# Cementing of geothermal wells

by,

Ilangkabilan a/l Manaharan

12586

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

MAY 2013

Universiti Teknologi PETRONAS
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**Supervisor: Mr. Amin Shoushtari**

CERTIFICATION OF APPROVAL

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Approved by,

_________________________

(MR. AMIN SHOUSHTARI)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2013

# CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

______________________________

(ILANGKABILAN A/L MANAHARAN)

# ABSTRACT

This project is related to drilling of well. Once a specific depth of well is drilled, casing will be run into the well. The casing will be cemented for a better support and to seal the well. [6]

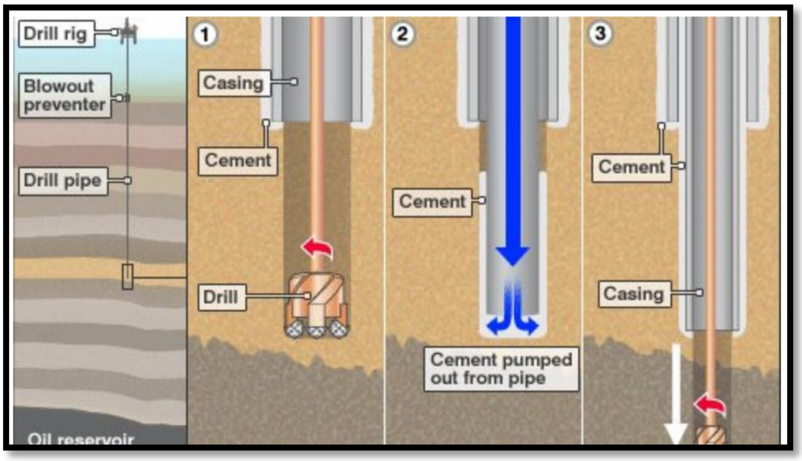


Figure 1: Drilling and cementing [9]

Drilling can only be continued after the cement slurries have reached an acceptable strength through hydration. Therefore, the drilling program can be done more efficiently if the time taken for the cement to hydrate and develop strength can be estimated. The main problem that brought up this project is, how long does it take for the cement slurry to achieve acceptable compressive strength and should temperature be considered? The aim is to determine the radius of thermal influence at cement hydration.. The objective will enable the understanding of the relationship between temperature or thermal influence and time taken for the cement hydration through the analysis of radius of thermal influence. The project mainly focuses on understanding the parameters involved in the research. The downhole temperature controls the pace of chemical reactions during hydration of cement. Besides that, the cement slurry hydrates and develops strength more rapidly with higher formation temperature. An analysis will be carried out using software to show how different formations have different waiting time for the cement to achieve strength based on radius of thermal influence. A semi-analytic formula which allows the estimation of the temperature increase versus setting time is used to describe the transient temperature at the cylinder's wall, while at the surface of the cylinder the radial heat flow rate is quadratic function of time.

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# NOMENCLATURE

| | |
|---|---|
| q | Rate of heat generation |
| $q_D$ | Dimensionless rate of heat generation |
| $q_r$ | Reference rate of heat generation per unit mass |
| $r_w$ | Well radius |
| $r_c$ | Outside radius of casing |
| $\rho_c$ | Density of cement |
| $T_V$ | Transient temperature at the cylinder's wall |
| $T_i$ | Initial temperature of formation |
| $\lambda$ | Thermal conductivity of formations |
| $t^*$ | Time since cement slurry placement |
| $t_0$ | Time interval due to cement retardation |
| $Q_D$ | Dimensionless cumulative heat flow rate |
| $A_0$ | Reference heat flow rate per unit of length |
| $R_{in}$ | Radius of thermal influence |

# 1 INTRODUCTION

The first oil well was drilled in the year 1859 and it was a well of 69.5 feet deep in Tituville, Pennsylvania by Colonel Drake. However, a large number of wells were drilled earlier to produce water, brine and even naphtha but the first oil well was in 1859. When a well is drilled, it is regularly cased. The well is lined with a steel pipe, or casing, which is lowered into the hole under its own weight in smaller and smaller diameters as the hole gets deeper. The first length of pipe is run when the bit has drilled the surface formation and is then cemented in the hole. The casing could not be run into the borehole without it being cemented in the hole.

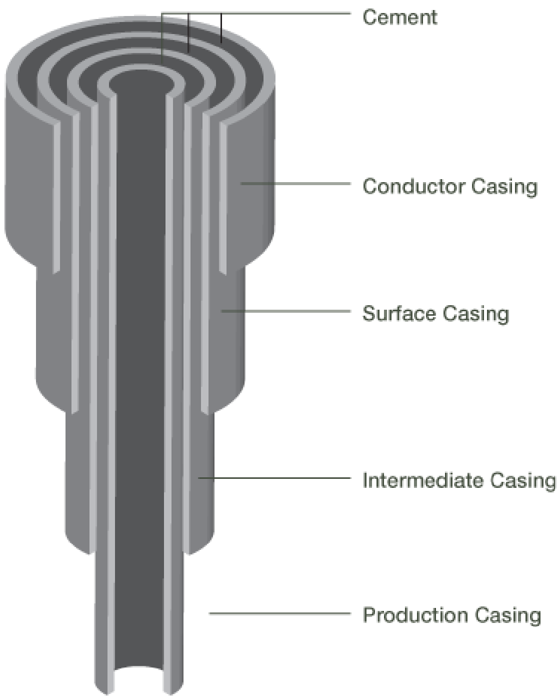



Figure 2: Typical well casing diagram [11]

Cementing is a crucial part in drilling operation. Lining a hole with casing prevents the hole from caving in after it has been drilled as well as sealing the wellbore from encroaching fluids and gasses. Cementing attaches the casing firmly to the wellbore wall and stabilizes the hole. Besides that, cementing protects and seals the wellbore. [8] An L-shaped cementing head is fixed to the top of the wellhead after casing to receive the slurry from the pumps. Two wiper plugs, or cementing plugs, that sweep the inside of the casing is used to prevent mixing. The bottom plug is introduced into the well while keeping the drilling fluids from mixing with the cement slurry and the cement slurry is pumped into the well behind it. The bottom plug is then caught just above the bottom of the wellbore by the float collar. This mechanism functions as a one-way valve that permits the entry of cement slurry. A top plug is pumped into the casing pushing the remaining slurry through the bottom plug after the proper volume of cement is pumped into the well. The pumps are turned off once the top plug reaches the bottom plug and the cement is allowed to set. The time taken for the cement to harden is called thickening time. [10]

Cement slurries are influenced by temperature and pressure. These two parameters affect how long the slurry will be pumped and how it develops the strength necessary to support the pipe. The pace of chemical reaction during cement hydration is controlled by the downhole temperature. On the other side, the shut in temperature affects the time taken for the slurry to be pumped and how well it develops. This project focuses mainly on the heat transfer from the formation to the cement slurry which determines how fast the cement will reach an acceptable compressive strength. Therefore, a semi-analytical formula which enables the estimation of temperature increase versus setting time is used to describe the transient temperature at the cylinder's wall. The developer will be able to start production more effectively by estimating the time taken for the cement to achieve acceptable compressive strength at specific formation and depth. The cement slurry hydrates faster and develops strength rapidly at high formation temperature. [5]

## 1.1 PROBLEM STATEMENT

The main issues to be studied in this project are how long it takes for the cement slurry to achieve acceptable compressive strength and should the temperature be considered? Temperature or degrees of heat of an object to be specific in this project is the downhole temperature is not constant when different formations are involved. What is the relationship between temperature or thermal influence and time taken for cement hydration? If the temperature is not considered during cementing, there will be a very rough estimation of time taken for the cement to achieve the acceptable compressive strength. Therefore, there will be a delay in the drilling programme if the assumed time is much more than the real time taken. Consideration of temperature by calculating the heat transfer from the formation to the cement will certainly help in a more accurate assumption of time taken by the hydration of cement to achieve required strength. Another problem will be, how to show the waiting time for the cement to achieve strength using considering different formations.

## 1.2 OBJECTIVES

The main objectives of the project are;

- To develop an analysis using software to show how different formations have different waiting time for the cement to achieve compressive strength based on radius of thermal influence of different formation.
- To determine the radius of thermal influence at cement hydration.
- To understand of the relationship between temperature or thermal influence and time taken for the cement hydration.

## 1.3 SCOPE OF STUDY

The project mainly focuses on understanding the parameters involved in the research. The theory of the research mainly divided into 3 parts namely, rate of heat generation versus time, temperature increase at cement hydration and radius of thermal influence as cementing. Therefore, calculations are done to obtain equations and values related to achieve the objective of the project. The composition of cement slurries is assumed constant. The thermal conductivity and the thermal diffusivity of formations are used as variable parameters.

## 1.4 RELEVANCY OF THE PROJECT

This project is relevant to the author’s field of study as cementing is a crucial part in drilling. According to the University’s curriculum structure of petroleum engineering, cementing was a part of the studies in subjects such as well completion and production, drilling engineering and advance drilling engineering. This research provides additional knowledge for the author to have better understanding not only in drilling but also process of heat transfer. This is because heat is one of the important forms of energy involved in cement hydration. Besides that, the project will enable the author to understand the whole process of drilling, casing and cementing which are the main processes in oil and gas field.

## 1.5 FEASIBILITY OF THE PROJECT

The project is feasible because it is within the scope and time frame. The author has planned very well the task to be done weekly for the project. The objectives of the project will be achieved at the before the end of the second semester. The first semester is dedicated in preparing the literature review as well as developing the ideas to illustrate the result whereas the second semester is used to implement the ideas to get the results. Calculations involved in the analysis are carried out in Microsoft Excel as well as the tabulation of data and the plotting of graph. However, the end result of obtaining radius of thermal influence involves complicated quadratic equation and require the use of Matlab software. Computational Method subject taken before has provided enough exposure to achieve the final result using the Matlab software.

# 2 LITERATURE REVIEW

## 2.1 RATE OF HEAT GENERATION VERSUS TIME

When cement is mixed with water, heat is produced by an exothermic reaction. This amount of heat is affected by chemical composition of the cement, additives and ambient temperature. It was observed that a quadratic equation can be used for short intervals of time to approximate the rate of heat generation (q) per unit of length as a function of time. [1], [2], [4]. Then

$$q = \pi({r_w}^2 - {r_c}^2)\rho_c q_r q_D \tag{1}$$

and

$$q_D = a_0 + a_1 t + a_2 t^2 \quad , \tag{2}$$

where $r_w$ is the well radius, $r_c$ is the outside radius of casing, $\rho_c$ is the density of cement, $q_r$ is the reference rate of heat generation per unit mass, $q_D$ is the dimensionless rate of heat generation, and $a_0$, $a_1$, $a_2$ are coefficients. The rate of heat generation together with the amount of heat transferred from the formation into the slurries is the parameters required for the project. These parameters can lead to the estimation of time taken for the cement to achieve acceptable strength. This study will help the developers to save waiting time during drilling.

