Probabilistic Heat Transfer in Variably Random Oil Shale Kerogen Deposit

by

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(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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BACHELOR OF ENGINEERING (Hons)
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Approved by,

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(Dr. William Pao)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2014

CERTIFICATION 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.

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WONG LEH HOE

ABSTRACT

Oil shale is one of most potential unconventional oil sources to replace the conventional crude oil in future. It is a fine sedimentary rock which rich in organic substances called kerogen. Kerogen is insoluble in normal organic solvent and when it is heated under elevated temperature and pressure, it will undergo pyrolysis. Through pyrolysis process, the kerogen will break down and yield combustible liquid which is known as shale oil. In situ retorting method is one of the methods that is usually used to extract oil shale. However, due to its random deposition, it is necessary to quantify the heat injection behavior in oil shale. Therefore the purpose of this research is to develop the correlation of the variability of oil shale kerogen's heat conduction and the heat transfer. To achieve the objective, simulation of oil shale field distribution is generated. The correlation of the variability of the oil shale and the heat input is observed and studied so the yield of the oil shale can be calculated and quantified. Previous researches show that high temperature will lead to high yield of oil shale. During high temperature, the thermal conductivity of oil shale will decrease. Various sampling techniques and up scaling methods are implement and analyzed to conclude the effect of element sizes on the heat transfer. Based on the result, there will be less than 4% error in pyrolysis temperature. This implies that there will be 96% accuracy in estimation of oil yield due to its randomness. At the end of this research paper, heat injection should be carried out at the depth of 281m to 560m to obtain the high yield of oil shale.

ACKNOWLEDGEMET

First and foremost, my name is Wong Leh Hoe, matrix no 13883, would like to thank Universiti Teknologi PETRONAS (UTP) for providing me a chance to apply the knowledge that I have learned throughout the years in UTP through Final Year Project.

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Last but not least, I would like to thank to my family members for being supportive throughout this final year semester.

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CHAPTER 1

1. INTRODUCTION

1.1 Background

According to the Swedish Energy Agency, about 81% of the total worldwide energy supply is came from fossil fuel. International Energy Agency stated that oil is the largest energy sources and the world has been highly rely on oil. Excessive dependence on oil can cause economic problem and instability of energy security in a high price oil period. Therefore, development of various alternatives sources for conventional oil is needed to maintain the balance between energy supply and demand.

Based on Na *et.al*. (2012), light sweet crude is the types of crude oils that has been widely used around the world and its reserves are estimated to be around 1 trillion barrels. Crude oil production is estimated to reach the peak in around year 2030 and then gradually decrease. The oil price hit record high in 2008, fell down due to the global recession in 2009, and sharply increases again recently (Na *et.al.*, 2012). It is estimated to remain stay high for a period of time. Moreover, oil demand of the developing countries such as China also increase recently. As a result, a lot of countries start to exploit other alternatives sources such as unconventional oil sources.

Oil shale is one of the unconventional oil sources. It is a fine grained sedimentary rock which is rich in organic substances called kerogen. Kerogen is an immature crude oil bearing and it is the source of most fossil fuel. Kerogen is insoluble in most of the organic solvent. Heating oil shale under elevated temperature and pressure will cause the kerogen to break down and yield combustible liquid fuel which known as shale oil (Speight, 2012). The heating process is known as pyrolysis. Kerogen can be converted into petroleum, gas, methane or other high quality products like jet fuel under elevated temperature and pressure. It can become the replacement for conventional crude oil.

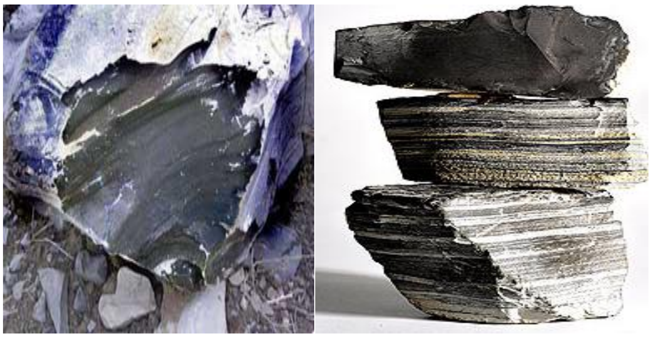


Figure 1.1: Oil Shale from Green River, United State (Sources: Institute for Energy Research)

Deposits of oil shale are found in many parts of the world. So far, around 600 oil shale deposits has been discovered. The world largest oil shale deposits is the Green River oil shale which located at western United State. It is estimated to have 213 billion ton of oil in place shale oil which equivalent to 1.5 trillion U.S. barrels. And the estimated total global deposits of oil shale correspond to around 3 trillion barrels of crude oil (Na *et.al.*, 2012). Therefore, oil shale have a great potential to replace the conventional oil.

Since the middle of the 19 century, oil shale has been discovered and processed into oil. Pyrolysis is the most conventional way to extract oil shale. Nowadays, two common pyrolysis methods are surface retorting and in-situ retorting (Biglarbigi & Carolus, 2008). For surface retorting method, oil shale is mined by conventional mining method and then the oil shale is crushed and sent to surface retorting facilities. After heating the oil shale at the temperature around 900 ◦F – 950 ◦F, the oil shale will break down and yield liquid and gas fuel. Removal of solid particles will be carried out and the liquid fuel will be further upgrade to crude oil before selling to market. On the other hand, the in-situ retorting involve heating the oil shale in place. Electric heater is placed in vertical holes drilled through entire thickness. Through the heater, oil shale is heated at the temperature around 650 ◦F – 700 ◦F. After that the liquid fuel will be extracted from underground through pipeline and sent to refining facilities.

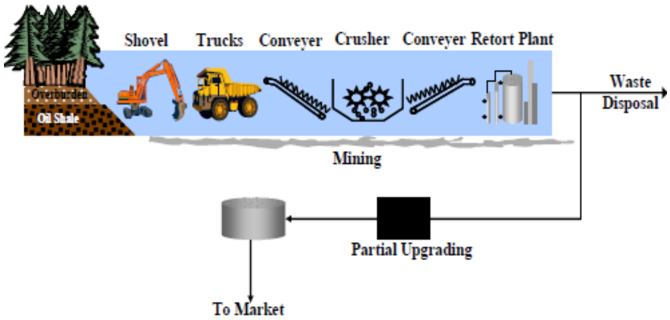


Figure 1.2: Surface Retorting Method (Source: Biglarbigi & Carolus, 2008)

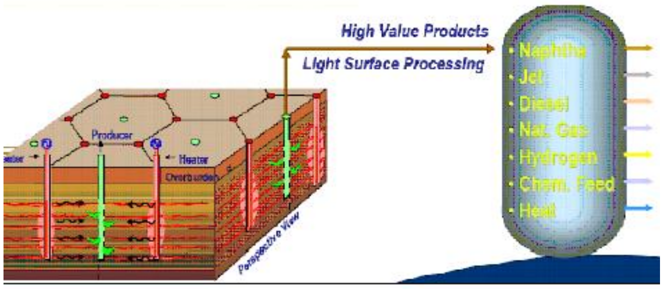


Figure 1.3*:* In-Situ Retorting Method (Source: Biglarbigi & Carolus, 2008)

1.2 Problem Statement

Oil shale is an unconventional fossil fuel and it is the last resort of reliable energy before the world runs out of fossil fuel. Moreover, continuation growth of global population and the energy demand has contributed to the increase in depletion of fossil fuel in recent years. Oil shale, which is rich in kerogen, a hydrocarbon substances has been chosen as future energy alternatives for fossil fuel. Under proper application of heat, the kerogen will undergo pyrolysis and decompose to become combustible liquid which can be further refined into high quality fuel. The oil shale is measured and valued in term of potential gallon per ton. However, due to its random deposition, it is necessary to quantify the heat injection behavior in oil shale.

1.3 Objective

The objective of this project is stated below:

- To develop the correlation of the variability of oil shale kerogen's content and the heat transfer.

1.4 Scope of Study

The scope of this study will be cover the variability of oil shale. The oil shale kerogen is randomly deposit and it is very hard to quantify. In addition, the heat conduction of the oil shale will be investigated in order understand the behavior of oil shale kerogen. The correlation of the variability of the oil shale and the heat transfer will be observed and studied so the yield of the oil shale can be calculated and quantified.

CHAPTER 2

2. LITERATURE REVIEW

Oil shale is a sedimentary rock that rich in kerogen. Kerogen is an organic substance that is insoluble in normal organic solvent and it is classified into 3 main types based on Hydrogen/Carbon and Oxygen/Carbon ratios. Most of the researches had been carried out based on Type I kerogen.

Table 2.1: Types of Kerogen and its Characteristic (Source: Geology.fm, 2010)

Kerogen		
Type I	Type II	Type III
H:C > 1.25	H:C < 1.25	H:C < 1
O:C < 0.15	O:C = 0.03 – 0.18	O:C = 0.03 – 0.30
Formed from proteins and lipids	Formed from lipid deposits under reducing conditions	Formed from tick material resembling wood or coal
Shows great tendency to rapidly produce liquid hydrocarbons	Tend to produce mix of oil and gas	Tend to produce coal

Pyrolysis is the most conventional way to extract oil shale. Under elevated temperature, the oil shale kerogen can be converted into hydrocarbon liquid such as petroleum. Na *et.al.* (2012) stated that the most challenging problem to exploit oil shale is that pyrolysis oil shale kerogen requires large energy consumption. Precise heat transfer and adequate heating conditions are also required in order to obtain high yield of oil. Therefore, retorting temperature and the heating rate of oil shale should be studied to determine the oil yield.

