Assessment of Imperfect Heater Contact due to in-situ Pyrolysis of Oil Shale

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

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(Dr. William Pao)

UNIVERSITI TEKNOLOGI PETRONAS
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January 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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HOR WENG YAO

Abstract

Oil shale, known as one of the unconventional oil sources, has world reserve of an equivalent to 3.2 trillion barrels of crude oil. Oil shale is a kerogen rich fine sedimentary rock which can be converted into crude oil via a heating process called as pyrolysis. In in-situ pyrolysis of oil shale, a resistive electric heater is installed in a wellbore and it is known as heater-well system. The heating element itself does not actually touches the wellbore which creates imperfect heater contact. In this project, the imperfectness of heater contact will be quantified and an assessment on the effect of air gap on in-situ pyrolysis of oil shale in between the electric heater and wellbore will be done. In that, the thickness of air gap in the heater-well system will be identified and the heat transmission performance between a perfect heater and an imperfect heater contact will be analysed through simulation. In this simulation, Green River Formation oil shale will be heated up to conversion temperature of 320^0C and above. The amount of oil shale converted will be compared for both perfect and imperfect heater contact by interpreting the temperature profile obtained from the simulation. The targeted oil shale layer will be in between 281 meters to 540 meters in depth with the starting temperature of 25^0C. At the same time, parameters that affects the heating process and its weight as well as sensitivity will be identified. Based on the result of this project, the air gap does affect the performance of in-situ pyrolysis of oil shale. It is observed that the thicker the air gap the lesser the oil shale converted. Furthermore, the present study also identifies that the input temperature of heater and the duration of heating are the most influential factors on distance of oil shale converted due to in-situ pyrolysis. The quality of oil shale and the initial temperature of air gap which have also been investigated has negligible effect on this study.

Acknowledgement

The success of this dissertation would not have been possible without the support and guidance of my sole supervisor, Dr. William Pao. The journey of final year project has not been an easy one, but with his constant meticulous and stringent supervision together with expert advice, this dissertation had shaped into what it should be.

I am indebted to the technical staff of Universiti Teknologi Petronas in CAE lab of block 18, Mr. Zuraimee Bin Anor, who provided me technical support in setting up ANSYS program in the lab.

Special thanks goes to my fellow friends who were also under the Dr. William Pao's wings too, Tang Quoc Thai, Ali Abidin and Mohamad Izat Fikri for sharing information and learning materials which are relevant to my final year project. I would also like to thank them for their constant moral support throughout the project.

The final gratitude will go to my family. They have been my main source of motivation for the heights I attained and of what I have become today. To my parents, thank you for the hardships that both of you had to went through to get me to where I am today. I cannot come this far without both of you, mum and dad.

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CHAPTER 1

1.0 Introduction

1.1 Background

Oil shale, known as one of the unconventional oil sources, has world reserve of an equivalent to 3.2 trillion barrels of crude oil (Allix *et al*, 2011). Oil shale is a fine grain sedimentary rock which is rich in organic substances called kerogen which is also an immature crude oil bearing formation. By heating kerogen under elevated temperature and pressure, it will break down and yield combustible liquid fuel which is known as shale oil (Speight, 2012). This 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. In-situ pyrolysis of oil shale is more preferable than ex-situ pyrolysis as it does not require surface mining that will result in geographical damage. It is also estimated that for an in-situ upgrading plant of 100000 barrels/day capacity to operate economically, the oil price must be at least USD 35 per barrel of oil (Biglarbigi *et al*, 2007). In that, it is now highly feasible to exploit oil shale via in-situ upgrading process because the current oil price is 81 USD/barrel (Bloomberg, 2014). However, in-situ pyrolysis of oil shale technologies are still under extensive development as full understanding about the process has not been achieved.

1.2 Problem Statement

In a heater-wellbore system which uses a resistive electric heater, within the borehole itself, the heating element does not actually touches the inner wall of the oil shale. In between the heater and the wall, there is a thin layer of air gap, and it is actually by convective radiation that the heat from the heater element is transmitted into the oil shale. In other words, the heater contact is imperfect. Furthermore, there is no study conducted regarding the effects of imperfect heater contact on the performance of in-situ upgrading of oil shale.

1.3 Objectives

The objective for the project is as following:

1. To quantify the imperfectness of heater contact and its effect on heat transmission to the oil shale layer in a heater-well system.

1.4 Scope of Study

The scope of studies for the project is as following:

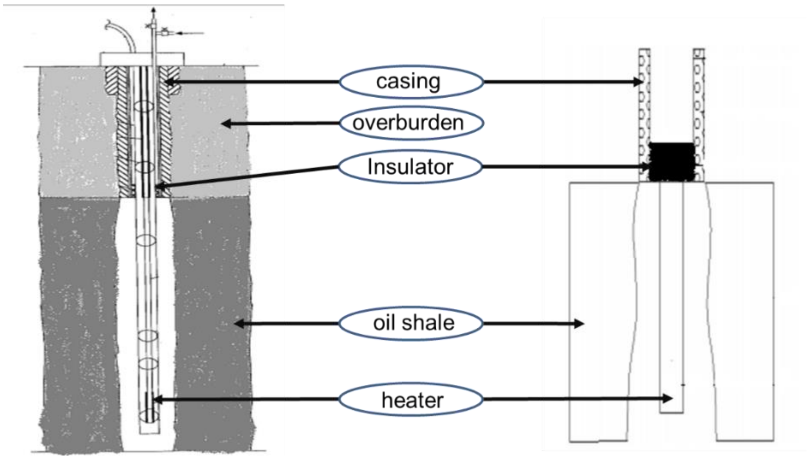
1. Identifying the thickness of air space between heater and wall of wellbore and comparing the amount of oil shale converted into shale oil for both perfect and imperfect heater contact heater-well system.
2. Developing relationship between thickness of air space and the performance of in-situ pyrolysis of oil shale.

CHAPTER 2

2.0 Literature Review

2.1 Modelling of Heater-Well System for in-situ Pyrolysis of Oil Shale

In the literature review of modelling of heater-well system for in-situ pyrolysis of oil shale, the discussion will revolve around the construction of modelling such as the thickness of overburden and various oil shale layers as well as dimensions of electric heater and borehole. In addition to that, a review of the region of oil shale converted with relative to the distance from the heater will be done. That will be followed by effect of arrangement oil shale layers on the production rate of shale oil and conversion temperature and heating rate of oil shale will also be discussed.



(a) (b)

Figure 2.1: (a) Full schematic diagram of heater-well system; (b) Simplified schematic diagram of heater-well system
(Source: Yang *et al*, 2014)

Figure 2.1 shows the schematic diagram for heater-well system. The main components of a heater well system as shown in Figure 2.1(a) are casing, the overburden layer, the oil shale layer, heater and the insulator. For numerical modelling purpose, this system is being simplified as shown in Figure 2.1(b) (Yang *et al*, 2014). However, this simplification neglected the overburden and underburden layer which is key in contributing to heat loss in in-situ pyrolysis of oil shale (Fan *et al*, 2009). Ironically, Brandt (2008) claimed that there was little heat lost to the overburden layer as it was shown that at 16 meters above the heated oil shale layer there was only an increment of 17^0C in temperature. The thickness of the overburden layer depends on the depth where the kerogen rich oil shale lies in. According to a research done by Wong (2014), in-situ pyrolysis of oil shale should be done at depth of 281 meters to 540 meters where the amount of kerogen rich oil shale is the highest. This figure falls in the range of Allix *et al* (2011) research which shows that the richest oil shale layer lies in between Mahogany zone, R6 and R5 which is in between 366m to 609m. In a modelling of Shell in-situ conversion process (ICP) by Brandt (2008), the thickness of overburden was set at 270 meters. Hence, it can be said that the thickness of overburden layer is acceptable within the range of 259 meters to 366 meters.

Table 2.1: Colorado's Piceance Basin oil shale resources
(Source: Allix *et al*, 2011)

Oil Shale Resources		
Zone	**10^9 ton US**	**10^9 bbl**
R-8	No data	No data
Mahogany	25.25	172.94
R-6	23.23	159.09
L-5	7.65	52.42
R-5	26.09	178.72
L-4	8.88	60.85
R-4	15.74	107.78
L-3	2.73	18.72
R-3	8.52	58.38
L-2	2.93	20.08
R-2	7.75	53.07
L-1	1.56	10.70
R-1	16.84	115.35

Effective heating distance is the distance oil shale that reaches conversion temperature of 340^0C (Allix *et al*, 2011) relative to the radial distance from the heater. According to Brandt's (2008) Shell ICP modelling, around 3m of oil shale is converted into shale oil.

