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

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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^{0}C 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^{0}C. 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.**

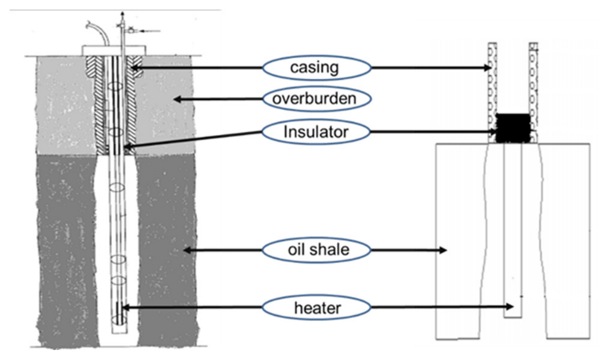
Key words: Imperfect heater contact, oil shale, air gap, wellbore, transient thermal, heater well, in-situ pyrolysis

I. Introduction

Oil shale, known as one of the unconventional oil sources, has world reserve of an equivalent to 3.2 trillion barrels [1]. 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 [2]. 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 [3]. 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. However, in-situ pyrolysis of oil shale technologies are still under extensive development as full understanding about the process has not been achieved.

II. Literature Review

Figure 1 shows the schematic diagram for heater-well system. The main components of a heater well system as shown in Figure 1(a) are casing of borehole, the overburden layer, the oil shale layer, heater and the insulator. For numerical modelling purpose, this system is being simplified as shown in Figure 1(b):



(a) (b)

Fig 1 (a) Full schematic diagram of heater-well system; (b) Simplified schematic diagram of heater-well system

However, this simplification neglected the overburden and underburden layer which is key in contributing to heat loss in in-situ pyrolysis of oil shale [4]. Ironically, a research 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 incremental of 17^{0}C in temperature [5]. The thickness of the overburden layer depends on the depth where the kerogen rich oil shale lies in. According to another research, 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 [6]. This figure falls in the range of a research which shows that the richest oil shale layer lies in between Mahogany zone, R6 and R5 which is in between 366m to 609m [1]. In a modelling of Shell in-situ conversion process (ICP), the thickness of overburden was set at 270 meters [5]. Hence, it can be said that the thickness of overburden layer is acceptable within the range of 259 meters to 366 meters.

TABLE I
Colorado's Piceance Basin oil shale resources [1]

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 [1] relative to the radial distance from the heater. According to Shell ICP modelling [5], around 3m of oil shale is converted into shale oil.

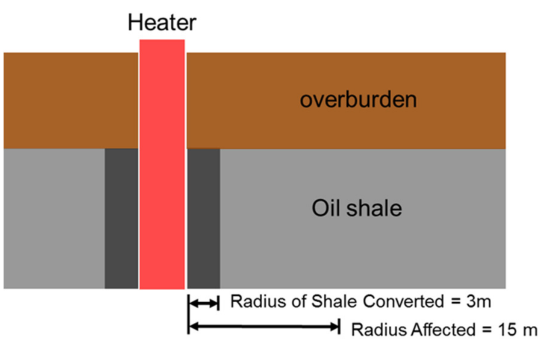


Fig 2 Radial distance converted into shale oil by heater [6]

This agrees with the Finite-Element-Heat-Mass (FEHM) modelling of in-situ upgrading process of oil shale [11] which stated that the temperature of oil shale at 4 meters away from the heater was only about 260^0C as shown in Figure 3.