Na *et.al.* (2012) had conducted research on the retorting temperature effect on shale oil yield. The results showed that at 400˚C (752˚F), oil shale was steadily produced until 80 min and then it started to decrease. At 450˚C (842˚F) and 500˚C (932˚F), shale oil was produced until 50 min and 60 min respectively. The figure below show the result of the shale oil yield.

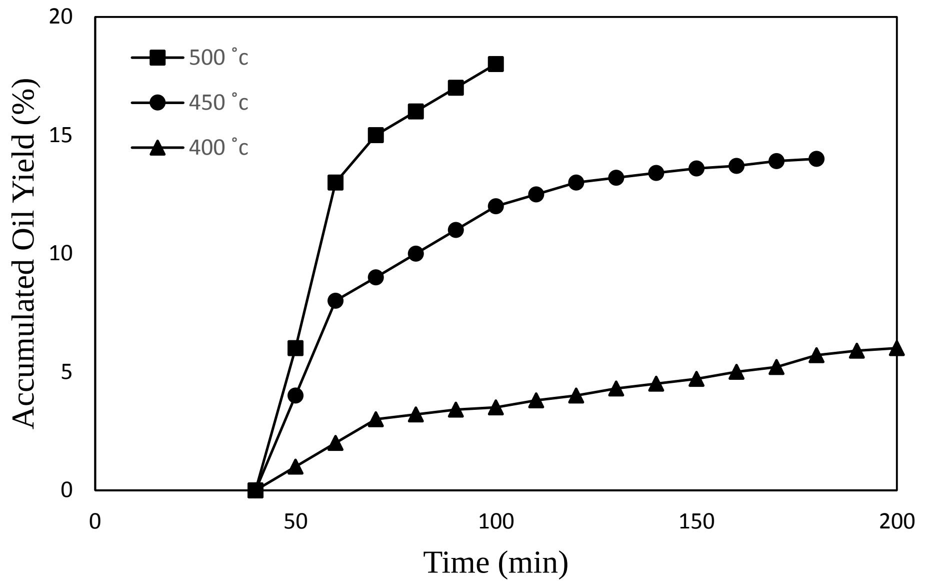


Figure 2.1: Shale Oil Yields with Time at different Retorting Temperatures. (Source: Na et.al., 2012)

As the retorting temperature was increased, the shale oil yield was also increased. The result was clearly shown that the retorting temperature can affect the yield of oil shale. Na *et.al.* (2012) discovered that the ratio of shale oil and non-condensable gas produced during the pyrolysis process were relatively large. Williams and Ahmad (2000) obtained similar results that the increase of gas yield was greater than the increase of oil yield with increasing retorting temperature. The reason behind this was because most of the kerogen were converted into gas instead of liquid due to active pyrolysis process. This is proven by the study of Burnham (1985) which stated that the kerogen will directly convert to bitumen and then the bitumen will change to non-condensate gas, shale oil and coke through pyrolysis reactions such as cracking and coking with increasing temperature.

Based on Shafik (2012), deposition of oil shale is random. In addition, the deposition environment of oil shale is varied from fresh water to high saline lakes or coal deposition places. Due to its random deposition, it is hard quantify the oil shale kerogen. Moreover, it is hard to extract oil from oil shale as the oil shale kerogen exist in solid form. It will only decompose into liquid form under high temperature.

Thermal conductivity values of oil shale kerogen are required to quantify the oil shale kerogen. Oil shale kerogen will be measured in term of gal/ton. Based on the experiment that conducted by Gavin and Sharp (1920) over the temperature range from 77 °F to 167°F, the thermal conductivity data of an oil shale was 42.7 gal/ton. On the other hand, Tihen et al (1968), reported that the thermal conductivity at room temperature of unconfined raw retorted and burned oil shale were ranging from 8.6 to 58.6 gal/ton. Therefore, temperature and the thermal conductivity of the oil shale will influence the yield of oil shale. Prants and O' Brien (1975) had conducted a study about thermal conductivity of oil shale over a wide range of temperature, fluid pressure and kerogen content.

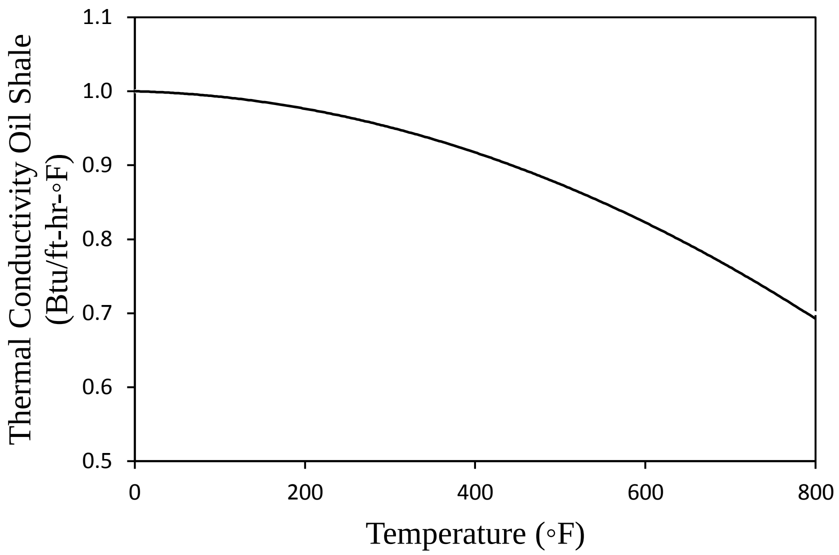


Figure 2.2: Heat Conductivity against Temperature (Source: Prants & O' Brien, 1975)

Based on the Figure 2.2, it is clearly shown that the thermal conductivity of the oil shale varies with temperature. As the temperature increases, the thermal conductivity of the oil shale will decrease. The relationship between the oil yield and the thermal conductivity had also been plotted.

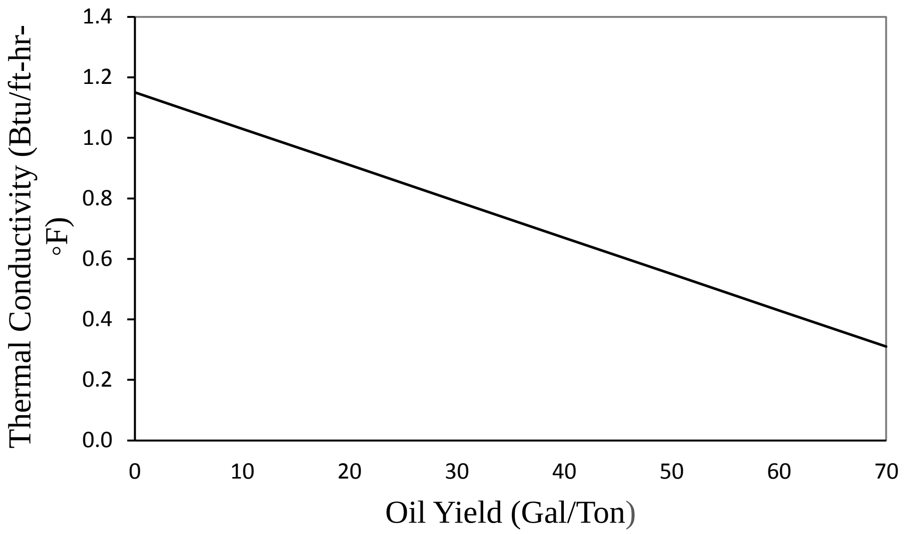


Figure 2.3: Heat Conductivity against Oil Yield (Source: Prants & O' Brien, 1975)

Based on Prants and O'Brien (1975), the yield of the oil shale is directly proportional to the temperature. The results show that in order to obtain high yield of the oil shale, high temperature is needed. In addition, increasing the temperature will shorten the reaction time for the kerogen to convert into fluid products. This can be proven by the study from Matzick et.al. (1966). The result of the study is shown below.

