EVALUATION OF TOE-TO-HEEL AIR INJECTION (THAI) COMBINED WITH WET
COMBUSTION

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การประเมินวิธีการฉีดอัดอากาศตามแนวหลุมจากปลายหลุมไปยังต้นหลุมร่วมกับการสันดาปเปียก

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ภุมรินทร์ ชาติพงศธร : การประเมินวิธีการฉีดอัดอากาศตามแนวหลุมจากปลายหลุมไปยังต้นหลุมร่วมกับการสันดาปเปียก (EVALUATION OF TOE-TO-HEEL AIR INJECTION (THAI) COMBINED WITH WET COMBUSTION) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ดร. ฟ้าลั่น ศรีสุริยชัย, 147 หน้า.

น้ำมันหนักไม่สามารถถูกผลิตอย่างง่ายดายด้วยวิธีการผลิตน้ำมันแบบปกติเนื่องมาจากความหนืดของน้ำมันที่มีค่าสูงมาก อย่างไรก็ตาม ด้วยการใช้วิธีการเพิ่มผลผลิตน้ำมันดิบบางวิธีน้ำมันหนักจะสามารถถูกผลิตได้ วิธีการสันดาปในแหล่งกักเก็บบวกกับวิธีการฉีดอัดอากาศตามแนวหลุมจากปลายหลุมไปยังต้นหลุม (THAI) จัดเป็นหนึ่งในวิธีดังกล่าว เทคนิคนี้สามารถทำได้โดยการฉีดอัดอากาศจากหลุมฉีดอัดแนวนอนหรือแนวตั้งเพื่อสร้างโซนการเผาไหม้และทำการผลิตน้ำมันที่ได้รับความร้อนจากการเผาไหม้จากหลุมผลิตแนวนอน การดัดแปลงวิธีดังกล่าวยังสามารถทำได้มากขึ้นไปอีกโดยการฉีดอัดน้ำเข้าไปพร้อมกับอากาศเพื่อสร้างให้เกิดไอน้ำเพื่อดึงความร้อนที่ถูกทิ้งไว้ในชั้นหินที่ผ่านการเผาไหม้ของโซนการเผาไหม้เรียกวิธีนี้ว่าการสันดาปเปียก ในการศึกษานี้ จะทำการศึกษาเทคนิครวมของ THAI และวิธีการสันดาปเปียกโดยศึกษาตัวแปรต่างๆที่มีผลต่อกระบวนการผลิตน้ำมัน

จากผลการทดลอง จะเห็นได้ว่าปริมาณก๊าซออกซิเจนเป็นตัวแปรออกแบบที่มีความสำคัญมากต่อการก่อให้เกิดการสันดาปในแหล่งกักเก็บ เนื่องจากโซนการเผาไหม้ต้องถูกสร้างขึ้นการเพิ่มออกซิเจนจึงมีความจำเป็นและการเพิ่มออกซิเจนด้วยการเพิ่มความเข้มข้นของออกซิเจนในอากาศให้ประสิทธิภาพที่ดีกว่าการเพิ่มอัตราการฉีดอัดอากาศ สำหรับตัวแปรที่เกี่ยวข้องกับการสันดาปเปียก เวลาในการเริ่มฉีดอัดน้ำเป็นตัวแปรที่มีความสำคัญมากกว่าปริมาณน้ำที่ใช้ในการฉีดอัด การเริ่มฉีดอัดน้ำอย่างรวดเร็วจะช่วยกระจายความร้อนที่เกิดขึ้นจากการสันดาปไปทั่วแหล่งกักเก็บได้รวดเร็วกว่า ยิ่งไปกว่านั้น อัตราการฉีดอัดอากาศที่ดีที่สุดที่ได้จากการวิธีการสันดาปแห้งสามารถถูกปรับเพิ่มค่าขึ้นได้เล็กน้อยในกรณีของการสันดาปเปียก เนื่องจากการฉีดอัดน้ำไปพร้อม ๆ กับอากาศจะช่วยทำให้ความสามารถในการไหลของอากาศลดลง โอกาสที่จะทำให้เกิดการเผาไหม้ที่หลุมผลิตจึงถูกขยายออกไป การฉีดอัดอากาศจากหลุมแนวตั้งได้รับผลดีมากกว่าหลุมแนวนอนอันเนื่องมาจากความสามารถในการฉีดอัดอากาศที่สูงกว่าซึ่งเป็นผลมาจากการที่หลุมแนวตั้งมีการเจาะผ่านบริเวณตื้นที่มีความดันของแหล่งกักเก็บต่ำ ด้วยการใช้ค่าการออกแบบที่ดีที่สุดสำหรับวิธีการสันดาปเปียก ปริมาณน้ำมันที่ผลิตได้จะอยู่ที่ประมาณ 55 เปอร์เซ็นต์ ซึ่งมากกว่ากรณีของการสันดาปแห้งอยู่ประมาณ 17 เปอร์เซ็นต์

การเพิ่มขึ้นของความจุความร้อนของเนื้อหินหรือในเวลาเดียวกันลดความสามารถในการนำพาความร้อนของหินส่งผลกระทบต่อประสิทธิภาพของการผลิต ผลกระทบจากการนำพาความร้อนมีความสำคัญมากกว่าความจุความร้อนและความสามารถในการพาความร้อนที่สูงเป็นเงื่อนไขที่เหมาะสมสำหรับเทคนิคการผลิตนี้ อัตราส่วนน้ำในชั้นหินที่ไม่สามารถลดได้ที่มีค่าต่ำช่วยส่งเสริมประสิทธิภาพการผลิตเนื่องจากไอน้ำซึ่งสามารถคืนกลับเป็นของเหลวจะไม่ถูกหน่วงไว้ด้วยปริมาณน้ำดังกล่าว จึงทำให้ไอน้ำสามารถเคลื่อนที่และขยายตัวได้รวดเร็ว ความสามารถในการซึมผ่านแนวตั้งที่มีค่าสูงเป็นเงื่อนไขที่พึงประสงค์เนื่องจากช่วยเพิ่มความสามารถในการฉีดอัดอากาศและช่วยเร่งให้เกิดโซนการเผาไหม้รวดเร็วยิ่งขึ้นระหว่างกระบวนการสันดาป การเผาไหม้อาจเกิดขึ้นที่หลุมผลิตในกรณีที่ตัวแปรเชิงปฏิบัติการไม่เหมาะสมหรืออาจเกิดมาจากความไม่แน่นอนของตัวแปรของแหล่งกักเก็บเองเช่นอัตราส่วนน้ำในชั้นหินที่ไม่สามารถลดได้สูงหรือต่ำจนเกินไป ความสามารถในการซึมผ่านแนวตั้งต่ำ และค่าความจุความร้อนของหินสูง ซึ่งสถานการณ์ดังกล่าวเป็นสิ่งที่อันตรายอย่างยิ่งยวดและจำเป็นต้องหลีกเลี่ยง

ภาควิชา วิศวกรรมเหมืองแร่และปิโตรเลียม ลายมือชื่อนิสิต ______________________

สาขาวิชา วิศวกรรมปิโตรเลียม ลายมือชื่อ อ.ที่ปรึกษาหลัก ______________________

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KEYWORDS: IN-SITU COMBUSTION / WET COMBUSTION / TOE-TO-HEEL AIR INJECTION

PHUMMARIN CHARDPONGSATHORN: EVALUATION OF TOE-TO-HEEL AIR INJECTION (THAI) COMBINED WITH WET COMBUSTION. ADVISOR: FALAN SRISURIYACHAI, Ph.D., 147 pp.

Heavy oil cannot be easily produced by means of conventional oil recovery methods due to its extremely high viscosity. However, by utilizing a suitable Enhanced Oil Recovery (EOR) technique, heavy oil can be produced. In-situ Combustion (ISC) with modification of well configuration called Toe-to-heel Air Injection (THAI) is one of the solutions. The technique is performed by injecting air from horizontal or vertical well to create fire front and producing heated oil from horizontal wells. Further modification of THAI is performed by co-injecting water with air to generate in-situ steam to recover heat in burnt zone. In this study, combination of THAI and wet combustion is performed and parameters affecting oil recovery are studied.

From the results, it is found that oxygen content is very important design parameter for in-situ combustion. As fire front must be generated, enrichment of oxygen is required and increasing oxygen through increment of oxygen concentration is more efficient than increase of air injection rate. For properties related to wet combustion, time to start injecting water plays more important role for wet combustion compared to amount of water injected as the early time to start wet combustion can speed up distribution of heat of combustion to entire reservoir. Moreover, optimal air injection rate that is obtained from dry combustion can be slightly increased in case of wet combustion as co-injection of water helps retarding air flow ability. So that chance of burning at production well is extended. Injecting air from vertical well obtained benefit from higher amount of air injected compared to horizontal well injector as reservoir pressure is low in shallow depth. By using the best conditions for wet combustion, oil recovery of about 55% is achieved which is higher than dry combustion case of about 17 %.

From an increase of heat capacity and a reduction of heat conductivity, effect of thermal conductivity is more pronounced than heat capacity and high value of thermal conductivity is preferable for this combined technique. Lower irreducible water saturation is favorable as it would provide benefit in steam propagation. Good vertical permeability is desirable as it increases amount of air injected which consecutively speeds up time to create fire front. During the combustion process, combustion may appear at production well when operating parameters are improper or can be from uncertainty of reservoir parameters such as low and high irreducible water saturation, low vertical permeability and high value of heat capacity and this situation is extremely dangerous and must be avoided.

Department:	Mining and Petroleum Engineering	Student's Signature	
Field of Study:	Petroleum Engineering	Advisor's Signature	
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LIST OF ABBREVIATIONS

EOR	Enhanced Oil Recovery
IFT	Interfacial Tension
THAI	Toe-to-Heel Air Injection
CMG	Computer Modeling Group Ltd.
LTO	Low Temperature Oxidation
WOR	Water-Oxygen Ratio
BBL	Barrel
SCF	Standard Cubic Feet
PV	Pore Volume
°API	Degree American Petroleum Institute gravity
WAR	Water-Air Ratio
m^3	Cubic Metre
H/C	Hydrogen/Carbon ratio
OOIP	Original Oil In Place
C-ISC	Conventional In-Situ Combustion
3-D	Three Dimensions
HIHP	Horizontal Injection Well and Horizontal Production Well Combination
VI2HP	Vertical Injection Well and Two Horizontal Production Wells Combination
CSI	Cyclic Steam Injection
SAGD	Steam-Assisted Gravity Drainage
ISC	In-Situ Combustion

HTO	High Temperature Oxidation
°F or F	Degree Fahrenheit
°C or C	Degree Celsius
hr	Hour
ft^2	Square Feet
kg	Kilogram
kcal	Kilocalorie
atm	Atmosphere
kgO_2	Kilogram of Oxygen
K	Degree Kelvin
cP	Centipoise
ft	Feet
HI2HP	Horizontal Injection Well and Two Horizontal Production Well Combination
mD	Millidarcy
psi	Pound per square inch
cal/gram	Calorie per gram
lb	Pound
lbmole	Pound per mole in unit of pound
std-ft^3	Standard Cubic Feet
Btu	British Thermal Unit
in	Inch
STB	Stock Tank Barrel

LIST OF NOMENCLATURES

t	Ignition time
ρ_o	Oil density
ρ_l	Oil-bearing formation density
c_l	Specific heat of oil-bearing formation
p_x	Partial pressure of oxygen
ϕ	Porosity
H	Heat of reaction
S_o	Oil saturation
T_0	Initial temperature
A	Constant for injection time calculation
B	Constant for injection time calculation
n	Pressure exponent
$\rho_l c_l$	Specific heat of the formation
ρ_g	Grain density
c_g	Specific heat of the formation grain
c_o	Specific heat of oil
ρ_w	Water density
c_w	Specific heat of water
S_w	Water saturation
K	Oxidant rate
Rs	Solution gas-oil ratio
B_o	Oil formation volume factor

B_g	Gas formation volume factor
$\boldsymbol{\mu}_o$	Oil viscosity
k_{ro}	Relative permeability to oil
k_{rw}	Relative permeability to water
k_{rg}	Relative permeability to gas
k_{row}	Relative permeability to oil in oil-water system
k_{rog}	Relative permeability to oil in gas-liquid system
k_{h}	Horizontal permeability
k_{v}	Vertical permeability
S_{wi}	Irreducible water saturation
S_{or}	Residual oil saturation

CHAPTER I

INTRODUCTION

1.1 Background

Heavy oil is a one type of oil in the reservoir that has high specific gravity and high viscosity. Due to its limitation properties mentioned earlier, the conventional oil recovery method cannot produce these oils. However, by using a suitable method from Enhanced Oil Recovery (EOR), heavy oil can be produced. EOR is a type of oil recovery method that is used to produce oil that cannot be produced by the conventional method. A certain technique can be called EOR when that technique can either commercially improve sweep efficiency or commercially improve displacement efficiency or both. EOR is mainly categorized into three groups including solvent extraction and/or miscible-type processes, interfacial tension (IFT) reduction processes, and viscosity reduction processes. EOR also can be separated by type of method into four groups including thermal methods, chemical methods, immiscible displacement methods, and miscible displacement methods. The thermal methods that can produce heavy oil are steam injection and in-situ combustion. A major criterion that makes in-situ combustion to overcome steam injection is the heat delivery which is not required due to the consumed heat is from reservoir itself.