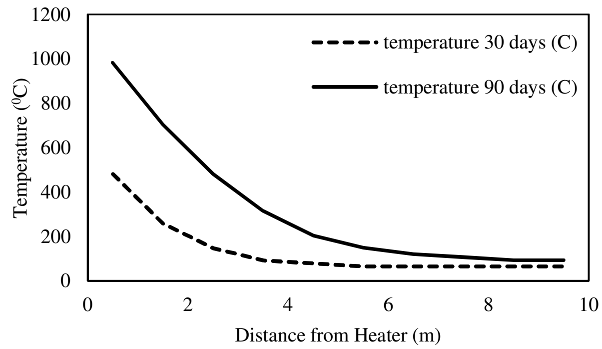


Fig 3 Result of in-situ pyrolysis modelling using FEHM and CMG STARS [11]

. 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 [8], it was found that the radius of heater is 0.1 meter (3.94 inches). According to standard well completion process, for well completion of small well less than 3500 feet, the diameter of the hole will be 14-14.75 inches. Therefore, it can be assumed that the thickness of the air gap will be around 5 inches to 5.5 inches.

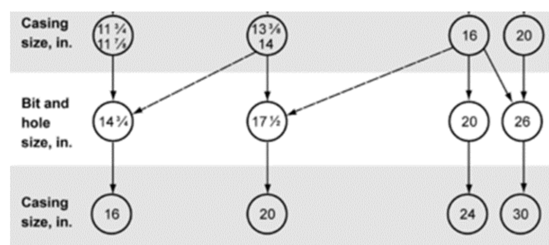


Fig 4 Standard combination of casing size for completion below 3500ft

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. It is reported that the average thermal conductivity of Green River Formation averaged at the value of 0.618 Btu/ft-hr-^{0}F [13]. This value fall within the range of value reported by a thermal conductivity test [7] by which was between 0.399 to 0.901 Btu/ft-hr-^{0}F. In an oil shale heat conduction analysis, 1.042 Btu/ft-hr-^{0}F is used [14]. All these well agrees with a work [15] 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 5. It can be observed that the thermal conductivity of oil shale decreases as temperature decreases.

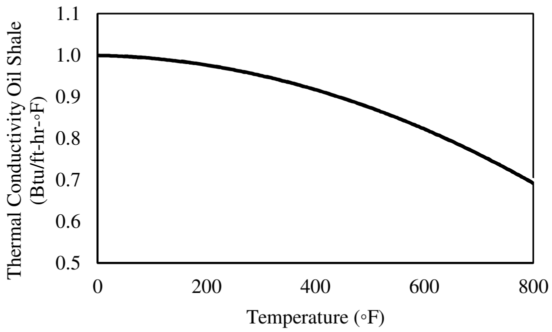


Fig 5 Thermal conductivity versus temperature [15]

Besides that, the thermal conductivity of Green River oil shale is anisotropic [13]. The anisotropy property of Green River oil shale is in such that the horizontal conductivity values are 50% higher than then vertical conductivity values [16]. Furthermore, thermal conductivity of oil shale is not significantly affected by pressure if the average porosity of shale is low. One test conducted 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 [17].

On the other hand, heat capacity of Green River oil shale is also a function of temperature. From Figure 6, it can be seen that the heat capacity increases as the temperature of pyrolysis increases.

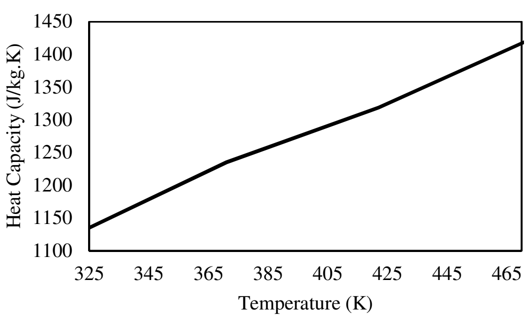


Fig 6 Heat capacity of Green River oil shale as function of temperature [14]

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 at around 340^0C [1]. In a numerical simulation [4], 371^0C is being used as the conversion temperature of their model. Conversion temperature in some researches may go as low as 300^0C [12] while that value agrees with the work who uses 260^0C to 325^0C [14]. Another range of conversion temperature value which is from 340^0C to 360^0C [5]. 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 [4]. From Figure 8, the reaction time for 90% decomposition of kerogen in Colorado oil shale decrease as temperature increases.

