1-31
8	Repeat First Year ?	○ YES	◉ NO
9			

Table 10. Simulation Parameters for 1 month. (Annex 6)

The Ground Heat Exchanger Parameters are the same in all the simulations (Table 8).

There are two options to do the simulation for the calculation of 12 boreholes. The first simulation is computed by the import parameter file generated by GLHEPRO. The other option consists on making the simulation by computing 'g-function' from the code.

For the simulation using the parameters the file generated '1620' is used to get the values. It is a test file with all the parameters needed. (Figure 20) (Annex 5)

Figure 20. Parameters file '1620' for the study of 12 boreholes. (Annex 5)

3rd simulation: 'Simulation3' file.(Annex 6)

It will consist in the program that measures all the data obtained with the 'Matlab' using Heat Rejected as a function of the Radiation. Ground Heat Exchanger Parameters appear in Table 8. And the parameters file with all the data is the same that the previous one, calculated for Temperature, '1620'. (Figure 16)

4.1.5. Results of the simulations.

The obtained results in the simulations are represented in the 2 new Excel Files 'Results1' and 'Results2'.

'Results1' (Annex 7) contains the results from 'simulation1'. In the first sheet the values of Heat Rejected represented with the 'g-function' are included in 'Qrej(1)XLS'. In the second sheet the values of Heat Rejected calculated with the parameter file are added to 'Qrej(1)PAR'.

'Results2' (Annex 7) contains the results from 'simulation2'and 'simulation3'. In the first sheet the values of Heat Rejected represented with the 'g-function 'related with Temperature are included in 'QrejT(12)XLS'. In the second sheet the values of Heat Rejected calculated with the parameter file are in 'QrejT(12)PAR'. In the third sheet the values of Heat Rejected with Radiation calculated with the 'g-function' are included in 'QrejR(12)XLS'. In the fourth sheet the values of Heat Rejected and the Radiation calculated with the par file are included in 'QrejR(12)PAR'.

Once the results are included in a new file it is necessary to calculate the average temperature. It is the sum of the inlet and outlet temperatures divided by 2. (Eq. 4-1)

$$T_{avg} = T_{in} + T_{out} 2 \qquad\qquad (4\text{-}1)$$

After this, it is possible to calculate the external borehole temperature. (Eq. 4-2)

$$T_{borehole} = T_{avg} - Q_{rejected} * R \qquad (4\text{-}2)$$

Where 'R' is the 'Calculated Borehole Resistance' that appears on the Simulation Files in Annex.6.

R = 0.095026744 K/(W/m)

In the case of the file 'Results1' it contains the results that are going to be compared with Finite Element Analysis so it must be divided by the depth of the borehole (121.9m) and divided by 1000 because it is in kW per hour (kWh) and it is necessary to have it in Watts per hour. In the file 'Results2' the results will be compared for 12 boreholes taking into account if it is use 'XLS' or 'PAR'.

Once all this steps are done it is possible to compare the data obtained with the one calculated with FEA. (Cagigal Bedia,M.E., 2016)

It will be compared the results for 12 boreholes. It will be also done error estimation.

4.1.6. Plot the results of the external borehole temperatures

Using Matlab it is possible to create a program to plot the results of the external borehole temperatures respect the hours.

To do this it is necessary to include the data in 3 different vectors and use plot function.

Vector 'X' represents hours, vector 'Y' represents the borehole temperatures (calculated with g-function) and the 'Z' vector represents the borehole temperatures (calculated with the file with the parameters).

A legend is included in order to make the interpretation of the data easier.