In-situ combustion is an EOR technique that utilizes heat generated from combustion reaction between injected air and fuel coke in the reservoir to either reduce oil viscosity or produce lighter oil from heavy oil by thermal cracking. Because conventional in-situ combustion has gas override in the injected air, this technique was modified into Toe-to-Heel Air Injection (THAI) to improve its efficiency by using vertical injection well to inject air to perform in-situ combustion and at least one horizontal production well to recover oil.

Nowadays, there are some methods to improve the in-situ combustion processes; one of the methods is wet combustion, performing by injecting water after fire front is generated to create in-situ steam from heat remained in burned zone of reservoir in order to optimize the heat remained in the reservoir and use benefit of both steam injection and in-situ combustion in oil recovery. Wet combustion can be classified from the water injection into three types including wet combustion, optimal wet combustion, and partially quenched combustion. The type of wet combustion is important as it may control heat capacity of in-situ combustion process.

In this study, black oil simulation program called **STARS®** commercialized by **Computer Modeling Group Ltd. (CMG)** is used to simulate the Toe-to-Heel Air Injection (THAI) combined with wet combustion process. A reservoir model is constructed and selected to use as base case simulation. After the reservoir is evaluated to define the operating parameters including well configuration, air injection rate, oxygen content of injected air, depth of injection well (for only horizontal well injection), water injection rate and time to start wet combustion, the sensitivity analysis is performed to study the effects of reservoir properties to the process including thermal properties of rock matrix, end-point saturation of relative permeability curves and vertical permeability. The criterion used to determine performance of the process is oil recovery factor. Moreover, energy consumed per barrel of oil is also used to assist some decisions.

1.2 Objective

1. To select appropriate operating parameters for Toe-to-Heel Air Injection (THAI) combined with wet combustion, including well configuration, air injection rate, oxygen content of injected air, depth of injection well, water injection rate and time to start wet combustion.

2. To evaluate effects of reservoir properties to the combined process including thermal properties of rock matrix, end-point saturation of relative permeability curves and vertical permeability.

CHAPTER II
LITERATURE REVIEW

2.1 Wet Combustion in Oil Field

Lapene et al. [1] studied effects of water on kinetics of wet combustion by performing dry and wet in-situ combustion in the combustion tube apparatus with variation of air injection rate or water injection rate. The experiment was divided into five different runs. The first two runs were dry combustion with different air injection rate and other three runs were wet combustion with different water injection rate which had one bad quality run that data was not usable. The results were interpreted into two parts consisting of experimental study and kinetics study. In the experimental study, in case of wet combustion, the temperature in the burned zone was lower than that of dry combustion at the same conditions and heat utilization was also better. In case of effects of steam plateau, observed oil recovery was better and fire front velocity was higher than the case of dry combustion. For organic residual after the experiment was performed, burned sand from wet combustion seemed to be cleaner. In the kinetics study, appearance of water in gas modified behavior of oxidation reaction powerfully. For example, oxygen addition during Low Temperature Oxidation (LTO) was greatly reduced. Oxygenation reaction was known to increase oil viscosity, so that oil mobility was increased. From this study it can be mentioned that water should be included in the reactive mechanism because it can affect strongly to combustion and indirectly to other mechanisms such as oil displacement.

Venkatesan et al. [2] performed experiment to determine maximum Water-Oxygen Ratio (WOR) for normal wet combustion. The experiment was performed in the automated combustion tube apparatus with oil sample from Esperson Dome Field, South Texas. The experiments were conducted at WOR ranging from 0 to 10 bbl/Mscf with constant oxygen flux and injection pressure. The synthetic mixture of oxygen and helium was injected first to perform the ignition without the occurrence of LTO and then the mixture of high concentration oxygen and nitrogen was injected after the fire front had moved at least two inches into the sand pack of combustion tube. Water was co-injected after the fire front had advanced 7 inches from the inlet end. Six tests were conducted in this experiment consists of one dry combustion test and five wet combustion tests with various WOR. The results were interpreted into four conclusions. The first was that in case of wet combustion, residual oil saturation in the burned zone was zero. After partially-quenched combustion occurred, residual oil was left behind up to 7% PV. The second was that the maximum WOR for normal wet combustion was 2.5 bbl/Mscf. In higher WOR than the maximum value, partially-quenched combustion occurred. The third conclusion was that fuel consumption and oxygen required in the combustion were decreased with increasing WOR. However, there was a transition region between normal wet combustion and partially-quench combustion that fuel consumption and oxygen required in the combustion remained constant. Fuel consumption was the lowest in partially-quenched combustion but oil recovery was lowered from increasing residual oil saturation. The final conclusion was that this study confirmed data from previous studies that water co-injection accelerates oil production, oxygen utilization at all WOR is almost 100%, and average peak combustion temperature is lower in wet combustion compared to dry combustion.

Bagci et al. [3] conducted dry and wet combustion tests with different crude oil gravities consist of 12.4, 19.8 and 28.4 °API consecutively from Camurlu Field, Raman Field, and Adiyaman Field in Turkey. Experiments were performed in an adiabatic thin-walled vertical tube packed with crushed limestone mixed with oil and water. The Water-Air Ratio (WAR) for wet combustion in this experiment was ranging from 0.209 to 0.607 m^3/Mm^3 (st). The combustion tube tests were summarized into six conclusions. The first was that average value of fire front temperature was not appreciably affected by WAR, in-situ steam zone front velocity increased with increasing water injection rate from injected WAR. Second conclusion was that atomic H/C ratio of the fuel decreased with increasing peak combustion temperature both in wet and dry combustions. The third conclusion was that fuel consumption in wet combustion was lower than that of dry combustion and decreased with increasing WAR. The fourth was that °API gravity of crude oils affected fuel consumption rate in both wet and dry combustion. For example, wet combustion can be sustained in high gravity oil reservoirs with relatively low fuel consumption. The fifth conclusion was that amount of air required decreased with increasing °API gravities of crude oils. And the final conclusion was that oil recovery in percentage of OOIP increased with increasing WAR in case of wet forward combustion.

Joseph et al. [4] performed a comparison study between dry and wet combustion with field test performed in the Bellevue field of Bossier Parish, Louisiana. The field test was initially performed with dry combustion followed by wet combustion. The field test started from September 1974 to July 1977 but the results can be analyzed only from September 1974 to May 1976 due to failures of casing in several key observation wells. The results can be summarized into three conclusions. First, volumetric sweep was much improved and therefore, overall oil recovery can be expected to increase due to wet combustion. Second, air volume required for combustion reduced by 63% by means of wet combustion so that wet combustion can offer significant economic incentives due to decreased combustion project costs and decreased required project time. And the final conclusion was that the field test results from temperature-monitoring wells had more potential for the further comparison study. A comparison between dry and wet combustion was very difficult using oil production data due to measurement and allocation problems. The observation wells allowed direct tracking of heat due to each injection well and also proved to be a source of operating security, always knowing that the water bank was not overtaking and quenching the fire.

2.2 Toe-to-Heel Air Injection (THAI)

Rojas et al. [5] performed a study on numerical simulation of THAI. First, the base case model was determined including reactions occurred in the simulation. Well array tests using THAI were performed afterward to determine the best well configuration by performing THAI with various well patterns. The combination of horizontal injector and two horizontal producers yielded the best oil recovery due to higher temperature, improving sweep efficiency. Then, comparison test between THAI and Conventional In-Situ Combustion (C-ISC) was performed at the same air injection rate and the same grid characteristics. Fire front of THAI model reached production well later compared to C-ISC and THAI model can control better the fire front. THAI model also yielded higher amount of oil recovery at the same time compared to C-ISC model. After that, sensitivity analysis of air injection rate and oxygen concentration was performed. It can be concluded that increasing in oxygen yielded more oil recovery than increasing of air injection rate because it stimulates directly combustion process. Then, effect of heterogeneities on THAI was performed, consisting of homogeneous base case, fully random properties heterogeneous grid, and stochastic property distribution grid. The results showed that gravity forces and pressure drop caused by production well to overcome effects of reservoir heterogeneities. The simulation of multi-segmented wells was also performed and this resulted in improvement of oil recovery due to heat transfer in production tubing. Finally, simulation with consideration of coke and combustion-inherent gases as additional components was performed. The result showed that coke is formed just ahead of fire front and coke acted as combustion fuel.

Xia and Greaves [6] studied combination of injector and producer well in THAI. The experiments were performed in 3-D combustion cell, using heavy oil and tar sand bitumen. Comparisons of experiment were separated into three cases. The first case was horizontal injection well and horizontal production well (HIHP) combination, using Wolf Lake Heavy Oil and Athabasca Tar Sand Bitumen. By using this well arrangement, stable fire front was sustained to propagate along horizontal well and gave good ignition. Oil recovery from the tests was very high at approximately 83% OOIP and recovered oil gravity was upgraded significantly in a range of 8 to 10 °API. The second case was vertical injection well and two horizontal production wells (VI2HP) combination, using Athabasca Tar Sand Bitumen. The case that THAI was performed as a secondary method after steamflooding was compared with the case that THAI was performed as primary method. Even though THAI was performed after steamflooding, fire front was still stable and propagated along combustion cell. Oil recovery was very high at 83% OOIP and recovered oil gravity was substantially upgraded in an average of 16 ^{o}API. However, oil production in the post-steamflood case was delayed due to higher initial water saturation and low heat capacity of air transferring low heat. The last case was vertical injection well and horizontal production well combination, using Athabasca Tar Sand Bitumen. The case using this combination was compared with post-steamflood case, using VI2HP combination mentioned earlier. In this case, oil production started later than post-steamflood case due to low initial temperature in the sandpack of combustion cell and low heat capacity of air. Oil recovery from this case was quite high at about 70% OOIP but was still lower than other two cases due to loss of amount of injected air after 960 minutes of the run.

Moreover, Greaves and Xia [7] also performed simulation studies of THAI process. The reference physical model experiments were for one dry and one for wet combustion test in 3-D cell, using heavy Wolf Lake Oil. The 3-D numerical model was constructed using STARS reservoir simulator with the data obtained from reference tests. Simulation can be categorized in four cases consisting of base cases of unstable dry combustion, stable dry combustion with sleeve-back, stable wet combustion and a stable dry combustion refined model case. From comparison between experiments and simulations of dry and wet combustion, combustion initially developed toward upper part of oil layer and away from horizontal production well in case of experiments. But in basic model case of numerical simulation, combustion developed initially at the lower part of oil layer toward the toe of horizontal production well. The later condition was unstable due to oxygen breakthrough in horizontal well, leading to insufficient fuel laydown. From the case of using a sleeve-back with horizontal production well, well section before the burned zone including toe position was sealed and it can stabilize the combustion. Sleeve-back can help to stabilize combustion in wet combustion too but in short period initially until the fire front became anchored on the horizontal well and sleeve-back movement was halted. The fire front still propagated in fully-stable manner afterward. In case of refined model including an additional coke pseudo-component as a part of heavy oil, a stable numerical simulation was obtained because thermal cracking reaction model in the basic cases caused the insufficient fuel laydown and it needed to be improved. Finally, simulation result predicted higher combustion temperature than that of the experiment, very stable fire front propagation, and virtually complete oil recovery.

According to literature reviews, it can be noticed that wet combustion can yield benefits in addition to dry in-situ combustion including increasing oil recovery, improving heat utilization, accelerating fire front propagation and lowering fuel and oxygen required in combustion with increasing WAR. Similarly, THAI also has additional effects to dry combustion including increasing oil recovery, improving sweep efficiency and upgrading oil gravity. From these benefits, the combination of these two techniques is expected to significantly improve oil recovery performance of dry in-situ combustion and hence it is chosen for this study.

CHAPTER III
THEORY AND CONCEPT

3.1 Thermal Recovery, In-situ Combustion, and Air Injection

3.1.1 Thermal Recovery

Thermal recovery is the oil recovery method utilizing heat generated from various sources to recover heavy oils or tar sands or both those are not recoverable by conventional oil recovery method due to their high viscosity. The heat generated from processes will be typically used to reduce oil viscosity at elevated temperature. The examples of thermal recovery are steam injection, cyclic steam injection (CSI), steam-assisted gravity drainage (SAGD), and in-situ combustion (ISC).

3.1.2 In-situ Combustion

In-situ combustion is a thermal recovery method that utilizes heat generated from combustion reaction between injected air and fuel coke to either reduce oil viscosity or extract lighter portion from heavy oil by thermal cracking. The process creates fire front from the combustion at the injection well and fire front will propagate throughout the reservoir to production well. According to Figure 3.1, temperature and heat content of the burned zone are much higher than the rest of reservoir.

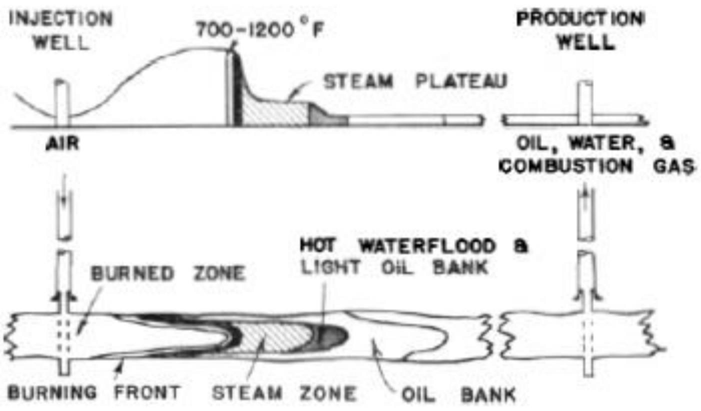


Figure 3.1 Schematic diagram of in-situ combustion, illustrating different zones [8]

There are two types of in-situ combustion classifying from its fire front direction which are forward combustion and reverse combustion. Forward combustion is the conventional in-situ combustion that fire front propagates from injection well toward production well. Moreover, there are two sub-category of forward combustion consists of dry combustion and wet combustion. Dry combustion is a typical forward combustion using only air injection in injection well, whereas wet combustion is forward combustion where water is also co-injected with air to create in-situ steam to increase oil recovery. Details of wet combustion are explained in the following section.