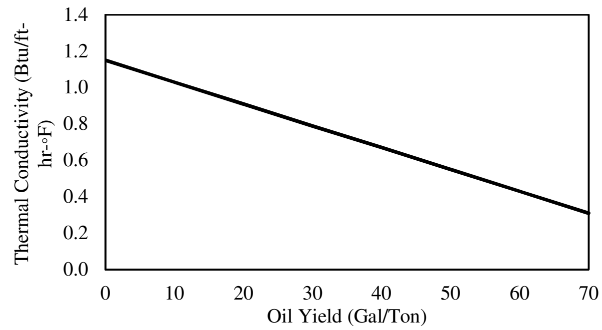


Fig 7 Heat conductivity against oil yield [15]

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 5, 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 7.

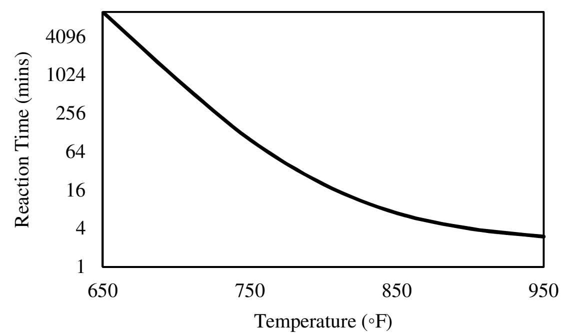


Fig 8 Reaction time for 90% decomposition of kerogen in Colorado oil shale [19]

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 [1]. Shell In-situ Conversion Process (ICP) uses 0.5^0C/day to produce 40 degree API gravity of oil [5]. Figure 9 below shows the relationship between heating rate and the shale oil quality produced.

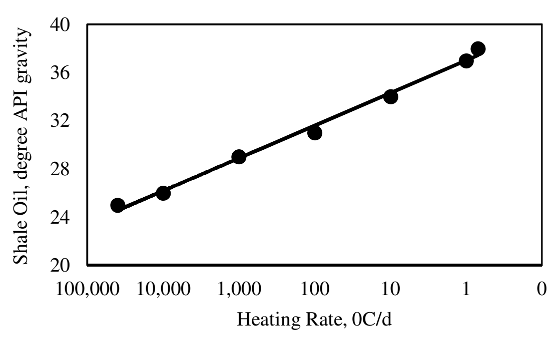


Fig 9 Relationship between heating rate and produced shale oil quality [1]

III. Methodology

This research paper will be focus on in-situ retorting method and develop the correlation between thickness of air gap and temperature profile of oil shale layer. First, base case based on the existing data is developed. From the existing data, temperature profile of 35GPT oil shale after 90 days of in-situ pyrolysis have been obtained using ANSYS Transient Thermal module. This result is then being validated by comparing to the result generated by FEHM and STAR CMG. After justifying the relevance of ANSYS Transient Thermal module, a full model of perfect and imperfect heater contact are modeled and simulation will be run to observe the effect of air gap between the electric heater of 1500^{0}C constant temperature and the wellbore on the resulting temperature profile of oil shale.

Since this research paper is deal with non-linear heat transfer due to non-linear thermal properties of oil shale, the governing equation is as followed [18]:

$$c\rho \frac{\partial T}{\partial t} - div[\lambda(T)\nabla T] = 0 \quad (1)$$

There is no heat flux on this case study, hence:

$$q = \bar{q} \text{ where } q = \lambda \frac{\partial T}{\partial n} = 0 \quad (2)$$

The convective boundary conditions in the air gap in this research is replaced by an equivalent solid element which has thermal properties of still air at 25^{0}C with density of 1.184kg/m^3, thermal conductivity of 0.026 W/m.^{0}C and specific heat capacity of 1005 J/kg.^{0}C.

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 quality of oil shale used in this model is 35GPT with anisotropic thermal conductivity. The model is shown as in figure below.

