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Konečně prvková analýza zemního výměníku
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Finite element analysis
of ground heat
exchanger

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Bachelor Thesis Assignment

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Description:

The work will be aimed at the preparation of Finite Element model of the vertical ground heat exchanger [1] that is part of ground source heat pump system. The numerical model will be prepared under the Ansys environment.

The work will consist of:

- (a) The preparation of Finite Element model of the ground heat exchanger with one borehole and comparison with analytical model as well as numerical model [1, 2].
- (b) Preparation of Finite Element model of the ground heat exchanger of the office building in Atlanta, GA (USA).

References:

- [1] SPITLER, JD (2005). "Ground-source heat pump system research - Past, present, and future", HVAC&R Research, Vol: 11/2 Pp: 165-167, DOI: 10.1080/10789669.2005.10391132, APR 2005.
- [2] XIAOWEI, X. (2007) Simulation and Optimal Control of Hybrid Ground Source Heat Pump Systems. Ph.D. Thesis, May 2005.
- [3] LIU, X. (2005). Development and Experimental Validation of Simulation of Hydronic Snow Melting Systems for Bridges. Ph.D. Thesis, May 2005.
- [4] LOGAN, D., L., First Course in the Finite Element method-3.rd ed., Brooks/Cole, Pacific Grove, USA, ISBN:0-534-38517-6.



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His knowledge about ANSYS program help me a lot into the modelling realization of our problem. It was really difficult to learn how to run a new program just from the beginning basic tools.

I have also to put into word my thankfulness to Ing. Miroslav Rosmanit to let Cristina Fernández Fernández and I carry out our Final Thesis as the first time in this Civil Engineering Faculty. It is a pleasure for me to start this new project and I hope it will be successful for all the parts involved. I guess next year, maybe with another timetable and organization schedule, other students could defense their thesis here based on our good and wrong situations.

In addition, to obtain an Erasmus scholarship was the best “prize” I get in my career to my continuous effort and persistence. Thanks to belong to VSB-Technická Univerzita of Ostrava, and in particular, to de Civil Engineering Faculty, I could assist to really interesting lectures, practices and conferences. Those activities make me grow as an engineer and I improve myself in several aspect as work in equip (really important for enterprises nowadays).

This Bachelor Thesis had marked my last time in Ostrava. It was exciting, difficult and sometimes exasperating, but always gratifying when results appear.



INDEX

1. INTRODUCTION	9
2. HEAT PUMPS	9
2.1. Operating Principles	9
2.1.1. Heat transport	10
2.1.2. Heat sources/sinks	10
2.2. Applications	10
2.2.1. HVAC	10
2.3. GROUND SOURCE HEAT PUMPS	11
2.3.1. Ground Source Heat Exchanger	11
2.3.1.1. Closed Loop	12
2.3.1.2. Open Loop	12
2.4. ASHRAE HQ GSHP	13
3. PROBLEM TO SOLVE AND OBJECTIVES	13
4. FINITE ELEMENT METHOD	14
4.1. Theory	14
4.2. Overview of the method	15
4.2.1. Steady state modeling for boreholes	16
4.2.1.1. Line Source Model	19
5. METHODOLOGY: ANSYS MECHANICAL APDL SOLVER	22
5.1. Step by step	22
5.1.1. Geometry	23
5.1.2. Element type	24
5.1.3. Material Properties	24
5.1.4. Key Points (KP), Lines and Arc	25
5.1.5. Areas and meshing definition	26
5.1.6. Loads	28
5.1.7. Transient Modeling	29
5.2. Complications	31
5.3. Results and Comparison	32
5.4. Conclusions	35
6. REFERENCES	36



7. LIST OF FIGURES.....	38
8. ANNEX.....	40
8.1. Screenshots	40
8.2. CD Annex.....	44
8.3. Plans	44



1. INTRODUCTION

From the beginning of life on the Earth, humans have tried to feel comfortable in their habitats. Whether in a cave or at their homes as nowadays. There have been different ways to stay warm and comfortable, from fire as the simplest way to provide heat, to ground heat pumps.

A geothermal heat pump or ground source heat pump (GSHP) is a central heating and/or cooling system that transfers heat to or from the ground. It uses the earth as a heat source (in the winter) or a heat sink (in the summer). (*Spitler, 2005*)

2. HEAT PUMPS

Heat pumps are devices that provides heat energy from a source of heat to a destination called heat sink. Heat pumps are designed to move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses some amount of external power to accomplish the work of transferring energy from the heat source to the heat sink. (*Young, 2001*).

Heat pumps are applicable to many HVAC (heating, ventilating, and air conditioning) devices used for space heating or space cooling. Heat pumps utilised for heating employed the same basic refrigeration-type cycle used by an air conditioner or a refrigerator, but in the opposite direction. It means, releasing heat into the conditioned space rather than the surrounding environment. In this use, heat pumps generally draw heat from the cooler external air or from the ground. (*ASHRAE, 2004*)

2.1. Operating Principles

Renedo (2014) talks about Operating Principles. He explains how mechanical heat pumps use physical properties of a volatile evaporating and condensing fluid called refrigerant. The refrigerant is compressed by the heat pump to make it hotter on the side to be warmed and releases the pressure at the side where heat is absorbed. This fluid is pressurized and circulated through the system by a compressor. The hotter and high pressurized vapor is cooled in a heat exchanger named condenser, just to the moment it will condenses into a high pressure and moderate temperature liquid.

Then, the refrigerant (now condensed) passes through a metering device, at low pressure, such as a valve or a turbine. Finally, the low pressure liquid refrigerant enters inside one more heat exchanger, the evaporator, in which the fluid absorbs heat and boils up. To repeat this cycle, the refrigerant returns to the compressor.

2.1.1. Heat transport

Heat is typically transported through engineered heating or cooling systems by using a flowing gas or liquid. It is common to use air or refrigerants, but they become impractical because of many circumstances. So, when large amounts of heat are to be transported, water is the best choice, often supplemented with antifreeze, corrosion inhibitors, and other additives.

2.1.2. Heat sources/sinks

Geothermal heat pumps or ground-source heat pumps use shallow underground heat exchangers as a heat source or sink and water as the heat transport medium. This is possible because below ground level, the temperature is relatively constant across the seasons and the earth can provide or absorb a large amount of heat.

Ground source heat pumps exchange heat with the ground via water pumped through pipes in the ground. Ground source heat pumps are more simple and therefore more reliable than air source heat pumps as they do not need fan or defrosting systems and can be housed inside.

2.2. Applications

It is possible to say that there are many domestic installations using common air source electric heat pumps. All of them are used in moderate space heating and cooling needs (HVAC) and may also provide hot water for domestic use. (*Renedo, 2014*)

2.2.1. HVAC

The three central functions of HVAC (heating, ventilation, and air-conditioning) are interrelated, especially with the need to provide thermal comfort and acceptable indoor air quality within reasonable installation, operation and maintenance costs. (*HVAC&R, 2004*)

HVAC systems can provide ventilation, reduce air infiltration, and maintain pressure relationships between spaces. The means of air delivery and removal from spaces is known as room air distribution.

2.3. GROUND SOURCE HEAT PUMPS

2.3.1. Ground Source Heat Exchanger

As *Rafferty (1997)* exposed, heat pumps provide winter heating by extracting heat from a source and transferring it into a building. Heat can be extracted from any source, but a warmer source allows higher efficiency. A ground source heat pump uses the top layer of the earth's crust as a source of heat, thus taking advantage of its seasonally moderated temperature.

In the summer, the process can be reversed so the heat pump extracts heat from the building and transfers it to the ground. Transferring heat to a cooler space takes less energy, so the cooling efficiency of the heat pump gains benefits from the lower ground temperature.

Ground source heat pumps employ a heat exchanger in contact with the ground. They extract heat from the ground using pipes buried in the garden. This piping system could be buried either horizontally in a shallow trench or vertically in a borehole (as in our case). The choice depends on the land area available, local ground conditions and excavation costs.

GSHP systems consist of three elements:

- **A ground heat exchanger** which collects heat from the ground.
- **A water-to-water or water-to-air heat pump** which raises the heat collected to a useful temperature and transfers it to the building.
- **A heat distribution system** which provides the heat to the building. It is possible to heat underfloor or warm air heating systems, radiators or hot water.

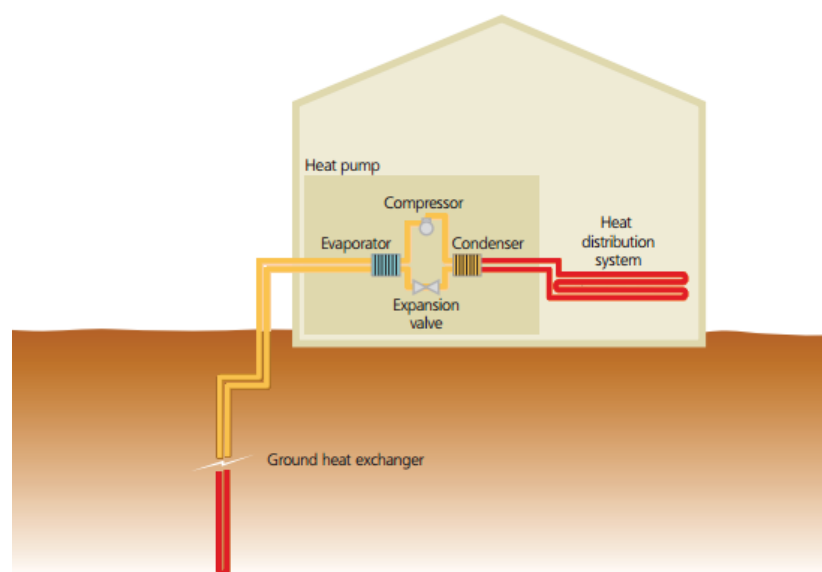


Figure 1. Typical GSHP system – [1]

2.3.1.1. Closed Loop

Following with *Rafferty (1997)* explanation, most installed systems have two loops on the ground side: the primary refrigerant loop is contained in the appliance cabinet where it exchanges heat with a secondary water loop that is buried underground. The secondary loop is typically made of high-density polyethylene pipe and contains a mixture of water and anti-freeze. There are two types of closed loops: vertical closed loop or horizontal closed loop.