Reverse combustion is the technique where fire front initially propagates to the production and after, air is injected from production well instead of injection well to alter fire front direction, producing oil from vicinity of former injection well. This technique cannot be economically implemented because of two reasons. The first reason is that products from the combustion are mainly hot fluids including un-reacted oxygen that requires special tubing and treatment. And the second is that heavy ends in the burned zone of reservoir can be burned to reverse to the forward combustion again. Different zones from reverse combustion are illustrated in Figure 3.2.

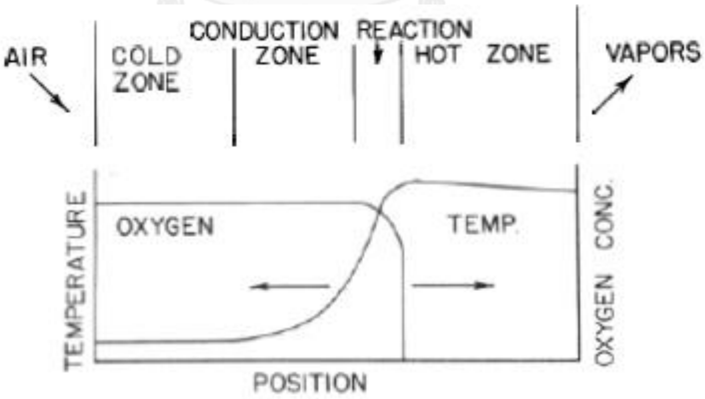


Figure 3.2 Schematic diagram of reverse combustion [8]

3.1.3 Oil Recovery Mechanism in In-situ Combustion

3.1.3.1 Combustion Reaction (High Temperature Oxidation (HTO))

Combustion reaction is an exothermic chemical reaction between hydrocarbon-based organic compounds and oxidants that typically is oxygen and reaction produces series of product such as carbon dioxides, carbon monoxides (depending on completeness of reaction), water, energy and other species depends on reactants. Heat of combustion can be expressed as either light or flame.

Complete combustion reaction is combustion where amount of oxygen is excessive with limited fuel compounds. Carbon and other elements in fuel compounds including nitrogen, sulfur, and iron (III) will turn into oxide form including carbon dioxide, nitrogen dioxide, sulfur dioxide and iron (III) oxide. For industrial applications, air that mainly consists of nitrogen and oxygen will be injected instead of pure oxygen and the ratio in moles between nitrogen and oxygen is 3.76:1. General complete combustion reaction is showed as follow;

$$C_XH_Y + zO_2 \rightarrow xCO_2 + \frac{y}{2}H_2O \qquad (3.1)$$

Even though nitrogen is not taken place in combustion reaction, it can be converted into oxides form at elevated temperature and thus, competes with hydrocarbon-based organic compounds for oxygen. General oxidation reactions of nitrogen are showed as follow;

$$N_2 + 2O_2 \rightarrow 2NO_2 \qquad (3.2)$$

$$N_2 + O_2 \rightarrow 2NO \qquad (3.3)$$

However, in case that the oxygen is not enough for the reactants to completely produce carbon dioxide and water, incomplete combustion will occur instead. Carbon monoxide and hydrogen are additional products in this case. General incomplete combustion is showed as follow;

$$C_XH_Y + O_2 \rightarrow aCO_2 + bCO + cH_2O + dH_2 \qquad (3.4)$$

3.1.3.2 Low Temperature Oxidation (LTO)

The fully developed fire front temperature is in the range from 650°F to 1,000°F. If heat loss is large or air fluxes are too low, combustion temperature will drop significantly and fuel availability will be increased. Fuel availability is amount of fuel laid down by the propagation of fire front. This region is so-called Low Temperature

Oxidation (LTO) in contrast to normal combustion (HTO). According to Figure 3.3, an oxidation temperature of 400°F gives the highest fuel availability

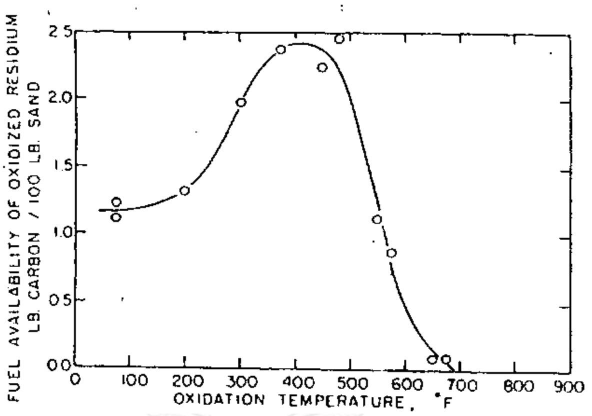


Figure 3.3 Effect of LTO on fuel burned at 800°F [9]

The fuel formed under LTO conditions is quite different from that obtained under HTO conditions. According to Figure 3.4, as combustion temperature is lower, apparent H/C ratio is also lower. The low temperature oxidation of crude oil produces carboxylic acids, aldehydes and alcohols in addition to products under HTO conditions, which incorporate oxygen into the reaction product instead of carbon dioxide or carbon monoxide.

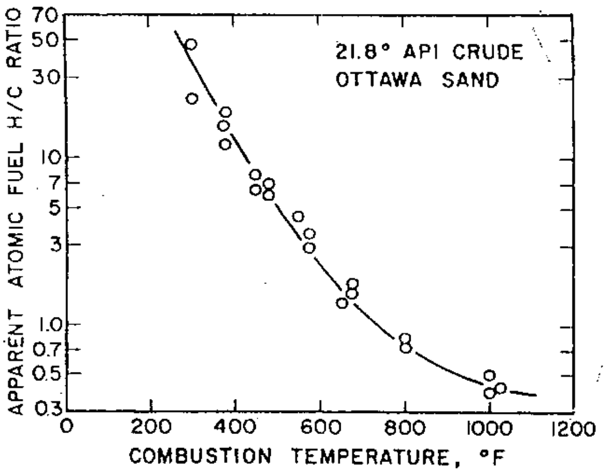


Figure 3.4 Effect of combustion temperature on apparent H/C ratio of fuel [8]

3.1.3.3 Pyrolysis

Pyrolysis is a thermal decomposition of organic compounds at elevated temperature without participation of oxygen. The products of decomposition are irreversible. Pyrolysis is typically used in metallurgy especially steelmaking. Pyrolysis reactions to yield lighter gaseous fuels from heavy solid fuels are endothermic and require constant energy input from combustion reactions.

Coke is a product from pyrolysis of coal or solid residue left in petroleum. Coking process occurs by heating material to very high temperature (up to 2,000 ^{o}C or 3,600 ^{o}F) in closed environment. The molecules of material are broken down into lighter volatile substances and hard residue that is mostly carbon and inorganic ash.

3.1.3.4 Air Injection, Ignition and Ignition Method

The designed rate of air injection prior to ignition is one of requirements in order to establish effective permeability in a selected reservoir. The less gas saturation in reservoir, the higher compressor pressures required. Injected gas for ignition is usually air, but in some cases, either fuel gas or recycle gas or both can be injected to control fire front velocity by lowering oxygen content. The air fluxes at injection site are typically in the range of 0.5-2.9 scf/hr-ft^2. Early breakthrough of injected gas can occur in pre-injection as well. Installing high-power heater in injection wells to facilitate auto-ignition process is recommended to improve the ignition. On the other hand, heating air results in coking process in vicinity of the wells and coke from this process is more difficult to ignite than crude oil. Preheating of injected air is required to reduce oxidation time and to control ignition location. Without preheating, ignition may occur at some distances away from injection well and reverse combustion may happen. Injection time required for generating fire front can be evaluated from the following equation;

$$t = \frac{\rho_l c_l T_0 \left(1+\frac{2T_0}{B}\right) e^{\frac{B}{T_0}}}{864 \phi S_o \rho_o H A p_x^n \frac{B}{T}} \times 10^{-2} \qquad (3.5)$$

where t = ignition time (days),

ρ_o = oil density (kg/m^3),

ρ_l = oil-bearing formation density (kg/m^3),

c_l = specific heat of oil-bearing formation (kcal/kg-°C),

p_x = partial pressure of oxygen (atm, = 0.209 p where p = injection press in atm),

ϕ = porosity,

H = heat of reaction (kcal/kgO_2,)

S_o = oil saturation,

T_0 = initial temperature (K),

A = constant (s^{-1}atm^{-n}),

B = constant (K), and

n = pressure exponent.

Specific heat of the formation ($\rho_l c_l$) can be determined from the following equation:

$$\rho_l c_l = (1-\phi)\rho_g c_g + \phi S_o \rho_o c_o + \phi S_w \rho_w c_w \qquad (3.6)$$

where ρ_g = grain density (kg/m^3),

c_g = specific heat of the formation grain (kcal/kg-°C),

c_o = specific heat of oil (kcal/kg-°C),

ρ_w = water density (kg/m^3),

c_w = specific heat of water (kcal/kg-°C), and

S_w = water saturation.

The values of A, B and n are determined by measuring oxidation rates of several crude oils and mixtures at different pressures and temperatures.

Oxidant rate (K) has relationship with oil temperature (T_0) and partial pressure of oxygen (p_x) as shown in the following equation;

$$K = Ap_x^n e^{BT_0} \qquad (3.7)$$

At desired pressure and temperature, laboratory condition, air is injected to contact with oil sample and the sample will be cooled afterward. Oxygen consumption will be determined by analyzing amounts of CO_2, O_2 and CO. Procedures are repeated at different values of pressure but temperature is maintained constant to determine value of K. From the slope of log K versus $1/T$, constant B can be determined and Ap_x^n can also be evaluated. Procedures are repeated again at different temperatures but constant pressure to determine the value of A and n.

There are two types of ignition method including spontaneous ignition and artificial ignition. Spontaneous ignition will occur after injection process is started for a few days if either the reservoir temperature is very high or the amount of heat released by oxidation of oil is sufficient or both. By measuring oil oxidation rate in laboratory, probability of the occurrence of spontaneous ignition can be determined. The lowest spontaneous temperature was recorded at 87 ^{o}F and the most likely value is around 131-140 ^{o}F.

There are some modifications to improve spontaneous ignition. The example is steam injection to increase temperature; shortening required ignition time and avoiding injection well damage due to burning by reduce the oil saturation. This results in high caution for spontaneous.

If spontaneous ignition cannot occur, artificial ignition can be initiated using special downhole ignition equipments including gas burners, electrical heaters and catalytic ignition system. The burner of electrical heater builds up temperature of the area around injection well to a desired value for rapid ignition. Methane and propane are mostly used for gas burners. Artificial ignition has advantage that it can be used to avoid chances of well damage from burning process.

3.2 Toe-to-Heel Air Injection (THAI)

Toe-to-Heel Air Injection (THAI) is a technique to improve in-situ combustion process proposed by Greaves. This technique combines in-situ combustion together with the use of horizontal well. The process requires at least one vertical injection well and at least one of horizontal production well to perform fire flood process. This requires high air injection rate which is mainly injected to push air toward fire front to propagate along the horizontal well from toe side to heel side. Sweep efficiency is reduced as fire front moves further away from injection well. Figure 3.5 illustrates concept of THAI process.

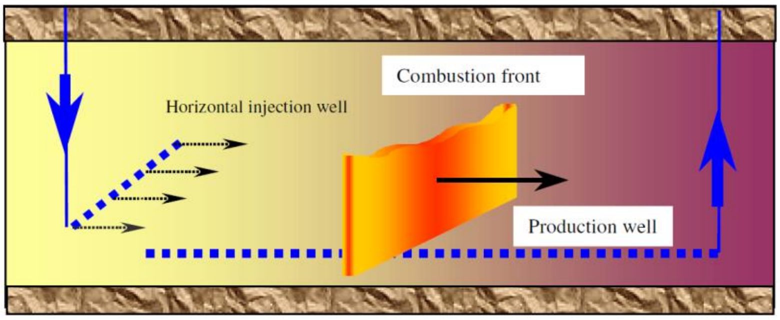


Figure 3.5 Illustration of Toe-to-Heel Air Injection (THAI) process [10]

One of the most important features of THAI process is an appearance of mobile oil zone showed at Figure 3.6. Overall sensitivity of the process to reservoir heterogeneity effects may also be significantly reduced because combustion and oil displacement process effectively takes place in a small section of reservoir similar to SAGD. The temperature of the mobile oil zone is much higher than the initial reservoir temperature, which makes THAI significantly more stable and robust than conventional in-situ combustion in the same operating conditions.