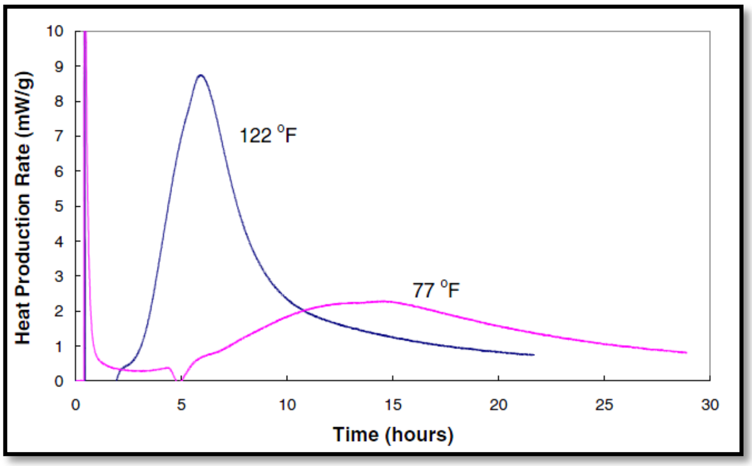



Figure 3: Heat production rate per unit of mass as a function of time for class "G" neat cement at 2 different temperatures [4]

## 2.2 TEMPERATURE INCREASE AT CEMENT HYDRATION

Temperature surveys following the cementing operation are used in order to locate the top of the cement column behind casing. The temperature of well casings increases significantly due to heat generation during cement hydration, which may lead to the development of thermal stresses in the casing strings and the cement behind them. The maximum value of heat generation occurs during the first 5 to 15hours [4]. Eq. (3) is a semi-analytical formula which enables to estimate the temperature increases versus setting time [3]. The radial heat flow rate at the surface of the cylinder is a quadratic function of time.

$$\Delta T = T_V(t) - T_i = \frac{A_0}{2\pi\lambda}[a_0G_0(t) + a_1G_1(t) + a_2G_2(t)], \tag{3}$$

$$G_0(t) = ln\frac{(b+2d\sqrt{t})^2}{b(b+d\sqrt{t})},$$

$$G_1(t) = -\ln(b)\left(t+\frac{B}{2}\right) - \frac{1}{2}t + \ln\left(b+2d\sqrt{t}\right)\left(2t+\frac{B}{2}\right) + \ln\left(b+2d\sqrt{t}\right)(B-t),$$

$$G_2(t) = -\ln(b)\left(t^2-\frac{7}{8}B^2+Bt\right) - \frac{1}{4}(3t^2+Bt) + \frac{3}{4}B\sqrt{Bt} + \ln\left(b+2d\sqrt{t}\right)\left(2t^2+\frac{1}{8}B^2 - Bt\right) - \ln\left(b+\sqrt{t}\right)(t-B)^2,$$

$$b = 2.6691, d = \frac{\sqrt{a}}{r_w}, B = \frac{b^2}{d^2},$$

$$t = t^* - t_0.$$

Where $T_V$ is the transient temperature at the cylinder's wall, $T_i$ is the initial temperature of formations, $a$ is the thermal diffusivity of formations, $\lambda$ is thermal conductivity of formations, $t^*$ is the time since cement slurry placement, $t_0$ is the time interval due to cement retardation. Therefore, the cement hydration starts at $t = 0$.

## 2.3 RADIUS OF THERMAL INFLUENCE AS CEMENTING

Thermal balance method is used to evaluate the value of radius of thermal influence, $R_{in}$ for the cement hydration period. This parameter will allow estimating the degree of thermal disturbance created by the heat of the cement hydration. The dimensionless temperature distribution around the wellbore during drilling circulation can be approximated by eq. (4), (5) and (6).

$$\left\{\begin{array}{l} T_D(r_D, t_D) = \frac{T(r,t)-T_f}{T_w-T_f} = 1 - \frac{\ln r_D}{\ln R_{in}}, \\ R_{in} = \frac{r_{in}}{r_w}, r_D = \frac{r}{r_w}, 1 \leq r_D < R_{in}. \end{array}\right\} \quad (4)$$

$$t_D = \frac{at}{{r_w}^2} = \frac{\lambda t}{c_p \rho {r_w}^2}. \quad (5)$$

The dimensionless cumulative heat flow rate from the wellbore per unit of length $(Q_D)$ was evaluated using eq. (6).

$$Q_D = \frac{1}{4}\frac{{R_{in}}^2 - 2\ln(R_{in}) - 1}{\ln(R_{in})}. \quad (6)$$

A quadratic function of the heat flow rate per unit length is shown through eq. (7).

$$q(t) = A_0(a_0 + a_1 t + a_2 t^2), \quad (7)$$

where $A_0$ is the reference heat flow rate per unit of length. The cumulative heat flow per unit of length is

$$Q(t) = \int_0^1 q(t)dt = q_0 t(a_0 + a_1\frac{t}{2} + a_2\frac{t^2}{3}). \quad (8)$$

The cumulative heat flow per unit of length can also be shown as

$$Q = 2\pi\rho c_p {r_w}^2(T_v - T_f)Q_D. \quad (9)$$

By combining Eqs. (3), (5), (6), (8), and (9), an equation to determine radius of thermal influence, $R_{in}$ is obtained .

$$\frac{{R_{in}}^2 - 2\ln(R_{in}) - 1}{4\ln(R_{in})} . \frac{a_0 G_0 + a_1 G_1 + a_2 G_2}{a_0 + \frac{a_1}{2}t + \frac{a_2}{3}t^2} = t_D \quad (10)$$

## 2.4 SIZE OF THE ANNULUS

It is clear from physical consideration that the maximum temperature anomaly caused by cement hydration depends on the actual well radius. When the well diameter is equal to the bit size which means a gauge well, the amount of cement slurry behind the casing can be estimated and transient temperature while cement hydration can be determined from formulas. To demonstrate the impact of annulus size on the maximum temperature increase, calculations are conducted using formulas listed below for a well drilled with a bit size of 12.250 inch and the outside diameter of casing is 8.625 inch. It was assumed that due to washouts the well diameter can be increased up to 8 inches. The rate of heat generation is presented in Figure 4, the density of cement slurry is $1874 kg/m^3$, and the surrounding wellbore formation is sandstone. The result of calculation is presented in Figure 5. As can be seen, the hole enlargement significantly affects the maximum value of $\Delta T_{ch}$.

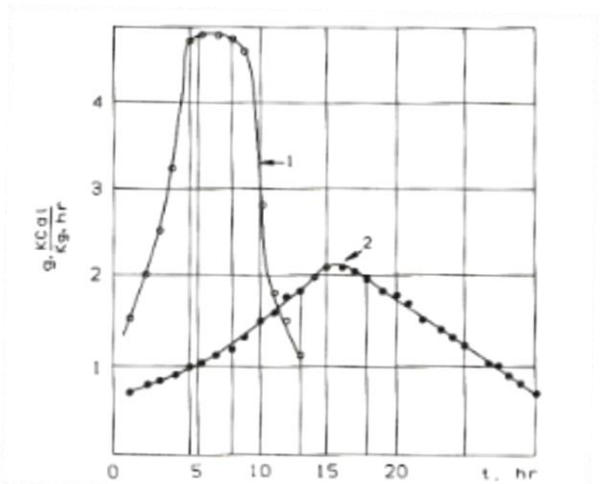



Figure 4: Rate of heat generation versus time hydration for cement

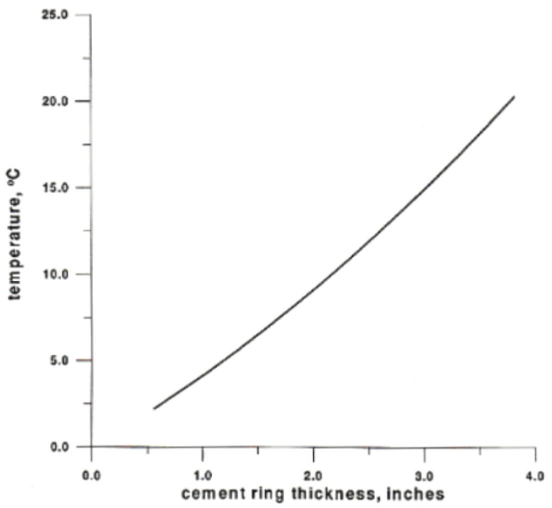



Figure 5: Maximum temperature increase versus cement ring thickness

# 3 METHODOLOGY

Methodology in this paper consists of the procedural plan to be followed or methods to be used in the study, key milestone, gantt-chart and tools.

## 3.1 PROCEDURAL PLAN

The research started by reading of books and papers related to the project. The auther started his understanding through reading the paper entitled "Cementing of Geothermal Wells" by I.M Kutasov and L.V Eppelbaum. This paper gave me the basic understanding of cementing and the parameters involved. Then, I the author referred to a book entitled "Applied Geothermics for Petroleum Engineers" by I.M. Kutasov to read about the heat transfer through porous medium. Various books and papers related to hydration heat on cement and well cementing were also used as literature review.

After a good understanding of the main idea and the parameters involved throughout the project, equations are derived and used to find the result for this paper. Matlab software is used to solve the complicated quadratic equation which involves ln function.