A vertical closed loop field is composed of pipes that run vertically in the ground formed a hole of 15–122 meters deep. Pipe pairs in the hole are joined with a U-shaped cross connector at the bottom of the hole. The borehole is commonly filled with grout surrounding the pipe to provide a thermal connection to the surrounding soil to improve the heat transfer. Thermally enhanced grouts are available to improve this heat transfer. Vertical loop fields are typically used when there is a limited area of land available. Boreholes are spaced at least 5–6 m apart and the depth depends on ground and building characteristics.

A horizontal closed loop field is composed of pipes that run horizontally in the ground. A long horizontal trench, deeper than the frost line, is dug and coils are placed horizontally inside this trench. Excavation for shallow horizontal loop fields is about half the cost of vertical drilling, so this is the most common layout used wherever there is adequate land available.

Their placement depth significantly influences the energy consumption of the heat pump in two opposite ways. On one hand, shallow loops tend to indirectly absorb more heat from the sun, which is helpful, especially when the ground is still cold after a long winter. On the other hand, shallow loops are also cooled down much more readily by weather changes, especially during long cold winters, when heating demand peaks.

2.3.1.2. Open Loop

In open loop systems (also named groundwater heat pump systems), the secondary loop pumps natural water from a well or body of water into a heat exchanger inside the heat pump. ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) calls open loop systems “groundwater heat pumps” or “surface water heat pumps”. Heat is extracted or added by the primary refrigerant loop and the water is returned to a separate injection well, irrigation trench, tile field or body of water. The supply and return lines must be placed far enough apart to ensure thermal recharge of the source. (*Rafferty, 1997*)

2.4. ASHRAE HQ GSHP

We are studying a GSHP system belonging to an ASHRAE HQ building. It is a two-floor office building located in Atlanta, USA. Inside of it, we could find GSHP in second floor and the entire heat pumps systems which comprises 14 individual heat pumps. All of them are differenced by three types of different models of heat pumps. I attached in annex part three plans to show how is the GSHP located in the building, the units of GSHP and the GSHP schemes.

This is not the first time that this building formed part of a modeling study. There are two references about this previous thesis. To be honest, I follow them to obtain all data of my Bachelor Thesis and the procedures I had done. Also to make the Finite Element study and the Analytical. (P. Konečný, L.E. Southard, Spitler, C., 2014) and (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)

3. PROBLEM TO SOLVE AND OBJECTIVES

This Final Thesis is based on the preparation of a Finite Element model of the vertical ground heat exchanger, which is part of a ground source heat pump system (GSHP).

For the purpose of this thesis, we will refer our study model to the FEA model with hourly time-step.

The objective we have is to accomplish a thesis based on three different ways to calculate the temperature at the borehole of the heat exchanger. This Final Thesis involves the application of a program based on Finite Element Analysis (ANSYS) to carry on the calculus in an easy way applying this method; the utilization of several equations of Line Source Model to obtain the same temperature; and, enclosed into (Fernández Fernández, C., 2016) the use of Excel to work with all data.

I have to mention that I simplify the model calculating only one borehole to prepare Finite Element study. I also simplify the numerical computation analysis of GSHP using 1 kW/m of heat extraction during the period of time of one month, instead of use 1.023 kW/h as in Fernández Fernández, C. bachelor thesis.

4. FINITE ELEMENT METHOD

4.1. Theory

Finite element method (FEM) is a numerical method used to solve problems of engineering and mathematical physics. The typical problems that are possible to solve with this method include heat transfer, fluid flow, structural analysis, mass transport and electromagnetic potential. (*Logan, 2015*)

It is applicable in problems which have complicated geometries, loadings and material properties due to it is impossible to obtain analytical mathematical solutions (using a mathematical expression).

Analytical equations are associated to different values referred to unknown quantities at any location in a body. Analytical solutions normally require the solution of partial differential equations, which are not obtainable because of the complicated geometries, loading and material properties.

Therefore, we need to utilize numerical methods as the finite element method for acceptable solutions. The finite element formulation of the problem results in a system of simultaneous algebraic equations for solution, rather than requiring the solution of differential equations.

These numerical methods yield approximate the values of the unknowns at discrete numbers of points in the continuum. Hence this process of modeling a body dividing it into an equivalent system of smaller bodies, also named units (finite elements), interconnected at common points to two or more elements (nodes or nodal points), boundary lines, surfaces is called “discretization”.

So, in the finite element method, instead of solving the problem for the entire body in just one operation, we formulate the equations for each finite element and combine them to obtain the solution of the whole body.

Briefly, in nonstructural problems, nodal unknowns may be temperatures or fluid pressures due to thermal or fluid fluxes.

But, this method had a problem few years ago. Matrix methods associated to finite element method were not readily adaptable for solving complicated problems. Even though the finite element method was being used to describe complicated structures, the resulting large number of algebraic equations associated with the finite element method of structural analysis made the method really difficult and impractical. That was solve with the development of the computer and computational program development.

To use the computer, it is necessary to have the finite element model defined and just input the information into the computer (position of the element nodal coordinates, elements' connection, element' material properties, applies loads, boundary conditions, constraints and the kind of analysis to be performed. Then the computer utilizes all this data to generate and solve the equations. (*Logan, 2015*)

There are two general computer methods of approach to the solution of the problems by the finite element method. One is to use large commercial programs, which are configured to run on personal computers. And the other is to develop many small, special-purpose programs to solve specific problems.

In this final thesis, I modeled a finite element of a ground heat exchanger using ANSYS program.

4.2. Overview of the method

It is possible to make a difference between three different methods we could use to develop the model borehole heat exchangers. We divided this method into two categories named: steady state and transient. (*Young, 2001*)

Conditions of quasi-steady state happens in borehole cross sections with two dimensions. In this moment, the fluid is circulating, grout and U-tubes within a borehole do not change its temperature with time for a constant heat flux. If we have constant temperatures of the internal borehole, the borehole resistance, defined as the resistance between the circulating fluid and the borehole, is constant too. As a result, when a borehole's internal temperature differences is set up for a constant heat flux, the borehole resistance can be modeled as a constant.

There is a separation into three different regions when we are talking about transient modeling of borehole heat exchangers. First region deals with transients that occur within the borehole before the borehole reaches steady state. For this region, it is necessary to model the borehole with the purpose to have infinite length since surface and bottom end effects can be neglected. The temperature response of this first region is influenced by two dimensional geometric and thermal properties of the borehole.

The second region happens next to the internal geometric and thermal properties of the borehole stop to influence the temperature response and before the surface and bottom end effects influence the temperature response. The third transient region take place when three dimensional effects such as surface, borehole to borehole interaction and bottom end effects influence the response of the temperature.

The g-function or borehole transient resistance is separated in two zones: the short time step (STS) g-function (Yavuzturk, 1999) and the long time step (LTS) g-function. (Eskilson, 1987). Both are interconnected to the three regions described above in that the short time step g-function represents region one and two, and also the long time step g-function represents region two and three.

So, as we could see, region two is possible to be represented by the short and long time step g-functions. This allows the two g-functions to be integrated into one continuous g-function curve and permit the borehole transient resistance the fact to be known for small times, to large times.

To follow with this review, we are going to distinguish part by part the steady state and transient borehole modeling.

4.2.1. Steady state modeling for boreholes

In this part of the thesis is important to emphasize the significance of the borehole resistance in the transient analysis. Borehole resistance is the thermal resistance in the middle of the fluid and the borehole wall. (Young, 2001)

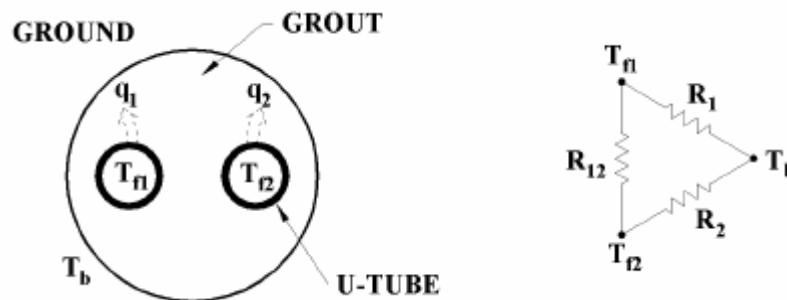


Figure 2. Borehole cross-section and related delta circuit – [2] Hellström, 1991

T_{f1} and $R_1(\frac{mK}{W})$ or $(\frac{h \cdot ft \cdot ^\circ F}{Btu})$ ($^\circ C$ or $^\circ F$): symbolize the fluid temperature in each leg of the U-tube.

q_1 and q_2 ($\frac{W}{m}$) or $(\frac{Btu}{h \cdot ft})$: the heat flux (heat transfer rate per unit length of borehole) from the circulating fluid.

T_b : represents the average temperature on the borehole wall.

To understand the delta circuit in Figure 2:

$R_1(\frac{mK}{W})$ or $(\frac{h \cdot ft \cdot ^\circ F}{Btu})$: thermal resistance between T_{f1} and T_b

$R_2(\frac{mK}{W})$ or $(\frac{h \cdot ft \cdot ^\circ F}{Btu})$: thermal resistance between T_{f2} and T_b

R_{12} : short circuit resistance for heat flow between T_{f1} and T_{f2}

Nevertheless, if the U-tube legs have similar fluid temperature, which happens at the borehole's bottom, R_{12} resistance can be ignored in the delta circuit. It is usually overlooked in the entire borehole. It causes a decoupling effect in one leg of the U-tube to another, simplifying the system.

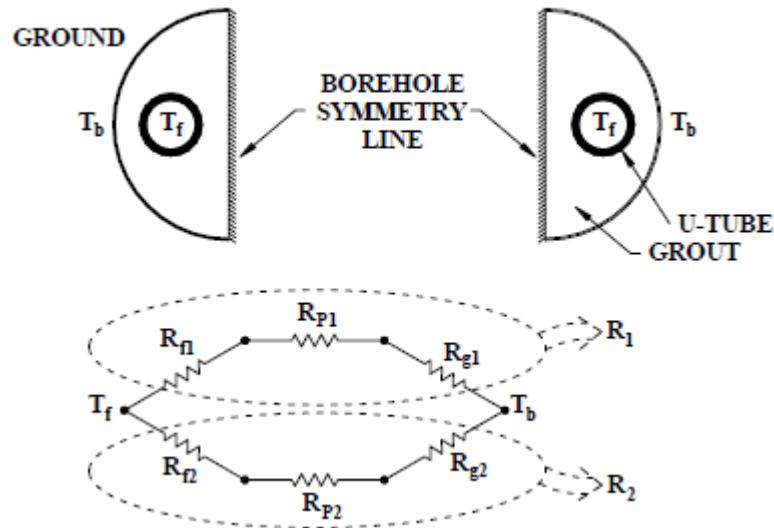


Figure 3. Decoupling borehole system – [3]

Figure 3 show the borehole cross section with symmetry line and the corresponding thermal circuit.