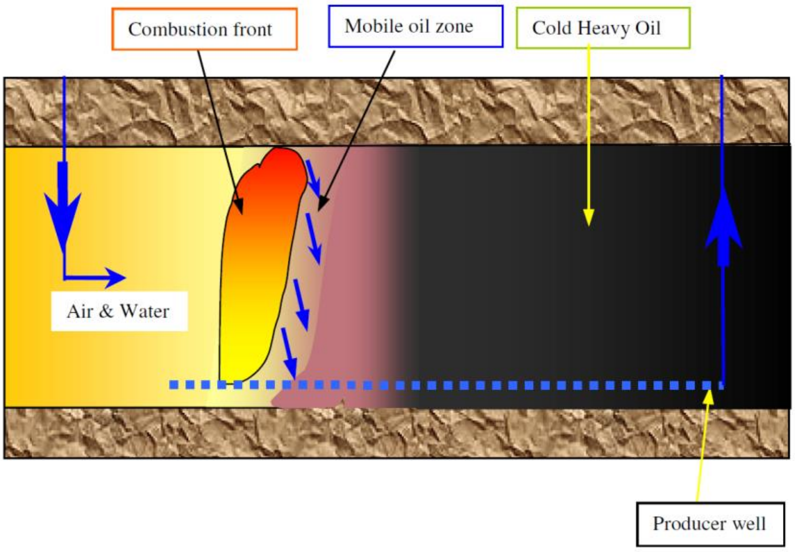
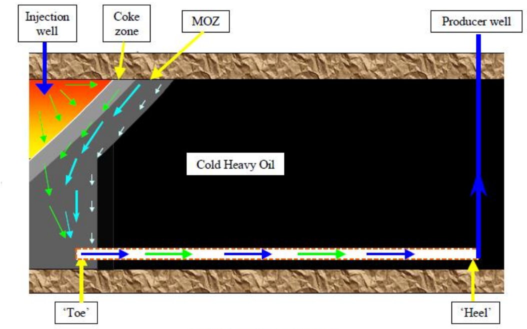


Figure 3.6 Mobilized oil draining from narrow zone into exposed section of the horizontal well [10]

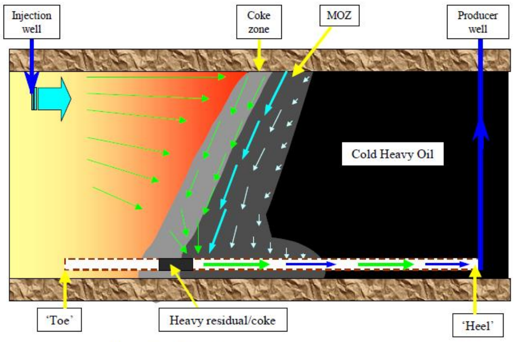
The operational purposes for THAI are the same as conventional in-situ combustion including coke burning to produce heat, thermal cracking and viscosity reduction by increasing temperature. The only one main difference between THAI and conventional in-situ combustion is that mobilized oil and fluids ahead of the combustion front are drawn down into horizontal producer well. Gas overriding is controlled and stability is ensured. Cold heavy oil region banking also does not occur because the gas flowing into this region is restricted by high viscosity oil. So that the short-distance displacement mechanism of THAI can prevent the undesirable effect occurred in conventional in-situ combustion.

The air channeling directly into the 'toe' position of the horizontal producer well is a main consideration for THAI during startup. To prevent this, the ignition temperature is needed at least 500°C to ensure that oxygen utilization is high during startup and the combustion takes place at high temperature in the top part of the oil layer. Because while the combustion zone is expanding downward and increasing in size, the high temperature ensures the rate of oxidation is rapid and the injected oxygen is completely consumed. Although the hot combustion gas flows directly into the 'toe' position of the horizontal producer well, it does not contain any oxygen.

After the fire front propagates beyond the ‘toe’ position, it becomes anchored onto the horizontal producer well. The stability of THAI then depends on a high temperature burning zone that exhibit as a gas override controller and deposition of coke which acts as a gas seal according to Figure 3.7.



(a) Startup phase



(b) Stabilized operating phase

Figure 3.7 Startup and stabilized operating phase of THAI [11]

3.3 Wet Combustion Technique

Wet combustion is a forward in-situ combustion process that water is simultaneously injected after appearance of fire front for a certain period of time. The objective of water injection is to capture heat remained in base rock and reservoir cap by injected water to generate in-situ steam. Even though both of superheated steam and air approach the fire front, only oxygen is utilized in combustion process, leaving steam to by-pass as it is one of the products of combustion process. The mixture after fire front consists of less oxygen but enriched in carbon dioxide and carbon monoxide. This gas mixture displaces oil adjacent to fire front and will be condensed. The size of steam zone in wet combustion depends on amount of heat recovered from burned zone.

Comparing to dry combustion, fire front will travel shorter to improve the same amount of oil recovery and the required amount of air injected is lower. The volumetric sweep efficiency is also improved. The economics is improved due to shorter project life and less cost due to less air injection process.

Wet combustion can be classified into three types which are normal wet combustion, optimal wet combustion and partially-quenched combustion. Normal wet combustion is a conventional wet combustion as discussed earlier.

Optimal wet combustion is normal wet combustion that is modified to recover maximally the heat remained. Major part of excess heat of the burned zone is transported into steam zone and generated steam zone would increase performance of wet combustion. Both distance of fire front and required amount of air injected are substantially decreased.

In partially-quenched combustion, water is injected to partially quench the moving fire front. This allows oxygen to propagate beyond fire front and comes in contact with oil. As oxidation reaction occurs beyond fire front, propagation of fire front is therefore travels at the speed of cooling water. Fire front will occur in both partial evaporation, heating of water, heat of combustion and heat recovery from the formation and it will propagate faster than under normal wet combustion. Figure 3.8 summarizes temperature and oil saturation distribution from injection well to production well compared among different techniques.

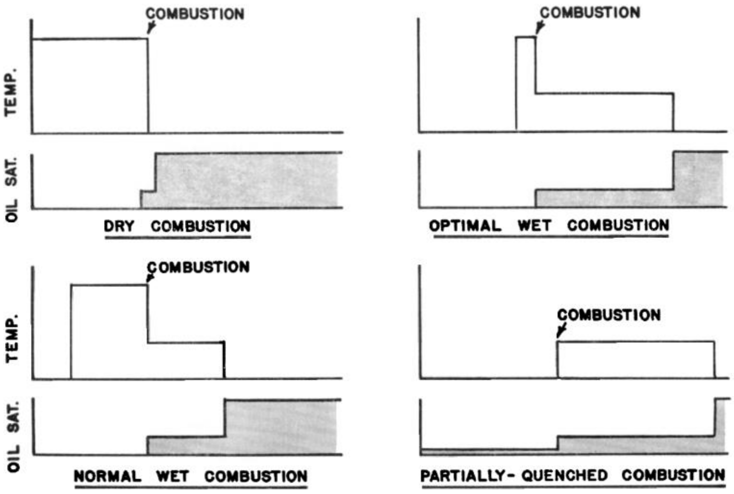


Figure 3.8 Schemetic diagram of wet combustion [8]

3.4 Screening Criteria for In-situ Combustion and THAI

In-situ combustion has some advantages to other EOR methods including economics and abundant of injectants (air and water), oil upgrading required only a small fraction of reservoir oil as fuel, and technique is compatible with wide range of field conditions not only in heavy oil reservoir. This method is recommended in low to medium gravity, not high viscosity oil (less than 5,000 cP) containing asphaltic components. High oil saturation (more than 50% PV), not very deep (less than 11,500 ft), quite high temperature (more than 100 ^{o}F), and high porosity reservoir is preferred for this technique. However, in-situ combustion also has some difficulties and it requires some considerations including minimum net thickness and average permeability, process control, process safety, and corrosion prevention.

CHAPTER IV

RESERVOIR SIMULATION MODEL AND METHODOLOGY

4.1 Reservoir Model

Reservoir model is constructed with Cartesian coordinate type. The model is 1,280 ft, 465 ft and 100 ft in x-, y- and z-directions. Each direction of reservoir model is divided into grid blocks of 32x31x10 blocks in three directions. Total number of grid blocks is 9,920 blocks which is still less than maximum number of grid blocks in educational license of STARS by CMG. Total area of model is 13.664 acre with thickness of 100 ft. Wells are located in model on a vertical injector well and 2 horizontal producer wells (VI2HP) and a horizontal injector well and 2 horizontal producer wells (HI2HP) well combinations.

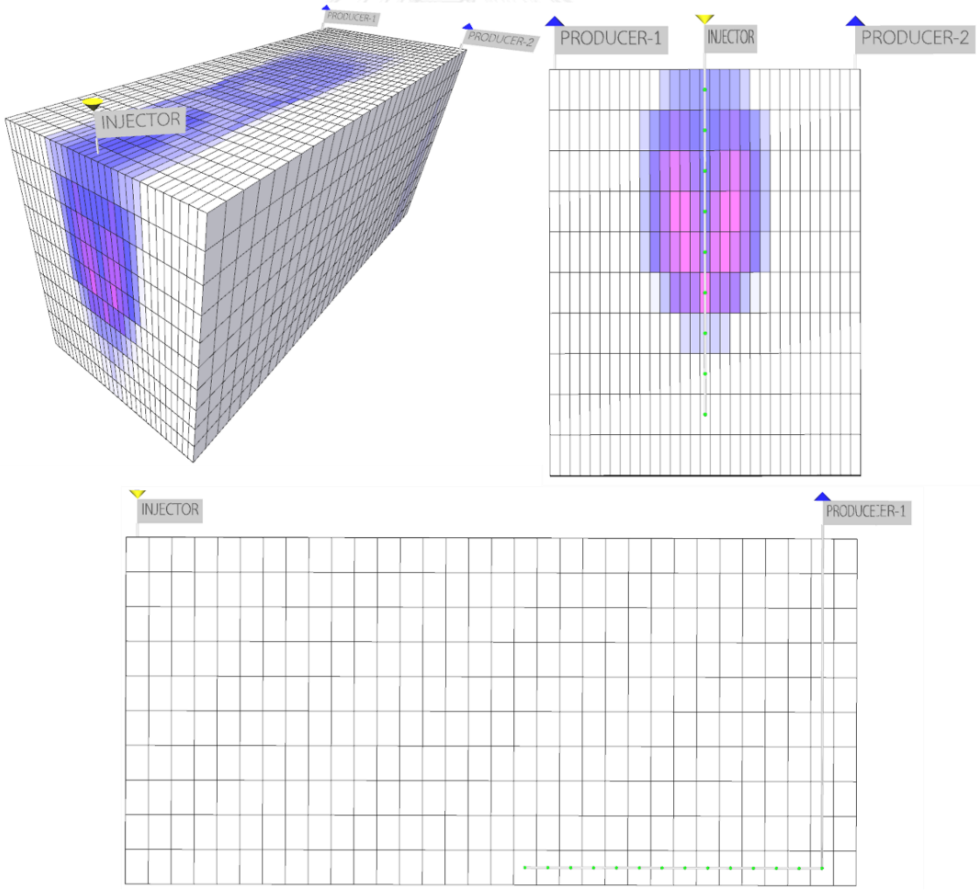


Figure 4.1 Location of wells in reservoir model, representing VI2HP well combination, top left: three-dimention view, top right: x-z view, and bottom: y-z view

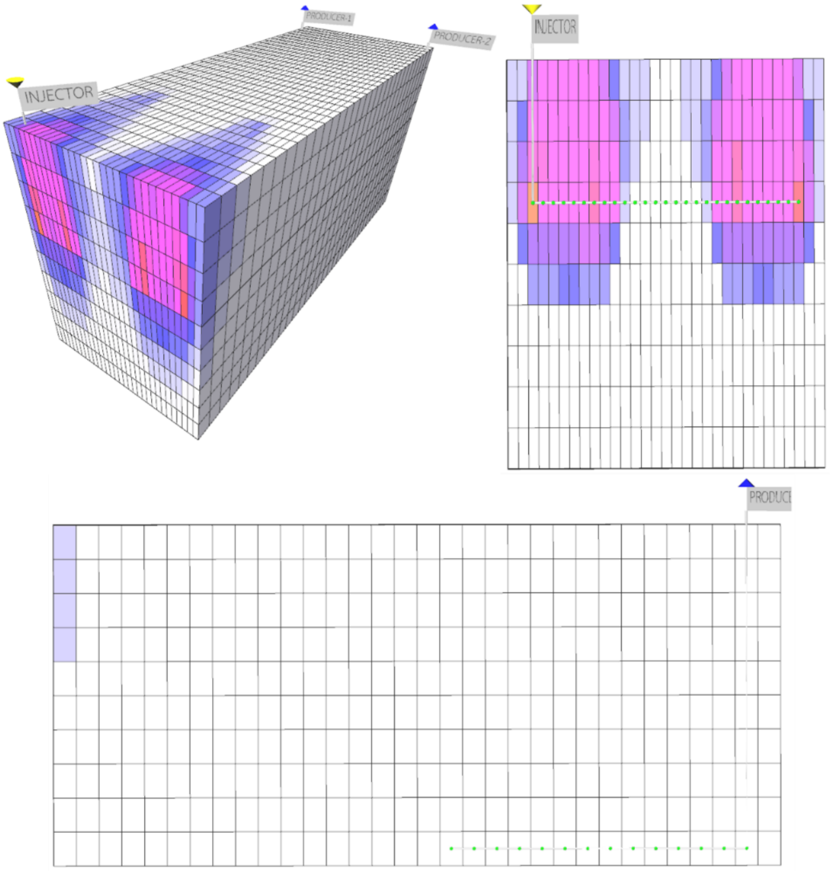


Figure 4.2 Location of wells in reservoir model, representing HI2HP well combination, top left: three-dimention view, top right: x-z view, and bottom: y-z view

Physical properties and required reservoir parameters for constructing reservoir model are summarized in Table 4.1.