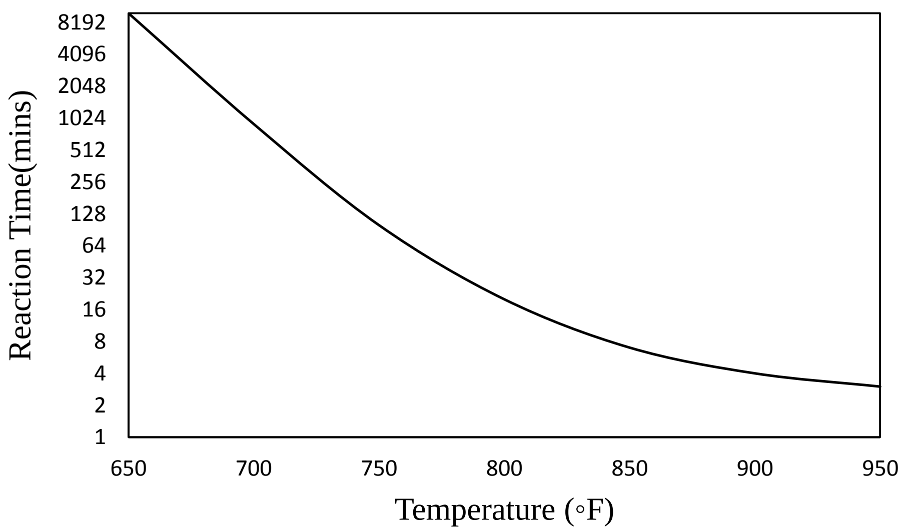


Figure 2.4: Reaction Time for 90% Decomposition of kerogen in Colorado Oil Shale. (Source: Matzick et.al., 1966***)***

This can be the fundamental data to analyze the thermal behavior of the oil shale. By understanding the thermal behavior, the correlation between the variability of oil shale and heat input can be investigated. In addition, pressure will not cause any significant changes to the thermal conductivity and the yield of oil shale (Prants & O'Brien, 1975).

2.1 Remarks

Oil shale kerogen is exists in solid form. In order to convert it to combustible liquid product, it has to undergo pyrolysis processes. Based on the literature surveys, high temperature will result a low thermal conductivity of oil shale. But, due to its low thermal conductivity, high oil yield can be achieved. Therefore, temperature play an important role in determine the yield of oil shale. Due to random deposition of oil shale, the pyrolysis temperature will be affected. Therefore, it is necessary to quantify and calculate the risk and error that temperature will projected due to it randomness. By knowing the error, adjustment can be made on the pyrolysis temperature and oil yield can be estimated accurately.

CHAPTER 3

3. METHODOLOGY

3.1 Model Development and Simulation

This project will be focus on in-situ retorting method and develop the correlation between variability of oil shale, heat conduction and heat input. First, base case based on the existing data is developed. From the existing data, standard deviation and different kind of mean of the sample data have been calculated. Comparison and validation have been carried out to identify the most accurate correlation length and averaging scale. And the averaging scale is used to determine the best range to obtain the oil yield distribution data. Then the data will be used to validate the result generated by FORTRAN compiler.

Since this project is deal with random numbers, averaging is necessary in order to obtain accurate results. There are three types of mean which are arithmetic mean, harmonic mean and geometric mean. The formula for each mean are shown below

$$\tilde{x}_{arithm} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{x_1+x_2+\cdots+x_n}{n} \tag{3.1}$$

$$\tilde{x}_{geom} = \sqrt[n]{\prod_{i=1}^{n} x_i} = \sqrt[n]{x_1 \cdot x_2 \cdot \ldots \cdot x_n} \tag{3.2}$$

$$\tilde{x}_{harm} = \frac{n}{\sum_{i=1}^{n}\frac{1}{x_i}} = \frac{n}{\frac{1}{x_1}+\frac{1}{x_2}+\cdots+\frac{1}{x_n}} \tag{3.3}$$

The mean which show the most accurate results will be used to measure the percentage of error. The percentage of error is calculated based on formula below

$$\%\ of\ error = \left|\frac{Theoritical - Experimental}{Theoritical}\right| \times 100\ \% \tag{3.4}$$

The standard deviation is also calculated in order to measure the amount of dispersion from the mean. A low standard deviation shows that it is closer to the mean compare to high standard deviation. The standard deviation formula is shown below

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (3.5)$$

The distribution of the oil shale kerogen is determined. After that, random field distribution of the oil shale kerogen will be generated through Excel and the result will be computed by FORTRAN. Percentage error of pyrolysis temperature of oil shale kerogen is calculated in order to develop the correlation between the random deposition of oil shale and its effect to the pyrolysis temperature.

Various sampling and upscaling methods has been used. During scaling, loss of information will occur. In order to obtain the optimum averaging scale, percentage error in oil yield and oil volume is calculated. By comparison, the optimum averaging scale can be identified as well as the error that it will represent. Effect of depth due to averaging scale on oil yield and oil volume was also been observed and the results will be plotted in graph.

3.2 Tools required

FORTRAN is a software that is required in order to complete the project. It is an imperative programming language which is used to numeric computation and scientific computation. This is useful to analyze the variability of the oil shale.