We realized that the grout, fluid and pipe belonging to each half of the borehole have the same geometry and thermal properties. So, assuming that $R_{f1}=R_{f2}$, $R_{p1}=R_{p2}$ and $R_{g1}=R_{g2}$, then $R_1=R_2$. And we can reduce in an easy way the equation which describes the overall borehole resistance:

$$R_{total} = R_{grout} + \frac{R_{pipe} + R_{fluid}}{2} \quad (4-1)$$

where,

$$R_{total} = \text{borehole thermal resistance} \left(\frac{mK}{W} \right) \text{ or } \left(\frac{h \cdot ft \cdot ^\circ F}{Btu} \right)$$

$$R_{grout} = \text{grout thermal resistance} \left(\frac{mK}{W} \right) \text{ or } \left(\frac{h \cdot ft \cdot ^\circ F}{Btu} \right)$$

$$R_{pipe} = \text{pipe thermal resistance for one tube} \left(\frac{mK}{W} \right) \text{ or } \left(\frac{h \cdot ft \cdot ^\circ F}{Btu} \right)$$

$$R_{fluid} = \text{fluid thermal resistance for one tube} \left(\frac{mK}{W} \right) \text{ or } \left(\frac{h \cdot ft \cdot ^\circ F}{Btu} \right)$$

The most important factors in the borehole resistance are the grout and pipe resistance. The fluid resistance supplies normally less than one percent to the complete steady state borehole resistance for turbulent flow.

For laminar flow the contribution made by the fluid resistance is greater and can exceed twenty percent of total R . Calculus of pipe resistance equations are (*Drake & Eckert, 1972*):

$$R_{pipe} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k} \quad (4-2)$$

where,

R_{pipe} = pipe thermal resistance ($\frac{mK}{W}$) or ($\frac{h \cdot ft \cdot ^\circ F}{Btu}$)

r_2 = outside diameter (m) or (ft)

r_1 = inside diameter (m) or (ft)

k = conductivity of the pipe ($\frac{W}{m}$) or ($\frac{Btu}{h \cdot ft}$)

Besides, fluid resistance can be calculated using this following equation (*Drake & Eckert, 1972*):

$$R_{fluid} = \frac{1}{2\pi r_1 h} \quad (4-3)$$

R_{fluid} = pipe thermal resistance ($\frac{mK}{W}$) or ($\frac{h \cdot ft \cdot ^\circ F}{Btu}$)

r_1 = U-tube inside diameter (m) or (ft)

h = convection coefficient of the fluid ($\frac{W}{m}$) or ($\frac{Btu}{h \cdot ft}$)

Grout resistance is calculated applying average temperature profile at the surface of the U-tubes and the borehole wall. It is the most complicated component of the borehole resistance. It changes a lot during the first few hours of heat rejection or extraction (*Hellström, 1991*).

$$R_{grout} = \frac{T_{U-tube} - T_{BH-tube}}{Q} \quad (4-4)$$

R_{grout} = grout thermal resistance ($\frac{mK}{W}$) or ($\frac{h \cdot ft \cdot ^\circ F}{Btu}$)

Q = Heat flux per unit length of U-tube ($\frac{W}{m}$) or ($\frac{Btu}{h \cdot ft}$)

T_{U-tube} = Average temperature at outer surface of U-tube (K) or ($^\circ F$)

$T_{BH-tube}$ = Average borehole wall temperature (K) or ($^\circ F$)

4.2.1.1. Line Source Model

To calculate the heat transfer among the earth and a line source was calculated by Kelvin and later solved by Ingersoll and Plass as the model of calculation most basic. To use this model, geometry of the borehole is ignored and modeled as a line source or a sink of no finite length. It is surrounded by an infinite homogeneous medium. As a consequence, the effects of the ending temperatures are depreciated by the line source mode. So, using the following equation, Ingersoll and Plass modeled the temperature at any point in an infinite medium for a line source or sink. The medium has to be at time zero, a uniform temperature. (Xiaowei, 2007)

$$\Delta T = \frac{q}{4\pi k_{soil}} \int_x^\infty \frac{e^{-\beta}}{\beta} d\beta \quad (4-5)$$

$$x = \frac{r^2}{4\alpha_{soil}t} \quad (4-6)$$

ΔT = change in ground temperature at a distance r from the line source ($^\circ C$) or ($^\circ F$)

q = heat transfer rate per length of line source ($\frac{W}{m}$) or ($\frac{Btu}{h \cdot ft}$)

r = radius from the line source (m) or (ft)

t = time duration of heat input q (s)

α_{soil} = soil thermal diffusivity ($\frac{m^2}{s}$) or ($\frac{ft^2}{s}$)

k_{soil} = conductivity of the soil ($\frac{W}{mK}$) or ($\frac{Btu}{h \cdot ft \cdot ^\circ F}$)

This equation is converted to the following to a m^{th} state of refinement:

$$I(x) = -\gamma - \ln(x) - \sum_{n=1}^m \frac{(-1)^n x^n}{n \cdot n!} \quad (4-7)$$

$$\gamma = \text{Euler's Constant} = 0.5772156649\dots$$

It shows the general form of the line source for m^{th} the stage of refinement. In most references the second stage of refinement is used. This method is only accurate for large times. For a typical borehole this equates to times greater than approximately 10 hours. For small times, less than 10 hours, the Gauss-Laguerre quadrature approximation, as shown in equation 4-8, is given. This approximation uses the fourth order Gauss-Laguerre quadrature to solve the infinite integral in equation 4-5.

$$I_{quad}(x) = e^{-x} \left(w_{41} \cdot \frac{1}{x+z_{41}} + w_{42} \cdot \frac{1}{x+z_{42}} + w_{43} \cdot \frac{1}{x+z_{43}} + w_{44} \cdot \frac{1}{x+z_{44}} \right) \quad (4-8)$$

$$w_{41} = 0.6031541043$$

$$z_{41} = 0.322547689619$$

$$w_{42} = 0.357418692438$$

$$z_{42} = 1.745761101158$$

$$w_{43} = 0.0388879085150$$

$$z_{43} = 4.536620296921$$

$$w_{44} = 0.00053929470561$$

$$z_{44} = 9.395070912301$$

Following equation (4-9) is a modification of equation (4-5). It shows how to use the line source model to model the borehole fluid temperature. If we do not use borehole resistance ($q \cdot R_{bh}$) the borehole temperature (T) would be the temperature at the borehole wall radius and not the fluid temperature.



$$T(t) = \frac{q}{4\pi k_{soil}} \cdot I\left(\frac{r_{bh}^2}{4\alpha_{soil}t}\right) + q \cdot R_{bh} + T_{ff} \quad (4-9)$$

T = Borehole fluid temperature ($^{\circ}\text{C}$) or ($^{\circ}\text{F}$)

q = heat transfer rate per length of line source ($\frac{W}{m}$) or ($\frac{Btu}{h \cdot ft}$)

k_{soil} = conductivity of the soil ($\frac{W}{mK}$) or ($\frac{Btu}{h \cdot ft \cdot ^{\circ}\text{F}}$)

r_{bh} = radius from the line source (m) or (ft)

α_{soil} = soil thermal diffusivity ($\frac{m^2}{s}$) or ($\frac{ft^2}{s}$)

R_{bh} = steady state borehole resistance ($\frac{mK}{W}$) or ($\frac{h \cdot ft \cdot ^{\circ}\text{F}}{Btu}$)

T_{ff} = far field temperature of the soil ($^{\circ}\text{C}$) or ($^{\circ}\text{F}$)

Equation (4-9) differs from equation (4-5) in that it uses the steady state borehole resistance to model the heat transfer from the borehole wall to the fluid. The line source model is utilized to model the heat transfer between the borehole wall and the far field. This required to know the steady state borehole resistance. The line source model is very easy to use and requires relatively few calculations compared to other methods.

5. METHODOLOGY: ANSYS Mechanical APDL solver

ANSYS, Inc. is an American Computer-aided engineering software developer headquartered south of Pittsburgh, United States. ANSYS publishes engineering analysis software across a range of disciplines including finite element analysis, structural analysis, computational fluid dynamics, explicit and implicit methods and heat transfer. (ANSYS, 2014)

Nowadays, there are several programs about finite element analysis (FEA) such as ABAQUS, COSMOS, PATRAN, NASTRAN, STRUDI, CAEPIPE... but we chose ANSYS because it is a versatile analysis program. It is possible to use this program for other analysis applications.

It is a program of general uses. It means that the program includes many general capabilities such as preprocessor functions (to generate a model), results, post processor, graphics, parametric modeling and utilities to make the program easy to use. In conclusion, there is not a specialized program to solve problems, but will allow us to satisfy many complex needs of design and analysis.

First of all, to start modeling our Ground-Heat Exchanger I will divide the geometry in four equal parts, taking into account only one quarter of them to analyze with ANSYS. In this way, the quarter is, in turn, divided into ground, grout and pipe, so we could see in an easy way all the components.

5.1. Step by step

The modeling basic scheme procedure for non-stationary numerical model is the following:

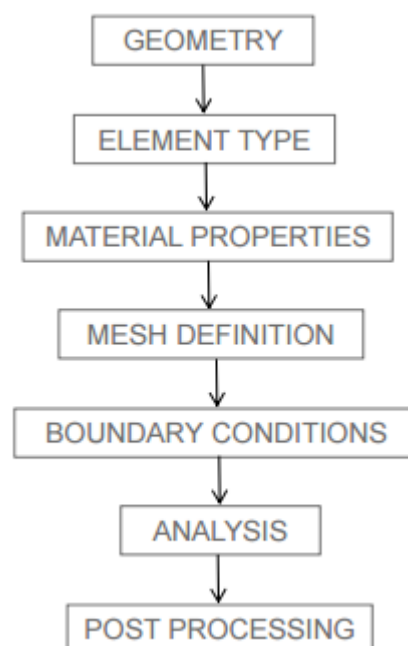


Figure 4. Scheme [4]

5.1.1. Geometry

I am going to model the borehole utilising ANSYS tools. It is necessary to take into account the different parameters and its magnitudes just to attempt to simplify as much as possible the form of the figure. Therefore, it is better to divide the circle into four parts with the aim of modelling a quarter, making the calculus easier.