Table 4.1 Physical properties of reservoir model and reservoir properties

Parameter	Value	Unit
Grid dimension	32 x 31 x 10	block
Grid size	40 x 15 x 10	ft
Top of reservoir	1,475	ft
Reservoir thickness	100	ft
Effective porosity	0.3	Fraction
Horizontal permeability	1,000	mD
Vertical permeability	0.2 x kh	mD
Initial oil saturation	0.73	Fraction
Initial water saturation	0.27	Fraction
Reservoir pressure	681.98	psi
Reservoir temperature	91.11	°F
Oil gravity	12	°API
Formation type	Sandstone	

4.2 Pressure-Volume-Temperature (PVT) Properties

Pressure-Volume-Temperature (PVT) properties of reservoir fluid are specified by using several correlations. Summary if correlation used for each PVT properties is shown in Table 4.2.

Table 4.2 Summary of correlation for each PVT property

Parameter	Option
Oil properties (bubble point, R_s, B_o) correlation	Standing
Dead oil viscosity correlation	Beggs and Robinson
Live oil viscosity correlation	Beggs and Robinson
Gas critical properties correlation	Standing

In order to generate PVT properties, several properties are required to initiate PVT functions which are oil gravity, solution gas-oil ratio, water phase density and undersaturated oil compressibility. From these data, bubble point pressure and in-situ oil viscosity are obtained. Initial input parameters and generated parameters are summarized in Table 4.3.

Table 4.3 Input parameters for PVT data and generated parameters

Parameter	Value	Unit
Oil gravity	12	^{o}API
Solution Gas-oil Ratio	80	ft^3/bbl
Water phase density	62.4	lb/ft^3
Undersaturated Oil Compressibility	1.173×10^{-5}	psi^{-1}
Bubble Point Pressure	620.96	psi
In-situ Dead Oil Viscosity	1,740.38	cP

Figures 4.3 to 4.7 depicts dry gas formation volume factor (B_g), oil formation volume factor (B_o), and solution gas-oil ratio (R_s) as a function of pressure and oil viscosity (μ_o) as a function of both pressure and temperature. As pressure affects liberation of solution gas, most properties are therefore plotted with pressure.

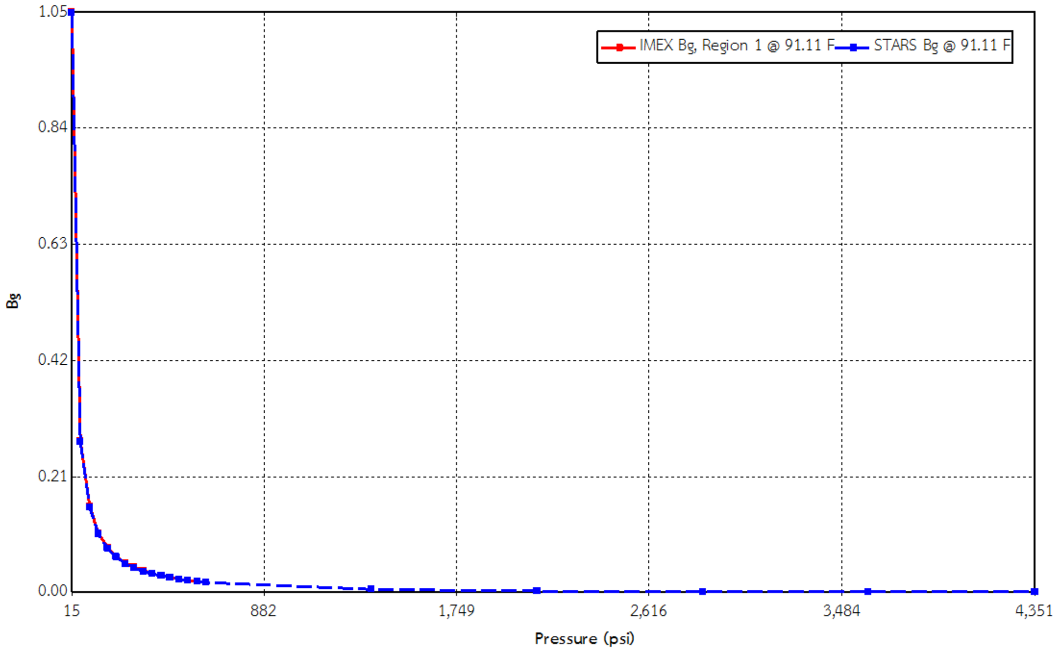


Figure 4.3 Dry gas formation volume factor (B_g) for reservoir model as a function of reservoir pressure

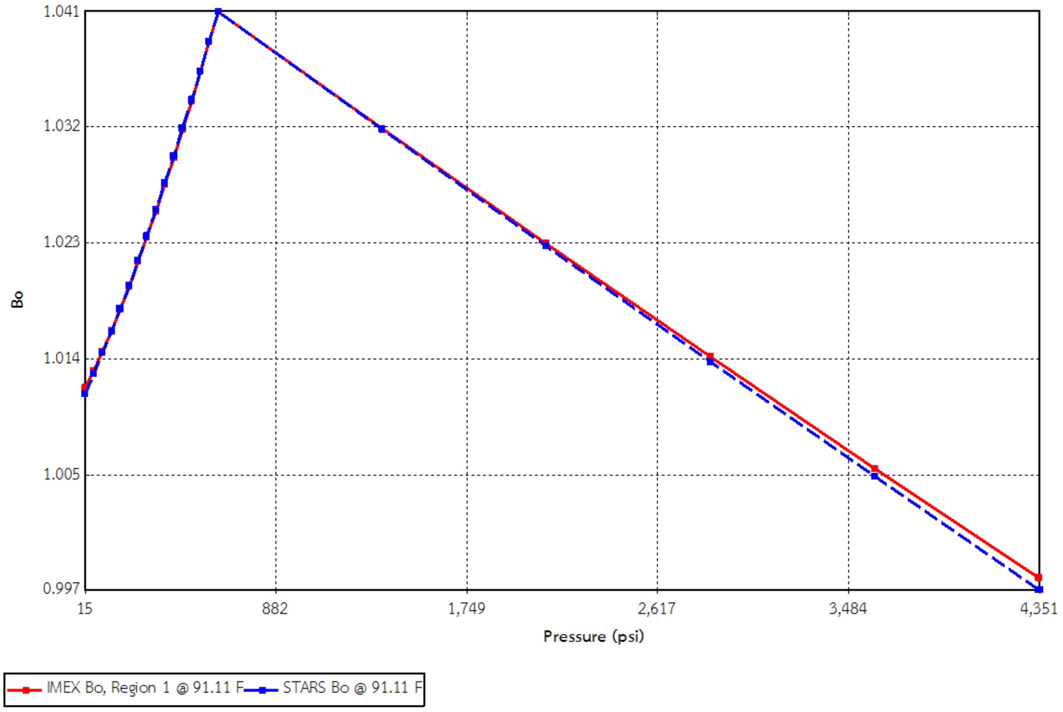


Figure 4.4 Oil formation volume factor (B_o) for reservoir model as a function of reservoir pressure

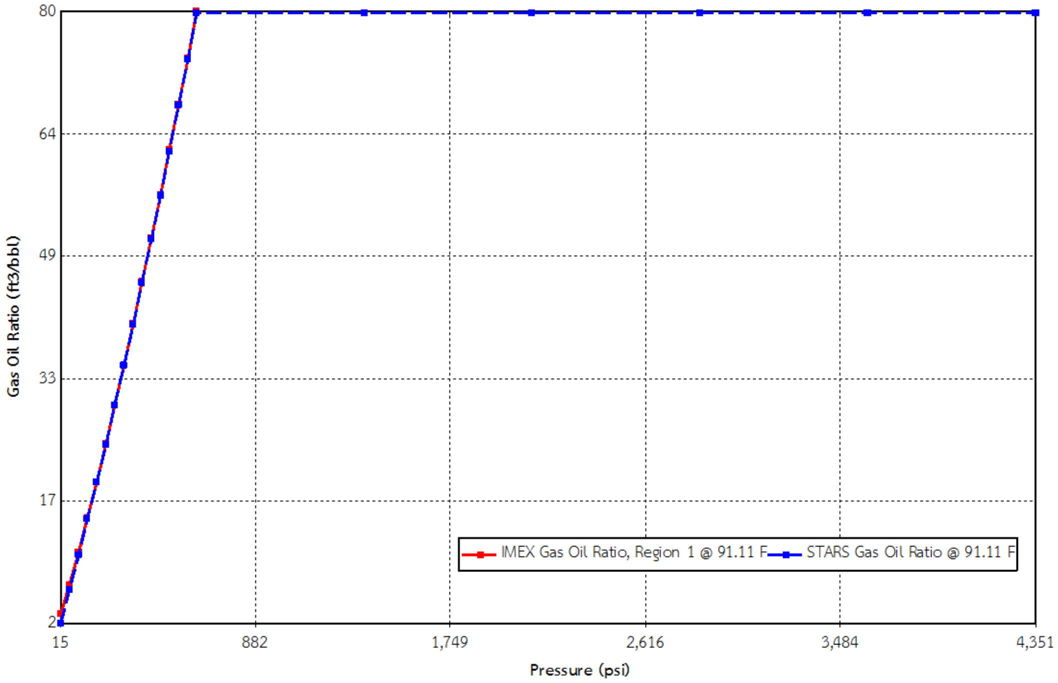


Figure 4.5 Gas-oil ratio for reservoir model as a function of reservoir pressure

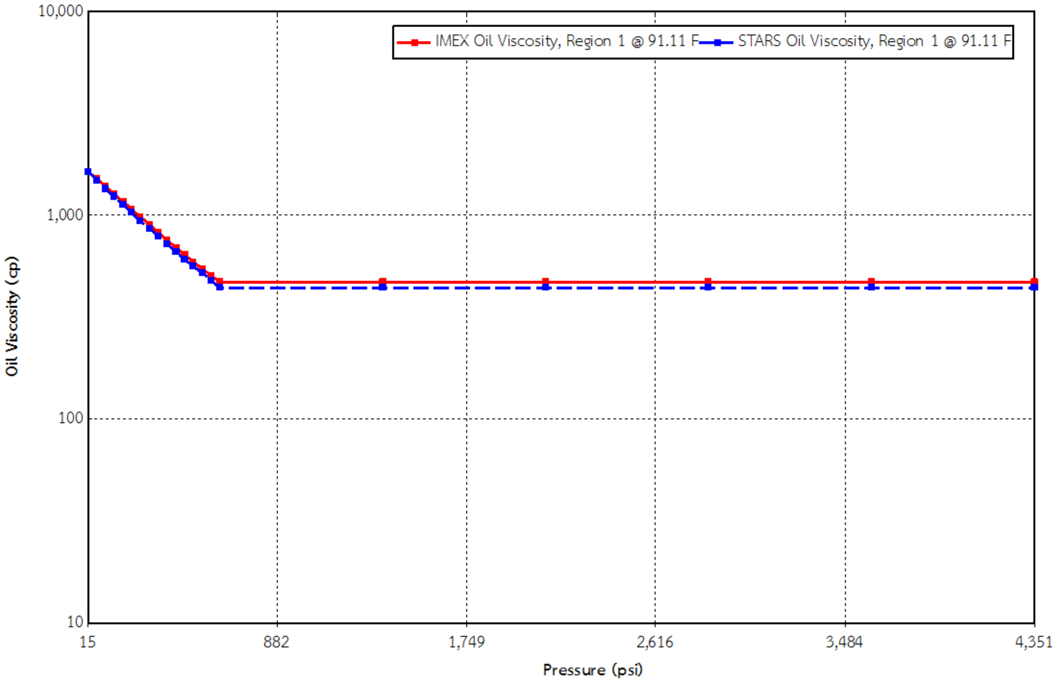


Figure 4.6 Live oil viscosity for reservoir model as a function of reservoir pressure

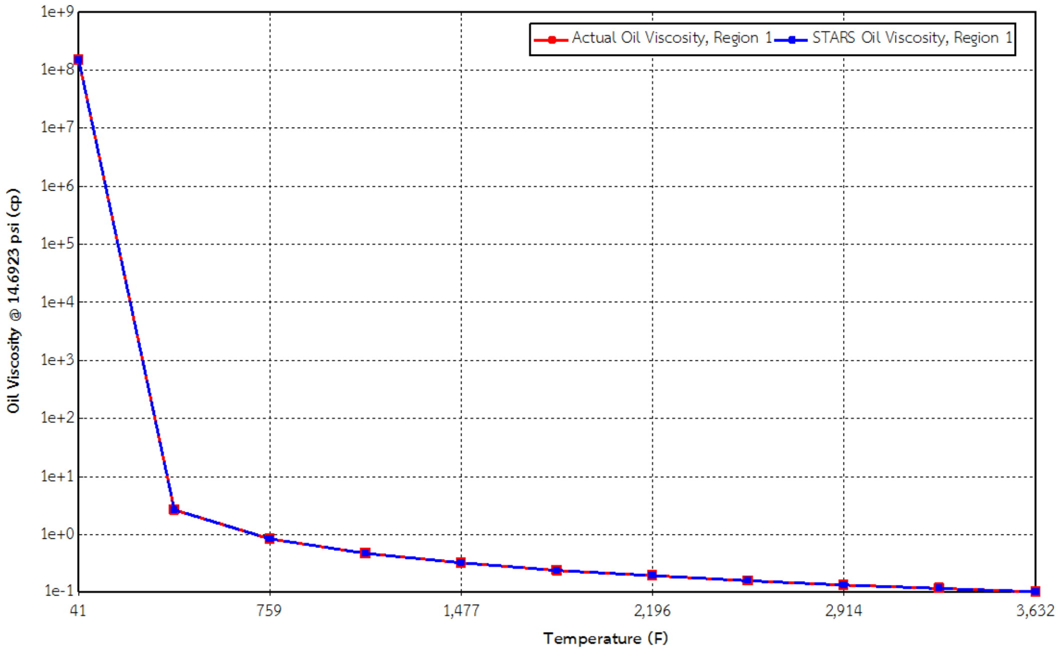


Figure 4.7 Live oil viscosity for reservoir model as a function of reservoir temperature

PVT property plotted with reservoir pressure possesses two functions. The blue color stands for correlation using in STARS advanced processes reservoir simulator while red color represents correlation using in IMEX black-oil reservoir simulator. In this study, blue color is utilized due to the simulations of this study are in-situ combustion processes and STARS is compatible for thermal process simulation.