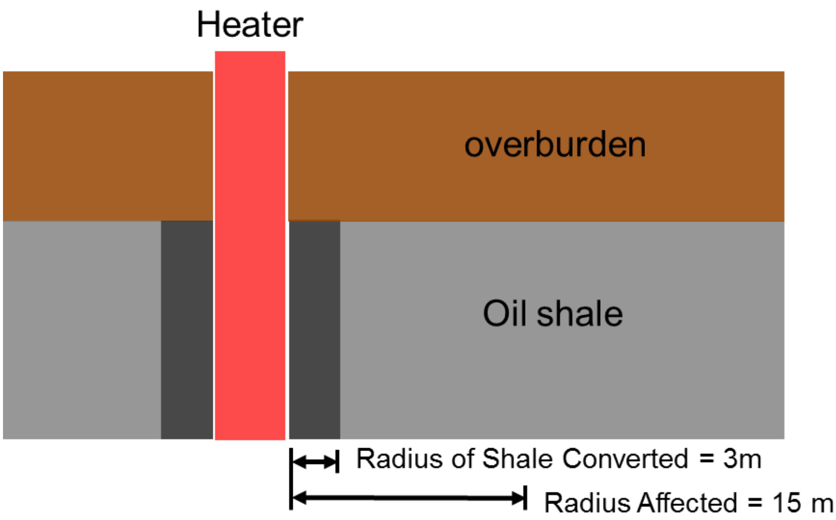


Figure 2.2: Radial distance converted into shale oil by heater
(Source: Brandt, 2008)

This agrees with the Finite-Element-Heat-Mass (FEHM) modelling of in-situ upgrading process of oil shale done by Hoda *et al* (2012) which stated that the temperature of oil shale at 4 meters away from the heater was only about 260^0C as shown in Figure 2.3.

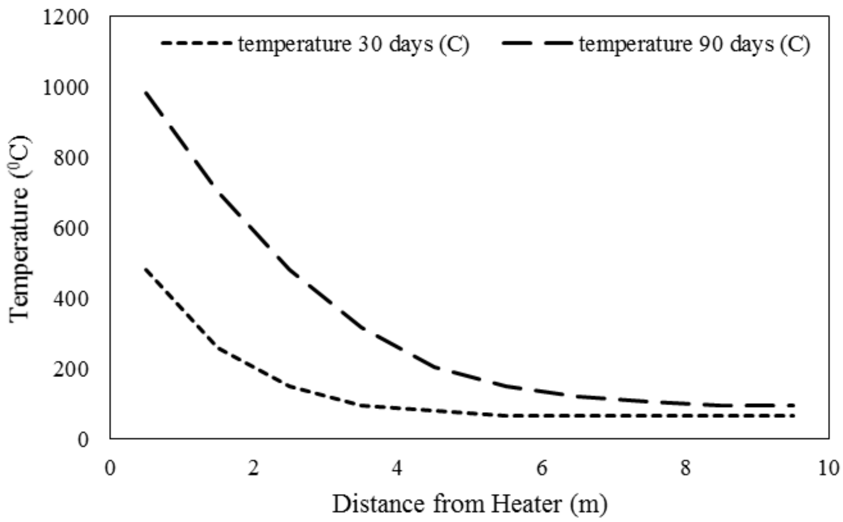


Figure 2.3: Result of in-situ pyrolysis modelling using FEHM and CMG STARS
(Source: Hoda *et al*, 2012)

The thickness of air space between the heater and wellbore wall, which implicates the main concern of this research, is not directly revealed by any literature as there is no study conducted about the perfect and imperfect heater contact. Nonetheless, the thickness of air space can be determined by knowing the difference between outer radius of heater and the radius of borehole. Based on the ICP electric down-hole heater design optimisation research done by Yang *et al* (2014), it was found that the radius of heater is 0.1 meter (3.94”). On the other hand, regarding the radius of borehole, RPS Energy Canada (2013), has been constructing boreholes with diameter of 14” for installing down-hole electric heater. According to well completion process by SPE (2012), for well completion of small well less than 3500 feet, the diameter of the hole will be 14.75’. Therefore, it can be assumed that the thickness of the air gap will be around 5” to 5.5”.

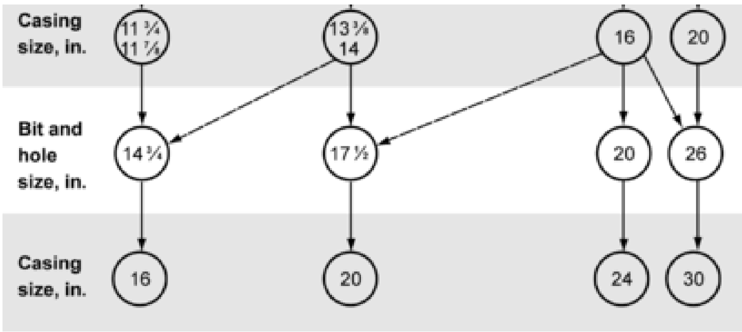
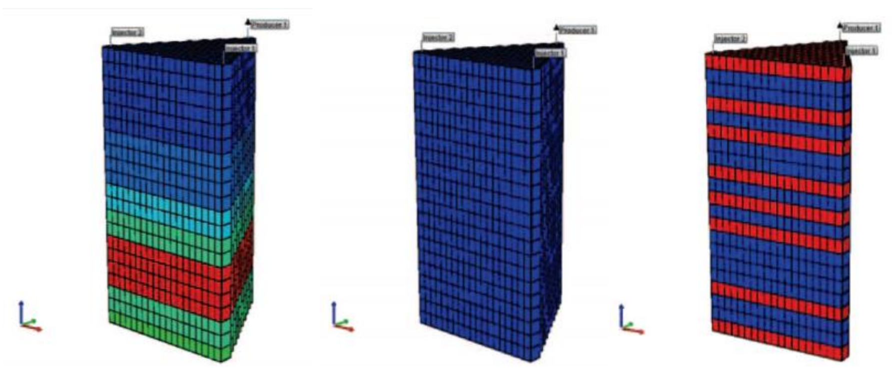


Figure 2.4: Standard combination of casing size for completion below 3500ft (Source: SPE, 2012)

There are many different model configurations of oil shale layer arrangements done by various research. However, Bauman and Deo (2012) tested three different configurations of kerogen rich oil shale layers based on Fischer Assay U059 core data, average richness uniformly dispersed throughout the section and disconnected kerogen rich layers as shown in Figure 2.5 shows no significant effect on oil recovery prediction. Likewise, in most numerical simulation studies of in-situ pyrolysis of oil shale done by Fan et al. (2009), Kelkar et al. (2011), Brandt (2008) and Hoda et al. (2012), constructed the oil layer as a homogenous layer where all the thermal, chemical, mechanical properties and phase behaviour were the same.



(a) (b) (c)

Figure 2.5: (a) Layer based on Fisher Assay U059 core data (b) Average richness uniformly dispersed throughout section (c) Disconnected kerogen rich layers (Source: *Bauman and Deo*, 2012)

2.2 Thermal Properties of Green River Oil Shale

The thermal properties of Green River oil shale such as κ the thermal conductivity is an important parameter for the thermal simulation of heater well system. Gilliam and Morgan (1987) reported that the average thermal conductivity of Green River Formation averaged 0.618 Btu/ft-hr-^{0}F. This value fall within the range of Tihen, Carpenter and Sohn (1968) which was between 0.399 to 0.901 Btu/ft-hr-^{0}F. Symington and Spiecker (2008) uses 1.042 Btu/ft-hr-^{0}F in their oil shale heat conduction analysis. All these well agrees with the work of Prats and O'Brien (1975) that found the range to be 0.264 to 1.110 Btu/ft-hr-^{0}F. However, it was also found that the relationship between thermal conductivity and temperature is non-linear as shown in Figure 2.6. It can be observed that the thermal conductivity of oil shale decreases as temperature decreases.

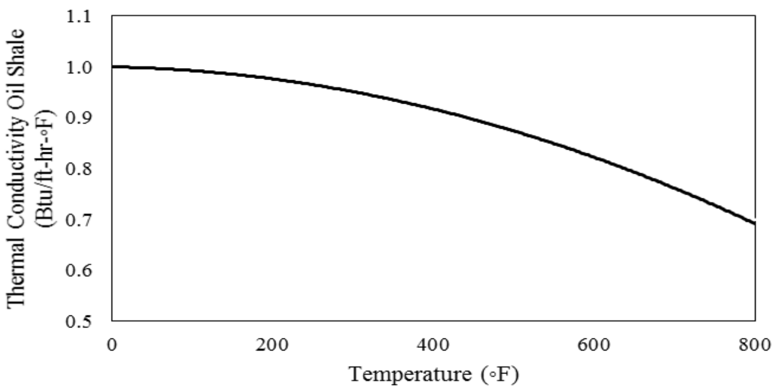


Figure 2.6: Thermal conductivity versus temperature (Source: Prats & O' Brien, 1975)

Besides that, the thermal conductivity of Green River oil shale is anisotropic (Gilliam & Morgan, 1987). The anisotropy property of Green River oil shale is in such that the horizontal conductivity values are 50% higher than then vertical conductivity values (Nottenburg *et al*, 1978). Furthermore, thermal conductivity of oil shale is not significantly affected by pressure if the average porosity of shale is low. Dell'Amico, Captain and Chansky (1967) conducted a test with shale of average porosity 1.45%

and found that the thermal conductivity increased 2.1% with pressure increasing from 2.5MPa to 10MPa at ambient temperature.