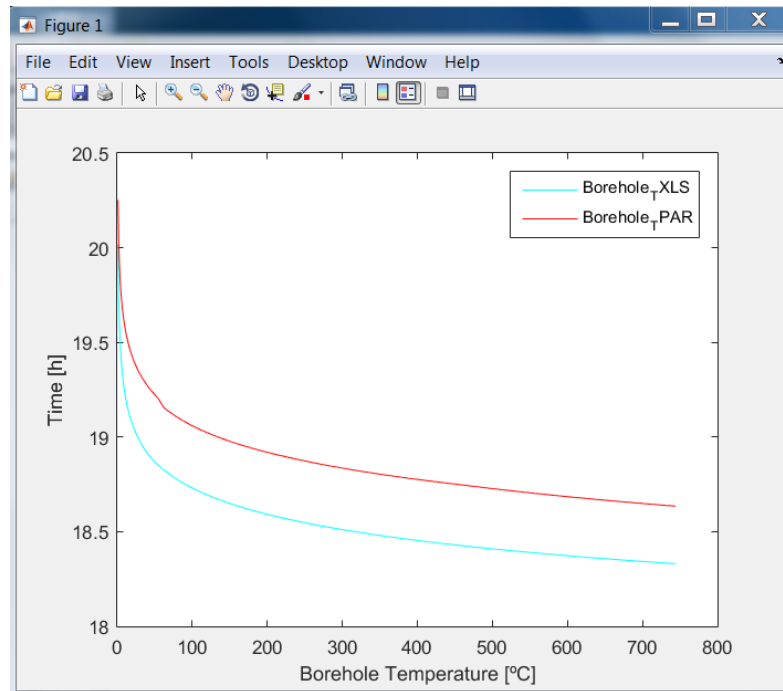**Figure 21. 'Matlab' plot of the fluid temperatures for 1 borehole using the 'g-function' (cyan) and the parameters file (red). Hours are represented in the 'x-axis' and Temperatures in the 'y-axis'. (Annex 9)**
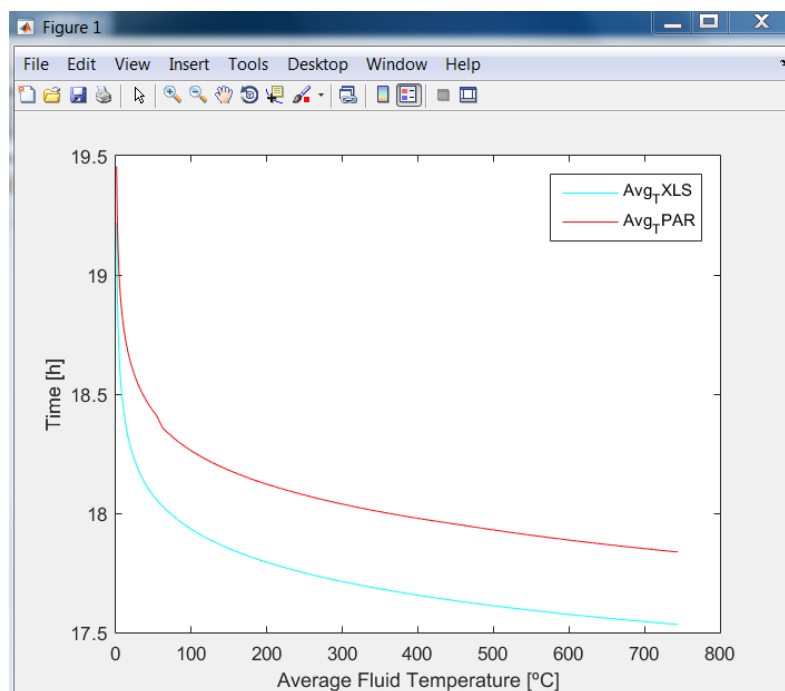
Figure 22. Average fluid temperature for 1 borehole calculated with the 'g-function'(cyan) and the parameters(red). Hours are represented in the 'x-axis' and Temperatures in the 'y-axis'. (Annex 9)

The 'Q_rejected' for 12 boreholes is represented in Figure 22 for Temperature and Figure 23 for Radiation. The Matlab programs to do these plots appear in Annex 9.