On the other hand, viscosity plotted with reservoir temperature also include two functions. The blue color represents correlation using in STARS that is Beggs and Robinson while the red color stands for the same correlation but imported from manual calculation in order to expand the temperature range that STARS can be used in simulation.

4.3 Combustion Reactions

The main mechanism occurred in in-situ combustion process are combustion reactions. STARS used reactions from Belgrave et al. [12] which are showed as follow:

Thermal cracking reactions of oil in reservoir:

$$Dead\ Oil + 7.5\ O_2 \rightarrow 0.5\ Dead\ Oil + 37.74\ Coke \tag{4.1}$$

$$Dead\ Oil \rightarrow 2.52 \times 10^{-4}\ Dead\ Oil + 38.54\ Coke \tag{4.2}$$

Low temperature oxidation reaction of oil in reservoir:

$$Dead\ Oil + 3.4315\ O_2 \rightarrow 1.22\ Dead\ Oil \tag{4.3}$$

Combustion reaction of oil in reservoir:

$$Dead\ Oil + 33.27\ O_2 \rightarrow 40.79\ H_2O + 8.32\ CO_2 + 16.63\ CO \tag{4.4}$$

Combustion reaction of solution gas in reservoir:

$$Solution\ Gas + 1.73\ O_2 \rightarrow 3.28\ H_2O + 0.22\ CO_2 + 0.45\ CO \tag{4.5}$$

Combustion reaction of coke in reservoir:

$$Coke + 0.86\ O_2 \rightarrow 0.5\ H_2O + 0.23\ CO_2 + 0.77\ CO \tag{4.6}$$

In order to generate in-situ combustion reaction, reaction properties including gross heat of combustion, oil molecular weight and air/fuel ratio for combustion are needed. The value of each reaction parameters are showed in Table 4.4 and the value of generated reaction parameters are summarized in Table 4.5.

Table 4.4 Input parameters for reaction data

Parameter	Value	Unit
Gross heat of combustion	10,358.1	cal/gram
Oil molecular weight	501.128	lb/lbmole
Air/fuel ratio for combustion	120	std-ft^3/lb

Table 4.5 Generated reaction data

Parameter (Unit)	Reaction Number					
	4.1	4.2	4.3	4.4	4.5	4.6
Reaction frequency factor	1×10^{16}	3.336×10^{16}	3.336×10^{16}	3.16×10^{13}	1.2×10^{7}	371,293
Enthalpy (Btu/lbmole)	1×10^{6}	0	0	3.214×10^{6}	429,923	85,984.5
Activation energy (Btu/lbmole)	81,685	90,069	90,069	65,223	19,994	15,136
Burning zone Temperature lower limit (^{o}F)	44.6	44.6	44.6	44.6	44.6	44.6
Burning zone Temperature upper limit (^{o}F)	914.5	996.9	996.9	898.8	611.8	828.4

4.4 Rock-fluid properties

End-point data and Correy's correlation exponent are essential for generating water/oil and gas/liquid relative permeability curves in STARS. Table 4.1 summarizes required data for this section.

Table 4.6 Summary of data required to generate relative permeability curves

Parameter	Value
SWCON - Endpoint Saturation: Connate Water	0.27
SWCRIT - Endpoint Saturation: Critical Water	0.27
SOIRW - Endpoint Saturation: Irreducible Oil for Water-Oil Table	0.2
SORW - Endpoint Saturation: Residual Oil for Water-Oil Table	0.2
SOIRG - Endpoint Saturation: Irreducible Oil for Gas-Liquid Table	0
SORG - Endpoint Saturation: Residual Oil for Gas-Liquid Table	0
SGCON - Endpoint Saturation: Connate Gas	0.05
SGCRIT - Endpoint Saturation: Critical Gas	0.05
KROCW - Kro at Connate Water	0.6
KRWIRO - Krw at Irreducible Oil	0.1
KRGCL - Krg at Connate Liquid	0.6
Exponent for calculating Krw from KRWIRO	1.8
Exponent for calculating Krow from KROCW	1.8
Exponent for calculating Krog from KROGCG	1.8
Exponent for calculating Krg from KRGCL	1.8

Figure 4.8 and Figure 4.9 show relative permeability curves at reservoir temperature which is 91.11 ^{o}F of oil-water and liquid-gas systems respectively. Since the main factor affected relative permeability in this study is temperature, additional 2 sets of relative permeability curve are generated. Relative permeability curves showing comparison between reservoir temperature (91.11^{o}F) and heating temperature (560.74 ^{o}F) are illustrated in Figure 4.10 and Figure 4.11. Furthermore, comparison between heating temperature (560.74 ^{o}F) and combustion temperature (1,500 ^{o}F) are showed in Figure 4.12 and Figure 4.13. This can be explained that before performing in-situ combustion, the reservoir temperature is not affected and relative permeability curve in oil-water system is still the same as in Figure 4.8. But after the heating process, consisted of heater and heated air at defined elevated temperature, is started, temperature around wellbore is increased and the reservoir temperature is averaged

between initial and heating temperature. Therefore, relative permeability curve for oil-water system is shifted as shown in Figure 4.10. At any time after heating period but before the time the combustion front is formed, relative permeability is interpolated between these two defined curves. After the combustion front is formed, temperature is increased by heat of combustion further than heating temperature. So that the relative permeability curve is shifted further as shown in Figure 4.12. At any temperature during in-situ combustion process after heating period, relative permeability curve is interpolated between these three defined curves.

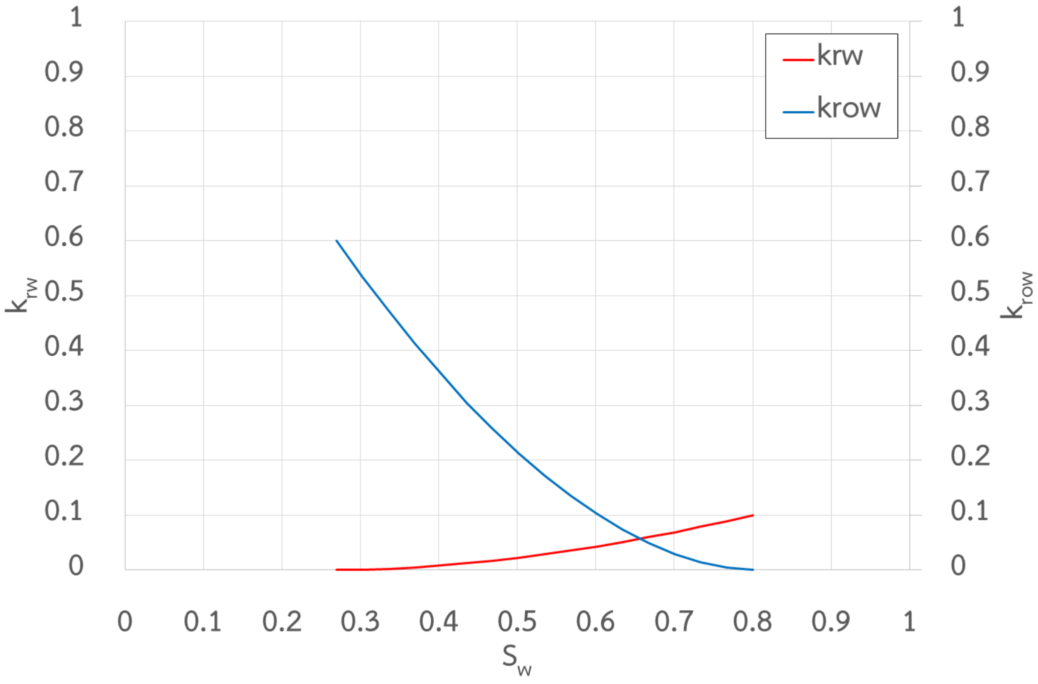


Figure 4.8 Relative permeability curves of oil-water system for reservoir model as a function of water saturation

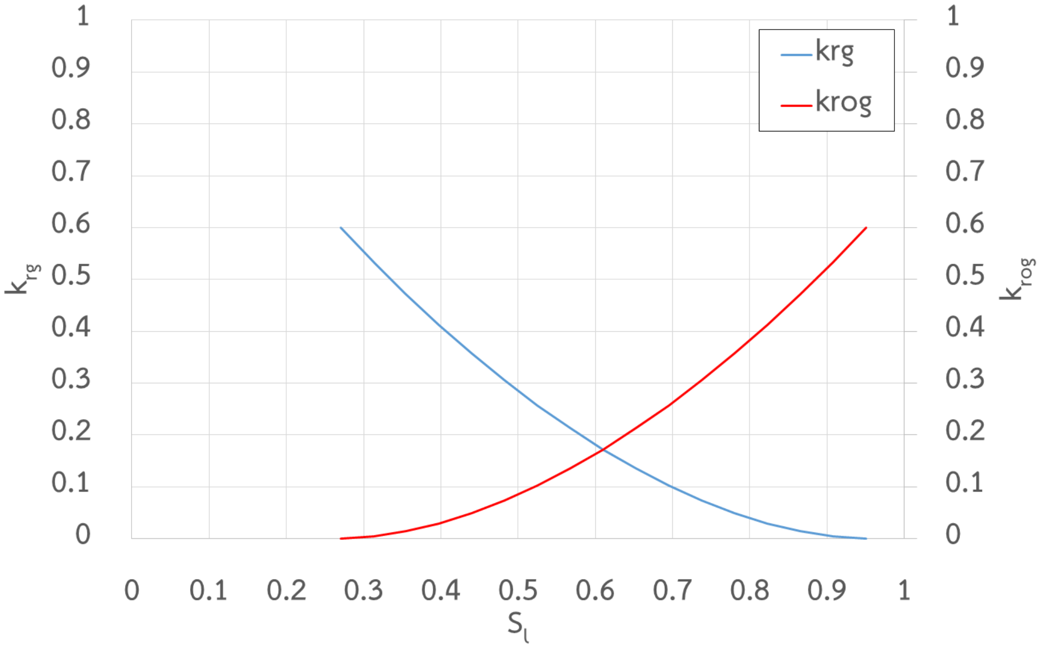


Figure 4.9 Relative permeability curves of liquid-gas system for reservoir model as a function of liquid saturation

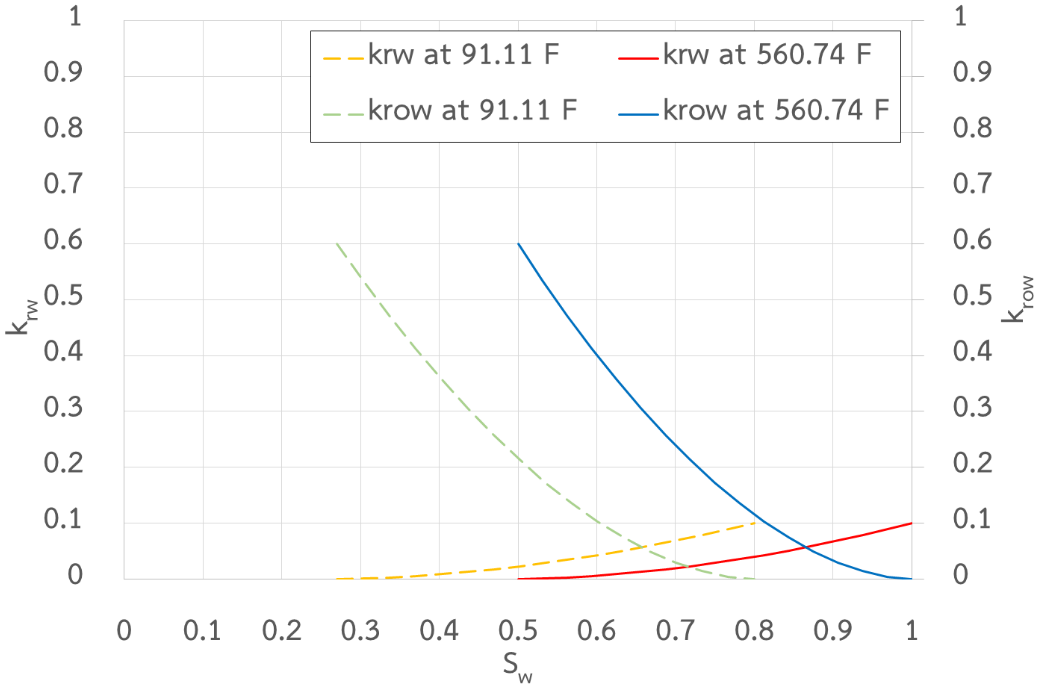


Figure 4.10 Relative permeability curves of oil-water system for reservoir model at initial reservoir temperature and at heating temperature as a function of water saturation