3.3 Project Workflow Chart

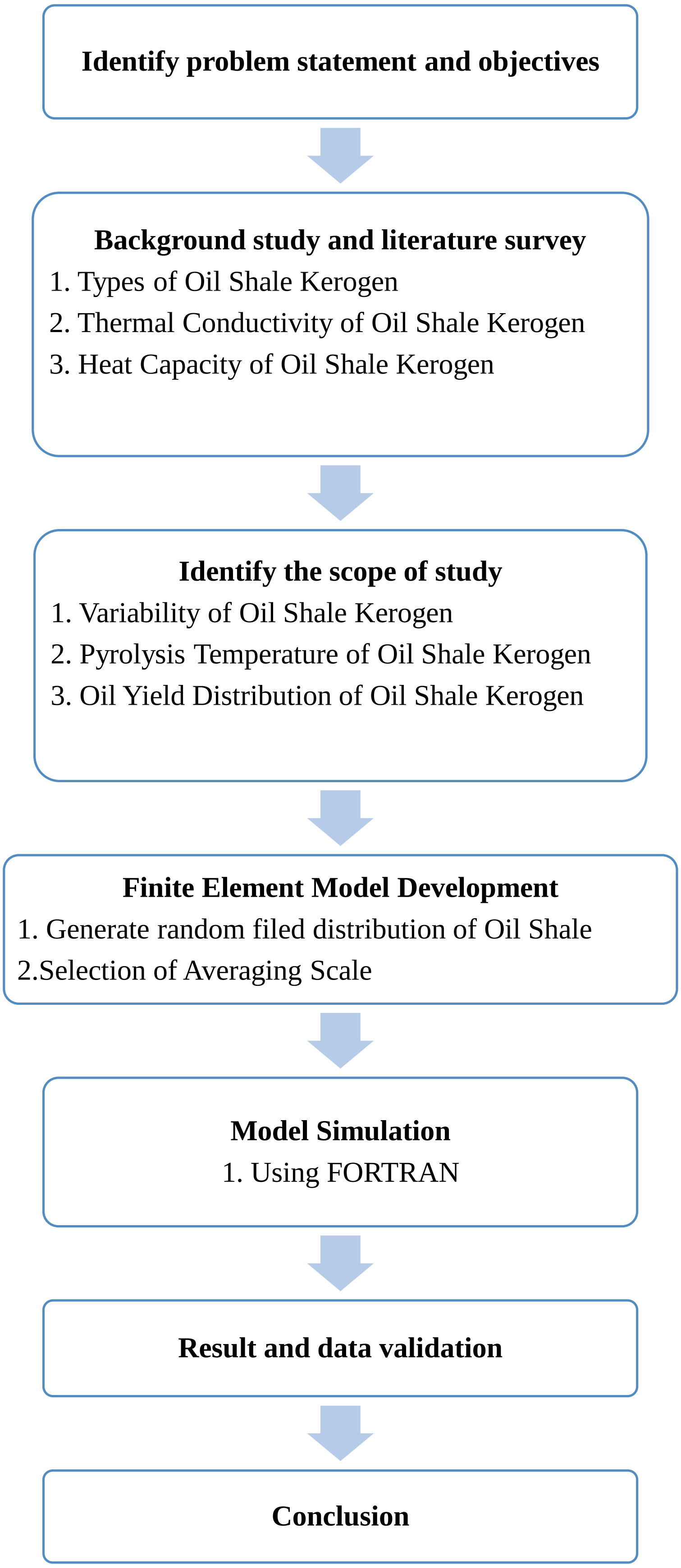


Figure 3.1: Project Workflow Chart

3.4 Gantt Chart

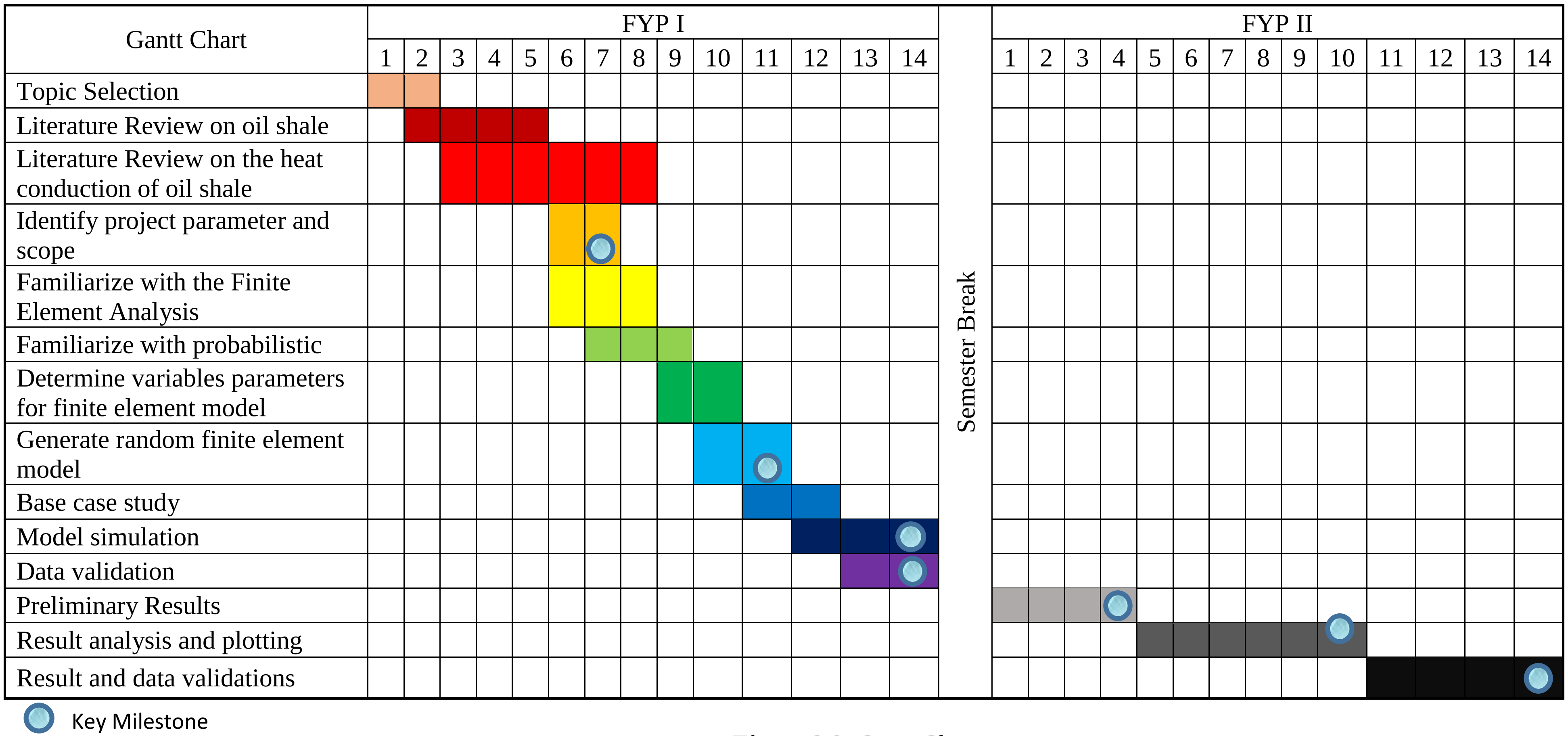


Figure 3.2: Gantt Chart

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Verification of Simulation Data with Governing Equation

Some validation have been done to ensure that the data obtained through FORTRAN software are accurate. The first validation that has been done is the nonlinear heat conduction. There will be 2 boundary condition which are a rod is subjected to constant temperature, T and constant heat flux, q. Based on Zill and Cullen (2001), the analytical solution is given as

$$T(x) = \left(\frac{q_b}{k} - \frac{Qb}{AK}\right)a + \frac{Qa^2}{2} + T_a - \left(\frac{q_b}{k} - \frac{Qb}{AK}\right)x - \frac{Q}{2Ak}x^2 \qquad (4.1)$$

The result are shown in figure below.

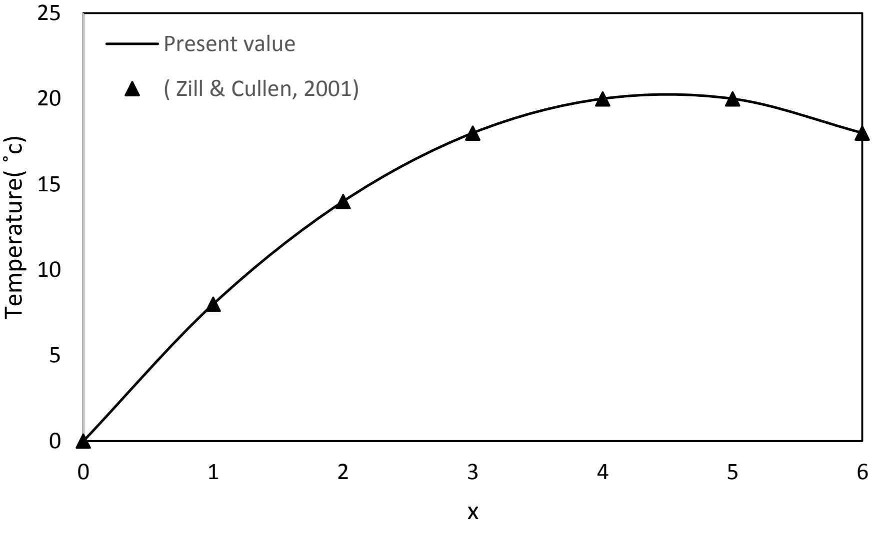


Figure 4.1: Temperature against Distance, x (Nonlinear heat conduction)

Based on Figure 4.1, the temperature shows nonlinear trend. The temperature increase until it reach the peak and then decrease. By using finite element method, the rod is break down into few node to determine its temperature. And the result turn out to be the same as the solution of Zill and Cullen (2001).

The next validation involved one dimensional nonlinear steady heat conduction. A rod of 11 node and 10 element is initially assumed to be at

0˚C and the end of the rod is heated up to a temperature of 1˚C. The analytical solution is given as

$$T(x) = \frac{-1+\sqrt{1+2\,\alpha\xi+\alpha^2\xi}}{\alpha} \qquad (4.2)$$

where $\xi = \frac{x}{L}$

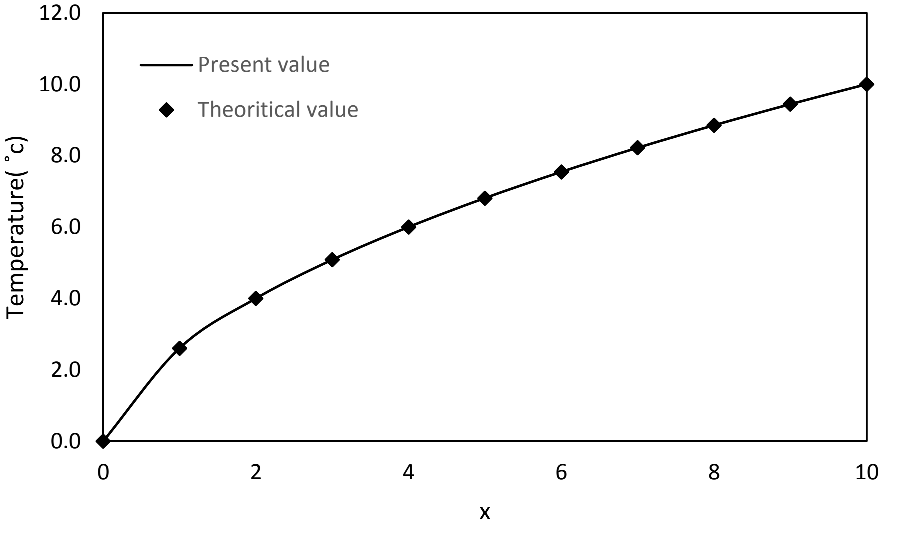


Figure 4.2: Temperature against Distance, x (Nonlinear heat conduction)

From Figure 4.2, the result generated by the FORTRAN is almost the same with the result that calculated by the analytical solution. The temperature is increasing along the rod. This is due to the heat that is supplied at the end of the rod. The distance from the heat source is the only factor that will affect the temperature as the rod is assumed to have constant thermal conductivity and heat capacity.

Another validation involved transient heat conduction with sudden heat flux. A rod of 1 unit width and 20 units in length is initially assumed to be at 0˚C. A uniform heat flux of 1 is applied at the end of the rod. The analytical solution is given by Carlaw and Jaeger (1959) as

$$T(x,t) = 2\sqrt{\frac{t}{\pi}}\left[\exp\left(-\frac{x^2}{4t}\right) - \left(\frac{1}{2}\right)x\sqrt{\frac{\pi}{t}}\,erfc\left(\frac{x}{2\sqrt{t}}\right)\right] \qquad (4.3)$$

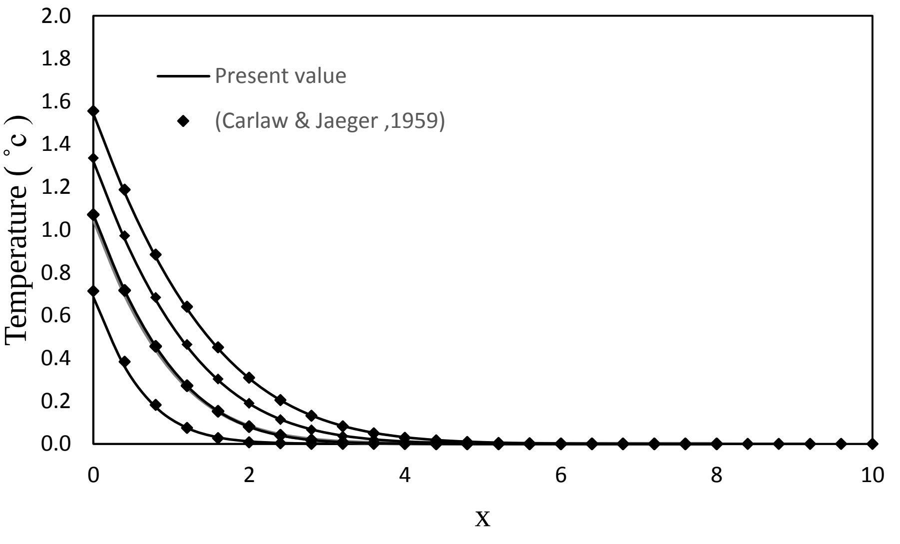


Figure 4.3: Temperature against Distance, x (Transient heat conduction)

In this case, the temperature is time and distance dependent. The heat is able to transfer to longer distance if the time for an object subjected to heat is longer. The result that computed by FORTRAN is fall on the value that calculated by Carlaw and Jaeger (1959). There is some error between two results but the error is very small.