The cross section of the borehole is illustrated in the following picture, showing as well, the different components (*Young, 2011*):

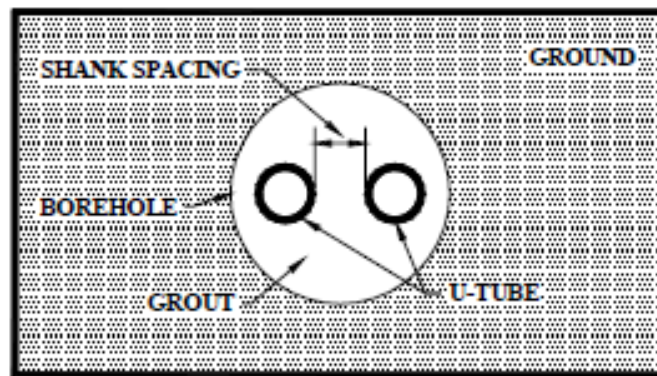


Figure 5. Borehole cross section - [3] Young, 2001

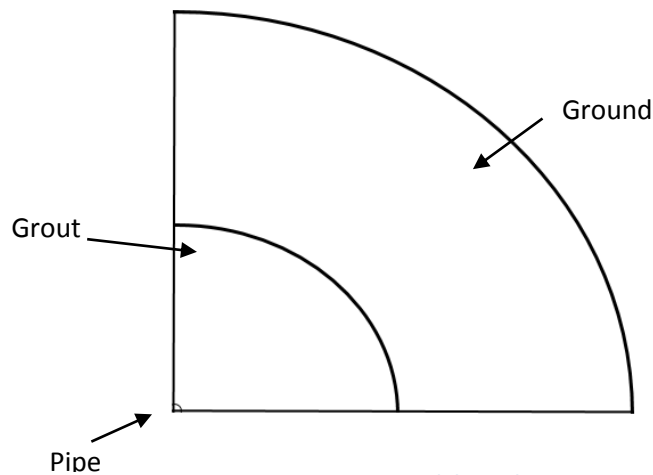


Figure 6. Model to solve

First of all, it is important to explain how we start modelling. We tried to model from the beginning this quarter of borehole utilising the three main parts (ground, grout and pipes). The parameters we had from the previous review are almost correct and it is necessary to enter them as the data.

When we start working with the program it is important and useful to select into the preferences part of material properties, the option thermal as the name of the individual discipline and h-Method. It will be useful to have later more commands during all the modelling.

5.1.2. Element type

To start de part os the Preprocessor, I shoul add our Element Type because is non defined at the beginning. To obtain Type 1 PLANE55 as defined Element Type, we have to select several parameters:

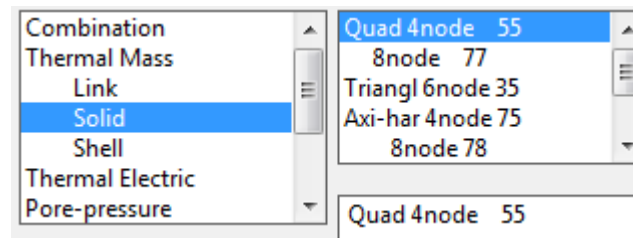


Figure 7. Element type-[A]

PLANE55 can be used as a plane element or as an axisymmetric ring element with a two-dimensional thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node. The element is applicable to a two-dimensional, steady-state or transient thermal analysis.

5.1.3. Material Properties

Continuing in the Preprocessor section, it is time to put in the material properties of each type of material, ground and grout. Then, we have to repeat the same steps in each Material Model Number, obtaining 1 and 2.

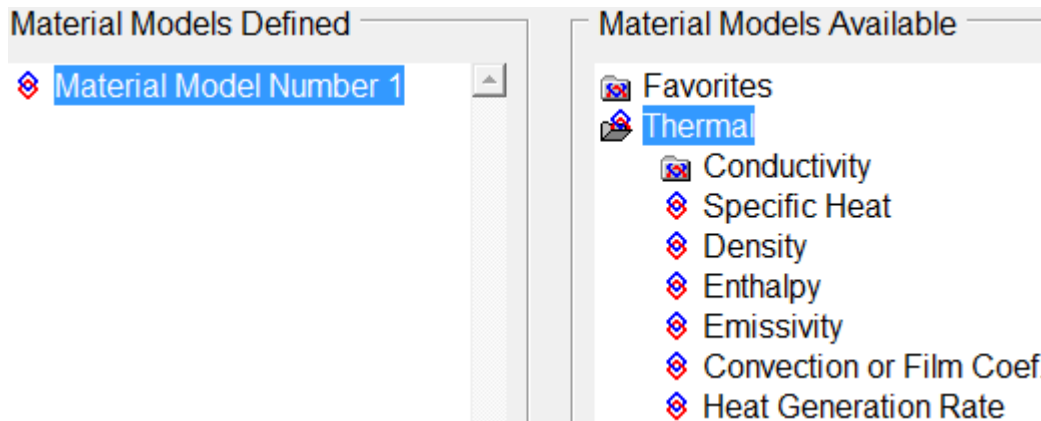


Figure 8. Material properties - [A]

I will introduce Isotropic Conductivity, Specific Heat and Density of Ground and Grout separately. I create a new one in Material-New Model.

MATERIAL MODEL N°1	Ground	MATERIAL MODEL N°2	Grout
Conductivity (W/mk)	3.25	Conductivity (W/mmk)	1.7
Specific Heat (KJ/Km ³)	2160000	Specific Heat (KJ/Km ³)	39010000
Density	1	Density	1

5.1.4. Key Points (KP), Lines and Arc

I need to create the basic structure of our quarter of region introducing just the primarily points. Le length will be of 10 meters. So, I add KP in Active CS option and inserting values in axis X and Y. It might be appearing dimensions of borehole.

MATERIAL MODEL N°2	Grout
Diameter (mm)	126
Radius (m)	0.063

When we add all the points we only achieve to see the KP owned to ground part. Borehole points does not appear on screen. That is because of the huge distance difference between the value of the borehole radius (0.063m) and the ground radius (10m). For this reason, I have to be careful in next steps.

Inside the same subsection of modeling, it is possible to create **straight lines** in anticlockwise way since the KPs.

To complete the figure with two **arcs** (in grout and ground part) I used CIRCLE command, in which I specify the length of the radius to make the arc, the degrees and division I need.

```
CIRCLE, PCENT, RAD, PAXIS, PZERO, ARC, NSEG  
CIRCLE, 1, 10000, ,, 90, 1
```

Figure 9. Command tool - [A]

There is a negligible spacing between the lines and arc and I must eliminate it. To do this I fix the arc using the commands:

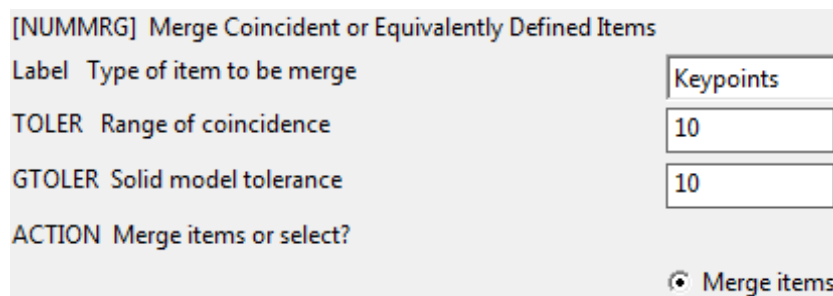


Figure 10. Merged elements - [A]

5.1.5. Areas and meshing definition

Once I have this previous steps, it is time to create the Areas by lines in an Arbitrary way.

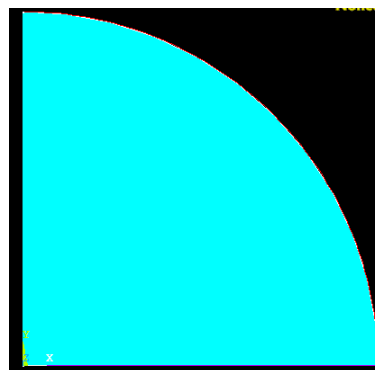


Figure 11. Only ground area - [A]

As we can observe, we could not appreciate grout area given that is too small. For this reason, I am going to disregard it as I did just before starting modelling with the pipe part. They do not influence significantly in the results I will obtain at the end of the modelling work.

We can model the **mesh** from the figure with the two (ground and grout) areas to examine the behavior the mesh has in this situation. There are three important step in the meshing part. First of all, I have to assign attributes (the material) of each area:

[AATT] Assign Attributes to Picked Areas	
MAT Material number	1
REAL Real constant set number	None defined
TYPE Element type number	1 PLANE55
ESYS Element coordinate sys	0
SECT Element section	None defined

Figure 12. Meshing - [A]

Next step is the most important and difficult. I need to find the better combination of divisions to mesh the areas. It means that each element has to be divided into a number of parts with a spacing ratio to obtain the best possible meshing.

After several attempts changing either number of divisions (NDIV) and spacing ratio (SPACE), I find the best meshing that is for horizontal and vertical lines:

[LESIZE] Element sizes on picked lines	
SIZE Element edge length	
NDIV No. of element divisions	50
(NDIV is used only if SIZE is blank or zero)	
KYNDIV SIZE,NDIV can be changed	<input checked="" type="checkbox"/> Yes
SPACE Spacing ratio	15

Figure 13. Divisions of meshing - [A]

And for the arc changes to NDIV=8 and SPACE=1. Last part consists in mapping the area using the corners. Here is the result modeled figure:

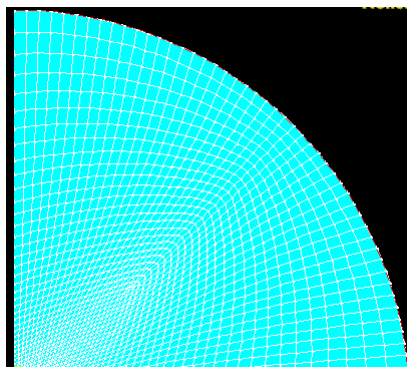


Figure 14. Only ground area model meshed - [A]

As we can see again, grout part is not appreciable, so I decide to only focus on ground area and I eliminate grout area and meshing, so.

5.1.6. Loads

There are two different type of loads to apply: uniform temperature and heat flow, both are define loads. The uniform temperature is the undisturbed ground temperature also called the edge-line temperature, and the heat flow is the total heat transferred divided by 4 because of the quarter figure I am calculating.