On the other hand, heat capacity of Green River oil shale is also a function of temperature. From Figure 2.7, it can be seen that the heat capacity increases as the temperature of pyrolysis increases.

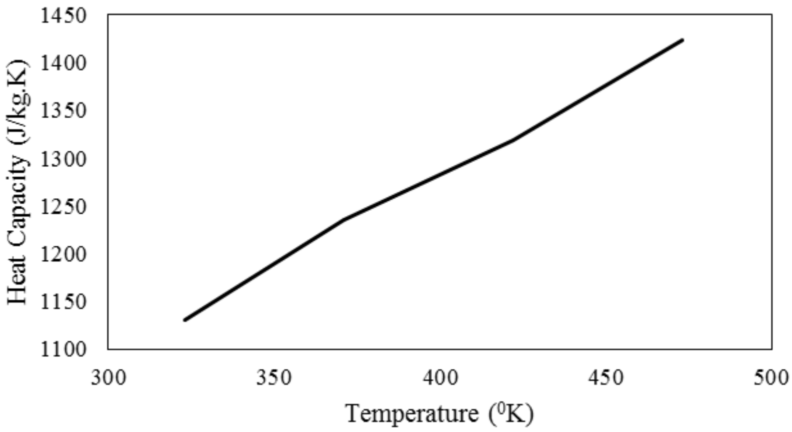


Figure 2.7: Heat capacity of Green River oil shale as function of temperature (Source: Gilliam & Morgan, 1987)

The heating process of oil shale is governed by fixed parameters such as conversion temperature and heating rate. It is found that the conversion temperature of in-situ pyrolysis of oil shale is around 340^{0}C (Allix *et al*, 2011). Fan *et al* (2009) used 371^{0}C as the conversion temperature of their model. Conversion temperature in some researches may go as low as 300^{0}C (Hoda *et al*, 2012) while that value agrees with the work from Symington and Spiecker (2008) who uses 260^{0}C to 325^{0}C. Brandt (2008) has another range of conversion temperature value which is from 340^{0}C to 360^{0}C. To be more relevant for commercial production purpose, it is said that reactions rates of oil shale is highly dependent on temperature and the higher the temperature the quicker it is to reach the peak production time (Fan *et al*, 2009). From Figure 2.9, the reaction time for 90% decomposition of kerogen in Colorado oil shale decrease as temperature increases.

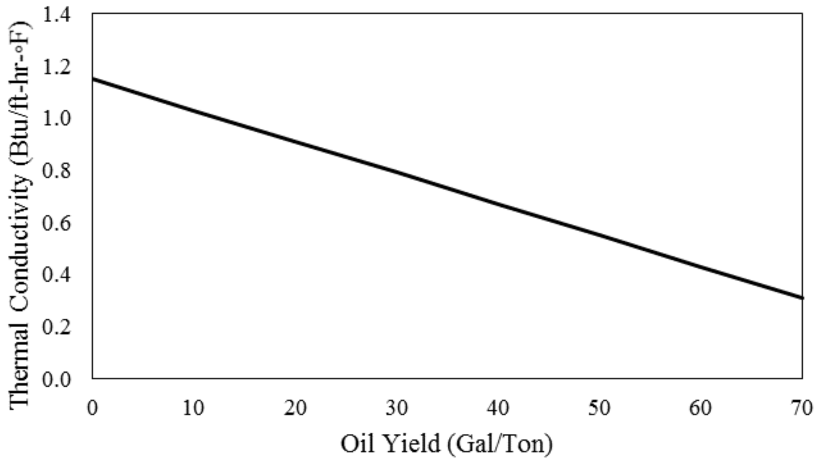


Figure 2.8: Heat conductivity against oil yield
(Source: Prats & O' Brien, 1975)

Although it can be seen that the conversion time decreases as temperature increases, this does not ensure a higher production rate as production rate is highly influenced by thermal conductivity while as shown in Figure 2.6, thermal conductivity of Green River oil shale decreases as the pyrolysis temperature increases. The relationship between the thermal conductivity and the oil yield can be seen in Figure 2.8.

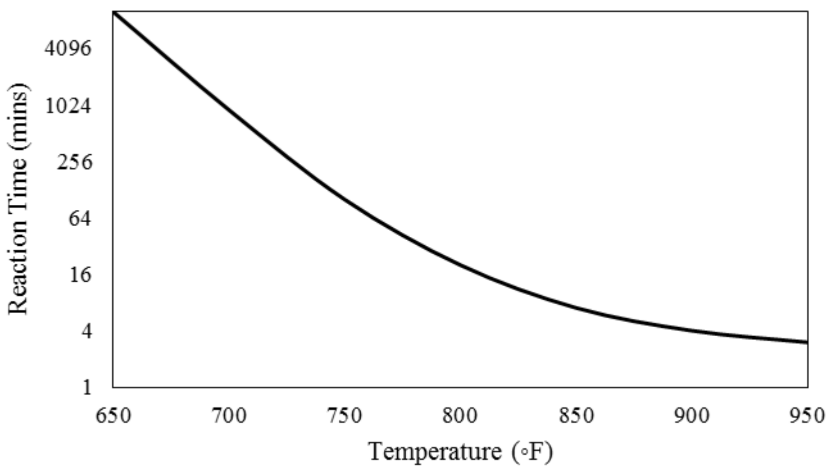


Figure 2.9: Reaction time for 90% decomposition of kerogen in Colorado oil shale
(Source: Prats & O'Brien, 1975)

Heating rate is crucial in in-situ upgrading process of oil shale. Heating rate can determine the quality of shale oil that is converted from oil shale (Allix *et al*, 2011). Shell In-situ Conversion Process (ICP) uses 0.5^0C/day to produce 40 degree API gravity of oil (Brandt, 2008). Figure 2.10 below shows the relationship between heating rate and the shale oil quality produced.

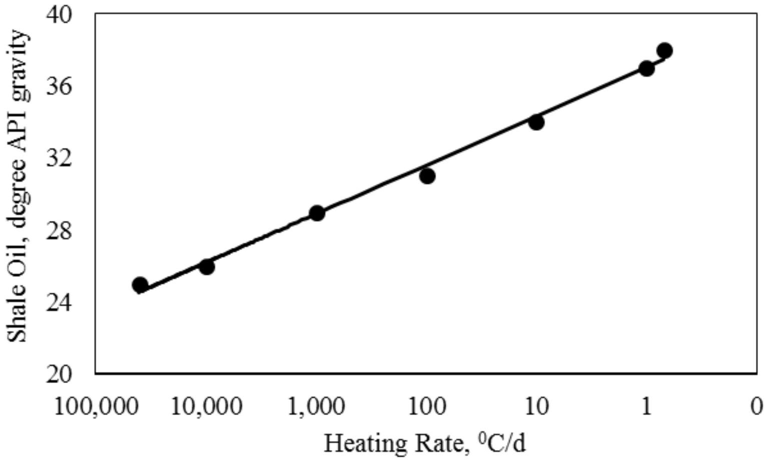


Figure 2.10: Relationship between heating rate and produced shale oil quality (Source: Allix *et al*, 2011)

2.3 Summary of Literature Review

The table below shows the summary of some important parameters from the literature review.

Table 2.2: Summary of important parameters from literature review

	Depth of Green River Oil Shale Layer (m)	Air Gap Thickness (inches)	Oil Shale Conversion Temperature (^{0}C)	Thermal Conductivity (Btu/ft-hr-^{0}F)
Wong (2018)	281-540	-	-	-
Allix et al (2011)	366-609	-	340	-
Brandt (2008)	270 and below	-	340-360	-
RPS Energy Canada (2013)	-	5	-	-
SPE (2012)	-	5.5	-	-
Fan et al (2009)	-	-	371	-
Symington & Spiecker (2008)	-	-	260-325	1.042
Hoda et al (2012)	-	-	300	
Gilliam & Morgan (1987)	-	-	-	0.618
Carpenter & Sohn (1968)	-	-	-	0.399-0.901
Prats & O'Brien (1975)	-	-	-	0.264-1.110

Based on the literature survey, temperature plays an important role in yielding shale oil from oil shale via in-situ pyrolysis. Ideally, high temperature leads to low thermal conductivity in oil shale which at the same time results in high shale oil production. Realizing that there is an air gap between the heater and wellbore, the effect of air gap on the performance of in-situ pyrolysis of oil shale must be assessed to ensure precise heat transferred into oil shale from the electric heater. Hence, the air gap thickness should be quantified in order to incorporate air layer into modelling of in-situ pyrolysis of oil shale and to study the effect of it on the heat transfer of in-situ pyrolysis of oil shale.

CHAPTER 3

3.0 Methodology

3.1 Research Flow Chart

This research follows the flow of research as being describe below in Figure 3.1.