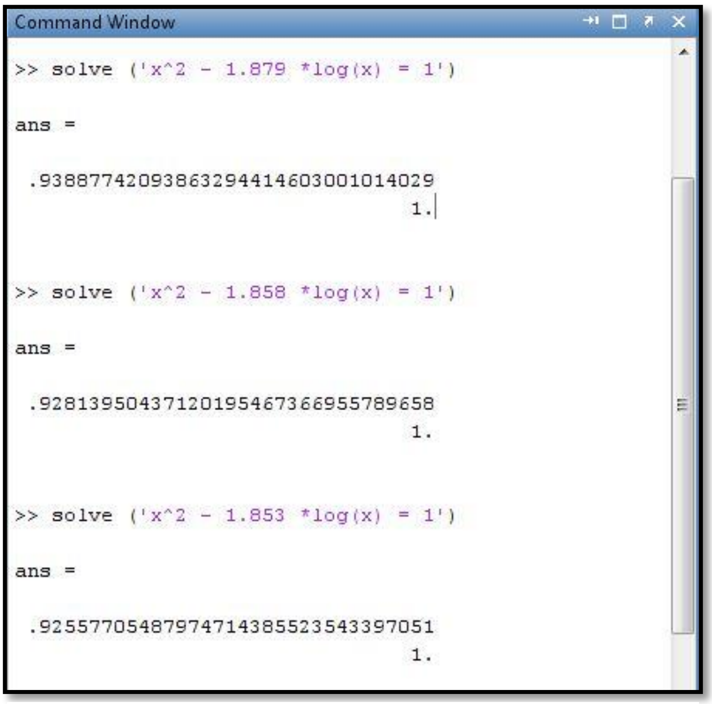
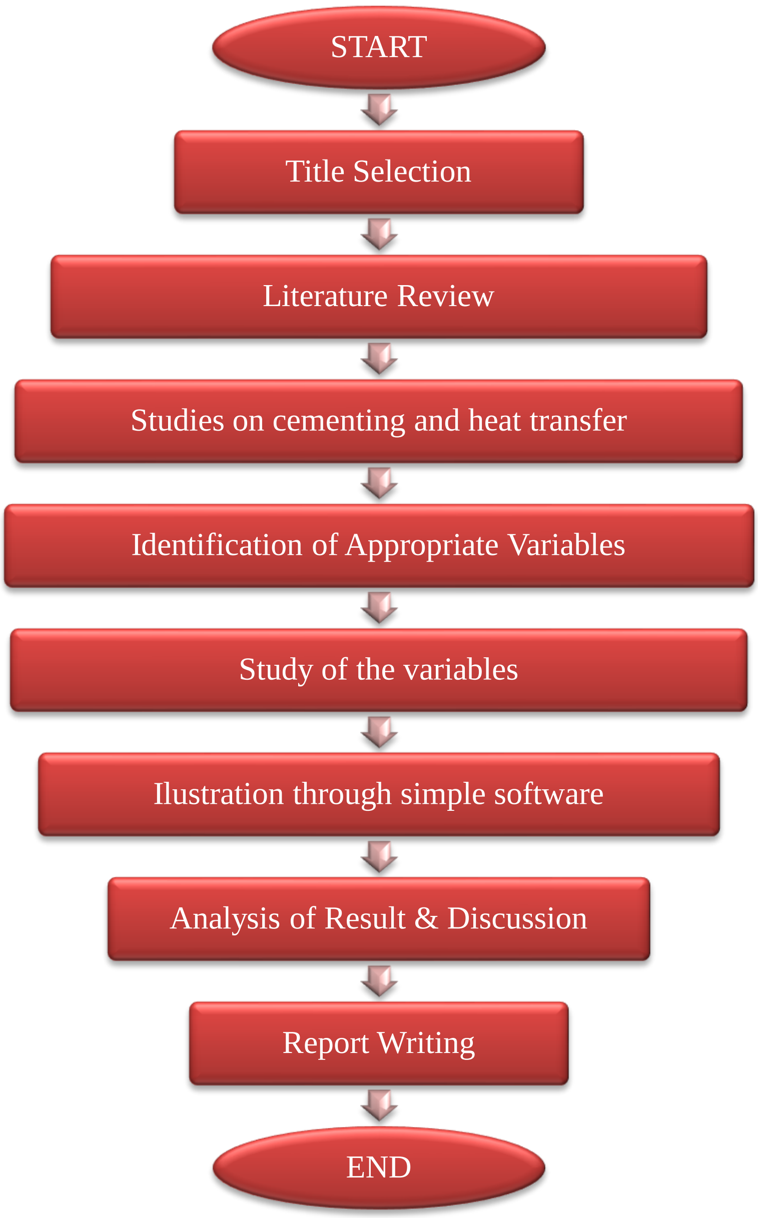


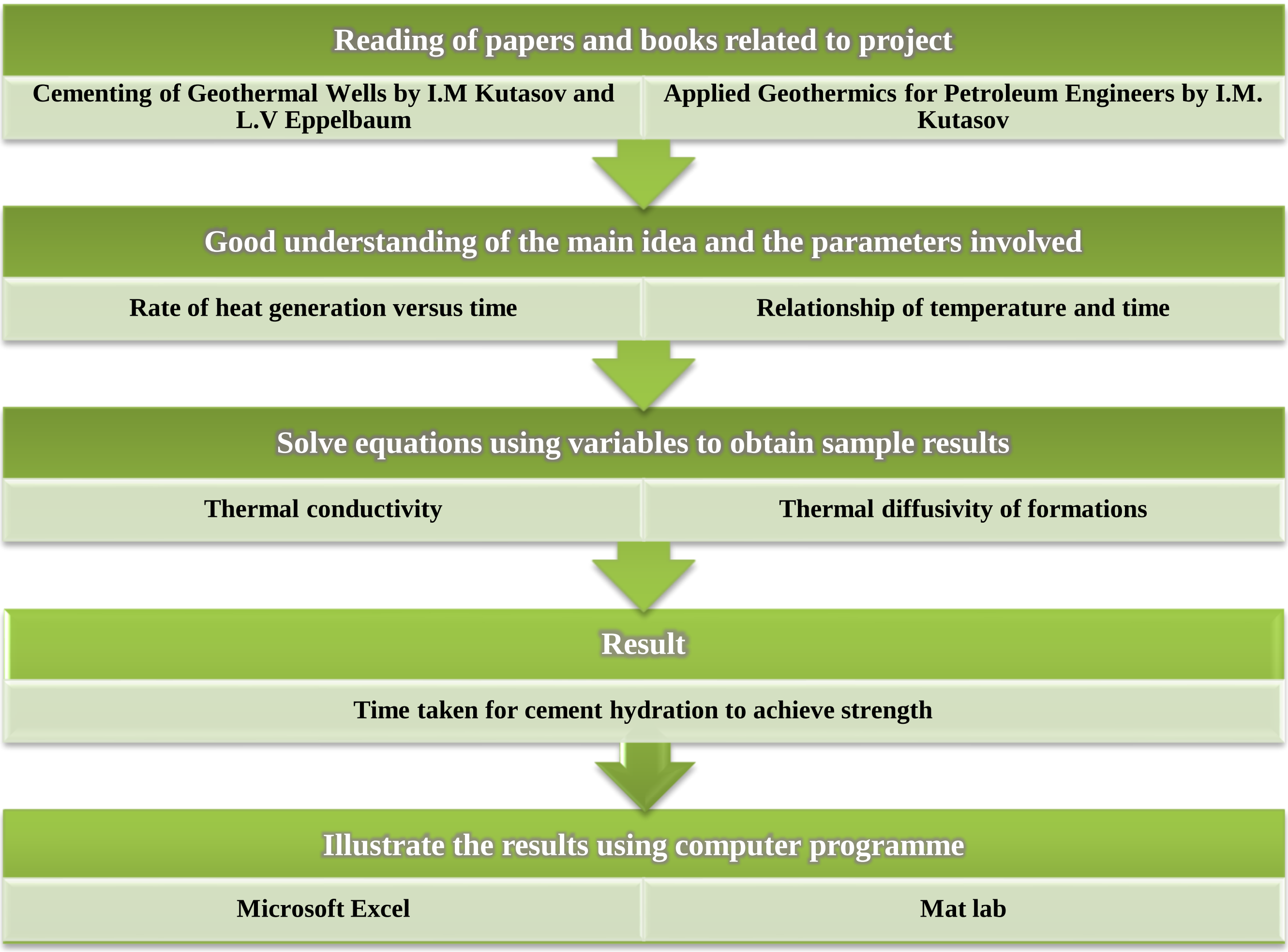

Figure 6: The calculation using Matlab

## 3.2 PROCESS FLOW

Below is the process flow diagram for the Project throughout Final Year Project 1(FYP1) and Final Year 2(FYP2) period. This diagram summarize the project flow and describe the activities or task that have been done and going to be done during the Final Year Project period. This is very important in order to make sure the project is going on the correct path and to know the work that have been left and have to be done in the future.



## 3.3 PROJECT WORK



## 3.4 KEY MILESTONES

The key milestone for Final Year Project consists of research which includes all the required work done to complete the project and administrative which includes the time given by administration to complete tasks such as the progress report and final report. The following is the tabulation of the key milestone of FYP 1 and FYP 2.

| **Event or Deliverable** | **Week** | **Responsibility** |
|---|---|---|
| **Project Selection and Acceptance by Supervisor** | Week 1-2 | Discuss the project topic and approval of topic from Supervisor. |
| **Project execution initiated** | Week 2-5 | Research of project. Understanding theories such as drilling, cementing and heat transfer. |
| **Submission of Extended Proposal** | Week 6 | Submission of Extended Proposal to FYP Coordinator |
| **Proposal Defence (Seminar Presentation)** | Week 8-9 | Report on the progress of project to supervisor, fellow students and other lecturer. |
| **Project execution continued** | Week 10-12 | Continue on project activities |
| **Submission of Interim Report** | Week 14 | Hand in Interim Report to FYP Coordinator |
| **FYP 2** | | |

Table 1: FYP 1 key milestone

| **Event or Deliverable** | **Week** | **Responsibility** |
|---|---|---|
| **Project execution continued** | Week 1-7 | Obtaining data and results using Microsoft Excel. |
| **Submission of progress report** | Week 8 | Submission of Progress Report to FYP Supervisor |
| **Project execution continued** | Week 9 | Project continued by testing of different parameters as variables. |
| **Pre-SEDEX** | Week 10 | Explain verbally to the audience through poster |
| **Submission of Draft report** | Week 11 | Submission of the Final draft report to FYP Supervisor |
| **Submission of Dissertation (soft bound) and Technical Paper** | Week 12 | Hand in Final Report in soft copy and Technical Paper to FYP Coordinator |
| **Oral Presentation (viva)** | Week 13 | Verbally report the result and outcome to the Supervisor and External Examiner |
| **Submission of Project Dissertation** | Week 14 | Hand in Final Report to FYP Coordinator |

Table 2: FYP 2 key milestone

## 3.5 GANTT CHART

| No. | Details / Weeks | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Selection of Project Topic | | | | | | | | MID SEM BREAK | | | | | | | |
| 2 | Preliminary Research work<br>i. Literature reviews<br>ii. Understanding the parameters | | | | | | | | | | | | | | | |
| 3 | Submission of Extended Proposal | | | | | | | ● | | | | | | | | |
| | Proposal Defence | | | | | | | | | | | | | | | |
| | Project work continues<br>i. Literature reviews (continue)<br>ii. Testing equations with parameters<br>iii. Further analysis of the different formations | | | | | | | | | | | | | | | |
| | Submission of Interim Draft Report | | | | | | | | | | | | | | ● | |
| | Submission of Interim Report | | | | | | | | | | | | | | | ● |

Table 3: FYP 1 Project Gantt Chart

| No. | Details / Weeks | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Project Work Continues | ■ | ■ | ■ | ■ | ■ | ■ | ■ | MID SEM BREAK | | | | | | | |
| 2 | Submission of Progress Report | | | | | | | | | ● | | | | | | |
| 3 | Project Work Continues | | | | | | | | | ■ | ■ | ■ | ■ | | | |
| 4 | Pre-SEDEX | | | | | | | | | | | ● | | | | |
| 5 | Submission of Draft Report | | | | | | | | | | | | ● | | | |
| 6 | Submission of Dissertion (soft bound) | | | | | | | | | | | | | ● | | |
| 7 | Submission of Technical Paper | | | | | | | | | | | | | ● | | |
| 8 | Oral Presentation (viva) | | | | | | | | | | | | | | ● | |
| 9 | Submission of Project Dissertation (hard bound) | | | | | | | | | | | | | | | ● |

| | |
|---|---|
| ■ | Process |
| ● | Suggested Milestone |

Table 4: FYP 2 Project Gantt Chart

## 3.6 TOOLS REQUIRED

The tools required for the project is Microsoft Word for the purpose of doing all the documentations, Microsoft Power Point for the purpose of doing project presentations. Besides that, programming software will be used to generate the results of the project using the codes developed. The software that will be use is C++ and Matlab. The following parameters will be used to show the results in the software.