Figure 23. Temperature of the 12 boreholes in comparison with temperature using 'PAR' (blue) and 'XLS'(red) files. Hours are represented in the 'x-axis' and Temperatures in the 'y-axis'. (Annex 9)

Figure 24. Temperature of the 12 boreholes in comparison with radiation using 'PAR' (blue) and 'XLS'(red) files. Hours are represented in the 'x-axis' and Temperatures in the 'y-axis'. (Annex 9)

4.1.7. Error estimation
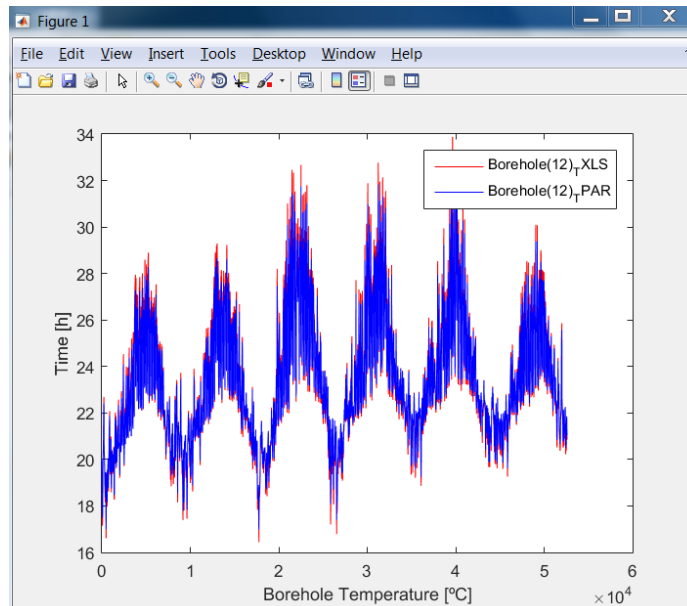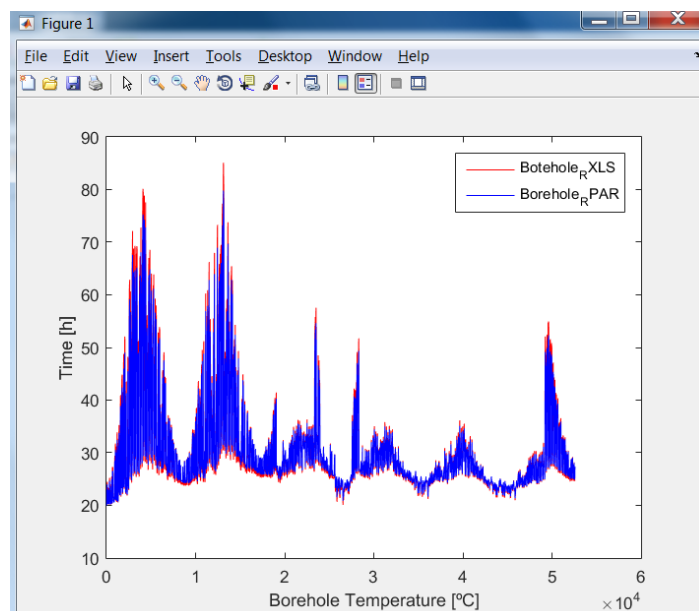
To estimate the error in the calculations, the Root Mean Squared Error will be computed. (Eq. 4-3)

$$\sqrt{\frac{1}{N}\sum_{}^{N}\left(T_{model}-T_{measured}\right)^2} \qquad (4\text{-}3)$$

Average-Mean signed error (MSE). (Eq. 4-4)

$$\frac{1}{N}\sum_{}^{N}\left(T_{model}-T_{measured}\right) \qquad (4\text{-}4)$$

N – Number of values with:

- Available measured data.
- Flow > 0.2 gpm

T_measured – measured heat rejected

This data appears in the file called 'Data-temp-q_rejected'.

T_model – modeled heat rejected

This appears in the file 'Data-temp-q_rejected'. (Annex 8)

Results of the error estimation are in file 'Borehole_Temperature_Errors'. Table 11 from Annex 10.

	QrejT_PAR_Model(Error)	QrejR_PAR_Model(Error)	QrejT_XLS_Model(Error)	QrejR_XLS_Model(Error)
Root Mean Squared Error	1.696391712	4.120873025	1.86300117	4.103693031

Table 11. Root Mean Squared Error as a function of Temperature and Radiation. (Annex 10).