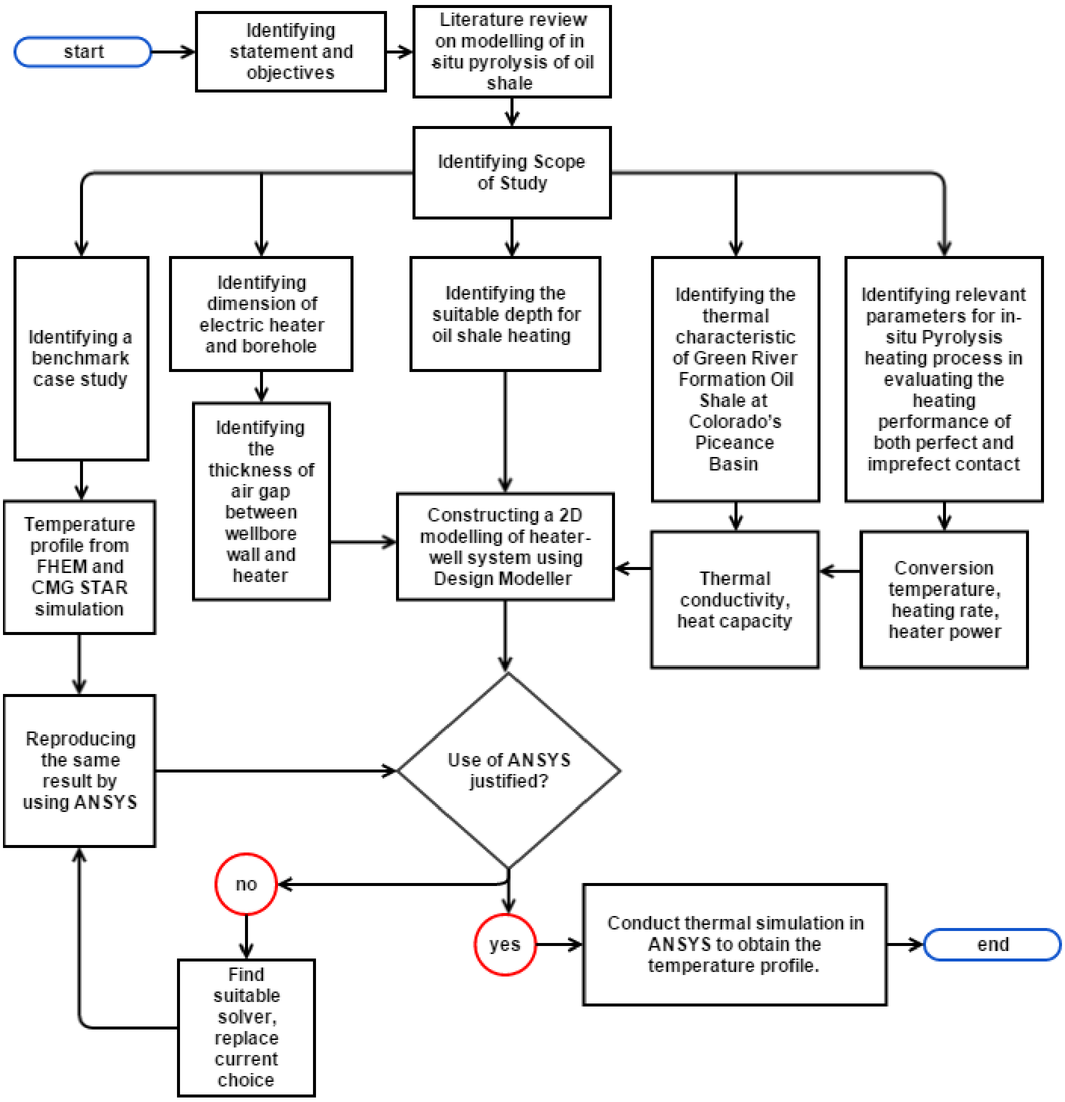


Figure 3.1: Research activities flow chart

3.2 Governing Equation of Non-Linear Heat Transfer

As the thermal conductivity and heat capacity of Green River Formation are thermal dependent parameters, heat transfer analysis of in-situ pyrolysis of oil shale will be governed by non-linear mathematical solutions. Temperature dependence of material properties causes nonlinearity in differential equation, non-linearity in the boundary conditions and nonlinearities in both (Buckley, 2010). In this project, thermal conductivity and heat capacity of oil shale are temperature dependent, thus the nonlinear partial differential equation is:

$$\rho(T)c(T)\frac{\partial T}{\partial t} = div[\lambda(T)\nabla T] + Q \qquad (1)$$

Where T is temperature, $\lambda(T)$ is temperature dependent thermal conductivity of the medium, $\rho(T)$ is the temperature dependent density, $c(T)$ is the temperature dependent specific heat capacity and Q is the internal heat generation. For this project, density and specific heat capacity are assumed to be constant and there is no internal heat generation. Therefore, this yields the following equation:

$$c\rho\frac{\partial T}{\partial t} - div[\lambda(T)\nabla T] = 0 \qquad (2)$$

Equation (2) is a transient equation with three spacial coordinates(x, y, z). The approximate solution along these spacial coordinates are themselves function of time and their values at any time instant are dependent on the earlier solutions. The function describing the temperature distribution in space and time is presented as $T(x, y, z, t)$. To solve the problem, the model is first discretize by time, followed by linearization to obtain solution of quasi-steady nonlinear problem.

As the pyrolysis is done in such a way that the heater has a constant thermal power supply, thus, there will be a constant heat flux in this case. This boundary condition is called as the Neumann boundary condition and the equation is as following:

$$q = \bar{q} \text{ where } q = \lambda\frac{\partial T}{\partial n} \qquad (3)$$

Since this project will be considering the air gap between the heater and well system, thus, there must be a convective boundary condition. The equation of convective boundary condition is as following:

$$q = -\alpha(T - T_{env}) \qquad (4)$$

Where α is the convective heat coefficient and T_{env} is the temperature of the medium surrounding the convective boundary.

3.3 Model Formulation

In order to reduce the computing time significantly, 2D heat transfer analysis will be conducted in ANSYS Transient Thermal module. 2D heat transfer analysis is highly probable for this case as the model is highly symmetrical therefore the effect of thickness can be ignored. In that, the degree of freedom (DOF) in this analysis will be reduced to 2 DOF. Both model are heated for 2 years and the initial temperature for the model will be 25^{0}C (average temperature gradient around the earth is 25^{0}C per km). In the analysis of these both models, the distance of oil shale converted will be obtained from the temperature profile results whereby oil shale that reaches 320^{0}C and above are considered converted. The model is shown as in figure below.

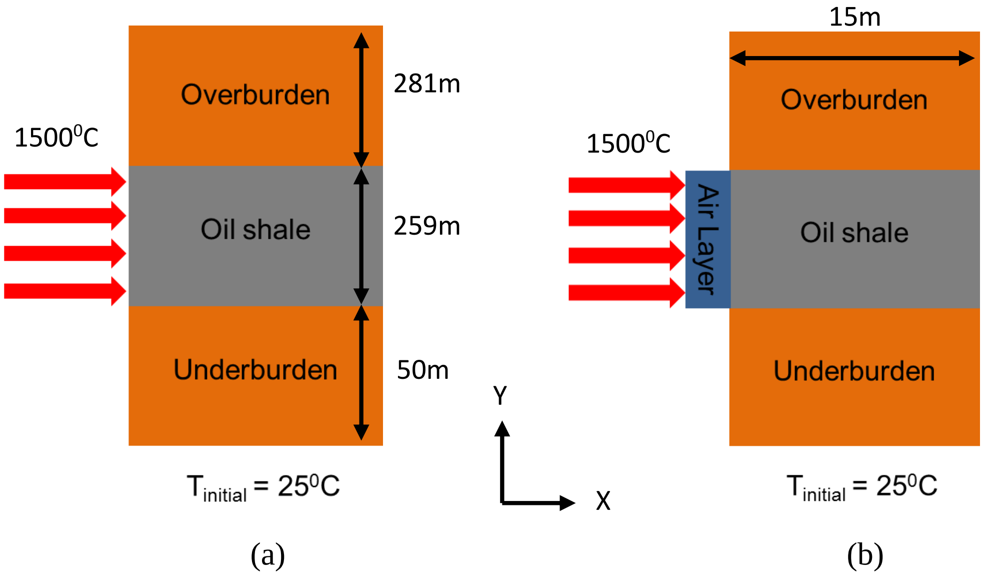


Figure 3.2: (a) Perfect heater contact model (b) Imperfect heater contact model

The quality of oil shale used in this model is 35GPT with anisotropic thermal conductivity. This oil shale has density of 1793.7 kg/m^3. The thermal conductivity and the specific heat capacity are non-linear; it changes according to different temperature.