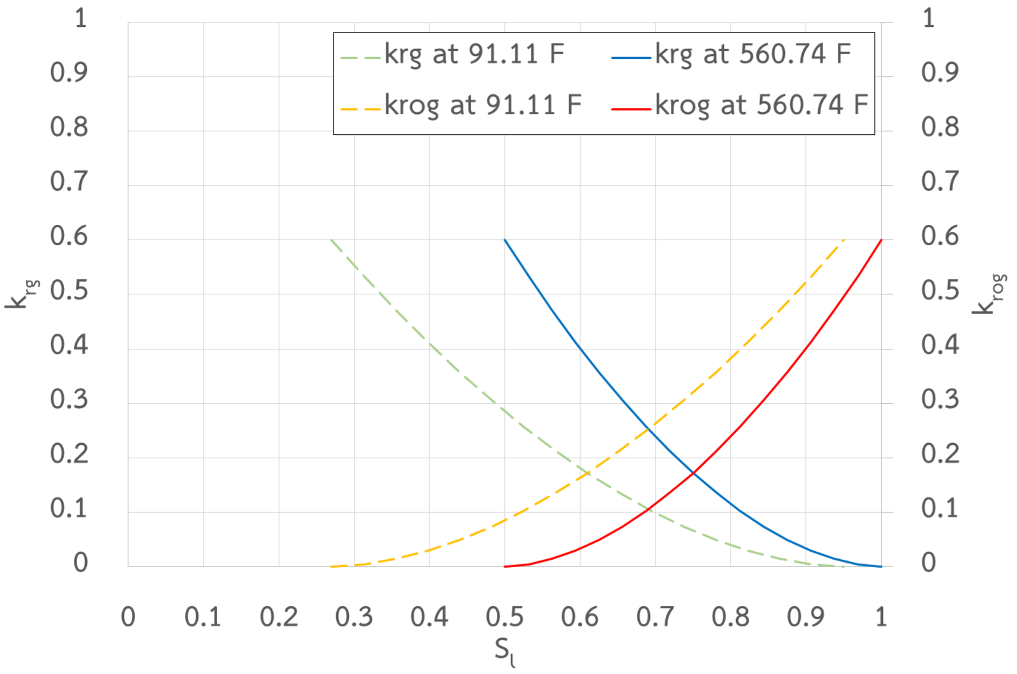


Figure 4.11 Relative permeability curves of liquid-gas system for reservoir model at initial reservoir temperature and heating temperature as a function of liquid saturation

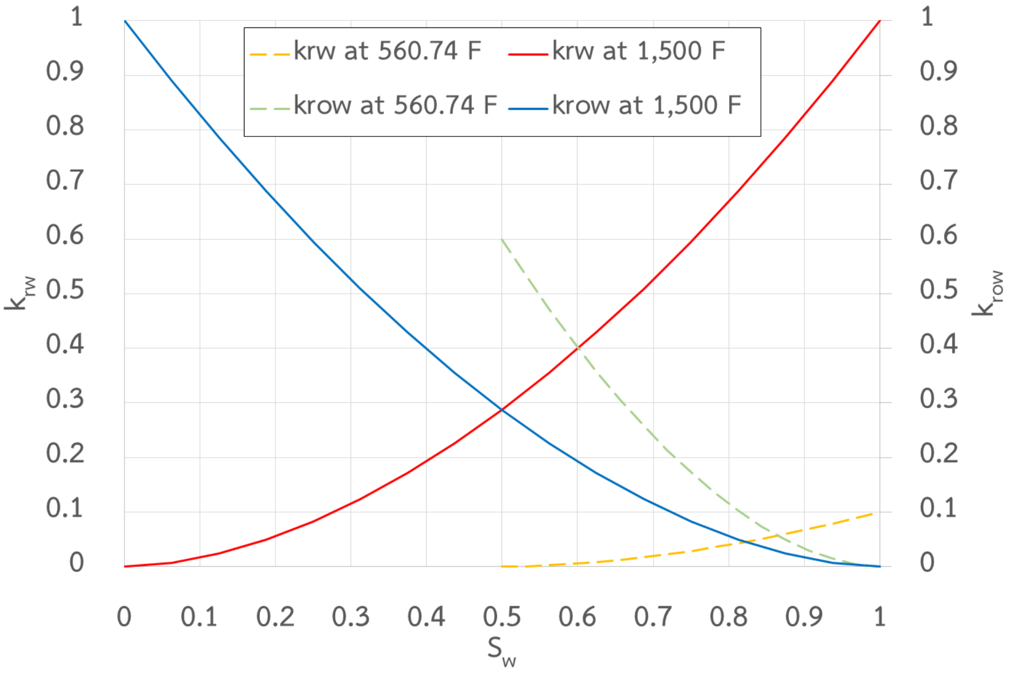


Figure 4.12 Relative permeability curves of oil-water system for reservoir model at heating temperature and at combustion temperature as a function of water saturation

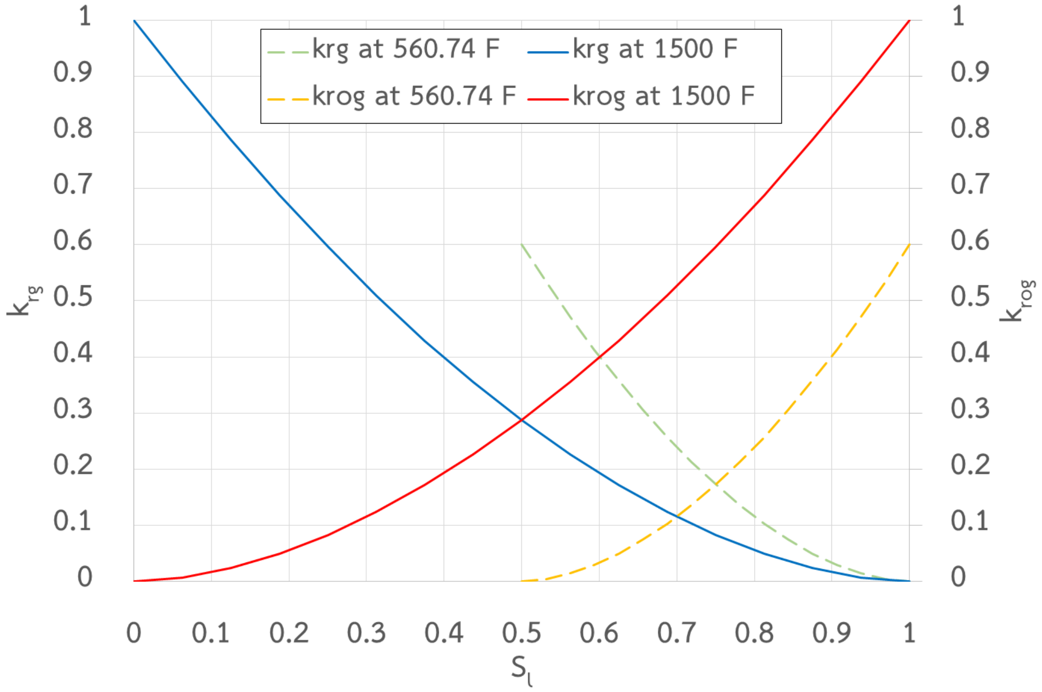


Figure 4.13 Relative permeability curves of liquid-gas system for reservoir model at heating temperature and at combustion temperature as a function of liquid saturation

4.5 Parameters Related to Injection and Production Wells

Wellbore radius of injection and production well is 0.1017 ft that equivalent to 2⅞ in tubing size. The skin factor is assumed to be zero. The well configurations are illustrated in Figure 4.1 and Figure 4.2. Vertical injector is perforated in top 90 ft of reservoir thickness while the horizontal injector is perforated in various depth of reservoir and the well length is 405 ft. On the other hand, both two horizontal wells length is 560 ft each and perforated at the bottom layer of the reservoir thickness. Wells are located in two configurations different in the type of injection well. The first configuration is VI2HP that the vertical injection well is placed in the center left of reservoir while HI2HP have the horizontal injection well placed the heel side at the upper left and the toe side at the lower left of the reservoir. Each of horizontal production well are placed the heel side at upper and lower right corner of the reservoir respectively. In case of dry combustion, oxygen-enriched air injection rate is determined in a unit of std-ft^3/day which is equivalent of gas volume. Horizontal injection well depth and air injection rate are varied. Selected horizontal injection well depth is utilized for the entire study while air injection rate is used as reference to compare with wet combustion cases. For wet combustion, mixture of water and oxygen-enriched air is specified in a unit of STB/day which is equivalent of liquid volume. Air injection rate, time to start wet combustion and water injection rate are varied.

Injection and production wells constraints are showed in Table 4.7 to Table 4.10. Both maximum bottomhole pressure and air injection pressure are determined to prevent fracture in reservoir. At the first 5 years of production which is heating period, injected air and wellbore is heated by electric downhole heater into specified temperature to accelerate the combustion in reservoir. After heating period the heater is closed and the air injection temperature is reverted into normal value. At the time that wet combustion is started, the water is co-injected with air to be heated into in-situ steam and recover additional oil in the reservoir. Air composition is remain the same as in dry combustion period. Time to start wet combustion and air and water injection rate are varied in this study. In case of production wells, minimum bottom hole pressure maximum water cut are determined in order to ensure that vertical lift performance condition is satisfied and the production is going to be performed properly. While maximum liquid production rate is specified in order to maintain reservoir pressure and ensure that combustion front is formed.

Table 4.7 Constraints of injection well at VI2HP configuration

Parameter	Value	Unit
Vertical injection well depth	1,475-1,565	ft
Maximum bottom hole pressure	950	psi
Injection pressure	950	psi
Air injection rate	Varied (480, 600, 720)	Mstd-ft^3/day
Oxygen concentration	Varied (0.4, 0.6, 0.8)	Mole fraction
Nitrogen concentration	Varied (0.2, 0.4, 0.6)	Mole fraction
Injection temperature after heating period	63	^{o}F
Heating period	5	years
Heating rate	2.457	MMBTU/day
Heating temperature	572	^{o}F

Table 4.8 Constraints of injection well at HI2HP configuration

Parameter	Value	Unit
Horizontal injection well depth	Varied (1,500, 1,510, 1,520)	ft
Maximum bottom hole pressure	950	psi
Injection pressure	950	psi
Air injection rate	Varied (480, 600, 720)	Mstd-ft^3/day
Oxygen concentration	Varied (0.4, 0.6, 0.8)	Mole fraction
Nitrogen concentration	Varied (0.2, 0.4, 0.6)	Mole fraction
Injection temperature after heating period	63	^{o}F
Heating period	5	years
Heating rate	2.457	MMBTU/day
Heating temperature	572	^{o}F

Table 4.9 Constraints of injection well at wet combustion period

Parameter	Value	Unit
Maximum bottom hole pressure	950	Psi
Injection pressure	950	Psi
Air injection rate	Varied (85,485, 106,857, 128,228)	STB/day
Water injection rate	Varied (120, 160, 200)	STB/day
Time to start wet combustion	Varied (5, 10, 15)	Years
Injection temperature	63	^{o}F

Table 4.10 Constraints of production well

Parameter	Value	Unit
Minimum bottom hole pressure	300	Psi
Maximum liquid production rate	100	STB/day
Maximum water cut	0.9	Fraction

4.6 Thesis Methodology

1. Construct reservoir model with VI2HP and HI2HP well configurations. A simple dry combustion is performed in all cases by controlling maximum air injection rate in a certain case to be constant throughout injection well length. In order to determine dry combustion base case, the following parameters are varied
    a. Horizontal injection well depth: 1,500, 1,510 and 1,520 ft
    b. Oxygen concentration in injected air: 40, 60 and 80%
    c. Air injection rate: 480,000, 600,000 and 720,000 ft^3/day

   Both parameters in this step are crossed to each other, resulting in total combination of 9 cases in VI2HP configuration and 27 cases in HI2HP configuration. The best parameter for dry combustion that yields the highest oil recovery is taken for wet combustion in the following step.

2. Perform wet combustion in the model from previous section with the same well configuration parameters. In order to perform the study of wet combustion the following parameters are varied:
    a. Water injection rate: 120, 160, and 200 STB/day
    b. Time to perform wet combustion: 5, 10 and 15 years

    Both parameters in this section are crossed to each other, resulting in total combination of 18 cases. The best parameters for wet combustion for each configuration is taken to increase air injection rate by 20% to study the effect of air injection rate. The concluding wet combustion base case is taken for the following steps to study effects of interest parameters.

3. Perform simulation studying interest parameters by performing wet in-situ combustion in the base case model with different shale volume, parameter involved in relative permeability and vertical permeability as follow:
    a. Thermal conductivity of rock matrix (44, 44.98, 34.94 BTU/ft×day×°F)
    b. End point saturations (S_{wi}) (0.18, 0.27, 0.36)
    c. Vertical permeability ($0.2k_h$, $0.1k_h$ and $0.01k_h$)
4. Analyze and discuss simulation outcomes for each study parameters and conclude new findings from the study.

Summary of thesis methodology is graphically illustrated in Figure 4.14 to Figure 4.16.