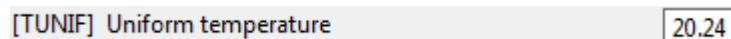


Figure 15. Uniform temperature of ground - [A]

The heat flow is the heat extracted in one month ($Q_{total}=744$ hours), therefore I convert it to obtain W/m each day of the month:

$$Q = - \frac{\frac{Q_{total}}{31 \text{ days} \cdot 24 \text{ hours}}}{Active \text{ Borehole Depth (m)} \cdot 1000(mm)} = -8.2 \text{ W/m} = -0.0082 \text{ W/mm}$$

$$q = - 2.05 \text{ W/m (Heat flow in each quarter).}$$

It is a thermal load applied on the KP closer to the pipe (closer to the heat source)

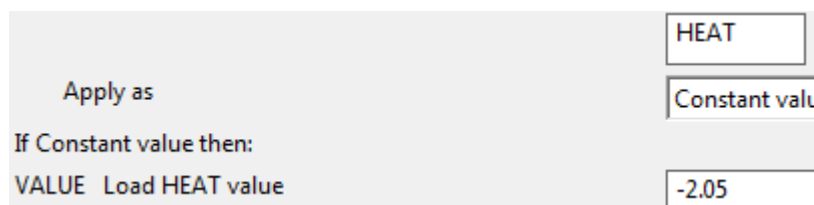


Figure 16. Load application - [A]

Now is time to **solve the model** in the corresponding command, selecting current LS (Load Step). When solution is done correctly, when can start with the transient part reading the file with the same name. I add information to continuing with de modeling calculus.

5.1.7. Transient Modeling

Continuing with the modelling, I need to find out the temperature at the borehole, at de distance= 0.063 m in X axis. To obtain it is necessary to work with the temperatures of the closest nodes to this point. I take a list of nodes in order to select them. This list will be adding into the annex part with the name “NLIST (List of nodes)”. There we can see how nodes 102 and 103 are the nearest ones to the point I am looking for.

After that, I will use the command General Postprocessor to read the results of the last hour of the available data set, the 744th hour.

Available Data Sets:

Set	Time	Load Step	Substep	Cumulative
742	2.67120E+06	1	742	742
743	2.67480E+06	1	743	743
744	2.67840E+06	1	744	744

[*GET],Par,NODE,N Get Nodal Results Data

Name of parameter to be defined

Node number N

Results data to be retrieved

DOF solution	VY
Stress	VZ
Strain-total	VSUM
Flux & gradient	Pressure PRES
Nodal force data	Temperature TEMP
Energy	
Strain-elastic	Temperature TEMP

Figure 18. Scalar parameter for each temperature - [A]

In this moment, next step is focus on the parameters. I need to retrieve the scalar data related to the nodes 102 and 103. Selecting the type of data to be retrieved: Results Data and after, Nodal Results I achieve the following screen:

I have to choose a parameter name to define it, write the number of the node, and the type of result bring back. Once I finish with both nodes, it is possible to obtain all items in a Scalar Parameter window:

```
Items
I_T = 744
N_TIME_RES = 744
T = 2678400
TEMP744N1 = 17.6177638
TEMP744N102 = 18.5356681
TEMP744N103 = 18.7854603
TIME_INC = 3600
```

Figure 19. All items achieved - [A]

So, we can see the selected period of time, the temperatures at the nodes we need (including node 1 to make a comparison later) and the scalar period step of the time in transient mode.

Following, I am going to work with the variable viewer, TimeHistPostPro (Time History Variables). I select Add Data (DOF Solution, Nodal Temperature) and named the variables as I prefer.

Variable List					
Name	Node	Result Item	Minimum	Maximum	X-Axis
TIME		Time	3600	2.6784e+006	<input checked="" type="radio"/>
TEMP_N1	1	Nodal Temp	17.6178	19.3075	<input type="radio"/>
TEMP_N102	102	Nodal Temp	18.5357	20.0476	<input type="radio"/>
TEMP_N103	103	Nodal Temp	18.7855	20.1669	<input type="radio"/>

Figure 20. TimeHistPosPro - [A]

In the moment I have all variables I want in the list, I can draw all the graphs I need to compare each two points I choose. For this reason, I had appended three graphs in the Annex comparing node 1 with node 102, node 102 to 103, and 1 to 103.

It is possible now to achieve the tables with all temperatures in axis X and Y belonging of nodes 1, 102 and 103. Utilizing values about temperatures in nodes 102 and 103, I will make a Linear Interpolation using Excel tools with the objective of achieve the temperatures just in the borehole. The file including that data is annexed later in the thesis. I need to apply this following formula (Levy, 2010):

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1} \cdot (x - x_1)$$

Figure 21. Linear Interpolation Formula [5]

We can consider y_1 as the temperature in node 102, y_2 is the temperature of node 103, x is the distance of the borehole (0.063 meters), x_1 is the distance of the node 102 and x_2 is the corresponding distance for node 103. So, we obtain y , temperature pertinent to borehole point. I had achieved a list of temperature corresponding to each hour, so it is possible to make a graphic to compared the three temperatures. It is annexed to in the corresponding part.

After reaching this tables of temperatures, it is possible to, using the equation (4-9), adding $R_{bh} = 0.00.0951 \frac{mk}{W}$ and $q = -8.02 \frac{W}{m}$ obtain the Borehole Fluid Temperature, given that the other part of the equation (borehole wall temperature) are already part of the ANSYS result. I will use Excel to resolve it because it is easier to work with so much data. The resulted table is added in de annexed part too.

Continuing with that, it is necessary to compare those temperatures (the interpolation one and the borehole fluid) with the temperatures of (Fernández Fernández, C., 2016) obtained in her thesis. I will present this comparison in the part which named the same in Index.

5.2. Complications

During the realization of the ANSYS modelling I had several complications. One of the most significant was the differentiation between modeling carried out using all parts of the original model (ground, grout and pipe) and removing the parts that no interfere in the calculations, taking not into account.

Another thing to consider was the order in which I perform the operations with the ANSYS program because if I do not use them in a properly order, some results vary and the get away from the proper exercise performance.

When trying to solve modeling with appropriate commands, usually appear errors due to small faults in the moment of introducing units or dimensions. This was because not all data I had was in the proper and necessary units I want. All these problems were solved successfully until I managed to finish the modeling without any warning.

The meshing part was, in my point of view, the most laborious one. This is because first of all, I had to do it several times with the two areas (ground and grout) and then only with one area (ground). In addition, when choosing the number of correct items to render the maximum result and to be as accurate as possible, I had to try multiple different numbers, varying them between positive and negative values and magnitudes to reach the most concrete values in each model line without getting element violations shape.

5.3. Results and Comparison

Once I finish the modelling in ANSYS, I can take several lists with the resulting nodes, the tables with the wall borehole temperature and some graphics plot using this data. Given that, there are some graphics, they are attached in the annex part of Screenshots with their corresponding descriptions.

Now, I will attach the last graph I achieved comparing borehole wall temperature and average borehole temperature (or borehole fluid temperature). It is made using Excel tools. This excel file will be at the annex part and its name is “LinealInterpolation”. Inside this file we could see all the values necessary to conform the following figure:

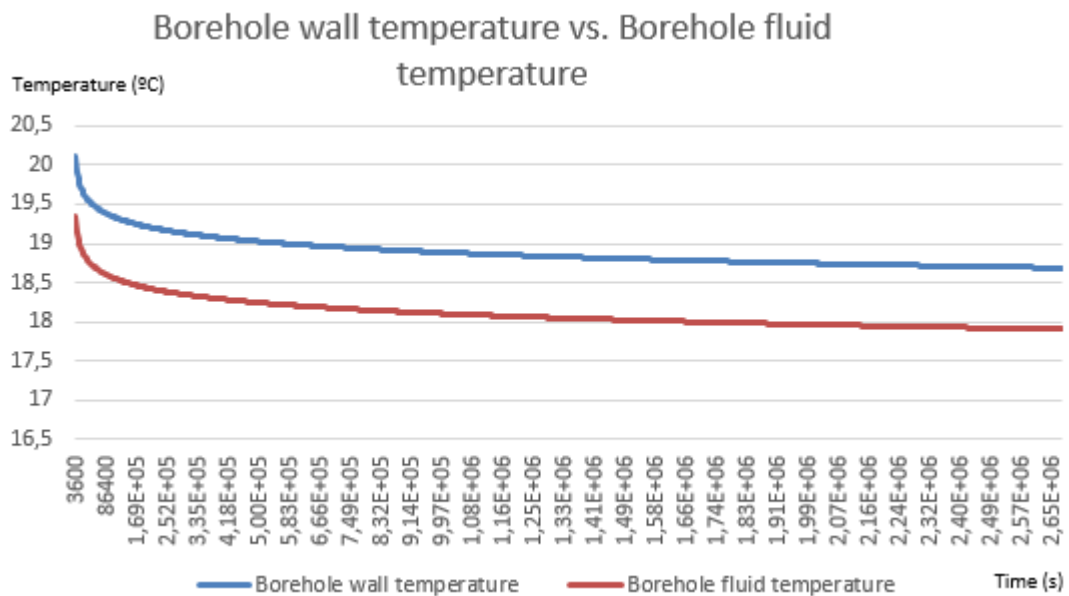


Figure 22. Wall and fluid borehole temperatures [A][E]

As we can appreciate, both temperatures were calculated by the values of ANSYS for one borehole and using some constant of the initial problem. Both descends in relation with the passage of time as I had expected.

It is important to remember that, both of us, are comparing 744 data values from de hours in a month and I have to convert them into seconds. This is the reason why axis “X” has huge values.