Table 5: Variable parameters

| **Primary sediment or rock** | **Thermal conductivity coefficient $\lambda$, W/(m.k)** | **Diffusivity coefficient $a$, $10^{-7}m^2/s$** |
|---|---|---|
| **Sand:** | | 2.54-20.43 |
| **Dry** | 0.18-3.49 | |
| **Moist** | 1.63-4.75 | |
| **Oil-saturated** | 2.3-4.28 | |
| **Sandstone:** | | 2.54-20.43 |
| **Dry** | 0.67-6.49 | |
| **Moist** | 1.1-7.41 | |
| **Oil-saturated** | 0.84-4.24 | |
| **Limestone:** | | |
| **Dry** | 0.69-2.51 | 3.91-16.94 |
| **Moist** | 0.92-4.4 | 7.8-12.0 |
| **Dolomite** | 1.63-6.5 | 8.26-16.8 |

## 3.7 KNOWLEDGE REQUIRED

There are several things that need to be understood in order to conduct the project successfully. They are:

1. Understanding the process of cementing
2. Understand the heat transfer involved between cement and formation
3. Understanding the relationship between temperature and time taken for cement hydration.
4. Understanding the study of radius of thermal influence.
5. Understanding the parameters involved in estimating the time taken.

Thus several papers and several books need to be referred to understand all the topics that are given above and one of the main book is "Applied Geothermics for Petroleum Engineers" by I. M. Kutasov.

# 4 RESULTS AND DISCUSSION

## 4.1 DATA GATHERING

The data required for the research is gathered from the references mentioned in the previous chapter. The main parameters to be used are thermal conductivity coefficient and diffusivity coefficient listed as follows which shows different values for different formations.

Table 6: Thermal conductivity and coefficient

| **Primary sediment or rock** | **Thermal conductivity coefficient $\lambda$, W/(m.k)** | **Diffusivity coefficient $a$, $10^{-7} m^2/s$** |
|---|---|---|
| Sand: | | 2.54-20.43 |
| Dry | 0.18-3.49 | |
| Moist | 1.63-4.75 | |
| Oil-saturated | 2.3-4.28 | |
| Sandstone: | | 2.54-20.43 |
| Dry | 0.67-6.49 | |
| Moist | 1.1-7.41 | |
| Oil-saturated | 0.84-4.24 | |
| Limestone: | | |
| Dry | 0.69-2.51 | 3.91-16.94 |
| Moist | 0.92-4.4 | 7.8-12.0 |
| Dolomite | 1.63-6.5 | 8.26-16.8 |

To understand the relationship between temperature and time taken for the cement hydration the values of quadratic function of time and also radius of thermal influence at different time need to be obtained. The main equation used is; Equation[10]:

$$\frac{{R_{in}}^2 - 2\ln(R_{in}) - 1}{4\ln(R_{in})} \cdot \frac{a_0 G_0 + a_1 G_1 + a_2 G_2}{a_0 + \frac{a_1}{2} t + \frac{a_2}{3} t^2} = t_D$$

Where by $R_{in}$ is radius of thermal influence, $t_D$ is the dimensionless time, $t$ is time, $a_0$, $a_1$, and $a_2$ is constants and $G_0$, $G_1$, and $G_2$ is functions represented by equation in following page.

$$G_0(t) = ln \frac{(b+2d\sqrt{t})^2}{b(b+d\sqrt{t})},$$

$$G_1(t) = -\ln(b)\left(t+\frac{B}{2}\right) - \frac{1}{2}t + \ln\left(b+2d\sqrt{t}\right)\left(2t+\frac{B}{2}\right) +$$
$$\ln\left(b+2d\sqrt{t}\right)(B-t),$$

$$G_2(t) = -\ln(b)\left(t^2-\frac{7}{8}B^2+Bt\right) - \frac{1}{4}(3t^2+Bt) + \frac{3}{4}B\sqrt{Bt} +$$
$$\ln\left(b+2d\sqrt{t}\right)\left(2t^2+\frac{1}{8}B^2-Bt\right) - \ln\left(b+\sqrt{t}\right)(t-B)^2,$$

$$b = 2.6691, d = \frac{\sqrt{a}}{r_w}, B = \frac{b^2}{d^2},$$

$$t_D = \frac{at}{{r_w}^2} = \frac{\lambda t}{c_p \rho {r_w}^2}$$

Table 7 : Constant values

| $a_0$ | $a_1$ | $a_2$ |
|---|---|---|
| 0.2211 | 0.4296 | -0.0228 |

The equations and values above are used to tabulate the results using Microsoft excel to meet the objective of the research.

## 4.2 RESULT TABULATION

### 4.2.1 SAND

The tabulation of dimensionless time for the sand formation.

Table 8: Sand dimensionless time

| $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $c_p\ (\frac{kJ}{kg.K})$ | $r_w\ (m)$ | $r_w{}^2\ (m^2)$ | $\rho\ (\frac{kg}{m^3})$ | $t_D$ |
|---|---|---|---|---|---|---|
| 1.835 | 1 | 2.01 | 0.127 | 0.016129 | 1874 | 0.030204 |
| 1.835 | 2 | 2.01 | 0.127 | 0.016129 | 1874 | 0.060408 |
| 1.835 | 3 | 2.01 | 0.127 | 0.016129 | 1874 | 0.090612 |
| 1.835 | 4 | 2.01 | 0.127 | 0.016129 | 1874 | 0.120816 |
| 1.835 | 5 | 2.01 | 0.127 | 0.016129 | 1874 | 0.151019 |
| 1.835 | 6 | 2.01 | 0.127 | 0.016129 | 1874 | 0.181223 |
| 1.835 | 7 | 2.01 | 0.127 | 0.016129 | 1874 | 0.211427 |
| 1.835 | 8 | 2.01 | 0.127 | 0.016129 | 1874 | 0.241631 |
| 1.835 | 9 | 2.01 | 0.127 | 0.016129 | 1874 | 0.271835 |
| 1.835 | 10 | 2.01 | 0.127 | 0.016129 | 1874 | 0.302039 |
| 1.835 | 11 | 2.01 | 0.127 | 0.016129 | 1874 | 0.332243 |
| 1.835 | 12 | 2.01 | 0.127 | 0.016129 | 1874 | 0.362447 |
| 1.835 | 13 | 2.01 | 0.127 | 0.016129 | 1874 | 0.392651 |
| 1.835 | 14 | 2.01 | 0.127 | 0.016129 | 1874 | 0.422855 |
| 1.835 | 15 | 2.01 | 0.127 | 0.016129 | 1874 | 0.453058 |
| 1.835 | 16 | 2.01 | 0.127 | 0.016129 | 1874 | 0.483262 |
| 1.835 | 17 | 2.01 | 0.127 | 0.016129 | 1874 | 0.513466 |
| 1.835 | 18 | 2.01 | 0.127 | 0.016129 | 1874 | 0.54367 |
| 1.835 | 19 | 2.01 | 0.127 | 0.016129 | 1874 | 0.573874 |
| 1.835 | 20 | 2.01 | 0.127 | 0.016129 | 1874 | 0.604078 |
| 1.835 | 21 | 2.01 | 0.127 | 0.016129 | 1874 | 0.634282 |
| 1.835 | 22 | 2.01 | 0.127 | 0.016129 | 1874 | 0.664486 |
| 1.835 | 23 | 2.01 | 0.127 | 0.016129 | 1874 | 0.69469 |
| 1.835 | 24 | 2.01 | 0.127 | 0.016129 | 1874 | 0.724894 |
| 1.835 | 25 | 2.01 | 0.127 | 0.016129 | 1874 | 0.755097 |
| 1.835 | 26 | 2.01 | 0.127 | 0.016129 | 1874 | 0.785301 |
| 1.835 | 27 | 2.01 | 0.127 | 0.016129 | 1874 | 0.815505 |
| 1.835 | 28 | 2.01 | 0.127 | 0.016129 | 1874 | 0.845709 |
| 1.835 | 29 | 2.01 | 0.127 | 0.016129 | 1874 | 0.875913 |
| 1.835 | 30 | 2.01 | 0.127 | 0.016129 | 1874 | 0.906117 |

The tabulation of G function which is required to obtain radius of thermal influence for the sand formation.

Table 9: Sand G function

| $a\ (\frac{m^2}{hr})$ | $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $d$ | $B$ | $G_0$ | $G_1$ | $G_2$ |
|---|---|---|---|---|---|---|---|
| 0.004135 | 1.835 | 1 | 0.506306 | 27.79097 | 0.469579 | - | 36.48471 |
| 0.004135 | 1.835 | 2 | 0.506306 | 27.79097 | 0.621402 | - | 79.87843 |
| 0.004135 | 1.835 | 3 | 0.506306 | 27.79097 | 0.726059 | - | 127.8075 |
| 0.004135 | 1.835 | 4 | 0.506306 | 27.79097 | 0.807589 | - | 179.6037 |
| 0.004135 | 1.835 | 5 | 0.506306 | 27.79097 | 0.874977 | - | 234.9504 |
| 0.004135 | 1.835 | 6 | 0.506306 | 27.79097 | 0.932695 | - | 293.6729 |
| 0.004135 | 1.835 | 7 | 0.506306 | 27.79097 | 0.983329 | -3.67994 | 355.6685 |
| 0.004135 | 1.835 | 8 | 0.506306 | 27.79097 | 1.028524 | -1.21668 | 420.8751 |
| 0.004135 | 1.835 | 9 | 0.506306 | 27.79097 | 1.069396 | -1.09331 | 489.2559 |
| 0.004135 | 1.835 | 10 | 0.506306 | 27.79097 | 1.106741 | -1.24599 | 560.7902 |
| 0.004135 | 1.835 | 11 | 0.506306 | 27.79097 | 1.14115 | -1.51703 | 635.4686 |
| 0.004135 | 1.835 | 12 | 0.506306 | 27.79097 | 1.173072 | -1.85576 | 713.2893 |
| 0.004135 | 1.835 | 13 | 0.506306 | 27.79097 | 1.202857 | -2.23949 | 794.256 |
| 0.004135 | 1.835 | 14 | 0.506306 | 27.79097 | 1.230787 | -2.65629 | 878.3765 |
| 0.004135 | 1.835 | 15 | 0.506306 | 27.79097 | 1.257087 | -3.09933 | 965.6612 |
| 0.004135 | 1.835 | 16 | 0.506306 | 27.79097 | 1.281946 | -3.56458 | 1056.123 |
| 0.004135 | 1.835 | 17 | 0.506306 | 27.79097 | 1.305519 | -4.04975 | 1149.776 |
| 0.004135 | 1.835 | 18 | 0.506306 | 27.79097 | 1.327938 | -4.55384 | 1246.636 |
| 0.004135 | 1.835 | 19 | 0.506306 | 27.79097 | 1.349313 | -5.07693 | 1346.719 |
| 0.004135 | 1.835 | 20 | 0.506306 | 27.79097 | 1.369742 | -5.62017 | 1450.043 |
| 0.004135 | 1.835 | 21 | 0.506306 | 27.79097 | 1.389308 | -6.18611 | 1556.624 |
| 0.004135 | 1.835 | 22 | 0.506306 | 27.79097 | 1.408082 | -6.7792 | 1666.48 |
| 0.004135 | 1.835 | 23 | 0.506306 | 27.79097 | 1.426128 | -7.40711 | 1779.63 |
| 0.004135 | 1.835 | 24 | 0.506306 | 27.79097 | 1.443503 | -8.08356 | 1896.091 |
| 0.004135 | 1.835 | 25 | 0.506306 | 27.79097 | 1.460255 | -8.83565 | 2015.881 |
| 0.004135 | 1.835 | 26 | 0.506306 | 27.79097 | 1.47643 | -9.72827 | 2139.018 |
| 0.004135 | 1.835 | 27 | 0.506306 | 27.79097 | 1.492067 | -10.9973 | 2265.52 |
| 0.004135 | 1.835 | 28 | 0.506306 | 27.79097 | 1.507201 | - | 2395.405 |
| 0.004135 | 1.835 | 29 | 0.506306 | 27.79097 | 1.521865 | - | 2528.691 |
| 0.004135 | 1.835 | 30 | 0.506306 | 27.79097 | 1.536088 | - | 2665.396 |