4.2 Generation of Random Field Distribution of Oil Shale

Random field distribution of oil shale has been generated through Excel by using the NORMINV (RAND (), mean, SD)) function.

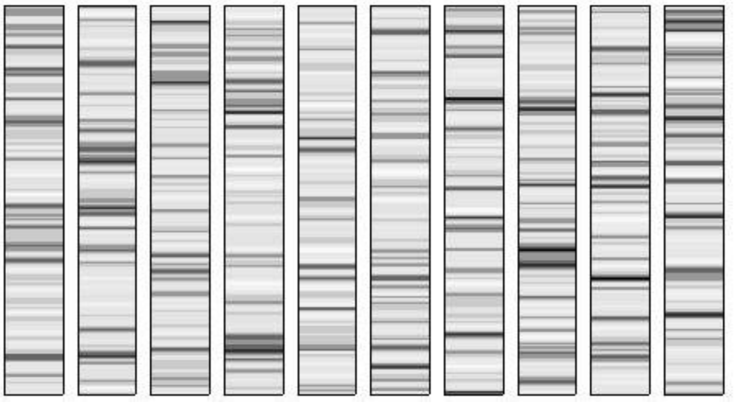


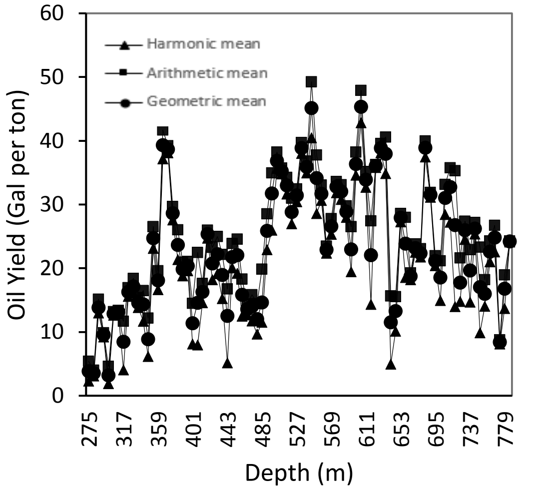
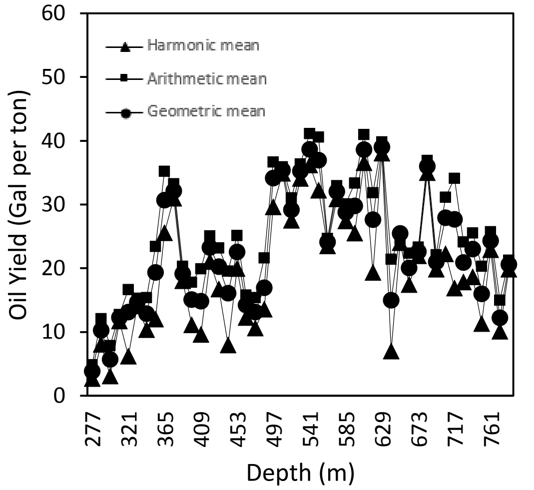
Figure 4.4: Random Field Distribution of Oil Shale

Figure 4.4 is the 10 random field distributions that generated by FORTRAN compiler based on the data from Excel. Based on the figure, the oil shale kerogen is randomly deposited

4.3 Selection of types of Mean at different Averaging Scale

As mention in Chapter 3 Methodology, there are three types of mean which are Harmonic mean, Geometric mean and Arithmetic mean. It is importance to identify types of the mean which can show the most accurate result in order to reduce the percentage of error and thereby reduce the risk. The result are shown in Table 4.1 below.

Table 4.1: Different mean for Oil Yield Distribution with different Averaging Scale

<table>
<tr><td>Averaging Scale: 5 m</td><td>Averaging Scale: 10 m</td></tr>
<tr><td>
</td><td>
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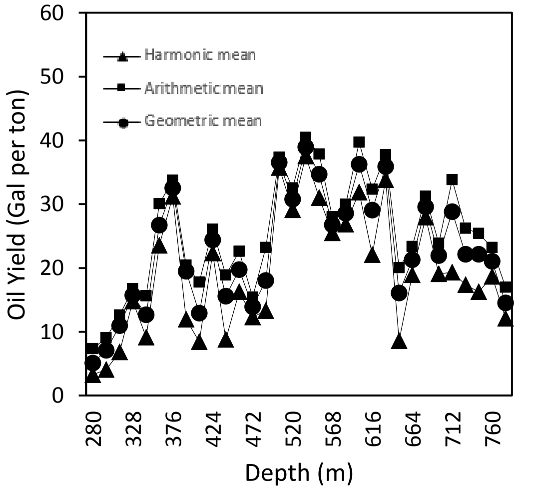
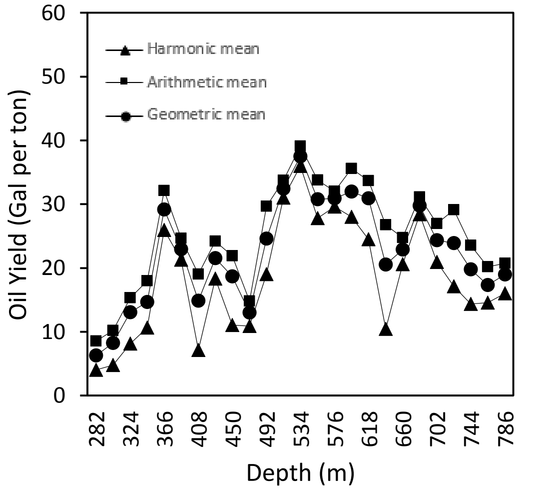
<tr><td>
</td><td>
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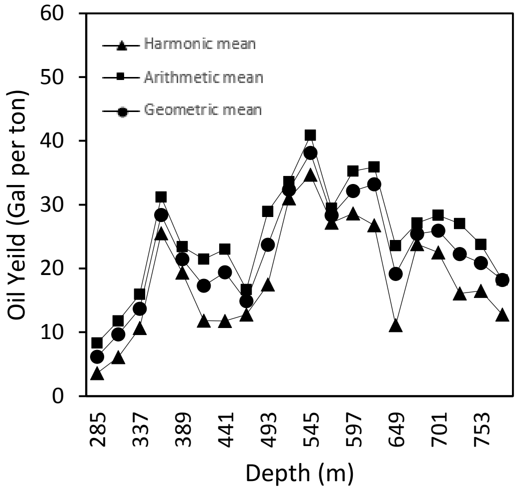
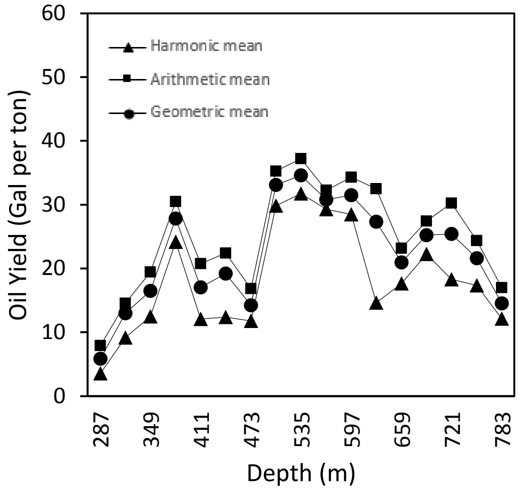
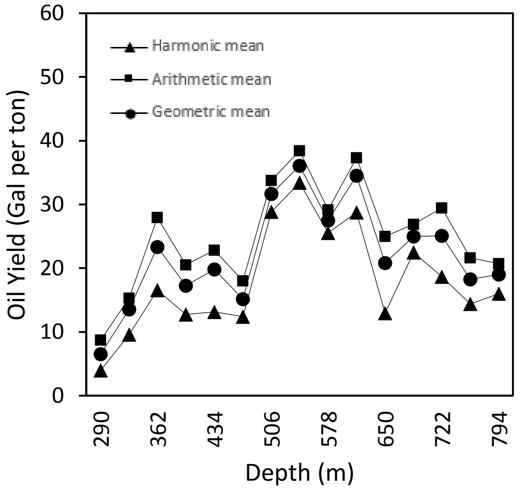
</table>

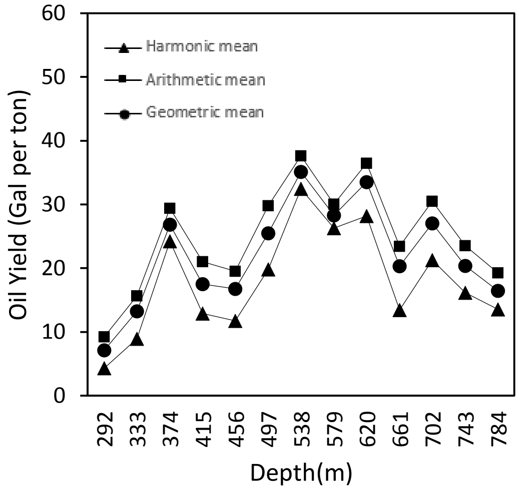




Averaging Scale: 35 m

Averaging Scale: 40 m





Based on Table 4.1, every graphs is plotted by using different averaging scale which is ranged from 5m, 10m, 15m, 20m, 25m, 30m, 35m and 40m. Based on the result, it is clearly showed that arithmetic mean is the largest mean that represent the oil yield distribution, followed by geometric mean and harmonic mean. The differences between each mean increase as the averaging scale increases. Geometric mean has been used as the standard to calculate the percentage of error between arithmetic mean and harmonic mean as it is the medium among those three mean. Percentage error among three mean were calculated and the results is shown in Figure 4.5 and Table 4.2 below.