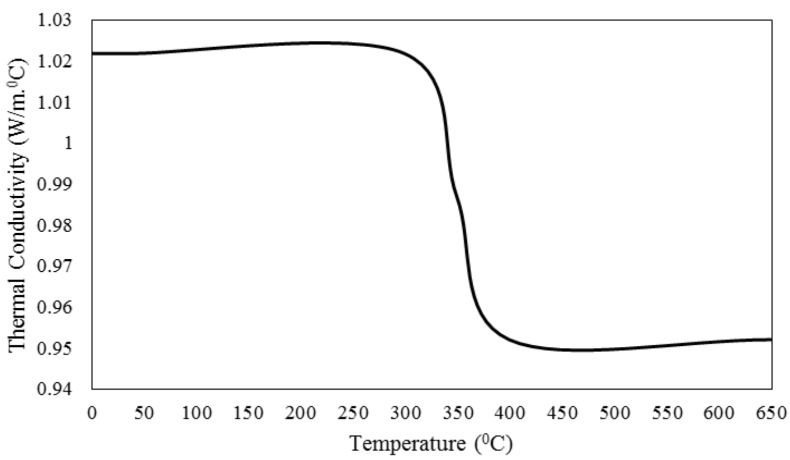


Figure 3.3: Thermal conductivity of 35GPT oil shale

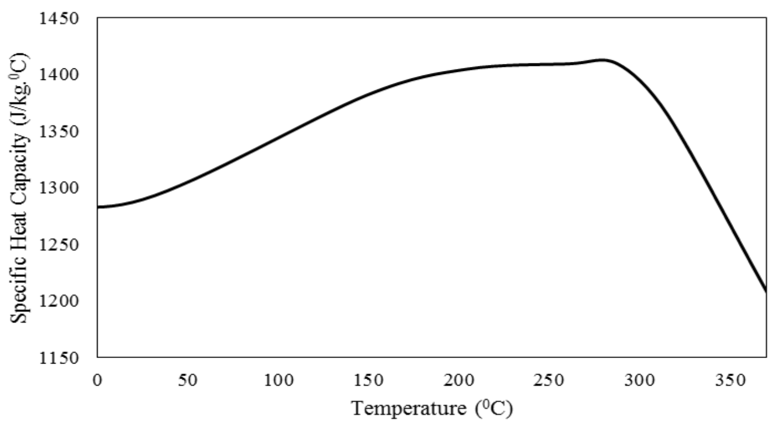


Figure 3.4: Specific heat capacity of 35GPT oil shale

As for the imperfect heater contact model, the air layer is modelled as solid of equivalent air element with thermal properties of still air at 25^{0}C. This implies that there will not be convection in the air layer, instead conduction will occur. The thermal properties of equivalent air element for still air at 25^{0}C has density of 1.184 kg/m^3, thermal conductivity of 0.026 W/m.^{0}C and specific heat capacity of 1005 J/kg.^{0}C.

3.4 Mesh Dependency

The accuracy and stability of numerical computation is largely affected by quality of mesh and the number of elements of a particular model. The quality of mesh is evaluated by orthogonal quality, aspect ratio, skewness and so on. In this project, as the geometry is very simple, the mesh generated on the model will be predominantly hexahedral in 3D models and quadrilateral in 2D modelling. Thus, cell quality is evaluated by using aspect ratio whereby aspect ratio of close to the value of 1 will be highly favourable.

High number of elements are definitely favourable in yielding accurate results but it comes at the expense of computational time. Therefore, a test on the minimum number of elements to achieve a stable and consistent result will be conducted whereby the number of elements will be gradually increased 1.5 to 2 times of the previous amount until the results stabilize.

The mesh dependency test is conducted on the full model of the project in both perfect and imperfect heater contact to determine the minimal number of elements to achieve an accurate simulation result. The result of the perfect heater contact simulation is as shown in the figure below.

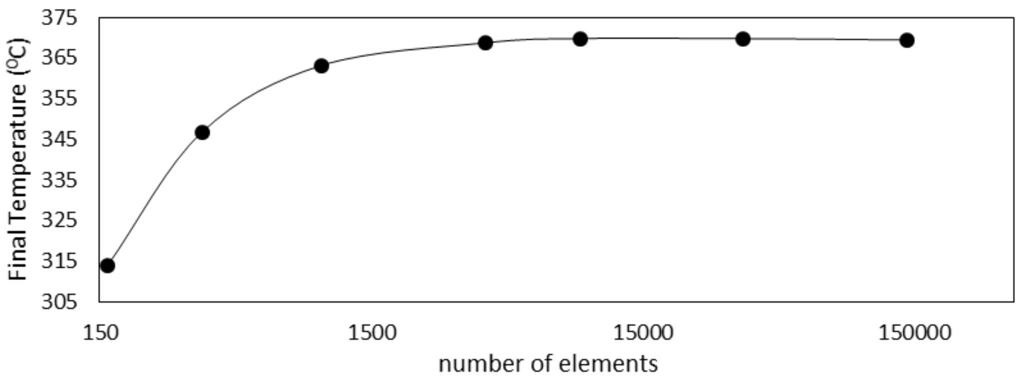


Figure 3.5: Mesh dependency test result of perfect heater contact

From Figure 3.5, it can be observed that the final temperature result of the simulation model stabilizes at starting from 8000 elements. Thus, it can be concluded that the model should be analysed at around 8000 elements to achieve accurate results at the least simulation time possible.

As for meshing of imperfect heater contact, the minimum size of the mesh is highly dependent on the thickness of the air gap. For example if the air gap is 0.1m, the maximum size of the uniform quadrilateral element must be 0.1m. The following table shows the mesh settings and the mesh qualities used for each different thickness of air gap.

Table 3.1: Mesh Settings

Air Gap Thickness (m)	Maximum Size of Element (m)	Minimum Number of Elements
0.050	0.050	3545180
0.075	0.075	1577054
0.100	0.100	887590
0.125	0.125	568472
0.150	0.150	395227

The figure below shows the example of mesh output inside ANSYS.

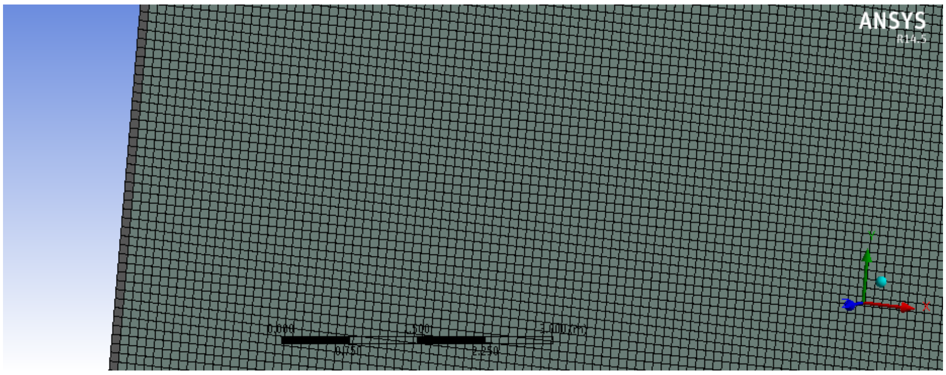


Figure 3.6: Mesh output for element size 0.1m

3.5 Gantt Chart

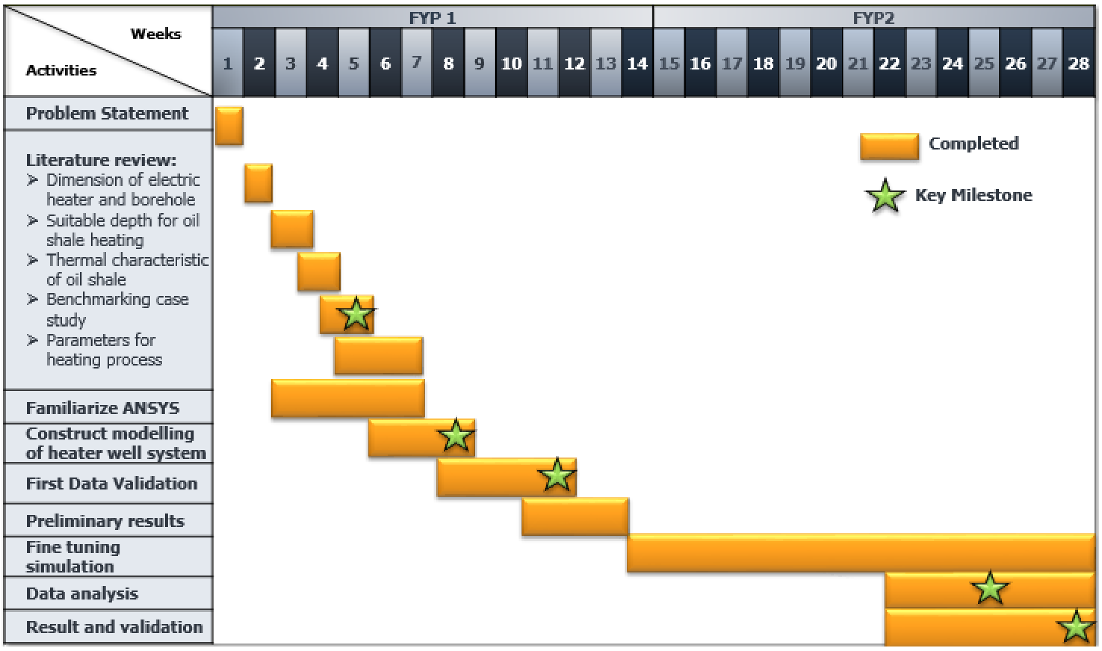


Figure 3.7: Gantt Chart

CHAPTER 4

4.0 Result and Discussion

4.1 Data Validation

The first validation done by comparing result from ANSYS Transient Thermal analysis model to FEHM and STAR CMG model. The model is as shown the figure below.