In order to achieve the best results for temperature measurements, it is necessary to do a comparison with the Numerical Method (Fernández Fernández, C., 2016). These measurements were calculated with respect of two variables. The first one 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. Borehole_T_KLS (cyan line)

-Numerical method based on the input parameters of “File 1620-text1”. Borehole_T_PAR (red line)

-Finite Element Method based on the modeling program done in ANSYS. Borehole_T_FEA (blue line)

This comparison is represented in the plots computed in Matlab from the data calculated with the Excel files and ANSYS program. Here, I attached the plots programmed with Matlab:

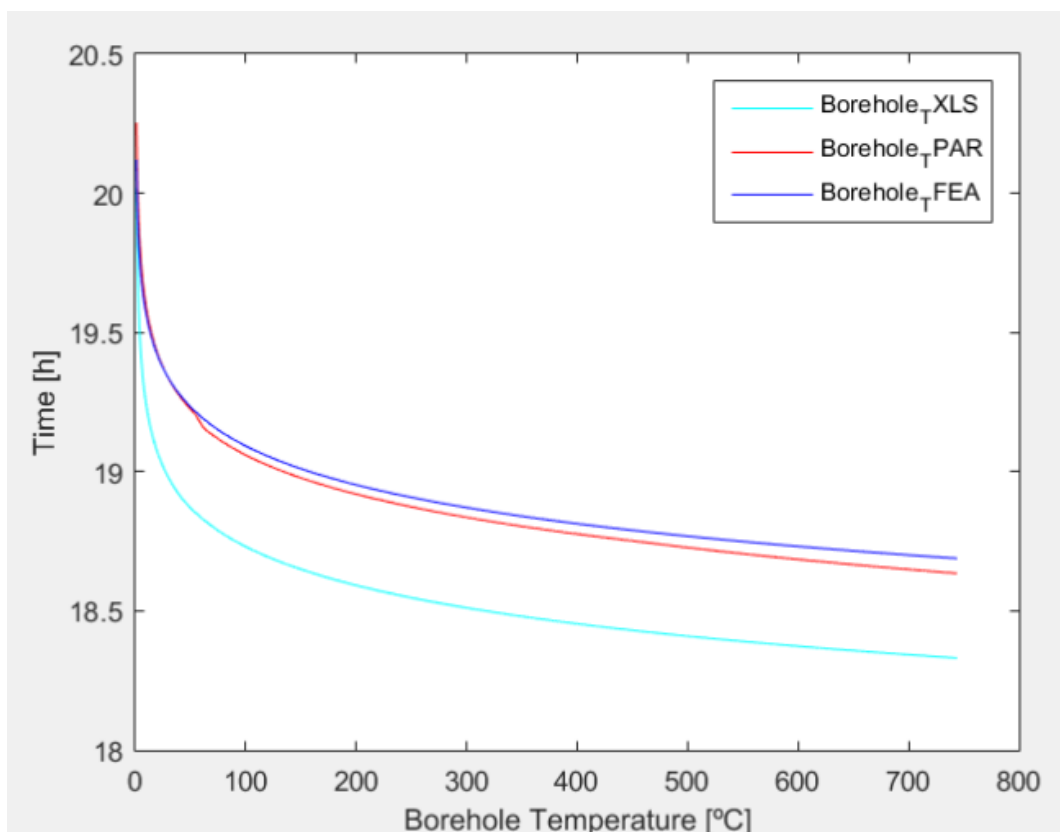


Figure 23. Matlab plot including Borehole Temperature [M].
Time in hours in axis “X” and Borehole Temperature in °C in axis “Y”

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. Avg_T_KLS (cyan line)

-Numerical method based on the input parameters of “File 1620-text1”. Avg_T_PAR (red line)

-Finite Element Method based on the modeling program done in ANSYS. Avg_T_FEA (blue line)

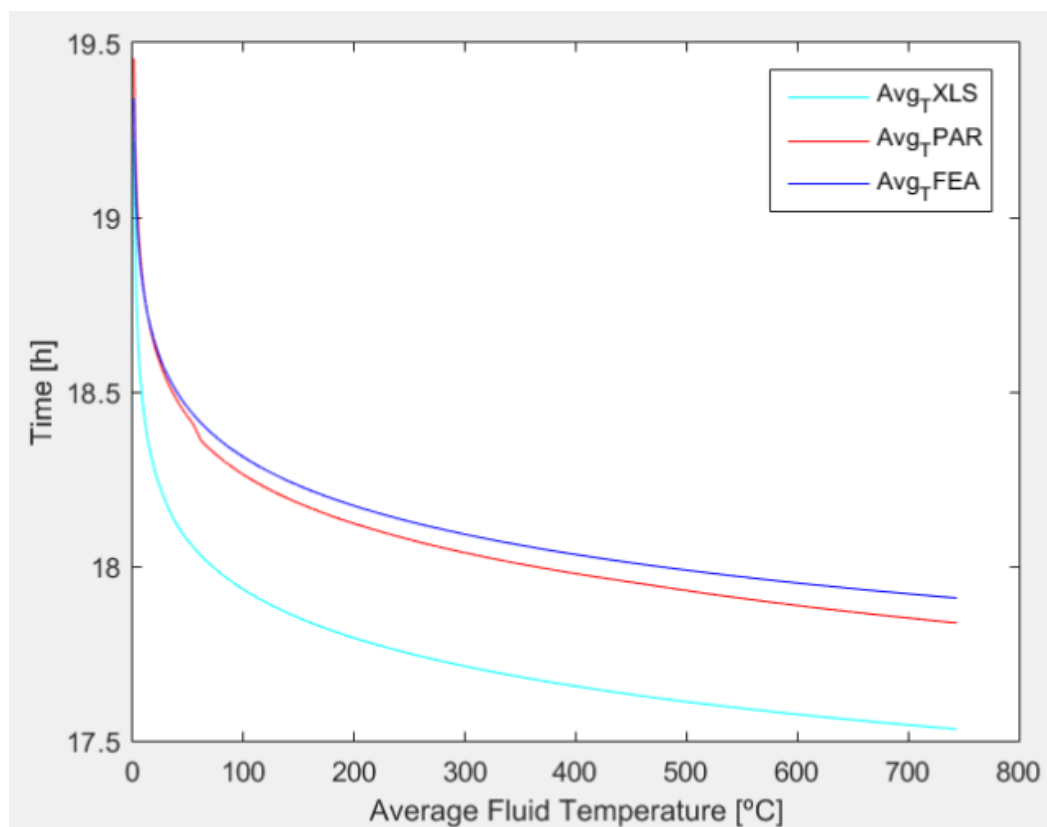


Figure 24. Matlab plot including Average Fluid Temperature [M].
Time in hours in axis “X” and Average Fluid Temperature in axis “Y”

5.4. Conclusions

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.

As it is seen in the figures on the calculations follow the descendent shape with a little variation of temperatures. The greatest temperatures are measured by the Finite Element Analysis (FEA) and the lowest ones are measured by the G-function procedure.

After having this results, with Numerical and Finite Element methods, it is necessary to complete the comparizon utilising the Analytical mehod explain in the theory part of the Finite Element Method.

Analytical method is a difficult part of the comparison made by Excel tools and long formulas. Although I try to have correct results applying this method, they will not appear. I have attached into the CD a Excel file named “AnalyticalMethod” to show how I procedured with all the equations I explained in the theory. As I did not achieve correct results to compare them with FEA Analysis and Numerical Method, it is necessary to check all the calculus in the future, just to complete the comparison.

I can also refer to the situation that in this Final Thesis, I only modeled one of the 12 boreholes of the system of the Atlanta building. It was expected to do the FEA using one borehole and then all of the building’s boreholes, but I do not have enough time to complete this second part. The modelling of all of them shall be prepare in futures thesis or repports. Results will be more complete and precise. Furthermore, utilizing ANSYS program, is easy to try to change parameter of the data and faster to plot all results.



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Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems
(2007 edition)

7. LIST OF FIGURES

Figure 1. Typical GSHP system. [1]-Domestic Ground Source Heat Pumps:
Design and installation of closed-loop systems (2007 edition)

Figure 2. Borehole cross-section and related delta circuit. [2]-Hellström, G., 1991.

Figure 3. Decoupling borehole system. [3]- Young, T.R. Thesis, 2001.

Figure 4. Scheme. [4]-University of Oviedo

Figure 5. Borehole cross section. [3]- Young, T.R. Thesis, 2001

Figure 6. Model to solve

Figure 7. Element type. [A]-ANSYS

Figure 8. Material properties. [A]-ANSYS

Figure 9. Command tool. [A]-ANSYS

Figure 10. Merged elements. [A]-ANSYS

Figure 11. Only ground area. [A]-ANSYS

Figure 12. Meshing. [A]-ANSYS

Figure 13. Divisions of meshing. [A]-ANSYS

Figure 14. Only ground area model meshed. [A]-ANSYS

Figure 15. Uniform temperature of ground. [A]-ANSYS

Figure 16. Load application. [A]-ANSYS

Figure 17. Data Set 744 hours. [A]-ANSYS

Figure 18. Scalar parameter for each temperature. [A]-ANSYS



Figure 19. All items achieved. [A]-ANSYS

Figure 20. TimeHistPostPro. [A]-ANSYS

Figure 21. Linear Interpolation Formula [4]-Doron Levy. “Introduction to Numerical Analysis”.

Figure 22. Wall and fluid borehole temperatures. [A]-ANSYS and [E]-Excel files annexed

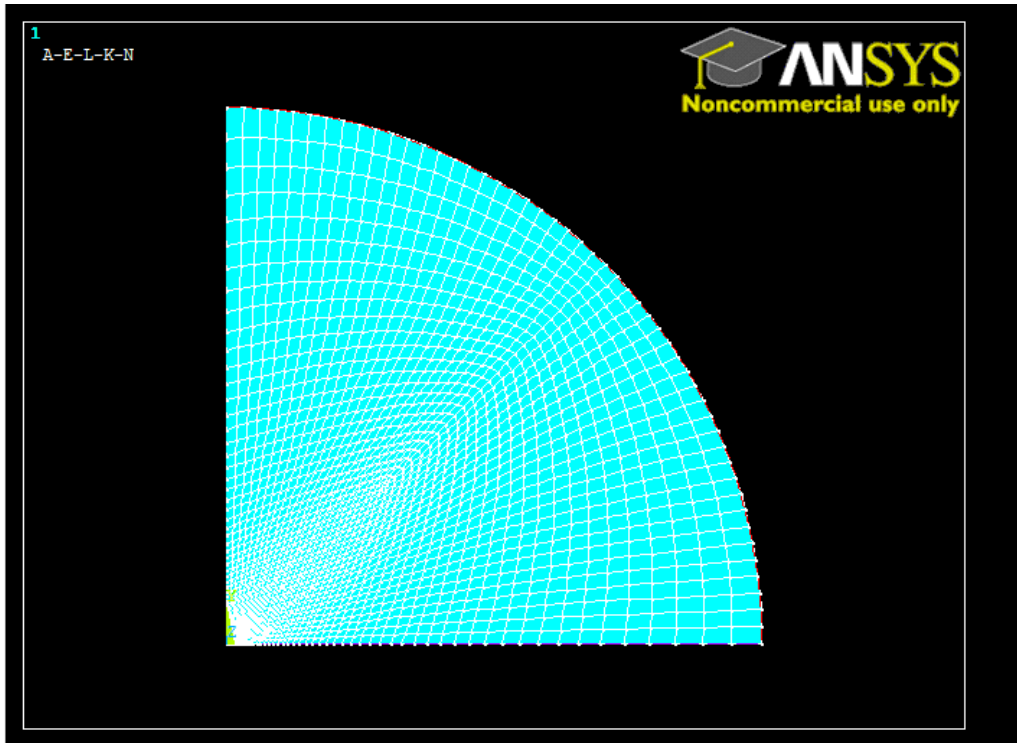
Figure 23. Matlab plot including Borehole Temperature. [M]-Matlab files annexed