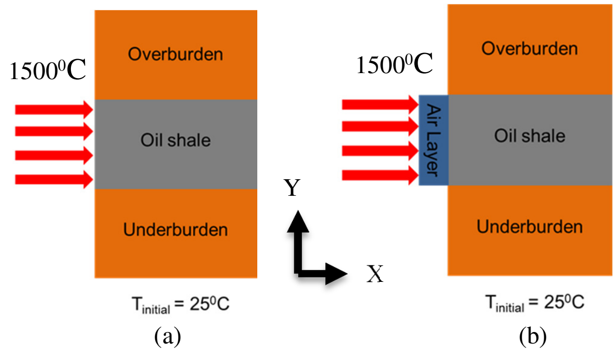


Fig 10 (a) Perfect heater contact model (b) Imperfect heater contact model

IV. Results and Discussion

A. *Justification of the Use of ANSYS Thermal Transient Module as Solver*

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.

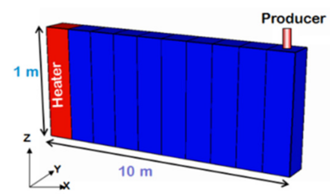


Fig 11 Model of Heater Well System [12]

The oil shale this model uses the following normalized thermal conductivity and specific heat capacity data.

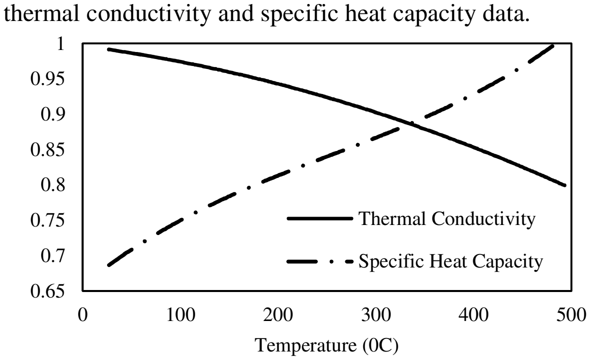


Fig 12 Normalized thermal conductivity and specific heat capacity data for validation model [12]

The results are as followed:

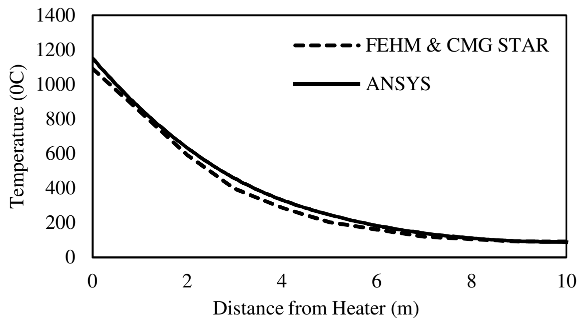


Fig 13 Comparison between the result of FEHM/CMG STAR and ANSYS

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.

B. Temperature Profile Result for Full Perfect and Imperfect Heater Contact Model

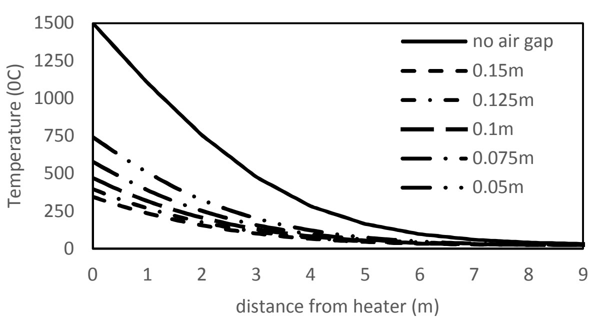


Fig 14 Temperature Profile of Perfect and Imperfect Heater Contact (legend showing the thickness of air gap)

From Figure 14, 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.