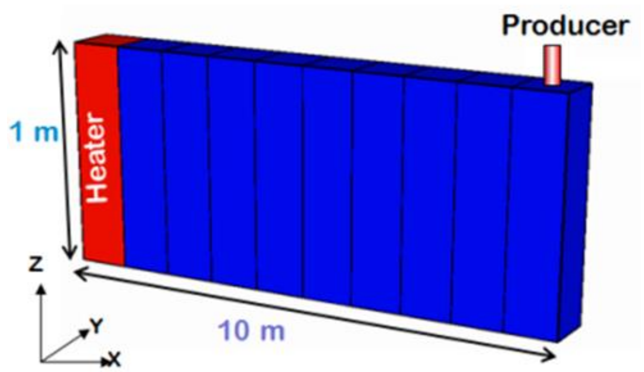


Figure 4.1: Model of Heater Well
(Source: Hoda *et al*, 2012)

The dimension of this model is (1m x 10m x 1m) and a heater heats the oil shale quality of 35 gallon per ton at 700W for 90 days. The effect of overburden and underburden were disregard in the model did by Hoda *et al*. Figure 4.2 shows the model that is modelled in ANSYS. The oil shale thermal conductivity and heat capacity data used is as shown in Figure 4.2.

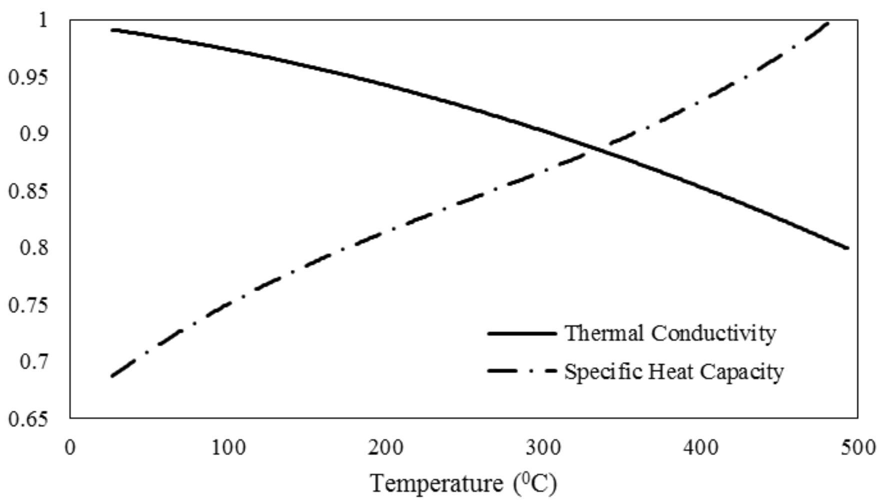


Figure 4.2: Normalized thermal conductivity and specific heat capacity data for validation model
(Source: Hoda *et al*, 2012)

The initial temperature of the model is 25^{0}C. The result of validation is as shown in Figure 4.3.

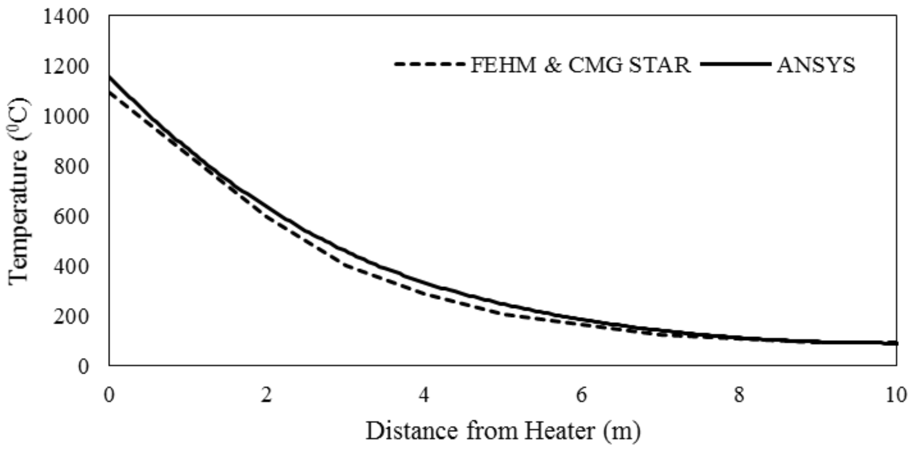


Figure 4.3: Comparison between the result of FEHM/CMG STAR and ANSYS

The validation model for this project has close agreement with the results from FEHM and CMG STAR model. In the FEHM and CMG STAR model, the final temperature 0 meter is 1093^{0}C while at 10 meters away is 93^{0}C. Using ANSYS thermal transient module, the final temperature at 0 meter is 1152.5^{0}C while 10 meters away is 90.1^{0}C. The slight discrepancy is mainly because the ANSYS model is pure conduction in solid with no phase changes in oil shale is assumed. In FEHM and CMG STAR model, both conduction and convection is being considered as phase changes of oil shale is included in the model. Thus, it is relevant that the ANSYS model achieves higher temperature as the energy is not lost via phase changes.

4.2 Temperature Profile of Full Model with Perfect and Imperfect Heater Contact

The simulation for full model of perfect and imperfect heater contact has been run and the temperature profile has been plotted starting from the wellbore.

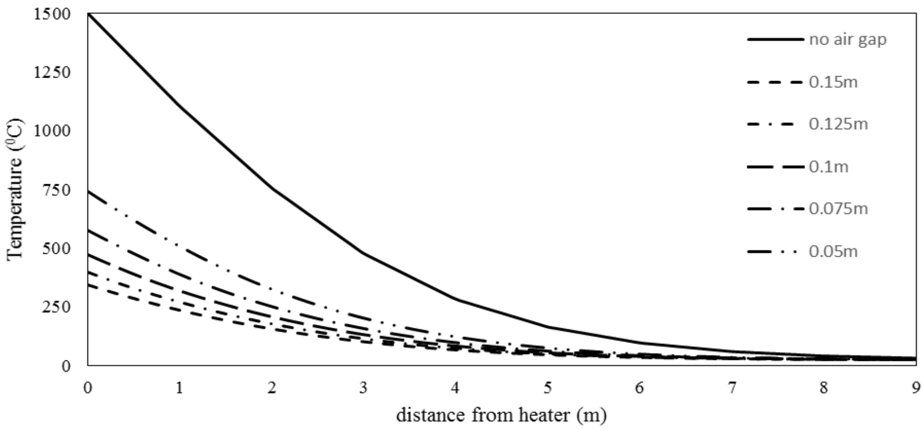


Figure 4.4: Temperature Profile of Perfect and Imperfect Heater Contact (legend showing the thickness of air gap)

From Figure 4.4, it can be seen that the perfect heater contact achieves the highest maximum temperature at 1500^{0}C, which is the temperature of the heater, as compared to those of imperfect heater contact. This is followed imperfect heater contact with the thinnest air gap of 0.05m with maximum temperature at 742.33^{0}C, 0.075m with maximum temperature at 577.8^{0}C, 0.1m with maximum temperature at 471.43^{0}C, 0.125m with maximum temperature at 397.49^{0}C and 0.15m with the lowest maximum temperature at 344.6^{0}C. The next figure below shows the temperature drop inside the air layer between the heater and the wellbore.

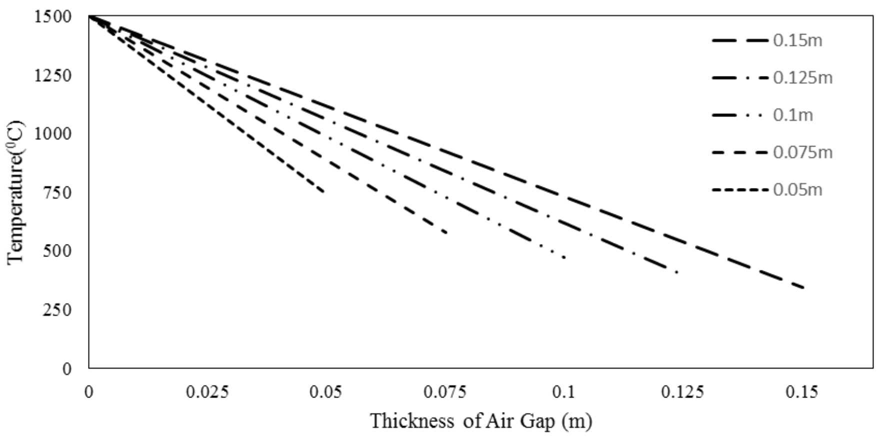


Figure 4.5: Temperature Profile Inside the Air Gap between the Heater and Wellbore

The temperature drop due to the air gap between the heater and the wellbore shows an obvious trend whereby the largest temperature drop is experienced by the thickest air gap of 0.15m, and the temperature drop decreases as the thickness decreases to 0.125m, 0.1m, 0.075m and 0.05m. To show how significant is the effect of air gap with various thickness on the performance of in-situ pyrolysis of oil shale, the temperature profile result is translated into the Figure 4.6.