The most accurate calculation will be done by computing the Heat Rejected with respect to temperature and using the parameters file, as it is shown in Table 11.

1.5.   Main difficulties and solutions

During this calculations many difficulties appeared because of the quantity of data that is managed throughout all the calculations. It is very important to be aware that if an error is comitted during one calculation this error will affect the following calculations making the next steps of the procedure practically useless. It supposes to repeat all the calculations and it is a taugh task.

Working with Macros was pretty difficult because it was a new topic to work with. As calculations are computed many times, learning was easy by calculus repetition.

Once of the main difficulties consisted in the determination of the borehole depth which is absolutely important to carried out the final results and make the comparison with the Finite Analysis Method. As far as data was registered in different files, the depth had different values because in some of them the variables taking into consideration were different to the others. The solutiuon of this problem was to fix a borehole depth of 121.9 m, value that was taken into account to do the FEA method. (Annex 11)

1.6.   Results and Comparison with Finite Element Analysis

The results obtained for the calculations for 12 boreholes related with temperature and radiation were showed on Table 11. The values obtained represent that the Mean Root Squared Error is higher in Radiation calculations than it is in Temperature calculations. As conclusion, it makes sense because of the previous calculations in which those related with temperature showed temperature values with higher accuracy. Root of Mean Squared errors are measured in kWh.

In the case of errors computed while plotting the ´g-function' and errors committed using the parameters, the most accurate ones are those for the 'g-function'. This also makes sense taking into account that its calculation is more accurate.

In order to achieve the best results for Temperature measurements it is necessary to do a comparison with the Finite Element Analysis. The comparison of a single borehole at 744 hours was computed. These measurements were calculated for two variables. The first variable computed is the external Temperature of the borehole.

This temperature has been calculated in three different ways:
- Numerical method based on the g-function calculation. Represented by 'Borehole_T_XLS' (Cyan line).

- Numerical method based on the input parameters of file '1620-test1'. Represented by 'Borehole_T_PAR' (Red line).

- Finite Element Method based on the modeling program done in ANSYS. Represented by 'Borehole_T_FEA'(Blue line)

This comparison it is represented in the plots computed in Matlab from the data calculated with the Excel Files and ANSYS Program. Here, the plots programmed with Matlab are attached. (Figure 25 and Figure 26).
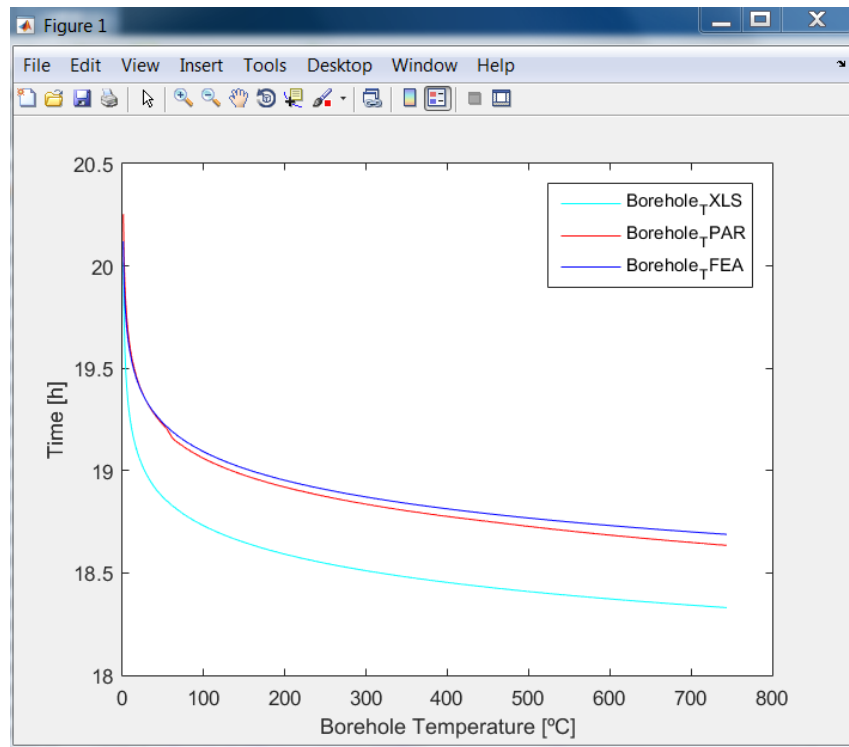

Figure 25. Comparison of the external borehole temperature of 1 borehole. Hours are represented on the 'x-axis' while temperatures are represented on the 'y-axis'.