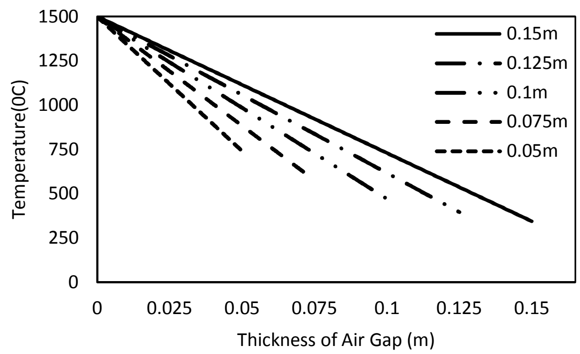


Fig 15 Temperature Profile Inside the Air Gap between the Heater and Wellbore

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 15.

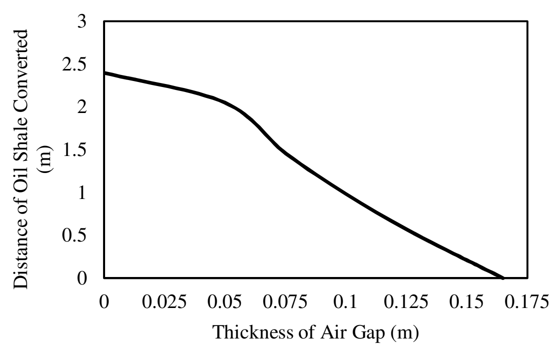


Fig 16 Distance of Oil Shale Converted into Crude Oil in Perfect and Imperfect Heater Contact in In-Situ Pyrolysis of Oil Shale

As mentioned, oil shale is assumed to be converted if it reaches the temperature of 320^{0}C and above. From Figure 16, 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.

C. 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 II
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 - 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

D. Correlation between Oil Shale Qualities (GPT) and the Temperature Profile of Anisotropic Oil Shale Layer at Heater Temperature of 1500^{0}C

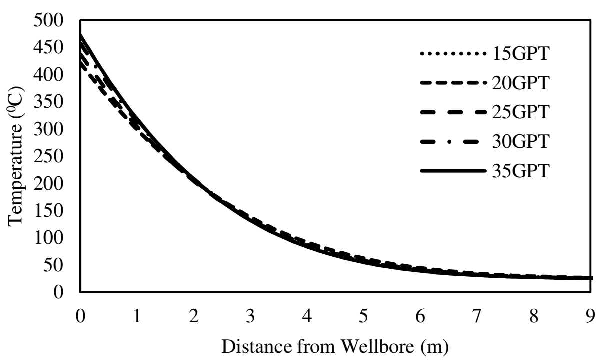


Fig 17 Temperature profile of imperfect heater contact (0.1m air gap) with various oil shale quality (GPT)

From Figure 17, 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.

E. Correlation between the Initial Temperature of Air Gap and the Temperature Profile of Anisotropic 35GPT Oil Shale Layer at Heater Temperature of 1500^{0}C

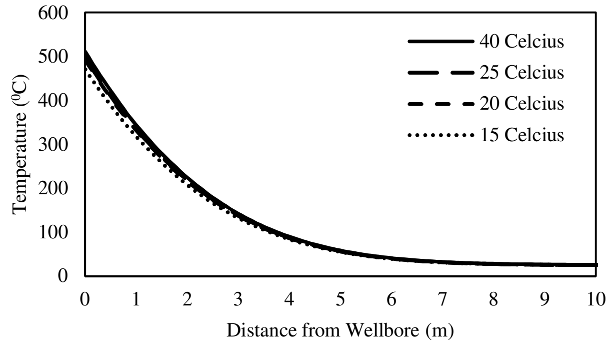


Fig 18 Temperature profile of imperfect heater contact (0.1m of air gap) with various initial temperature of air gap

From Figure 18, 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^{0}C to 40^{0}C, 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.