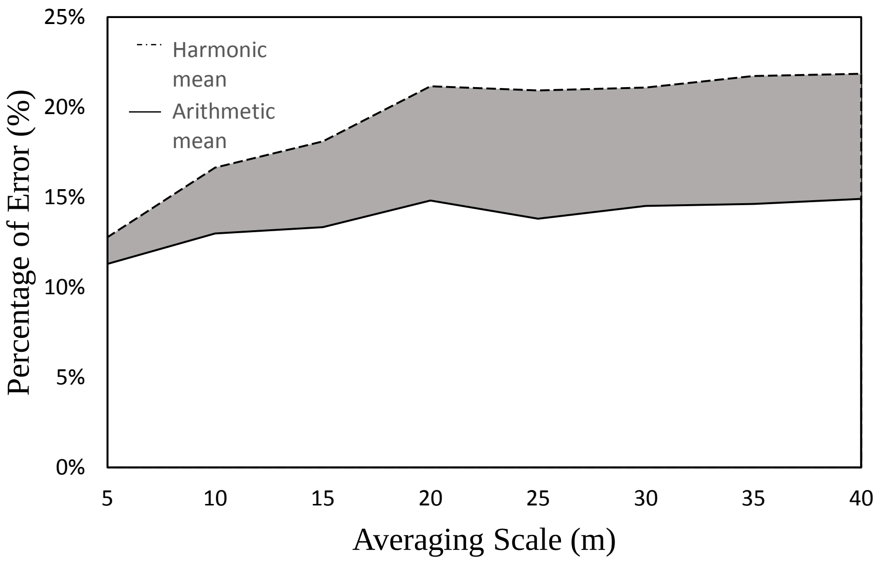


Figure 4.5: Percentage Error between Harmonic Mean and Arithmetic Mean

Based on the Figure 4.5, the percentage error of the harmonic mean and arithmetic mean increase as the averaging scale increase. Start from averaging scale of 20m and onwards, the percentage error seem to be stabilized. The details calculations had been done and tabulated on Table 4.2.

Table 4.2: Percentage Error between Harmonic Mean and Arithmetic Mean with Geometric Mean

Averaging Scale(m)	Harmonic Error (%)	Arithmetic Error (%)	Difference (%)
5	12.8	11.3	1.5
10	16.7	13.0	3.7
15	18.1	13.3	4.8
20	21.2	14.4	6.8
25	20.9	13.7	7.1
30	21.1	14.2	6.9
35	21.7	14.6	7.1
40	21.9	14.9	7.0

From Table 4.2, there is only slight difference in averaging scale of 25m to 40m. Therefore, further analysis had been carried out to determine the optimum averaging scale that can be used to determine the pyrolysis temperature.

4.4 Correlation between different Averaging Scale on Oil Yield

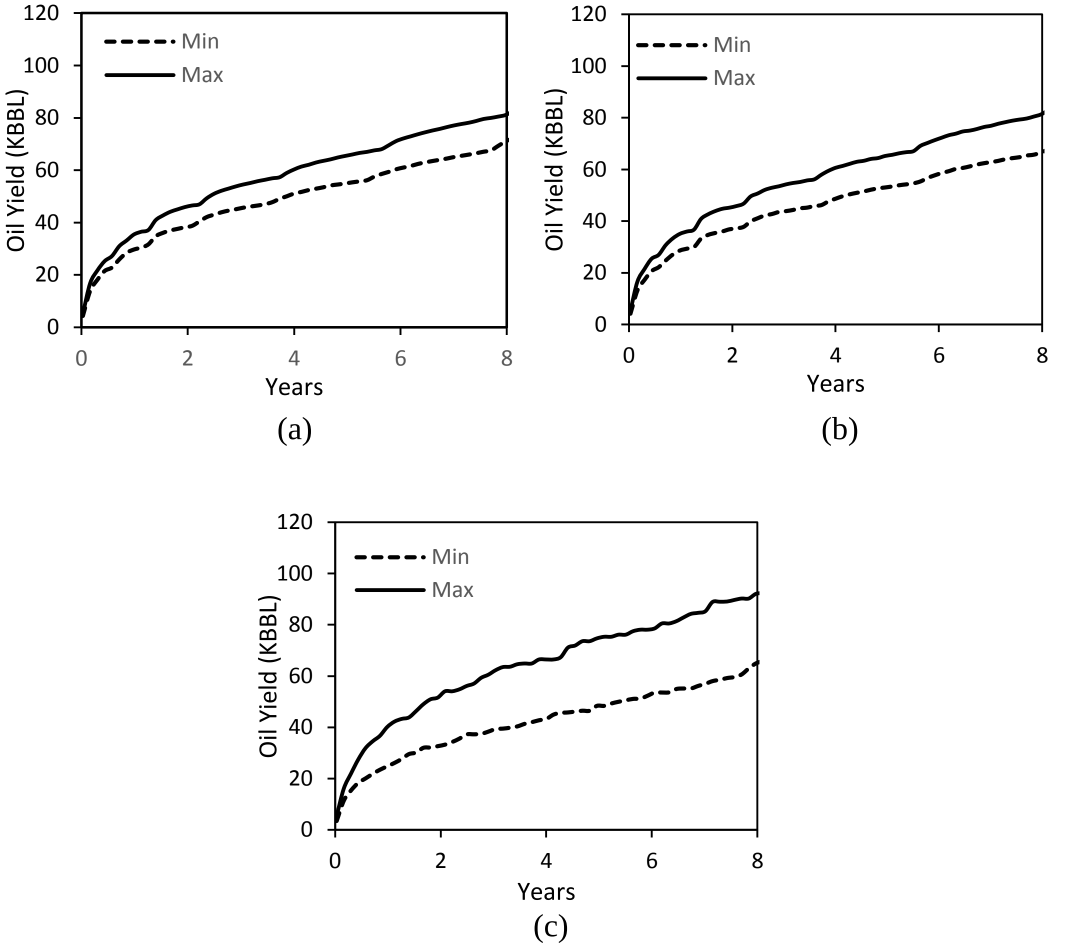


Figure 4.6: Correlation between different Averaging Scale on Oil Yield: (a)5m (b)20m (c)40m

Based on Figure 4.6, each of the graphs represent the estimation of oil yield overs 8 years by using averaging scale of 5m, 20m and 40m. These three range is chosen in order to determine whether the 40m averaging scale can be used to determine the oil yield instead of 20m as both of these 2 range represent almost the same percentage error in geometric mean. Every graph shows the maximum and minimum estimated oil yield. The percentage error between the maximum and minimum oil yield was calculated and summarized in the Table 4.3 below.

Table 4.3: Percentage Error in Oil Yield with respective Averaging Scale

Averaging Scale (m)	Maximum Oil Yield (KBBL)	Minimum Oil Yield (KBBL)	Percentage Error (%)
5 m	82.52	72.16	~ 14%
20 m	82.80	67.71	~ 22%
40 m	92.36	65.86	~ 40%

From Table 4.3, it shows that as the higher the averaging scale used to calculate oil yield, the higher the percentage error. This can be clearly seen in Figure 4.7 where the range between maximum and minimum oil yield is getting larger as the averaging scale increase. All the graph show an increasing trend. Therefore, the percentage error is estimated to continue increase for following years.