The other file computed in 'Matlab' is the fluid average Temperature.This temperature has been calculated in three different ways:

- Numerical method based on the g-function calculation.

  Represented by 'Avg_T_XLS' (Cyan line).

- Numerical method based on the input parameters of file '1620-test1'.

  Represented by 'Avg_T_PAR' (Red line).

- Finite Element Method based on the modeling program done in

  ANSYS. Represented by 'Avg_T_FEA'(Blue line).
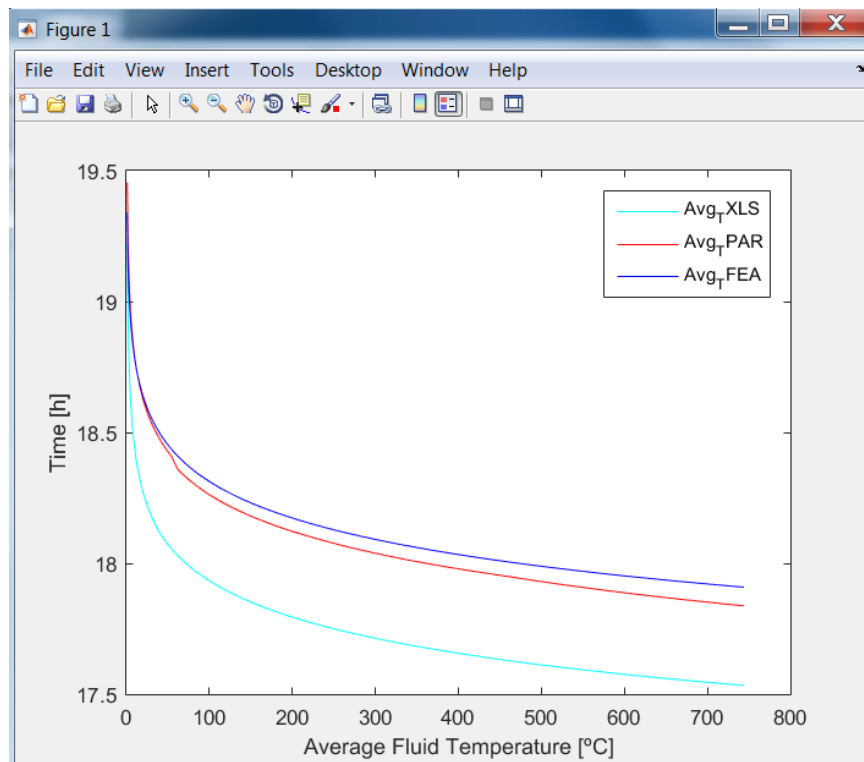
Figure 26. Comparison of the average fluid temperature for 1 borehole. Hours are represented on the 'x-axis' and temperatures are represented on the 'y-axis'.

As it is shown in the figures all the calculations follow the descendent shape with a little variation of temperatures. The greatest temperatures are measured by the Finite Element Analysis and the lowest ones are measured by the g-function calculation. The most accurate calculation is done by the parameter file Numerical Method.

1.7. Conclusions

First, it is mandatory to make a reference about the behavior of the 12 boreholes with respect to temperature and radiation. As it is shown in the graphs the values obtained using the 'par-file' (1620) and the 'g-function' demonstrate that both calculus have convergence.

Conclusion taken from the error analysis is that the error is bigger in radiation than in temperature when using the parameters file. On the other way round, when the function is used, the error is bigger when it is calculated with respect to temperature. The error values represent that computations had been done in a good manner.