The tabulation of time and the radius of thermal influence for sand formation

Table 10: Radius of thermal influence of sand

| $\boldsymbol{R_{in}}$ | $\boldsymbol{t(hr)}$ |
|---|---|
| 0.9388 | 7 |
| 0.9281 | 8 |
| 0.9256 | 9 |
| 0.9246 | 10 |
| 0.9246 | 11 |
| 0.9256 | 12 |
| 0.9271 | 13 |
| 0.9286 | 14 |
| 0.9312 | 15 |
| 0.9337 | 16 |
| 0.9373 | 17 |
| 0.9409 | 18 |
| 0.9445 | 19 |
| 0.9491 | 20 |
| 0.9531 | 21 |
| 0.9582 | 22 |
| 0.9633 | 23 |
| 0.9688 | 24 |
| 0.9744 | 25 |
| 0.9799 | 26 |
| 0.986 | 27 |

### 4.2.2 SANDSTONE

The tabulation of dimensionless time for the sandstone formation.

Table 11: Sandstone dimensionless time

| $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $c_p\ (\frac{kJ}{kg.K})$ | $r_w\ (m)$ | $r_w{}^2\ (m^2)$ | $\rho\ (\frac{kg}{m^3})$ | $t_D$ |
|---|---|---|---|---|---|---|
| 2.775 | 1 | 2.01 | 0.127 | 0.016129 | 1874 | 0.045676 |
| 2.775 | 2 | 2.01 | 0.127 | 0.016129 | 1874 | 0.091352 |
| 2.775 | 3 | 2.01 | 0.127 | 0.016129 | 1874 | 0.137029 |
| 2.775 | 4 | 2.01 | 0.127 | 0.016129 | 1874 | 0.182705 |
| 2.775 | 5 | 2.01 | 0.127 | 0.016129 | 1874 | 0.228381 |
| 2.775 | 6 | 2.01 | 0.127 | 0.016129 | 1874 | 0.274057 |
| 2.775 | 7 | 2.01 | 0.127 | 0.016129 | 1874 | 0.319733 |
| 2.775 | 8 | 2.01 | 0.127 | 0.016129 | 1874 | 0.36541 |
| 2.775 | 9 | 2.01 | 0.127 | 0.016129 | 1874 | 0.411086 |
| 2.775 | 10 | 2.01 | 0.127 | 0.016129 | 1874 | 0.456762 |
| 2.775 | 11 | 2.01 | 0.127 | 0.016129 | 1874 | 0.502438 |
| 2.775 | 12 | 2.01 | 0.127 | 0.016129 | 1874 | 0.548114 |
| 2.775 | 13 | 2.01 | 0.127 | 0.016129 | 1874 | 0.593791 |
| 2.775 | 14 | 2.01 | 0.127 | 0.016129 | 1874 | 0.639467 |
| 2.775 | 15 | 2.01 | 0.127 | 0.016129 | 1874 | 0.685143 |
| 2.775 | 16 | 2.01 | 0.127 | 0.016129 | 1874 | 0.730819 |
| 2.775 | 17 | 2.01 | 0.127 | 0.016129 | 1874 | 0.776495 |
| 2.775 | 18 | 2.01 | 0.127 | 0.016129 | 1874 | 0.822171 |
| 2.775 | 19 | 2.01 | 0.127 | 0.016129 | 1874 | 0.867848 |
| 2.775 | 20 | 2.01 | 0.127 | 0.016129 | 1874 | 0.913524 |
| 2.775 | 21 | 2.01 | 0.127 | 0.016129 | 1874 | 0.9592 |
| 2.775 | 22 | 2.01 | 0.127 | 0.016129 | 1874 | 1.004876 |
| 2.775 | 23 | 2.01 | 0.127 | 0.016129 | 1874 | 1.050552 |
| 2.775 | 24 | 2.01 | 0.127 | 0.016129 | 1874 | 1.096229 |
| 2.775 | 25 | 2.01 | 0.127 | 0.016129 | 1874 | 1.141905 |
| 2.775 | 26 | 2.01 | 0.127 | 0.016129 | 1874 | 1.187581 |
| 2.775 | 27 | 2.01 | 0.127 | 0.016129 | 1874 | 1.233257 |
| 2.775 | 28 | 2.01 | 0.127 | 0.016129 | 1874 | 1.278933 |
| 2.775 | 29 | 2.01 | 0.127 | 0.016129 | 1874 | 1.32461 |
| 2.775 | 30 | 2.01 | 0.127 | 0.016129 | 1874 | 1.370286 |

The tabulation of G function which is required to obtain radius of thermal influence for the sandstone formation.

Table 12: Sandstone G function

| $a\ (\frac{m^2}{hr})$ | $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $d$ | $B$ | $G_0$ | $G_1$ | $G_2$ |
|---|---|---|---|---|---|---|---|
| 0.0041346 | 2.775 | 1 | 0.506306 | 27.79096531 | 0.469579 | - | 36.48471 |
| 0.0041346 | 2.775 | 2 | 0.506306 | 27.79096531 | 0.621402 | - | 79.87843 |
| 0.0041346 | 2.775 | 3 | 0.506306 | 27.79096531 | 0.726059 | - | 127.8075 |
| 0.0041346 | 2.775 | 4 | 0.506306 | 27.79096531 | 0.807589 | - | 179.6037 |
| 0.0041346 | 2.775 | 5 | 0.506306 | 27.79096531 | 0.874977 | - | 234.9504 |
| 0.0041346 | 2.775 | 6 | 0.506306 | 27.79096531 | 0.932695 | - | 293.6729 |
| 0.0041346 | 2.775 | 7 | 0.506306 | 27.79096531 | 0.983329 | -3.67994 | 355.6685 |
| 0.0041346 | 2.775 | 8 | 0.506306 | 27.79096531 | 1.028524 | -1.21668 | 420.8751 |
| 0.0041346 | 2.775 | 9 | 0.506306 | 27.79096531 | 1.069396 | -1.09331 | 489.2559 |
| 0.0041346 | 2.775 | 10 | 0.506306 | 27.79096531 | 1.106741 | -1.24599 | 560.7902 |
| 0.0041346 | 2.775 | 11 | 0.506306 | 27.79096531 | 1.14115 | -1.51703 | 635.4686 |
| 0.0041346 | 2.775 | 12 | 0.506306 | 27.79096531 | 1.173072 | -1.85576 | 713.2893 |
| 0.0041346 | 2.775 | 13 | 0.506306 | 27.79096531 | 1.202857 | -2.23949 | 794.256 |
| 0.0041346 | 2.775 | 14 | 0.506306 | 27.79096531 | 1.230787 | -2.65629 | 878.3765 |
| 0.0041346 | 2.775 | 15 | 0.506306 | 27.79096531 | 1.257087 | -3.09933 | 965.6612 |
| 0.0041346 | 2.775 | 16 | 0.506306 | 27.79096531 | 1.281946 | -3.56458 | 1056.123 |
| 0.0041346 | 2.775 | 17 | 0.506306 | 27.79096531 | 1.305519 | -4.04975 | 1149.776 |
| 0.0041346 | 2.775 | 18 | 0.506306 | 27.79096531 | 1.327938 | -4.55384 | 1246.636 |
| 0.0041346 | 2.775 | 19 | 0.506306 | 27.79096531 | 1.349313 | -5.07693 | 1346.719 |
| 0.0041346 | 2.775 | 20 | 0.506306 | 27.79096531 | 1.369742 | -5.62017 | 1450.043 |
| 0.0041346 | 2.775 | 21 | 0.506306 | 27.79096531 | 1.389308 | -6.18611 | 1556.624 |
| 0.0041346 | 2.775 | 22 | 0.506306 | 27.79096531 | 1.408082 | -6.7792 | 1666.48 |
| 0.0041346 | 2.775 | 23 | 0.506306 | 27.79096531 | 1.426128 | -7.40711 | 1779.63 |
| 0.0041346 | 2.775 | 24 | 0.506306 | 27.79096531 | 1.443503 | -8.08356 | 1896.091 |
| 0.0041346 | 2.775 | 25 | 0.506306 | 27.79096531 | 1.460255 | -8.83565 | 2015.881 |
| 0.0041346 | 2.775 | 26 | 0.506306 | 27.79096531 | 1.47643 | -9.72827 | 2139.018 |
| 0.0041346 | 2.775 | 27 | 0.506306 | 27.79096531 | 1.492067 | -10.9973 | 2265.52 |
| 0.0041346 | 2.775 | 28 | 0.506306 | 27.79096531 | 1.507201 | - | 2395.405 |
| 0.0041346 | 2.775 | 29 | 0.506306 | 27.79096531 | 1.521865 | - | 2528.691 |
| 0.0041346 | 2.775 | 30 | 0.506306 | 27.79096531 | 1.536088 | - | 2665.396 |

The tabulation of time and the radius of thermal influence for sandstone formation

Table 13: Radius of thermal influence of sandstone

| $\boldsymbol{R_{in}}$ | $\boldsymbol{t(hr)}$ |
|---|---|
| 0.9071 | 7 |
| 0.8905 | 8 |
| 0.8874 | 9 |
| 0.8853 | 10 |
| 0.8853 | 11 |
| 0.8869 | 12 |
| 0.8889 | 13 |
| 0.8915 | 14 |
| 0.8952 | 15 |
| 0.8993 | 16 |
| 0.9045 | 17 |
| 0.9096 | 18 |
| 0.9158 | 19 |
| 0.9225 | 20 |
| 0.9292 | 21 |
| 0.9363 | 22 |
| 0.9445 | 23 |
| 0.9526 | 24 |
| 0.9607 | 25 |
| 0.9698 | 26 |
| 0.9789 | 27 |

### 4.2.3 LIMESTONE

The tabulation of dimensionless time for the limestone formation.