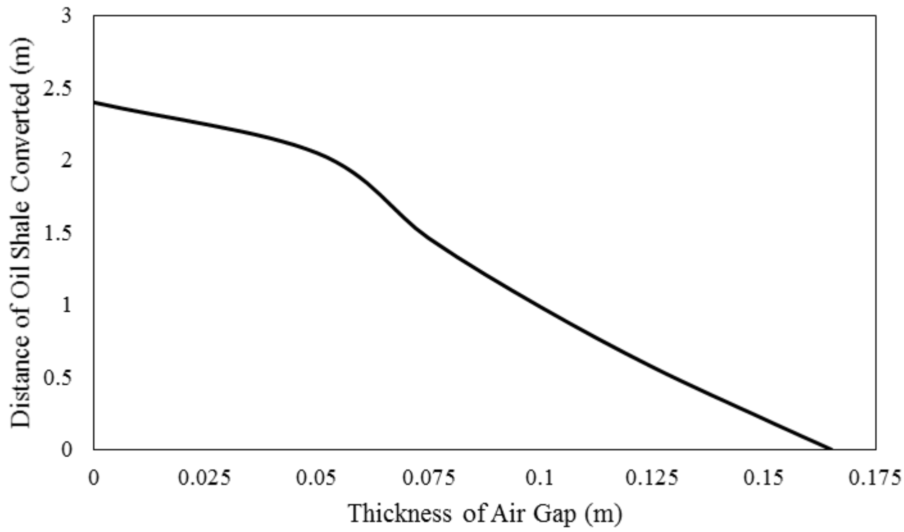


Figure 4.6: Distance of Oil Shale Converted into Crude Oil in Perfect and Imperfect Heater Contact in In-Situ Pyrolysis of Oil Shale

As mentioned, oil shale is assumed to be converted if it reaches the temperature of 320^0C and above. From Figure 4.6, it can be seen perfect heater contact system converts the most distance of oil shale at around 2.4m. The distance of oil shale convert drops as the thickness of air gap increases. At 0.05m of air gap, 2.1m of oil is convert. The trend continues to decrease with 1.46m of oil shale pyrolysed at 0.075m of air gap, 0.99m of oil shale pyrolysed at 0.1m of air gap, 0.57m of oil shale pyrolysed at 0.125m of air gap, 0.21m of oil shale pyrolysed at 0.15m of air gap and eventually no oil shale is pyrolysed at 0.165m of air gap.

4.3 Parametric Study

A parametric study has been established in this project to gain further insight between the relationships of some variables and the result of the study.

Table 4.1: Parametric Study Comparison

Input parameters	**Validation**	**Present study**
Oil Shale Quality (GPT)	35	15 - 35
Initial temperature of Air Gap (^{0}C)	No air gap	15, 25, 40
Heater Input	Heat flux of 700W/m.^{0}C	Constant temperature of (1000 - 2500)^{0}C
Oil shale heating duration (days)	90	90, 135, 180

The first parametric study done is to establish the relationship between the oil shale qualities (GPT) and the temperature profile of anisotropic oil shale layer at heater temperature of 1500^{0}C

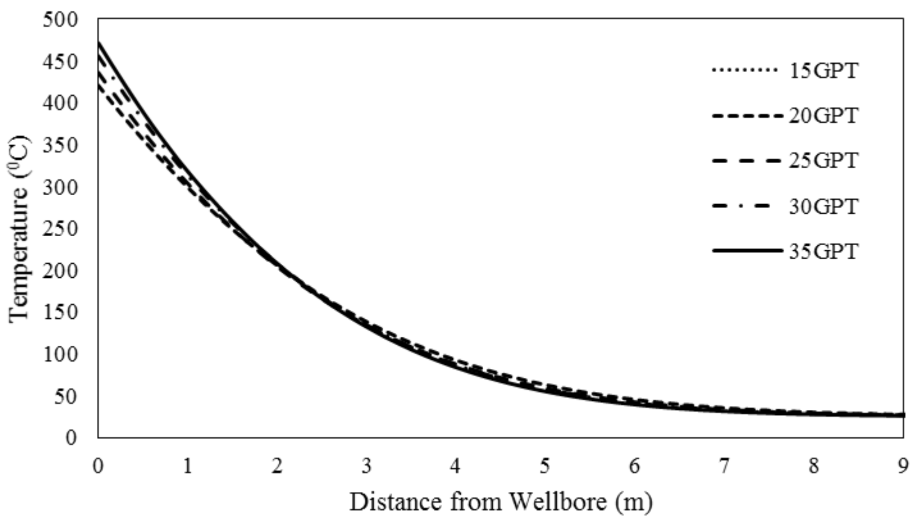


Figure 4.7: Temperature profile of imperfect heater contact (0.1m air gap) with various oil shale quality (GPT)

From Figure 4.7, the trend shows that the maximum temperature increases from oil shale of 15GPT to 35GPT. This phenomenon is due to the fact that the thermal conductivity of the oil shale decreases as the amount of oil shale increases in the rock. The second parametric study done is to establish the relationship between the initial temperature of air gap and the temperature profile of anisotropic 35GPT oil shale layer at heater temperature of 1500^0C.

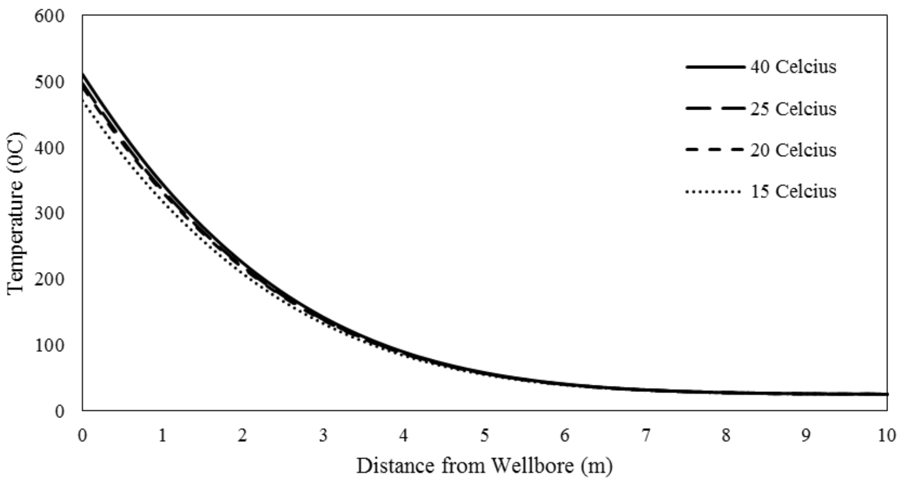


Figure 4.8: Temperature profile of imperfect heater contact (0.1m of air gap) with various initial temperature of air gap

From Figure 4.8, it can be observed that the overall temperature of oil increases as the initial temperature of the still air increases. This can be explained by the fact that the air has non-linear thermal characteristics. Between the temperatures of 15^0C to 40^0C, the thermal conductivity of the air increases along with the temperature from 0.024 W/m. ^{0}C to 0.027 W/m. ^{0}C. At the same time, the density of the still air decreases from 1.23 kg/m^3 to 1.27 kg/m^3. Due to the changes in thermal conductivity and density of the air along with the temperature, thermal diffusivity increases as the temperature increases (from 2.0E-5m^2/s to 2.4E-5m^2). This implies that the rate of heat transmitted is quicker at higher temperature. The third parametric study done is to establish the relationship between the constant temperature heater input and the temperature profile of anisotropic 35GPT oil shale layer.

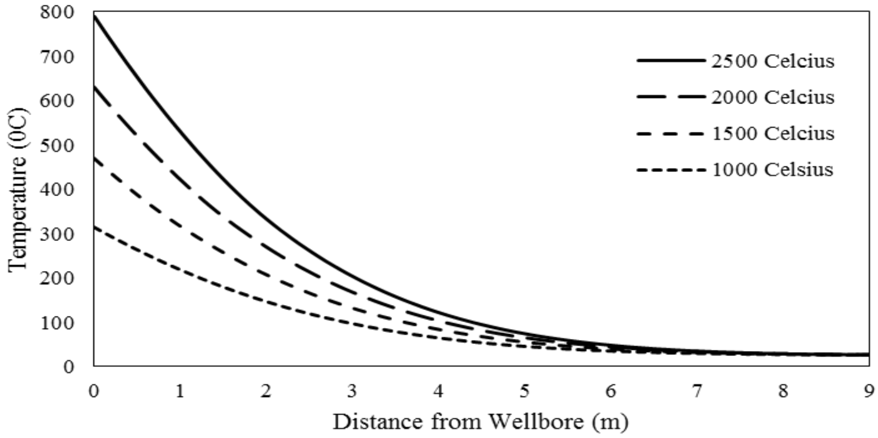


Figure 4.9: Temperature profile of imperfect heater contact (0.1m of air gap) with heater temperature of 1000^0C, 2000^0C and 2500^0C.