As far as comparison with Finite Element Analysis was also fulfilled, it is necessary to analyze the work. To determine the temperature at the external surface of the borehole both methods can be used. The numerical methods required big effort because there is a lot of data to deal with and representing it in a correct manner can result a little bit difficult. Both plots are coherent and represent a difference caused by the 'q' value.

The main difficulty is that, as there are too many data, it is very important to be very careful and avoid committing errors. The biggest problem faced with the numerical method was the amount of data to manage. As there are too many values it is necessary to taste if every step is coherent in order to avoid errors on further calculations.

As it is shown in the figure, the plots have the same shape but there is a little variation of temperatures. The different is more or less constant so it represents that measurements are correct but values are a little bit different.

The main conclusion is that with both methods it is possible to calculate the external borehole temperature and the average temperature of the fluid but Numerical Method is more precise because of the amount of data that is needed.

5. References

CENGEN, Y.A. and MENDERES, A. (2015) Heat and Mass Transfer: Fundamentals and Applications, McGraw-Hill

Energy Solutions Center Inc., (2007). Online:
http://www.pickheaters.com/energy_efficiency.cfm 3/2007;

XIAOWEI, X. (2007). Simulation and Optimal Control of Hybrid Ground Source Heat Pump Systems, Ph.D.Thesis,May 2005.

Green spec. (2016). Online: http://www.greenspec.co.uk/building-design/ground-source-heat-pumps/;

CRAWLEY,J., HAND,J. and Lawrie, L.(1999). Improving the Wheather Information Available to Simulation Programs.

Microsoft Excel. (2010). Microsoft Office Proffesional Plus 2010.
Version:14.0.47.60.1000 (32bits)

Matlab R2015a (2015). Mathworks Inc. (8.5.0.1197613) 64-bit (win64)

Microsoft Excel Macro. (2010). 'GSHPSystem__Type620_var_flow'. Oklahoma State University.

GLHEPro 4.1 for Windows, User's Guide (2014). School of Mechanical and Aerospace Engineering Oklahoma State University, International Ground Source Heat Pump Association.

P. Konečný, L.E. Southard, Spitler, C.,(2014) - Performance Analysis of HVAC Systems in the ASHRAE Headquarters Building. *Partial progress internal materials*, Oklahoma State University, 2014

CAGIGAL BEDIA, M.E. (2016). "Finite Element Analysis of Ground Heat Exchanger", Bachelor Thesis, Ostrava.

Cullin, J. R., J. D. Spitler, C. Montagud, F. Ruiz-Calvo, S.J. Rees, S. S. Naicker, P. Konečný, L.E. Southard, L. E., (2015). Validation of vertical ground heat exchanger design methodologies. Science and Technology for the Built Environment. 2015, vol. 21, issue 2, February s. 137-149.

LIU, X. (2005). Development and Experimental Validation of Simulation of Hydronic Snow Melting Systems For Bridges. Ph.D. Thesis, May 2005.

Claesson, J. And Javed, S. (2011). An analytical method to calculate the borehole fluid temperatures for time-scales from minutes to decades. ASHRAE Transactions, 117(2):279-288,2011.

6. Annexes

6.1. Screen shoots

6.2. Files recorded on the CD

- Annex.1 *'Wheather_data_atlanta'*
- Annex.2 *'Plots_Days'*
- Annex.3 *'Qrej_Temperature_Radiation'*
- Annex.4 *'Script_Hours'*
- Annex.5 *'Parameters_files'*
- Annex.6 *'Simulation1','Simulation2','Simulation3'*
- Annes.7 *'Results1' & 'Results2'*
- Annex.8 *'Data-temp-qrejected'*
- Annex.9 *'Plots_BoreholeT' 'Plots_AvgFluidT'*
- Annex.10 *'Borehole_Temperatures_Errors'*
- Annex.11 *'Finallinearinterpolation'* (Cagigal Bedia,M.A., 2016)
- Annex.12 *'Mechanical Copy'* (P. Konečný, L.E. Southard, Spitler, C., 2014)