4.5 Correlation between different Averaging Scale on Pyrolysis Oil Volume

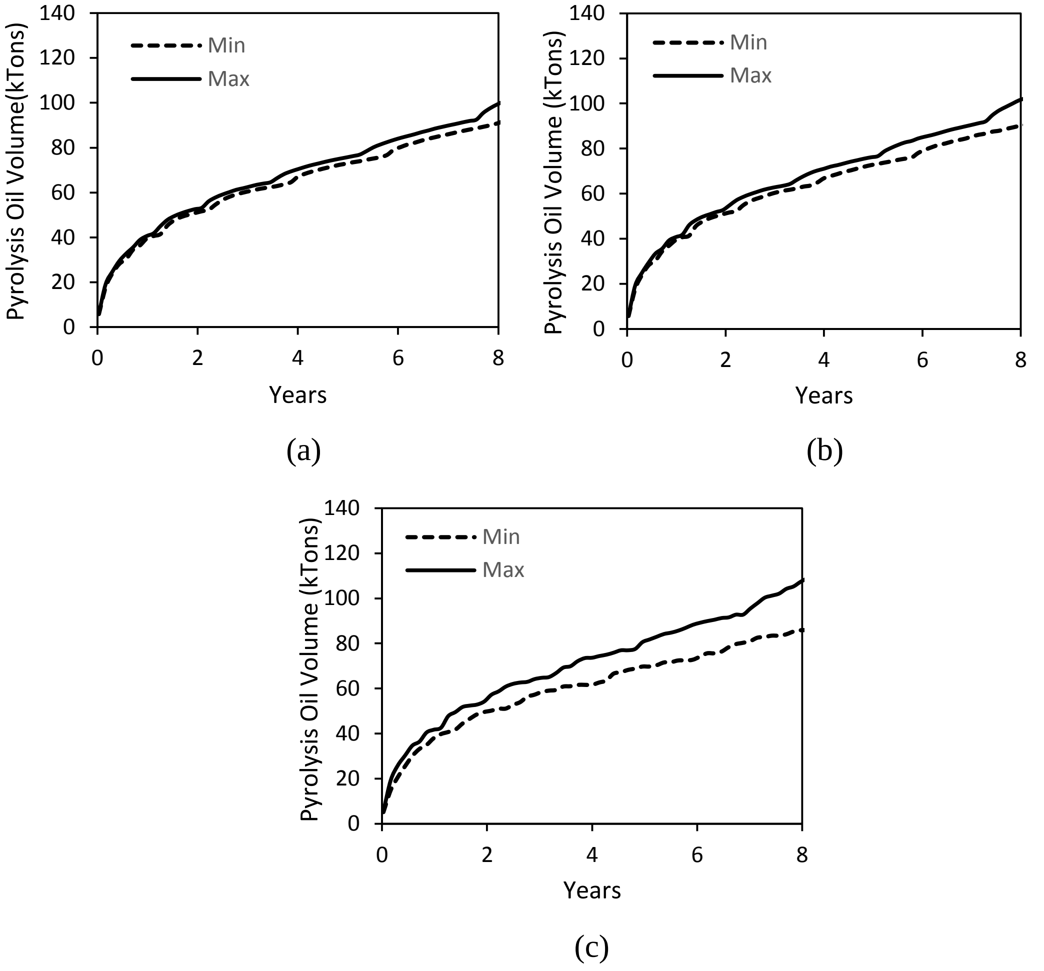


Figure 4.7: Correlation between different Averaging Scale on Pyrolysis Oil Volume: (a) 5m (b) 20m (c) 40m

Figure 4.7 show the correlation between different averaging scales on pyrolysis oil volume. Maximum and minimum pyrolysis oil volume were plotted based on different averaging scales which are 5m, 20m and 40m. Compare to Figure 4.6, the range between the maximum and minimum line in Figure 4.7 is much smaller. Percentage difference were calculated and summarized in Table 4.4 below.

Table 4.4: Percentage error in Pyrolysis Oil Volume with respective averaging scale

Averaging Scale (m)	Maximum Pyrolysis Oil Volume (kTons)	Minimum Pyrolysis Oil Volume (kTons)	Percentage Error (%)
5 m	100.66	91.79	~ 10%
20 m	102.40	90.28	~ 13%
40 m	109.02	85.83	~ 27%

Based on Table 4.4, the percentage error is the smallest at 5m averaging scale and it is largest at 40m. Therefore, the larger the averaging scale, the larger the percentage error.

4.6 Correlation between different Depths on Oil Yield

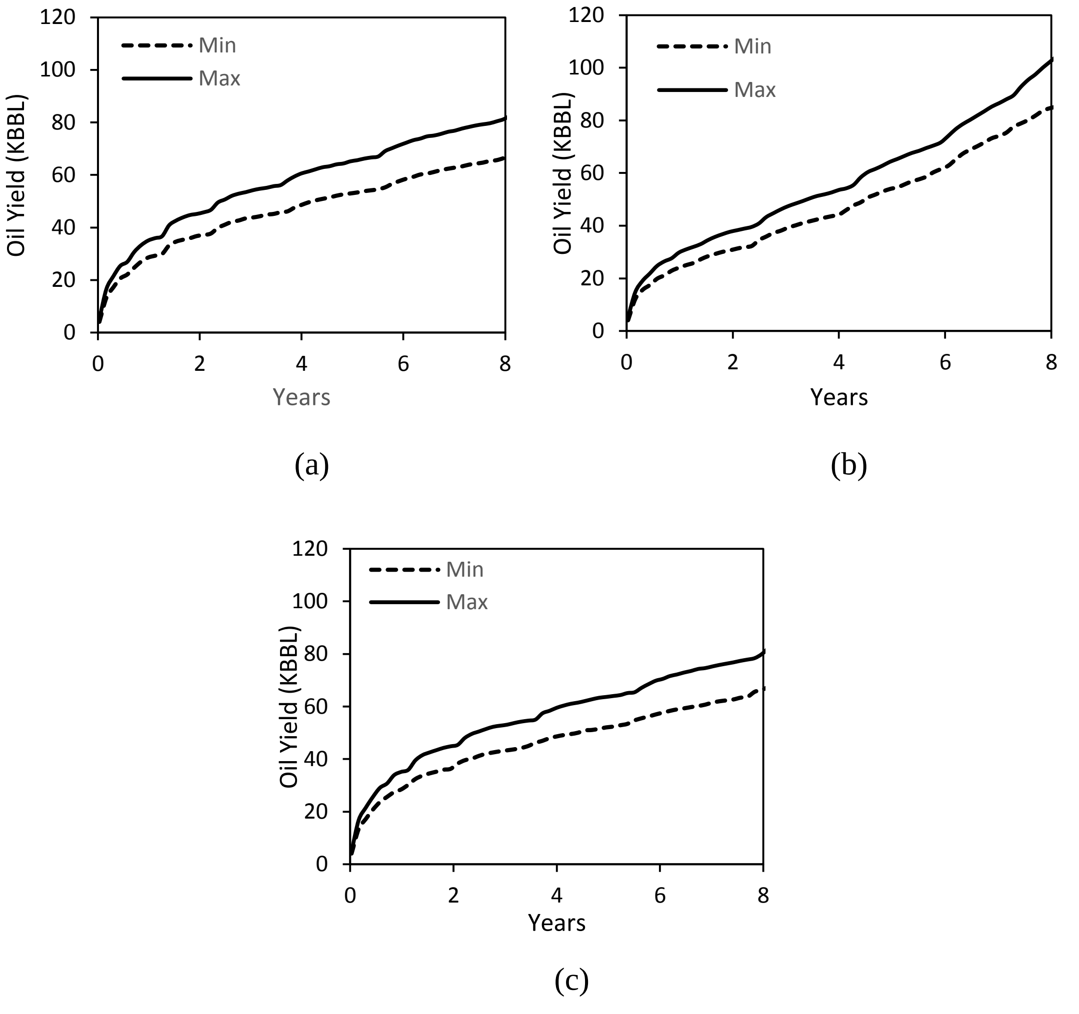


Figure 4.8: Correlation between different Depths on Oil Yield:
(a)0m - 280m (b)281m - 560m (c)561m – 840m

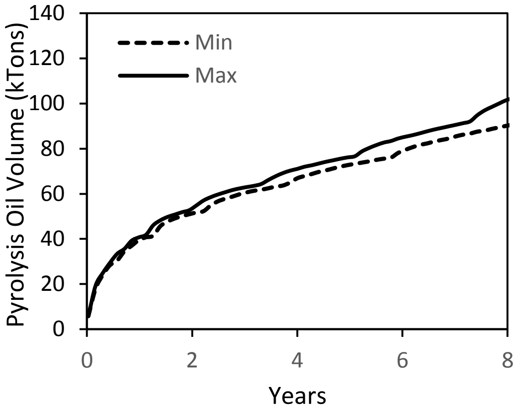
Each graph in Figure 4.8 is the estimation of maximum and minimum oil yield overs 8 years at different depths which are 0m-280m, 281m-560m and 561m-840m. From the graphs, oil yield is increase gradually at the depth of 0m-280m and 561m-840m. However at the depth of 281m-560m, oil yield is increase sharply compared to others. Relevant details of each graphs is shown in Table 4.5 below.