From Figure 4.9, it can be seen that the overall temperature of oil shale increases as the heater temperature increases. The forth parametric study done is to establish the relationship between the anisotropic thermal conductivity of oil shale and the temperature profile of anisotropic 35GPT oil shale layer at heater temperature of 1500^0C.

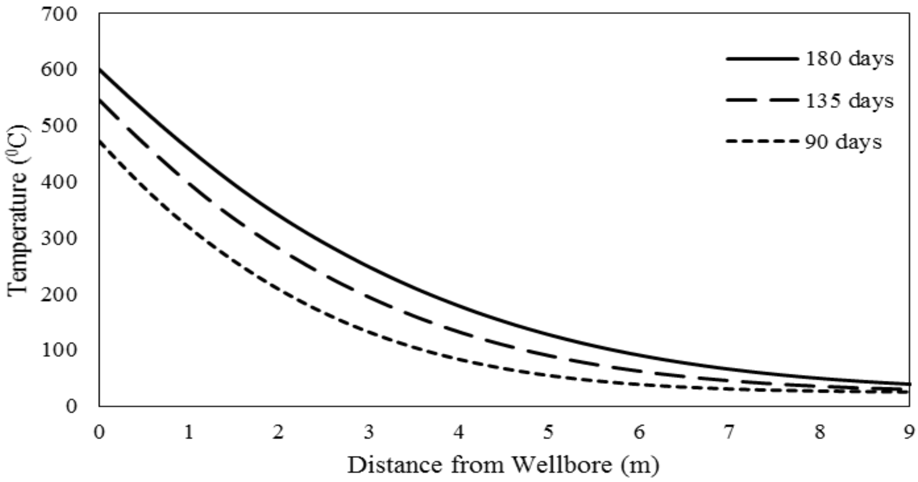


Figure 4.10: Temperature profile of imperfect heater contact (0.1m of air gap) with various heating duration

The relationship between the heating period and temperature profile of oil shale is straightforward as the longer is the heating of oil shale, the higher the overall temperature as more heat energy is supplied.

After establishing the relationship between the variables, the next step is to establish the parameters' weighting factor. Figure 4.11 shows the bar chart of the parameter's weighting factor:

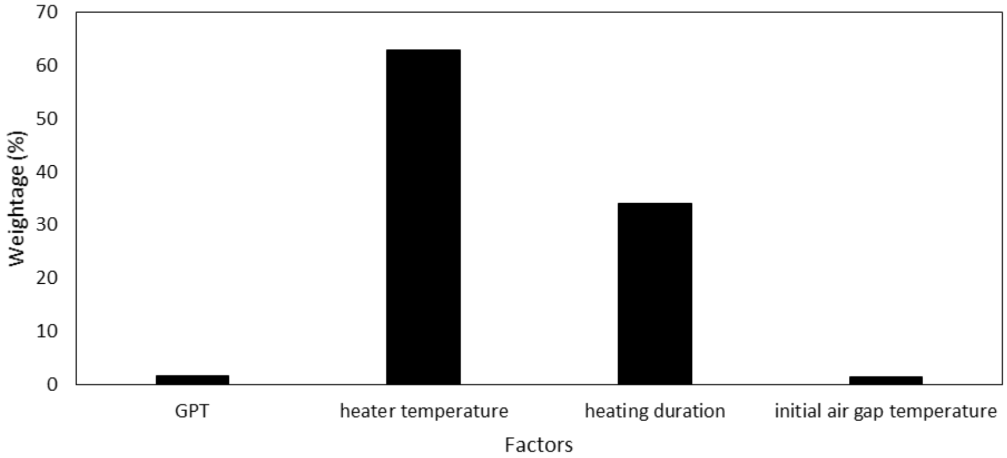


Figure 4.11: Parameters' weighting factor on in-situ pyrolysis of oil shale with air gap of 0.1m

From the figure above, it can be observed that the heater temperature has the highest weightage and this is followed by heating duration, GPT and initial air gap temperature. This implies that more focus should be allocated on the electric heater performance as well as the heating duration in improving the in-situ pyrolysis process. The next chart, which is a tornado chart shows the sensitivity of parameters to the distance of oil shale converted in in-situ pyrolysis of oil shale.

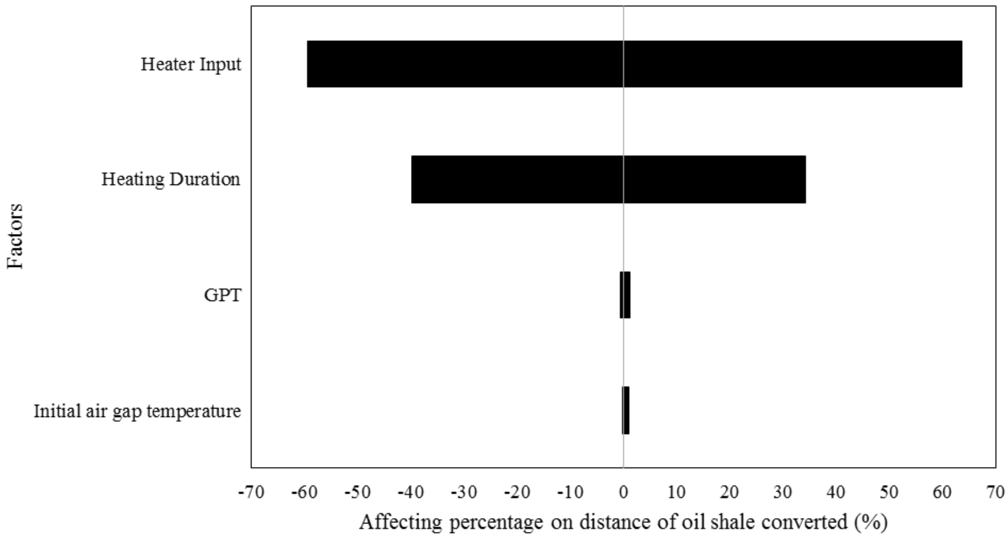


Figure 4.12: Parameters' sensitivity to distance of oil shale converted

From the sensitivity analysis, heating duration has the highest sensitivity and this is followed by heater input temperature, initial air gap temperature and GPT of oil shale. As for the resulting percentage for both low and high value of heater temperature input, the resulting percentage is slightly higher for high value which is 63.62% as compared to 59.4%. The same pattern are also seen in the sensitivity for GPT of oil shale (from 1.14% to 0.54%) and initial air gap temperature (from 1.07% to 0.27%). On the other hand, while the previous three factors' sensitivity are decreasing with lower input value, a reverse trend is seen on the sensitivity for heating duration of oil shale when the input goes from high to low value (from 34.18% to 39.79%). This implies that as heater temperature increases the heating duration to convert more distance of oil shale will be shorter and other factors such as GPT of oil shale and initial air gap of temperature become negligible.

CHAPTER 5

5.0 Conclusion and Recommendation

As global conventional oil resources depletion is accelerating with increasing demand for energy from developing countries, it is only the matter of time that the attention will be put on exploitation of conventional oil. With an estimated 3 trillion equivalent barrels of oil that can be produced from world oil shale reserves, it is totally viable to continue to improve and innovate in-situ pyrolysis of oil shale technologies as they do not reach maturity stage where it can be commercially implemented. In this research, it has been identified that a conventional electric down-hole heater-well system has an air gap which its effect on the performance and efficiency of heating oil is relatively unknown and no research has been done on it. Thus, this research will attempt to create a heater-well system modelling and a thermal simulation of the effect of air gap on the performance of oil shale heating process will be done.

This project has achieved its objective which is to quantify the air gap between the heater and wellbore whereby its thickness is in the range of 0m to 0.14m. Based on the results of simulation using ANSYS Transient Thermal module at 1500^0C heater temperature, it can be conclude that the larger the air gap, the lower the overall temperature profile of the oil shale layer. Translating this result into the distance of oil shale converted, at perfect heater contact, 2.4m of oil shale is converted while for the air gap thickness of 0.1m, only 0.985m of oil shale is converted. In the perspective of shale oil production through in-situ pyrolysis of oil shale, that implies around 60% decrease in production if the air gap is 0.1m as compared to perfect heater contact. An extended testing shows that no oil shale is converted if the air gap is 0.165m.

In the parametric study, it can be seen that both GPT of oil shale and initial temperature of air gap has negligible effect on the resulting distance of oil shale converted. The factors that impose the highest weightage are heater temperature input and heating duration of oil shale.

As for the future work, more focus should be channelled into developing the relationship between the heat input and the heat transfer in heater as precise heat transfer is vital for in-situ pyrolysis of oil shale. Furthermore, the optimum retorting condition should be extensively explored. On top of that, wellbore stability analysis can be carried as the sedimentary rocks may experience thermal expansion due to very high temperature heating.

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Appendices