Table 14: Limestone dimensionless time

| $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $c_p\ (\frac{kJ}{kg.K})$ | $r_w\ (m)$ | ${r_w}^2\ (m^2)$ | $\rho\ (\frac{kg}{m^3})$ | $t_D$ |
|---|---|---|---|---|---|---|
| 1.6 | 1 | 1.066 | 0.127 | 0.016129 | 1874 | 0.049658 |
| 1.6 | 2 | 1.066 | 0.127 | 0.016129 | 1874 | 0.099315 |
| 1.6 | 3 | 1.066 | 0.127 | 0.016129 | 1874 | 0.148973 |
| 1.6 | 4 | 1.066 | 0.127 | 0.016129 | 1874 | 0.19863 |
| 1.6 | 5 | 1.066 | 0.127 | 0.016129 | 1874 | 0.248288 |
| 1.6 | 6 | 1.066 | 0.127 | 0.016129 | 1874 | 0.297946 |
| 1.6 | 7 | 1.066 | 0.127 | 0.016129 | 1874 | 0.347603 |
| 1.6 | 8 | 1.066 | 0.127 | 0.016129 | 1874 | 0.397261 |
| 1.6 | 9 | 1.066 | 0.127 | 0.016129 | 1874 | 0.446918 |
| 1.6 | 10 | 1.066 | 0.127 | 0.016129 | 1874 | 0.496576 |
| 1.6 | 11 | 1.066 | 0.127 | 0.016129 | 1874 | 0.546234 |
| 1.6 | 12 | 1.066 | 0.127 | 0.016129 | 1874 | 0.595891 |
| 1.6 | 13 | 1.066 | 0.127 | 0.016129 | 1874 | 0.645549 |
| 1.6 | 14 | 1.066 | 0.127 | 0.016129 | 1874 | 0.695206 |
| 1.6 | 15 | 1.066 | 0.127 | 0.016129 | 1874 | 0.744864 |
| 1.6 | 16 | 1.066 | 0.127 | 0.016129 | 1874 | 0.794522 |
| 1.6 | 17 | 1.066 | 0.127 | 0.016129 | 1874 | 0.844179 |
| 1.6 | 18 | 1.066 | 0.127 | 0.016129 | 1874 | 0.893837 |
| 1.6 | 19 | 1.066 | 0.127 | 0.016129 | 1874 | 0.943494 |
| 1.6 | 20 | 1.066 | 0.127 | 0.016129 | 1874 | 0.993152 |
| 1.6 | 21 | 1.066 | 0.127 | 0.016129 | 1874 | 1.04281 |
| 1.6 | 22 | 1.066 | 0.127 | 0.016129 | 1874 | 1.092467 |
| 1.6 | 23 | 1.066 | 0.127 | 0.016129 | 1874 | 1.142125 |
| 1.6 | 24 | 1.066 | 0.127 | 0.016129 | 1874 | 1.191782 |
| 1.6 | 25 | 1.066 | 0.127 | 0.016129 | 1874 | 1.24144 |
| 1.6 | 26 | 1.066 | 0.127 | 0.016129 | 1874 | 1.291098 |
| 1.6 | 27 | 1.066 | 0.127 | 0.016129 | 1874 | 1.340755 |
| 1.6 | 28 | 1.066 | 0.127 | 0.016129 | 1874 | 1.390413 |
| 1.6 | 29 | 1.066 | 0.127 | 0.016129 | 1874 | 1.44007 |
| 1.6 | 30 | 1.066 | 0.127 | 0.016129 | 1874 | 1.489728 |

The tabulation of G function which is required to obtain radius of thermal influence for the limestone formation.

Table 15: Limestone G function

| $a\ (\frac{m^2}{hr})$ | $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $d$ | $B$ | $G_0$ | $G_1$ | $G_2$ |
|---|---|---|---|---|---|---|---|
| 0.003753 | 1.6 | 1 | 0.482376 | 30.61671 | 0.450974 | - | 39.75637 |
| 0.003753 | 1.6 | 2 | 0.482376 | 30.61671 | 0.598167 | - | 86.77766 |
| 0.003753 | 1.6 | 3 | 0.482376 | 30.61671 | 0.699977 | - | 138.5234 |
| 0.003753 | 1.6 | 4 | 0.482376 | 30.61671 | 0.779471 | - | 194.2638 |
| 0.003753 | 1.6 | 5 | 0.482376 | 30.61671 | 0.845291 | - | 253.6464 |
| 0.003753 | 1.6 | 6 | 0.482376 | 30.61671 | 0.901744 | - | 316.4724 |
| 0.003753 | 1.6 | 7 | 0.482376 | 30.61671 | 0.951327 | - | 382.6212 |
| 0.003753 | 1.6 | 8 | 0.482376 | 30.61671 | 0.995627 | -2.29993 | 452.0169 |
| 0.003753 | 1.6 | 9 | 0.482376 | 30.61671 | 1.035724 | -1.4778 | 524.6117 |
| 0.003753 | 1.6 | 10 | 0.482376 | 30.61671 | 1.07239 | -1.46326 | 600.3761 |
| 0.003753 | 1.6 | 11 | 0.482376 | 30.61671 | 1.106195 | -1.65336 | 679.2928 |
| 0.003753 | 1.6 | 12 | 0.482376 | 30.61671 | 1.137576 | -1.94101 | 761.3536 |
| 0.003753 | 1.6 | 13 | 0.482376 | 30.61671 | 1.166874 | -2.28704 | 846.5565 |
| 0.003753 | 1.6 | 14 | 0.482376 | 30.61671 | 1.194359 | -2.67279 | 934.9043 |
| 0.003753 | 1.6 | 15 | 0.482376 | 30.61671 | 1.220254 | -3.08804 | 1026.403 |
| 0.003753 | 1.6 | 16 | 0.482376 | 30.61671 | 1.24474 | -3.52668 | 1121.062 |
| 0.003753 | 1.6 | 17 | 0.482376 | 30.61671 | 1.267968 | -3.98496 | 1218.892 |
| 0.003753 | 1.6 | 18 | 0.482376 | 30.61671 | 1.290067 | -4.46056 | 1319.904 |
| 0.003753 | 1.6 | 19 | 0.482376 | 30.61671 | 1.311146 | -4.95218 | 1424.113 |
| 0.003753 | 1.6 | 20 | 0.482376 | 30.61671 | 1.331297 | -5.45931 | 1531.533 |
| 0.003753 | 1.6 | 21 | 0.482376 | 30.61671 | 1.350603 | -5.98216 | 1642.179 |
| 0.003753 | 1.6 | 22 | 0.482376 | 30.61671 | 1.369133 | -6.5217 | 1756.066 |
| 0.003753 | 1.6 | 23 | 0.482376 | 30.61671 | 1.38695 | -7.07983 | 1873.21 |
| 0.003753 | 1.6 | 24 | 0.482376 | 30.61671 | 1.404108 | -7.65974 | 1993.627 |
| 0.003753 | 1.6 | 25 | 0.482376 | 30.61671 | 1.420655 | -8.2666 | 2117.334 |
| 0.003753 | 1.6 | 26 | 0.482376 | 30.61671 | 1.436636 | -8.90909 | 2244.346 |
| 0.003753 | 1.6 | 27 | 0.482376 | 30.61671 | 1.452089 | -9.60269 | 2374.68 |
| 0.003753 | 1.6 | 28 | 0.482376 | 30.61671 | 1.467048 | -10.3785 | 2508.353 |
| 0.003753 | 1.6 | 29 | 0.482376 | 30.61671 | 1.481545 | -11.3147 | 2645.38 |
| 0.003753 | 1.6 | 30 | 0.482376 | 30.61671 | 1.495609 | -12.7354 | 2785.779 |

The tabulation of time and the radius of thermal influence for limestone formation

Table 16: Radius of thermal influence of limestone

| $\boldsymbol{R_{in}}$ | $\boldsymbol{t(hr)}$ |
|---|---|
| 0.8936 | 8 |
| 0.8869 | 9 |
| 0.8843 | 10 |
| 0.8837 | 11 |
| 0.8849 | 12 |
| 0.8863 | 13 |
| 0.8889 | 14 |
| 0.8926 | 15 |
| 0.8967 | 16 |
| 0.9014 | 17 |
| 0.9071 | 18 |
| 0.9132 | 19 |
| 0.9194 | 20 |
| 0.9266 | 21 |
| 0.9343 | 22 |
| 0.9419 | 23 |
| 0.9506 | 24 |
| 0.9592 | 25 |
| 0.9683 | 26 |
| 0.9779 | 27 |
| 0.9875 | 28 |
| 0.9975 | 29 |
| 1.0075 | 30 |

### 4.2.4 DOLOMITE

The tabulation of dimensionless time for the dolomite formation.

Table 17: Dolomite dimensionless time

| $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $c_p\ (\frac{kJ}{kg.K})$ | $r_w\ (m)$ | ${r_w}^2\ (m^2)$ | $\rho\ (\frac{kg}{m^3})$ | $t_D$ |
|---|---|---|---|---|---|---|
| 4.065 | 1 | 1.0565 | 0.127 | 0.016129 | 1874 | 0.127296 |
| 4.065 | 2 | 1.0565 | 0.127 | 0.016129 | 1874 | 0.254592 |
| 4.065 | 3 | 1.0565 | 0.127 | 0.016129 | 1874 | 0.381887 |
| 4.065 | 4 | 1.0565 | 0.127 | 0.016129 | 1874 | 0.509183 |
| 4.065 | 5 | 1.0565 | 0.127 | 0.016129 | 1874 | 0.636479 |
| 4.065 | 6 | 1.0565 | 0.127 | 0.016129 | 1874 | 0.763775 |
| 4.065 | 7 | 1.0565 | 0.127 | 0.016129 | 1874 | 0.89107 |
| 4.065 | 8 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.018366 |
| 4.065 | 9 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.145662 |
| 4.065 | 10 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.272958 |
| 4.065 | 11 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.400254 |
| 4.065 | 12 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.527549 |
| 4.065 | 13 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.654845 |
| 4.065 | 14 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.782141 |
| 4.065 | 15 | 1.0565 | 0.127 | 0.016129 | 1874 | 1.909437 |
| 4.065 | 16 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.036733 |
| 4.065 | 17 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.164028 |
| 4.065 | 18 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.291324 |
| 4.065 | 19 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.41862 |
| 4.065 | 20 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.545916 |
| 4.065 | 21 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.673211 |
| 4.065 | 22 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.800507 |
| 4.065 | 23 | 1.0565 | 0.127 | 0.016129 | 1874 | 2.927803 |
| 4.065 | 24 | 1.0565 | 0.127 | 0.016129 | 1874 | 3.055099 |
| 4.065 | 25 | 1.0565 | 0.127 | 0.016129 | 1874 | 3.182395 |
| 4.065 | 26 | 1.0565 | 0.127 | 0.016129 | 1874 | 3.30969 |
| 4.065 | 27 | 1.0565 | 0.127 | 0.016129 | 1874 | 3.436986 |
| 4.065 | 28 | 1.0565 | 0.127 | 0.016129 | 1874 | 3.564282 |
| 4.065 | 29 | 1.0565 | 0.127 | 0.016129 | 1874 | 3.691578 |
| 4.065 | 30 | 1.0565 | 0.127 | 0.016129 | 1874 | 3.818874 |

The tabulation of G function which is required to obtain radius of thermal influence for the dolomite formation.