Table 4.5: Percentage Error in Oil Yield with respective Depths

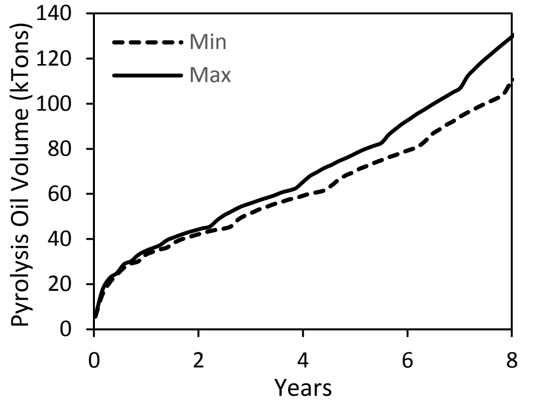
Depth range (m)	Maximum Oil Yield (KBBL)	Minimum Oil Yield (KBBL)	Percentage Error (%)
0m – 280m	82.81	67.71	~ 22%
281m – 560m	104.58	85.22	~ 23%
561m – 840m	82.45	67.64	~ 22%

Based on Table 4.5, there is only slight difference between the maximum and minimum oil yield at different depth range. However, at the depth range of 281m to 560m, it shows the highest oil yield (85.22KBBL - 104.58 KBBL) compared to other depth range. On the other hand, the percentage error is also the highest (23%) at 281m to 540m.

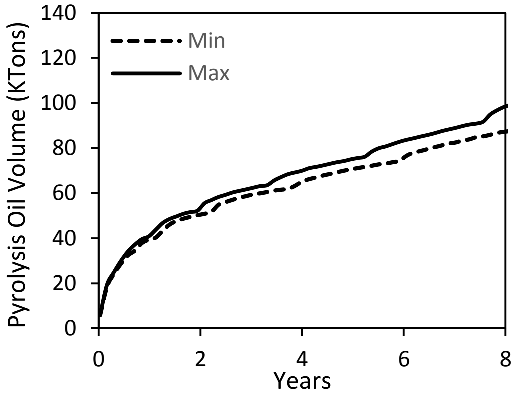
4.7 Correlation between different Depths on Pyrolysis Oil Volume



(a)



(b)



(c)

Figure 4.9: Correlation between different Depths on Pyrolysis Oil Volume: (a)0m-280m (b)281m-560m (c)561m–840m

Based on Figure 4.9, at the depth range of 0m to 280m and 561m to 840m, the pyrolysis oil volume overs 8 years increase gradually and both graphs show similar increasing trend. However, at the depth range of 281m to 560m, the oil yield increases sharply. This phenomena will also been observed when calculating the oil yield as shown in Figure 4.9. Additional information is summarized in the Table 4.6 as shown below.

Table 4.6: Percentage Error in Pyrolysis Oil Volume with respective Depths

Depth range (m)	Maximum Pyrolysis Oil Volume (kTons)	Minimum Pyrolysis Oil Volume (kTons)	Percentage Error (%)
0m – 280m	102.40	90.68	~ 13%
281m – 560m	131.73	111.68	~ 18%
561m – 840m	87.61	99.24	~ 13%

Based on Table 4.6, it is clearly shown that at the depth range of 281m to 560m, the pyrolysis oil volume is the highest compared to the depth range of 0m to 280m and 561m to 840m. But, the percentage error at 281m to 560m is also the highest among all of them.

4.8 Pyrolysis Temperature of Oil Shale

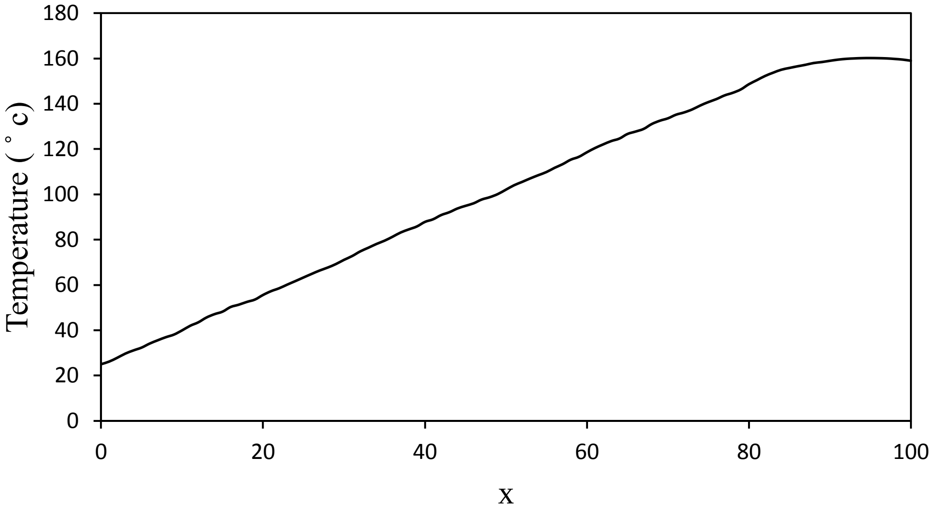


Figure 4.10: Temperature Distribution of Oil Shale

Figure 4.10 shows the pyrolysis temperature distribution of oil shale. From the graph, the temperature increase linearly until it reach the peak of 160˚C. 10 random field distribution had been used to calculate the temperature distribution. All of the results show the same trend as shown in Figure 4.10

above. Detailed calculation had been done and the result s shown in Figure 4.11 below.

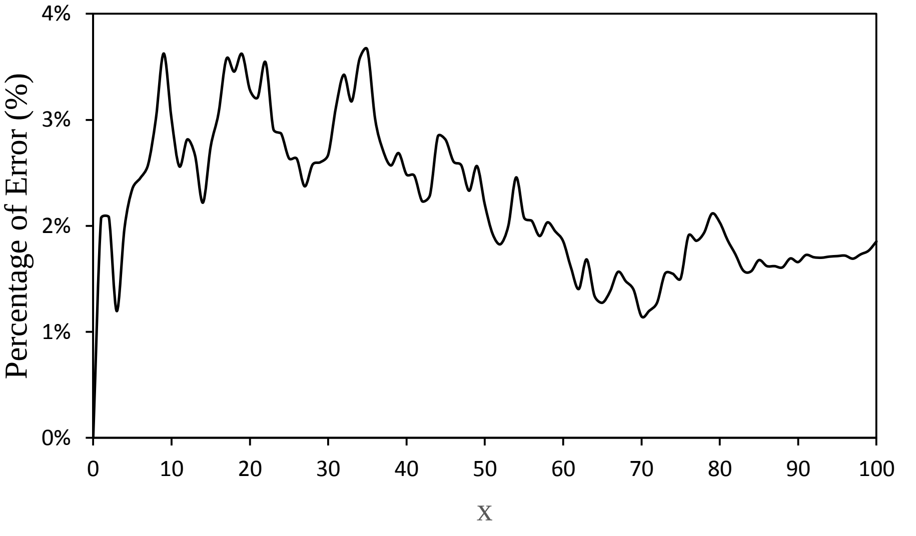


Figure 4.11: Percentage error of the pyrolysis temperature

Percentage error of pyrolysis temperature among all the 10 random field distribution had been calculated. From Figure 4.11, the maximum percentage error is around 3.8%.

4.9 Discussion and Concluding Remarks

Based on all the findings, geometric mean is the best compared to harmonic mean and arithmetic mean. From Figure 4.5, the percentage error between harmonic mean and arithmetic mean for 20m averaging scale and above are almost the same which is around 7%. This probably might lead to a conclusion that 40m can also be used as averaging scale instead of 20m. However, based on the Figure 4.6 and Figure 4.7, as the averaging scale increase, the percentage error in term of oil yield and pyrolysis oil volume will also increase. Therefore, 20m averaging scale will lead to a more accurate result compared to 40m averaging scale. 5m averaging scale show the most accurate result but it is too time consuming. Therefore, 20m is the optimum averaging scale. Last but not least, randomness of oil shale distribution do affect the pyrolysis temperature. Figure 4.11 illustrated that maximum percentage error of the pyrolysis temperature is 3.8%. Therefore, pyrolysis temperature of oil shale can be estimated and calculated with not more than 3.8% error.

CHAPTER 5

5. CONCLUSION AND RECOMMENDATIONS

Oil shale is randomly deposited. It is hard to obtain an accurate oil yield distribution of oil shale. Various sampling techniques and up scaling methods was implement and analyzed to conclude the effect of element sizes on the heat transfer. While performing the scaling, there will be loss of information even though they all originates from the same data sources. Based on all the results, 20m is the optimum averaging scale. 20m averaging scale will cause around 22% in oil yield estimation and 13% in pyrolysis oil volume estimation. Since the oil shale kerogen is exists in solid form, therefore It is necessary to pyrolysis the oil shale so that it can be converted into liquid then extracted from the underground. Due to its random deposition, there will be around 3.8% difference in pyrolysis temperature. On the other hand, heat should be subjected at the depth range of 281m to 540m as oil yield and pyrolysis oil volume is the highest compare to other depth range. However, there will be 5% higher risk at this depth as the percentage error between the maximum and minimum oil yield and oil volume is higher.

This project had developed the correlation between the depth and pyrolysis temperature of oil shale kerogen due to its variability. For future work, the correlation between the heat input and the heat transfer in the heater can studied. This is because pyrolysis of oil shale kerogen requires precise heat transfer. Moreover, future research can also focus on the adequate and optimum heating condition for pyrolysis. Improper contact between heater and oil shale kerogen might affect the oil yield. So it would be interesting if the correlation between them can be developed.

CHAPTER 6

6. REFERENCES

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