Figure 24. Matlab plot showing Average Fluid temperature. [M]-Matlab files annexed

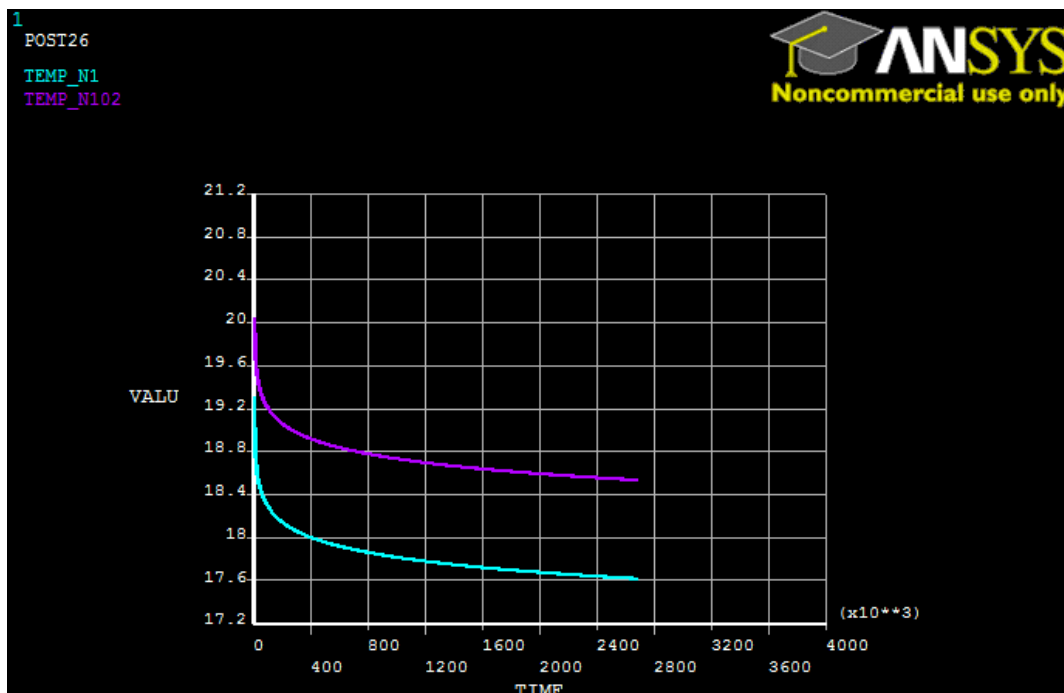
8. ANNEX

8.1. Screenshots

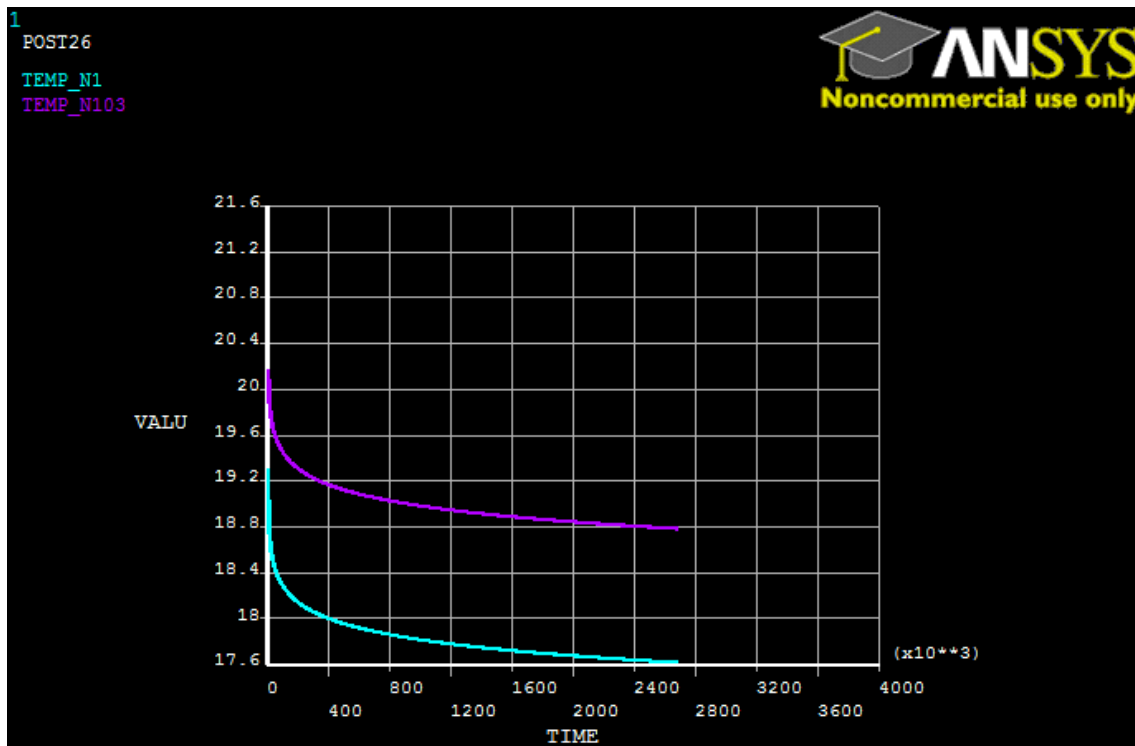
- Final screenshot of the ANSYS program.



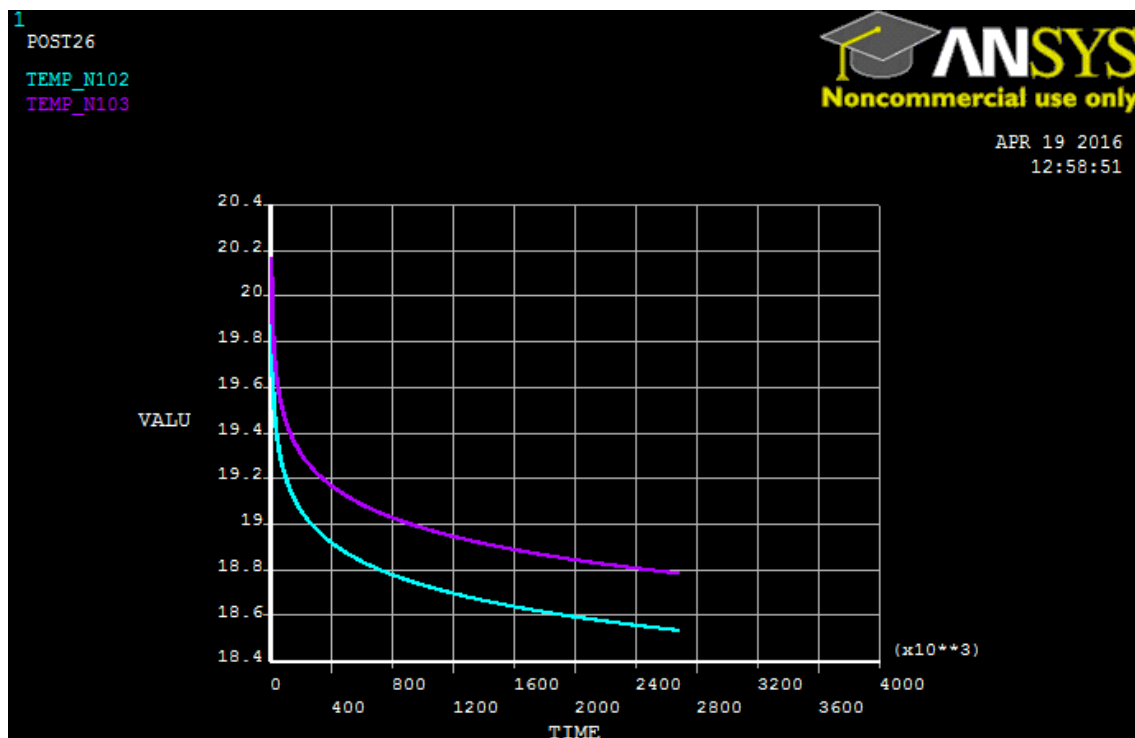
- Final screenshot of the graphic made with temperature at node 1 and 102:



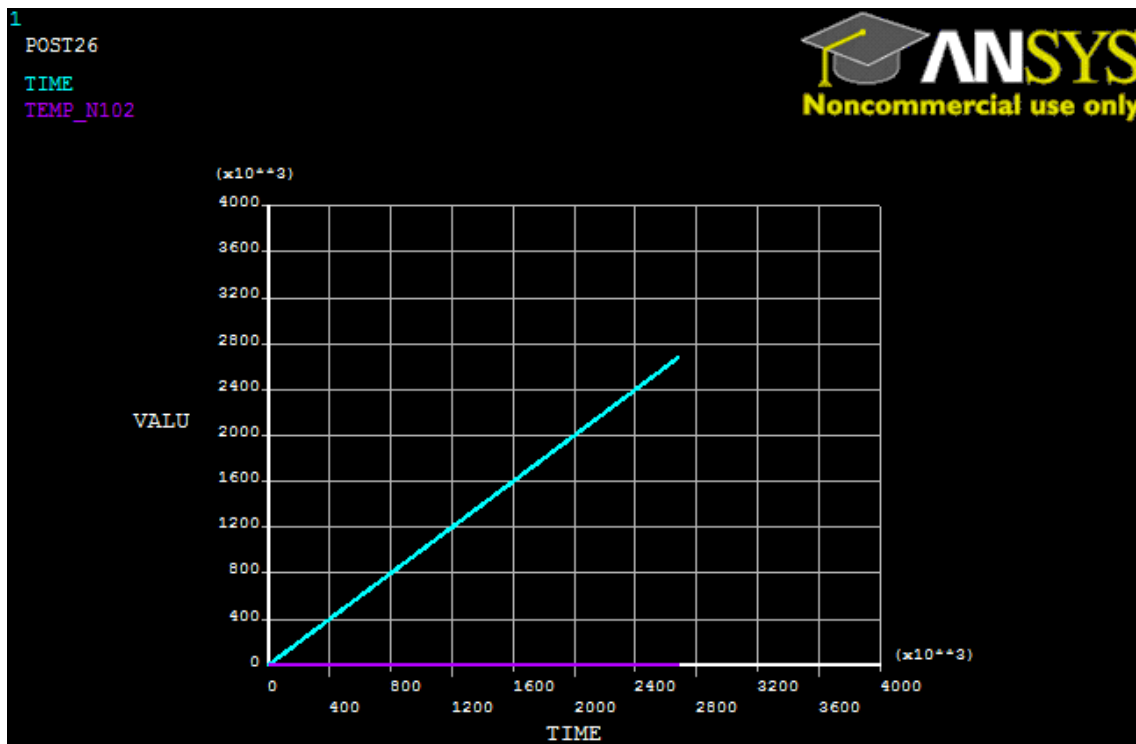
- Final screenshot of the graphic made with temperature at node 1 and 103:



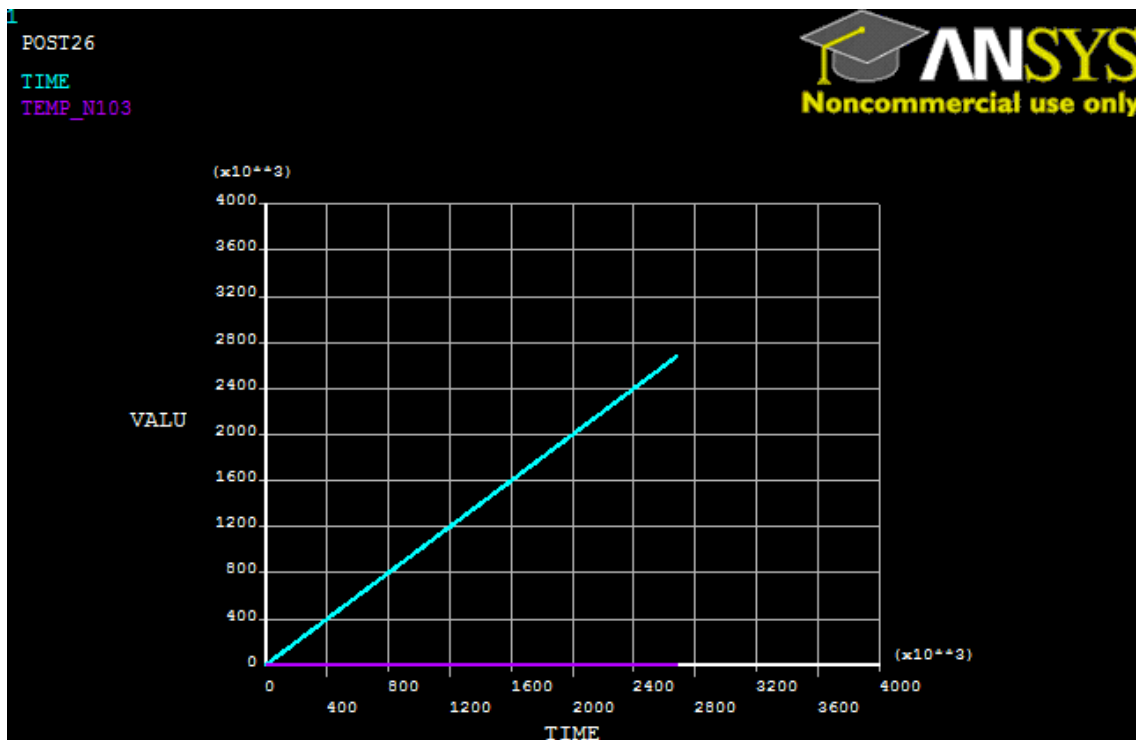
- Final screenshot of the graphic made with temperature at node 102 and 103:



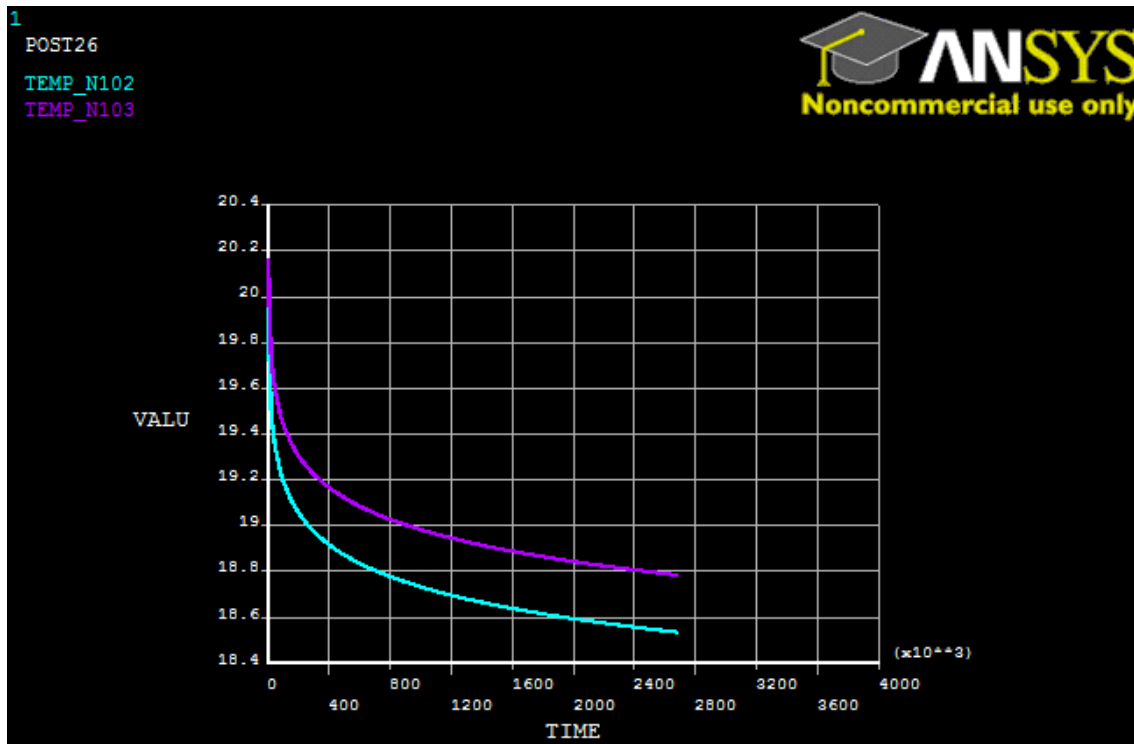
- Graph comparing time and temperature in node 102:



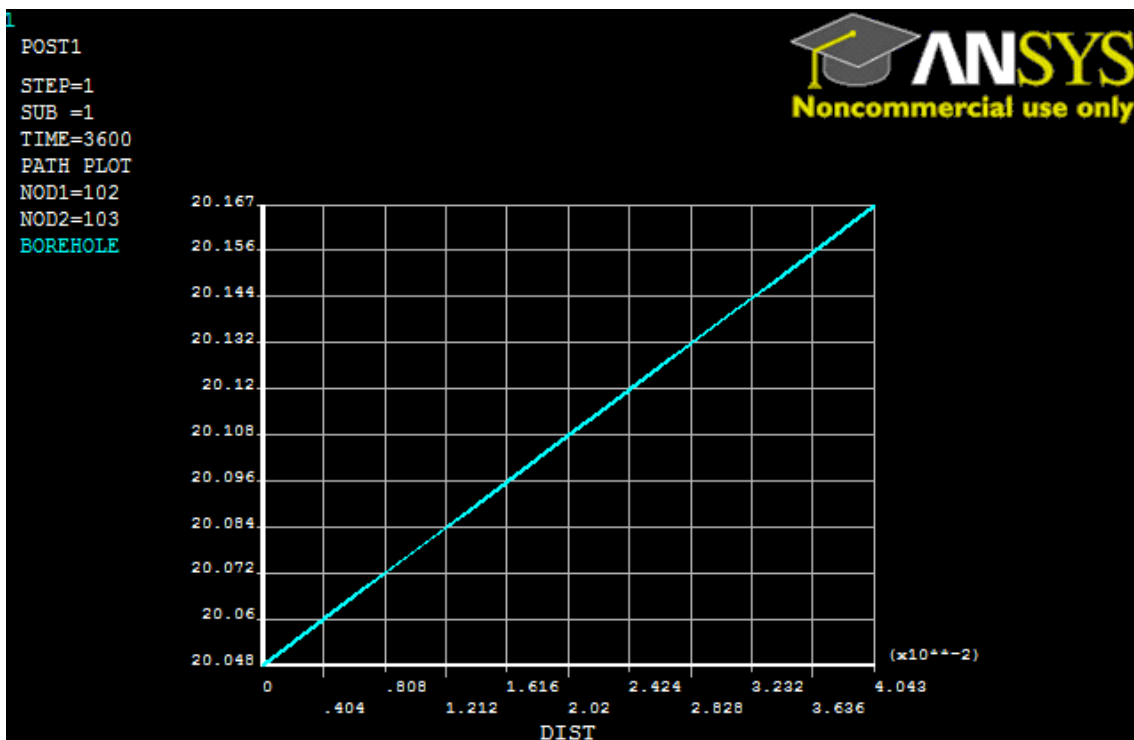
- Graph comparing time and temperature in node 103:



- Graph comparing time and temperature in node 102 and 103:



- Plot results between node 102 and 103, based on temperature and distance:



8.2. CD Annex

- **TrueFinal:** ANSYS modelling program.
- **NLIST:** List of nodes achieved in meshing.
- **TempListN1.102:** List of temperatures of nodes 1 and 102.
- **TempListN1.102.103.Time:** Temperatures of nodes 1, 102, 103 in relation to the time.
- **TrueFinalN1.N102:** Screenshot of the graphic involves node 1 and 102.
- **TrueFinalN1.N103:** Screenshot of the graphic involves node 1 and 103.
- **TrueFinalN102.N103:** Screenshot of the graphic that involves node 102 and 103.
- **PathItemsHorizontalLine:** All items results.
- **Results Summary:** Summation of the results.
- **FinalLinearInterpolacion:** Excel which includes tables with temperatures and the calculation of the interpolation temperature in the borehole. Also the borehole fluid temperature and the graph of both.
- **Transient.mac:** macro file to use transient modelling using the time.
- The rest of files are produced by the ANSYS program.

8.3. Plans

- GSHP Location Level 2
- GSHP Units
- GSHP Wells Scheme