Table 18: Dolomite G function

| $a\ (\frac{m^2}{hr})$ | $\lambda\ (\frac{W}{mk})$ | $t(hr)$ | $d$ | $B$ | $G_0$ | $G_1$ | $G_2$ |
|---|---|---|---|---|---|---|---|
| 0.004511 | 4.065 | 1 | 0.528839 | 25.4732 | 0.48684 | - | 33.78368 |
| 0.004511 | 4.065 | 2 | 0.528839 | 25.4732 | 0.642874 | - | 74.17546 |
| 0.004511 | 4.065 | 3 | 0.528839 | 25.4732 | 0.750101 | - | 118.9455 |
| 0.004511 | 4.065 | 4 | 0.528839 | 25.4732 | 0.833459 | - | 167.4785 |
| 0.004511 | 4.065 | 5 | 0.528839 | 25.4732 | 0.90225 | - | 219.4887 |
| 0.004511 | 4.065 | 6 | 0.528839 | 25.4732 | 0.961095 | - | 274.8222 |
| 0.004511 | 4.065 | 7 | 0.528839 | 25.4732 | 1.012664 | -1.21206 | 333.3915 |
| 0.004511 | 4.065 | 8 | 0.528839 | 25.4732 | 1.058653 | -0.80998 | 395.1463 |
| 0.004511 | 4.065 | 9 | 0.528839 | 25.4732 | 1.100211 | -0.88489 | 460.0592 |
| 0.004511 | 4.065 | 10 | 0.528839 | 25.4732 | 1.138157 | -1.1215 | 528.1174 |
| 0.004511 | 4.065 | 11 | 0.528839 | 25.4732 | 1.173098 | -1.44272 | 599.3178 |
| 0.004511 | 4.065 | 12 | 0.528839 | 25.4732 | 1.205496 | -1.81768 | 673.6643 |
| 0.004511 | 4.065 | 13 | 0.528839 | 25.4732 | 1.235711 | -2.23115 | 751.1654 |
| 0.004511 | 4.065 | 14 | 0.528839 | 25.4732 | 1.264031 | -2.67482 | 831.833 |
| 0.004511 | 4.065 | 15 | 0.528839 | 25.4732 | 1.290688 | -3.14402 | 915.6814 |
| 0.004511 | 4.065 | 16 | 0.528839 | 25.4732 | 1.315874 | -3.63637 | 1002.727 |
| 0.004511 | 4.065 | 17 | 0.528839 | 25.4732 | 1.339749 | -4.15115 | 1092.986 |
| 0.004511 | 4.065 | 18 | 0.528839 | 25.4732 | 1.362447 | -4.68914 | 1186.478 |
| 0.004511 | 4.065 | 19 | 0.528839 | 25.4732 | 1.384082 | -5.25286 | 1283.222 |
| 0.004511 | 4.065 | 20 | 0.528839 | 25.4732 | 1.404754 | -5.84722 | 1383.235 |
| 0.004511 | 4.065 | 21 | 0.528839 | 25.4732 | 1.424546 | -6.48107 | 1486.539 |
| 0.004511 | 4.065 | 22 | 0.528839 | 25.4732 | 1.443532 | -7.171 | 1593.152 |
| 0.004511 | 4.065 | 23 | 0.528839 | 25.4732 | 1.461779 | -7.95166 | 1703.095 |
| 0.004511 | 4.065 | 24 | 0.528839 | 25.4732 | 1.479342 | -8.91453 | 1816.386 |
| 0.004511 | 4.065 | 25 | 0.528839 | 25.4732 | 1.496273 | -10.4983 | 1933.046 |
| 0.004511 | 4.065 | 26 | 0.528839 | 25.4732 | 1.512617 | - | 2053.093 |
| 0.004511 | 4.065 | 27 | 0.528839 | 25.4732 | 1.528413 | - | 2176.548 |
| 0.004511 | 4.065 | 28 | 0.528839 | 25.4732 | 1.543699 | - | 2303.429 |
| 0.004511 | 4.065 | 29 | 0.528839 | 25.4732 | 1.558508 | - | 2433.755 |
| 0.004511 | 4.065 | 30 | 0.528839 | 25.4732 | 1.572868 | - | 2567.544 |

The tabulation of time and the radius of thermal influence for dolomite formation

Table 19: Radius of thermal influence of dolomite

| $\boldsymbol{R_{in}}$ | $\boldsymbol{t}(\boldsymbol{hr})$ |
|---|---|
| 0.6778 | 7 |
| 0.6559 | 8 |
| 0.6474 | 9 |
| 0.6451 | 10 |
| 0.6468 | 11 |
| 0.6519 | 12 |
| 0.6593 | 13 |
| 0.6694 | 14 |
| 0.6817 | 15 |
| 0.6956 | 16 |
| 0.7117 | 17 |
| 0.7288 | 18 |
| 0.7479 | 19 |
| 0.7681 | 20 |
| 0.7896 | 21 |
| 0.8124 | 22 |
| 0.8361 | 23 |
| 0.8608 | 24 |
| 0.8869 | 25 |

## 4.3 DISCUSSION

The results obtained from the steps taken to achieve the objective of the project. The dimensionless time increases as the time in hour increases for all the formations based on the observation from the tables shown in Section 4.2:

$$\frac{{R_{in}}^2 - 2\ln(R_{in}) - 1}{4\ln(R_{in})} \cdot \frac{a_0 G_0 + a_1 G_1 + a_2 G_2}{a_0 + \frac{a_1}{2} t + \frac{a_2}{3} t^2} = t_D$$

In the equation above, the values of G function and dimensionless time has been calculated and tabulated using Microsoft Excel and tabulated. These values were used to determine the radius of thermal influence in order to understand the relationship between temperature and time taken for the cement hydration based on the objective of the project. A graph of radius of thermal influence versus time is plotted using the data obtained from the calculations.