F. Correlation between Various Constant Temperature Heater Input and the Temperature Profile of Anisotropic 35GPT Oil Shale Layer

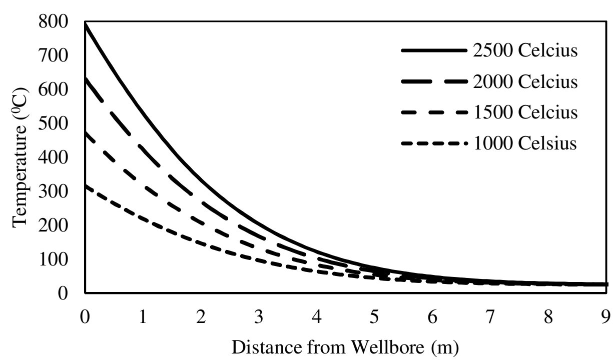


Fig 19 Temperature profile of imperfect heater contact (0.1m of air gap) with various constant heater temperature input

From Figure 19, it can be seen that the overall temperature of oil shale increases as the heater temperature increases.

G. Correlation between Oil Shale Heating Duration and the Temperature Profile of Anisotropic 35GPT Oil Shale Layer at Heater Temperature of 1500^{0}C

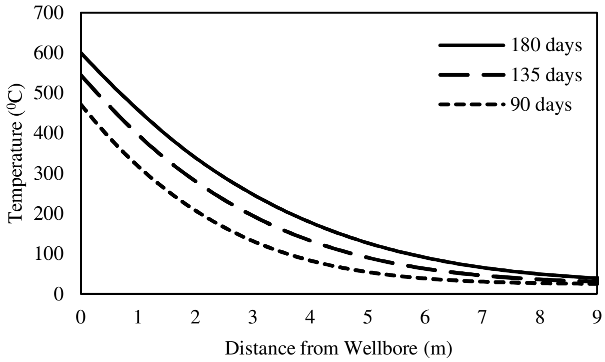


Fig 20 Temperature profile of imperfect heater contact (0.1m of air gap) with various heating duration

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

H. *Parameters' Weighting Factor Analysis*

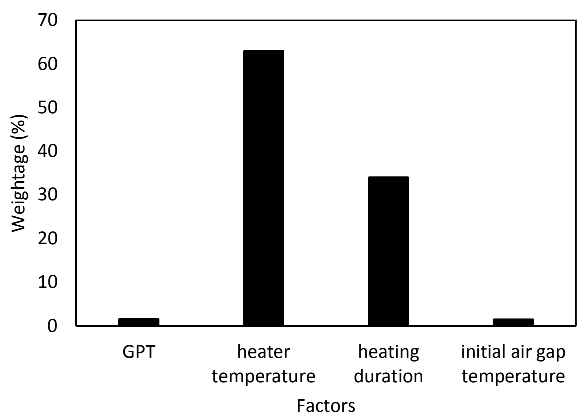


Fig 21 Parameters' weighting factor on in-situ pyrolysis of oil shale with air gap of 0.1m

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.

I. *Parameters' Sensitivity Analysis*

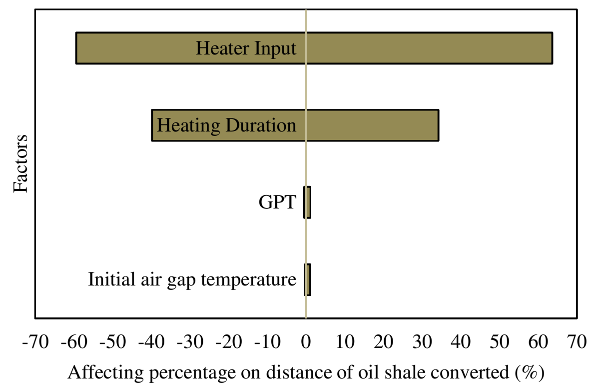


Fig 22 Parameters' sensitivity to distance of oil shale converted

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.

V. Conclusion

Based on the results of simulation using ANSYS Transient Thermal module at 1500^{0}C 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 brings the highest weightage are heater temperature input and heating duration of oil shale.

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