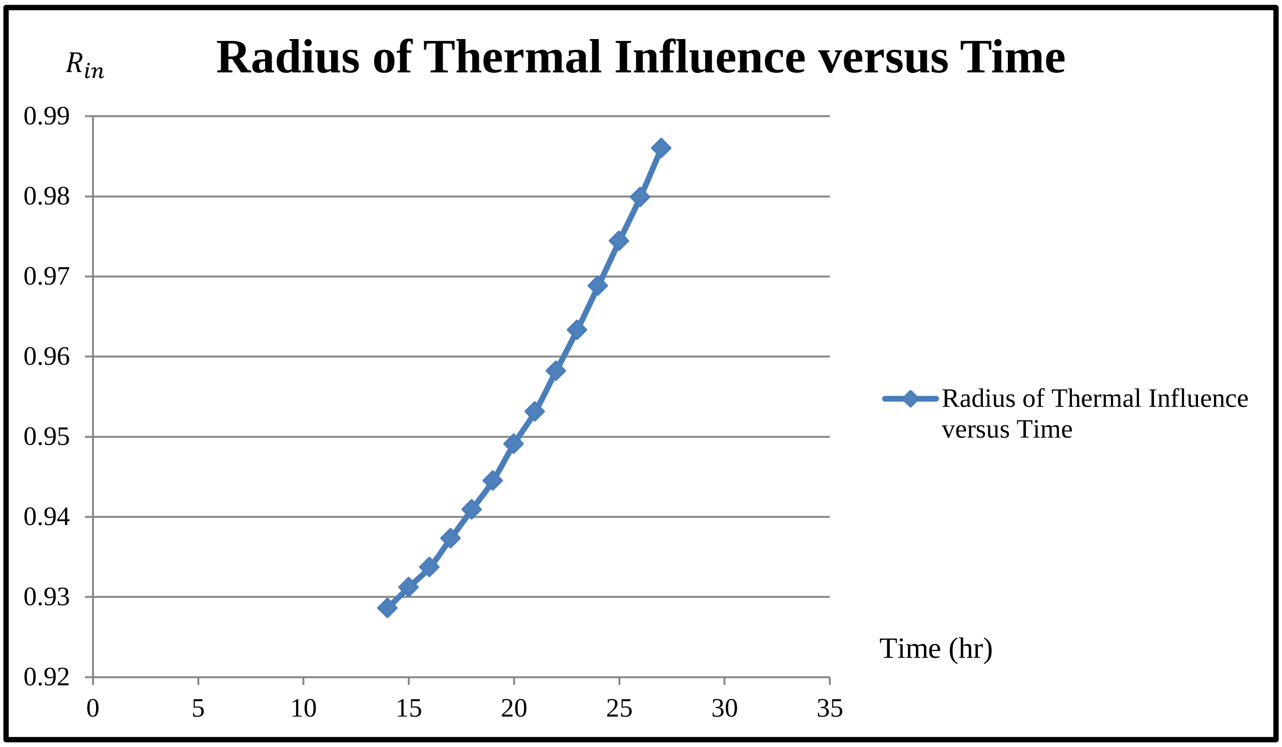



Figure 7: Graph of radius of thermal influence versus time for sand formation

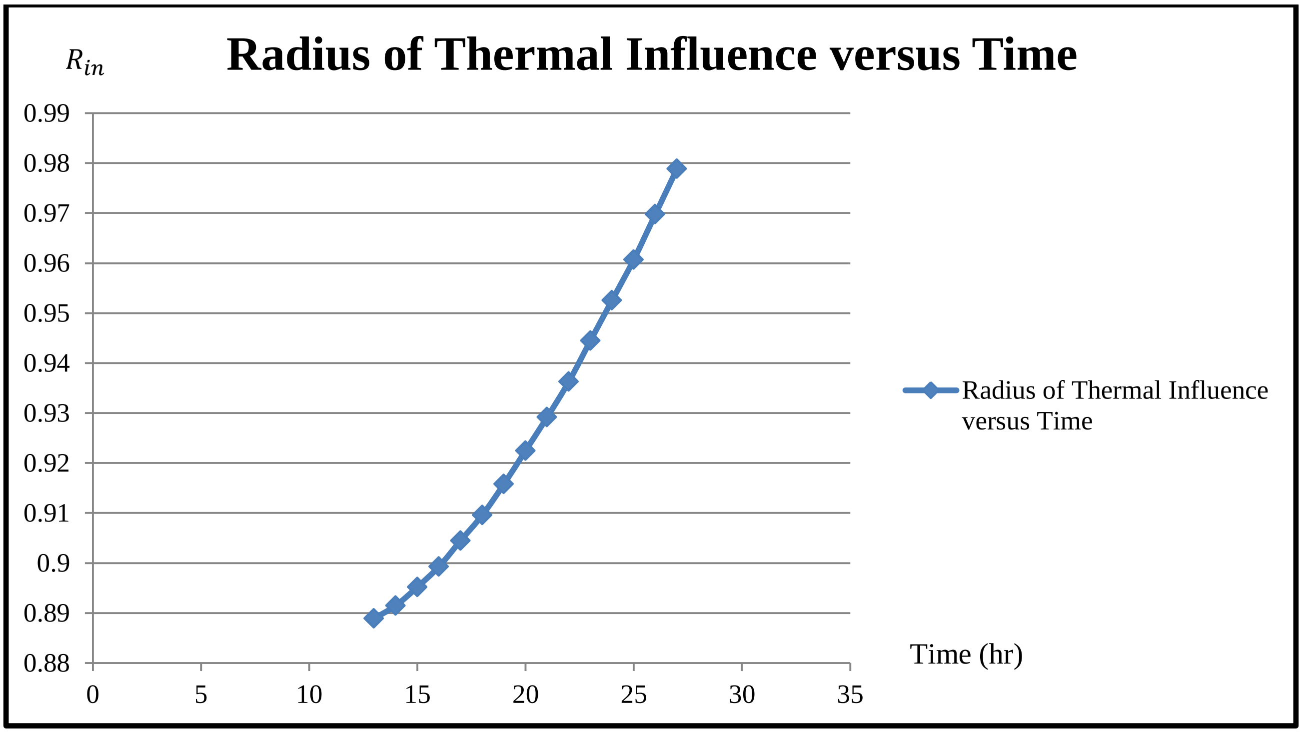



Figure 8: Graph of radius of thermal influence versus time for sandstone formation

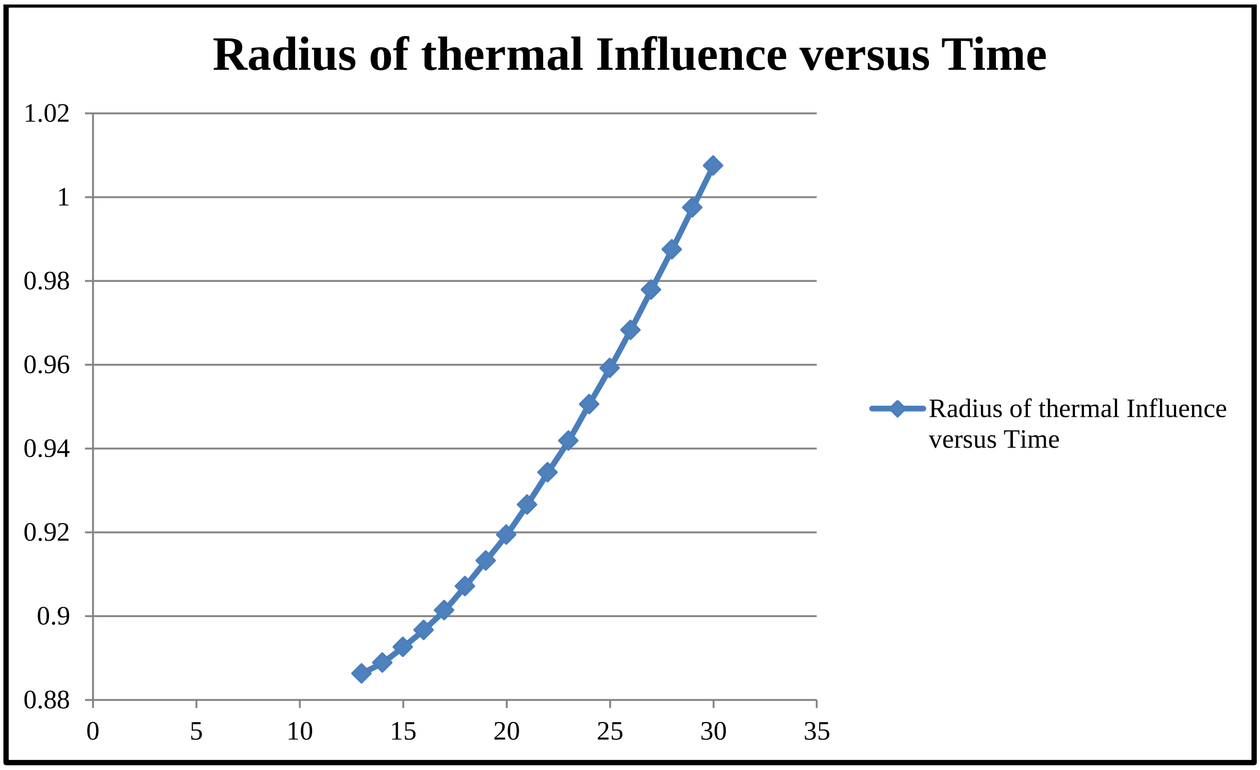



Figure 9: Graph of radius of thermal influence versus time for limestone formation

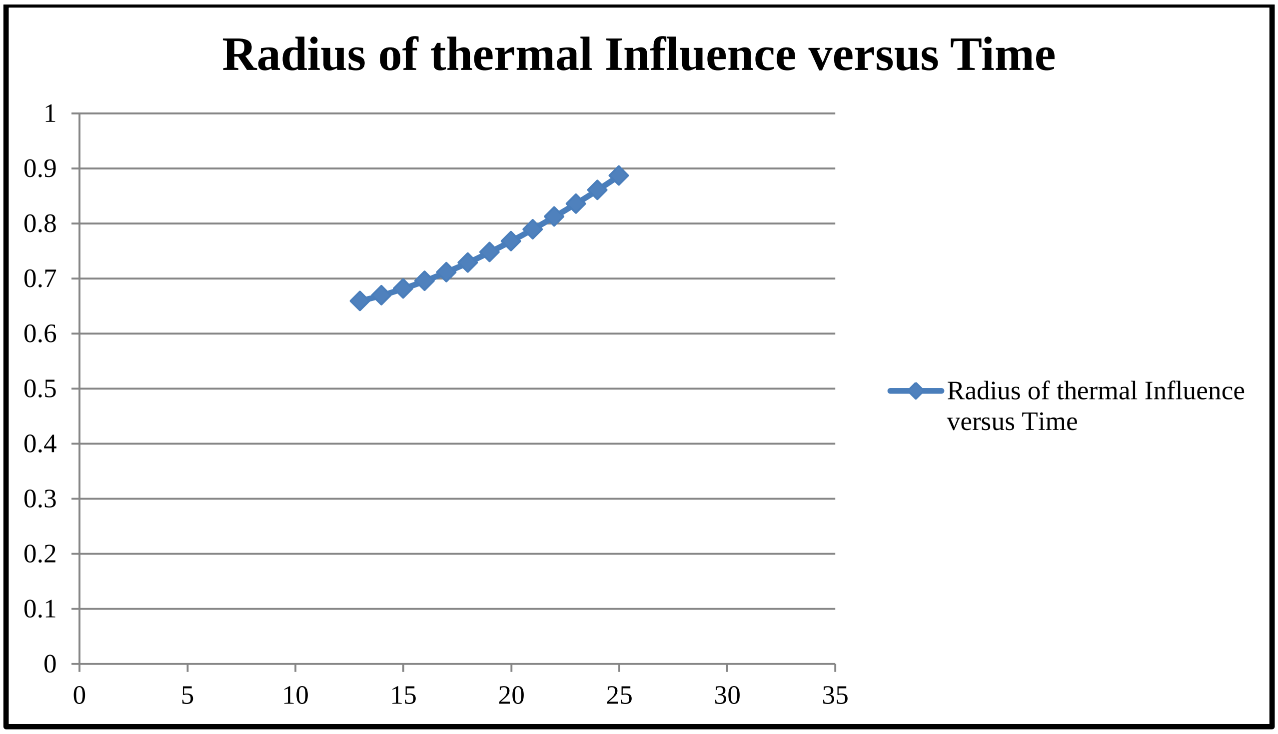



Figure 10: Graph of radius of thermal influence versus time for dolomite formation

Figure 7 shows the result of the research presented in graph for the sand formation. From the graph, it can be observed that the radius of thermal influence for sand formation increases drastically with time.  The radius of thermal influence is obtained based on the thermal conductivity and diffusivity of the formation.  The dimensionless radius of thermal influence is obtained using the formula;

$$\frac{{R_{in}}^2 - 2\ln(R_{in}) - 1}{4\ln(R_{in})} . \frac{a_0 G_0 + a_1 G_1 + a_2 G_2}{a_0 + \frac{a_1}{2} t + \frac{a_2}{3} t^2} = t_D$$

Figure 8, 9 and 10 shows the plot of the graph dimensionless radius of thermal influence against time for different formations. The results vary due to the different thermal conductivity and diffusivity coefficient of the formations. Thermal conductivity value used to form the analysis are 1.835, 2.775, 1.6 and 4.065 respectively for sand, sandstone, limestone and dolomite formation. However, the effect of thermal influence on different formation is observable on the gradient of the graph. Dolomite formation is less steep compared to other formation as it has the highest thermal conductivity value. Its shows that dolomite has the capability to transfer heat faster. The analysis allows the estimation of the degree of thermal disturbance created by the heat of cement hydration at a particular time. Therefore, on the hand, the time taken can also be estimated with the data of thermal influence. The dimensionless temperature distribution around the wellbore during drilling fluid circulation can be approximated.

# 5 CONCLUSION

The objective of the project so far has been successfully achieved according to the planned milestone. The cement hydration process is understood based on the studies of papers and books. The project mainly focuses on using the parameters to estimate the time. The thermal conductivity and the thermal diffusivity of formations are used as variable parameters whereas the composition of cement slurries is assumed constant. A new semi-analytical equation for estimation of the radius of thermal influence at cement hydration is proposed. The dimensionless radius of thermal influence has been obtained for different time. The relationship between temperature and time has been studied using the graph plotted.

# 6 RECOMMENDATION AND FUTURE WORK

The research can be continued in future to have a better understanding on this process which can help the oil and gas industry.  The research can be carried out considering the moist condition of formation as moist formation has a higher thermal conductivity than the dry formation. The readings are established in tables and graph in the analysis is this paper. In future, it will be more convenient to develop coding in C++ programme to get the output values of radius of thermal influence and time in a more fast and convenient manner.

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