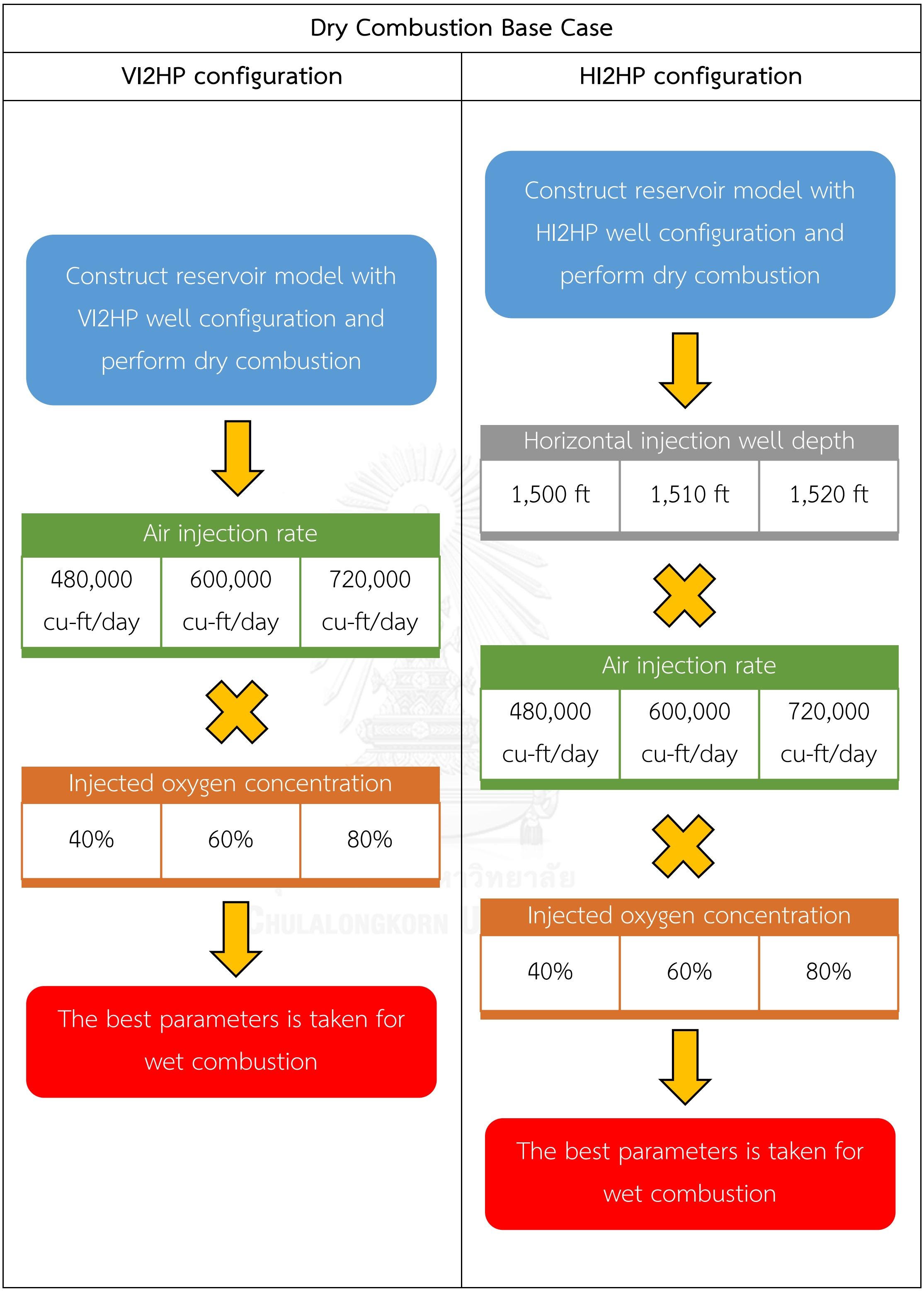


Figure 4.14 Flow chart of methodology for identification of dry combustion base case model

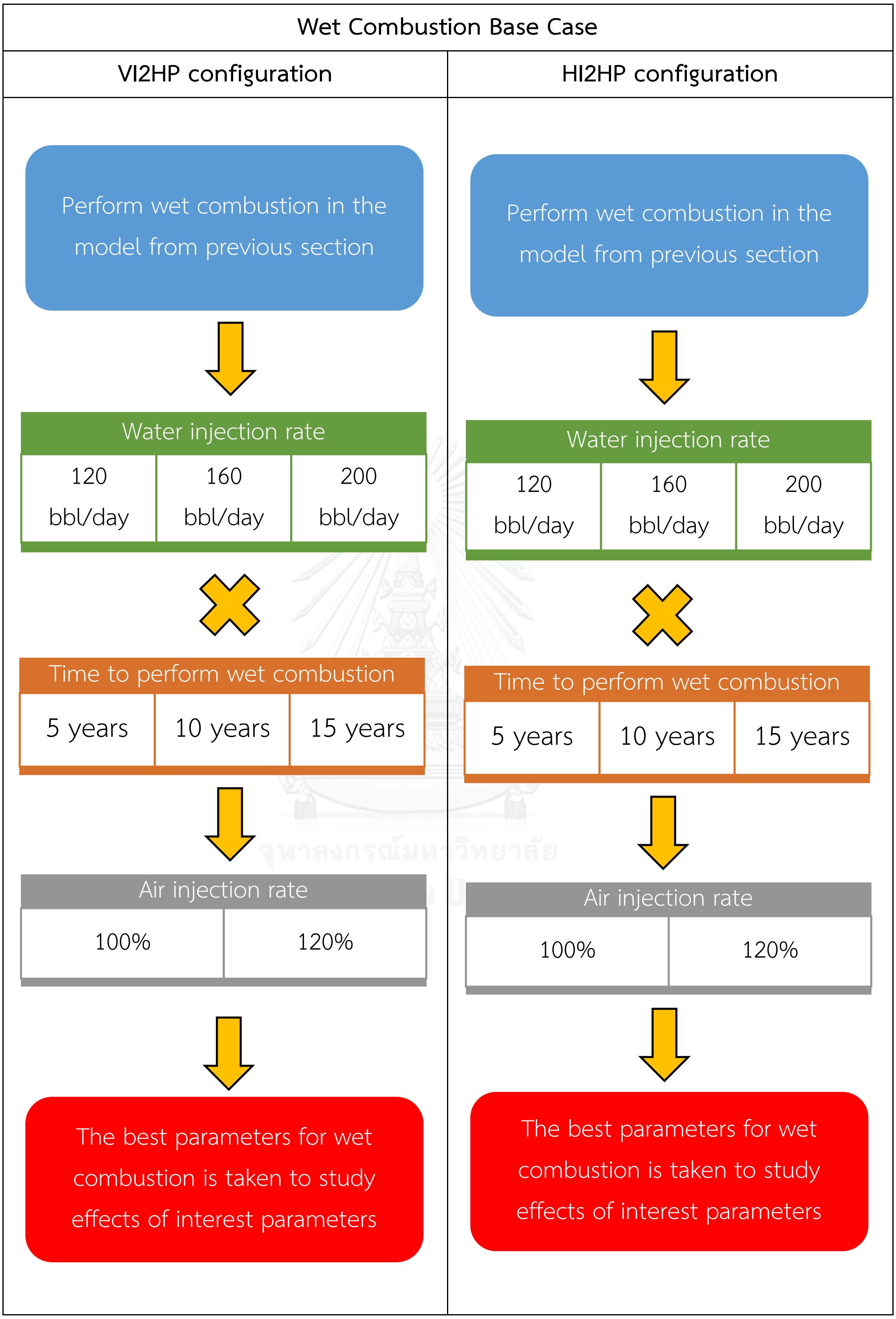


Figure 4.15 Flow chart of methodology for identification of wet combustion base case model

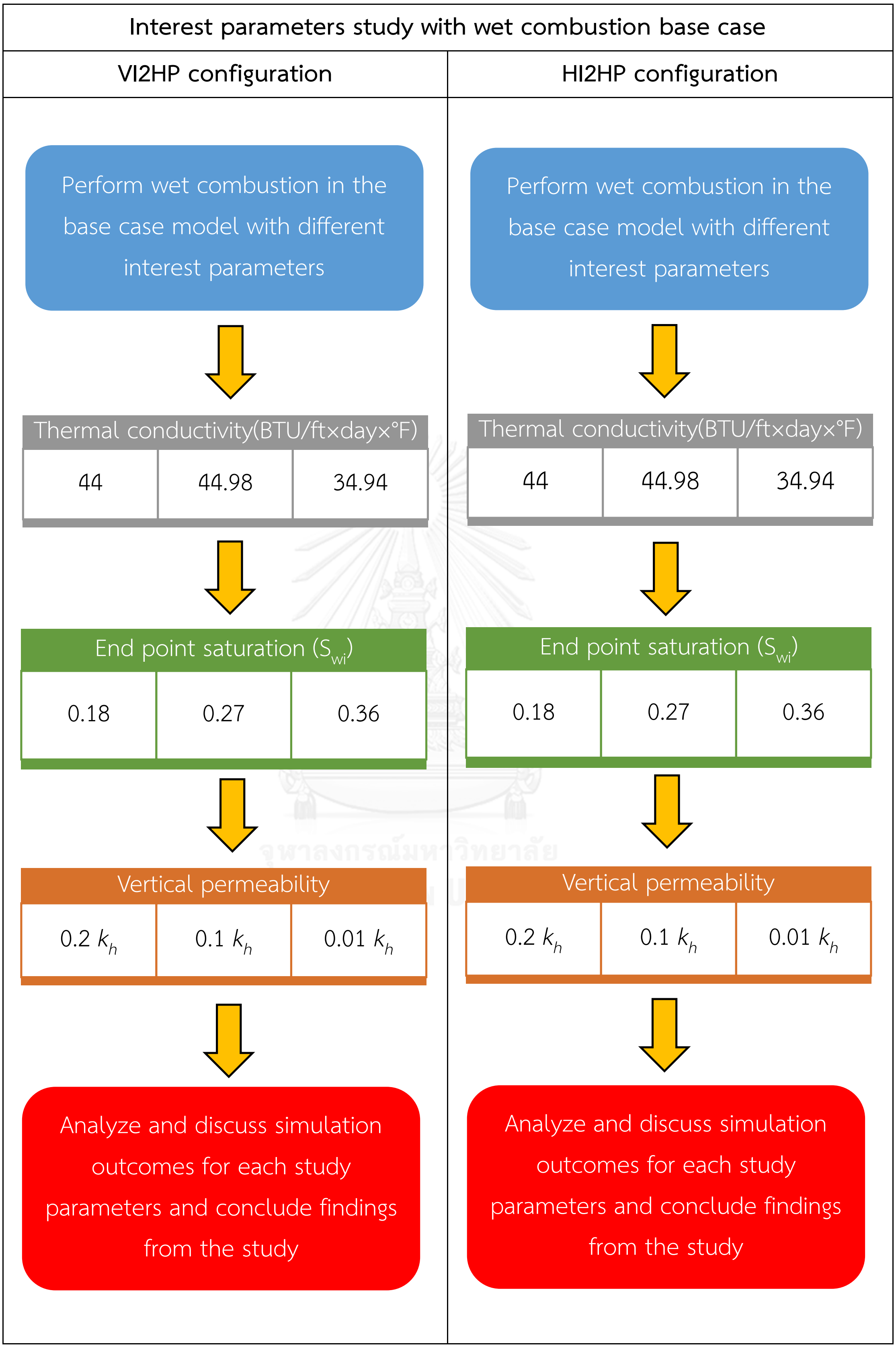


Figure 4.16 Flow chart of methodology for study of interest parameters

CHAPTER V
RESULTS AND DISCUSSION

In this section, dry combustion in THAI configuration will be performed and explained first. Then the best parameters of operating parameters in dry combustion will be performed prior to combining with wet combustion. In wet combustion step, oil recovery mechanism is explained and is compared to that of dry combustion. The best parameters of operating parameters in wet combustion is determined afterward and wet combustion base case will be used in order to evaluate effects of selected reservoir parameters in the final part which include shale volume, relative permeability endpoint, and horizontal permeability.

5.1 Dry In-situ Combustion Base Case

After reservoir model is constructed with all selected properties dictated in previous chapter, dry in-situ combustion or so-called dry combustion in THAI configuration is performed with various values of operating parameters including depth of injection well (for case of horizontal injection well), air injection rate and concentration of oxygen in injected air in order to determine optimal values of these parameters. Oil recovery factor and energy consumed per barrel of oil (shown as enthalpy) are used for discussion of effectiveness of the process.

Other operating parameters which are not selected to study are kept constant in every case. Maximum air injection rate is varied while maximum liquid production rate is remained constant in every case. Injection well is controlled from maximum bottomhole pressure at 950 psi to prevent undesired fractures and pressure is maintained by injected air at early years of process. Maximum production period is 30 years which can be earlier terminated if water cut at production well attains 90%.

5.1.1 Oil Recovery Mechanisms in Dry In-situ Combustion Process

During the dry in-situ combustion process, several oil recovery mechanisms emerge and the evidences of each period are described in this section. VI2HP configuration with one vertical injection well and two horizontal production wells is explained first followed by the case of one horizontal injection well and two horizontal production wells configuration or so called HI2HP. The selected cases are equipped with operating parameters which are 80 percent of oxygen concentration and 600,000 ft^3/day of air injection rate for VI2HP configuration and 60 percent of oxygen concentration, 720,000 ft^3/day of air injection rate and 1,510 ft of horizontal injection well depth in HI2HP configuration.

Oil production rate and reservoir pressure as a function of production time of VI2HP are illustrated in Figure 5.1. For the case of VI2HP, oil production rate oil recovery is subdivided into 5 periods which are 1) increment of oil production rate (0 to 500th day), 2) declining of oil production rate with fluctuation (500th to 2,000th day), 3) constant oil production rate (2,000th to 4,500th day), 4) rapid increment of oil production rate (4,500th to 5,500th day), and 5) steady oil production rate before the end of production period (5,500th to 10,958th day).

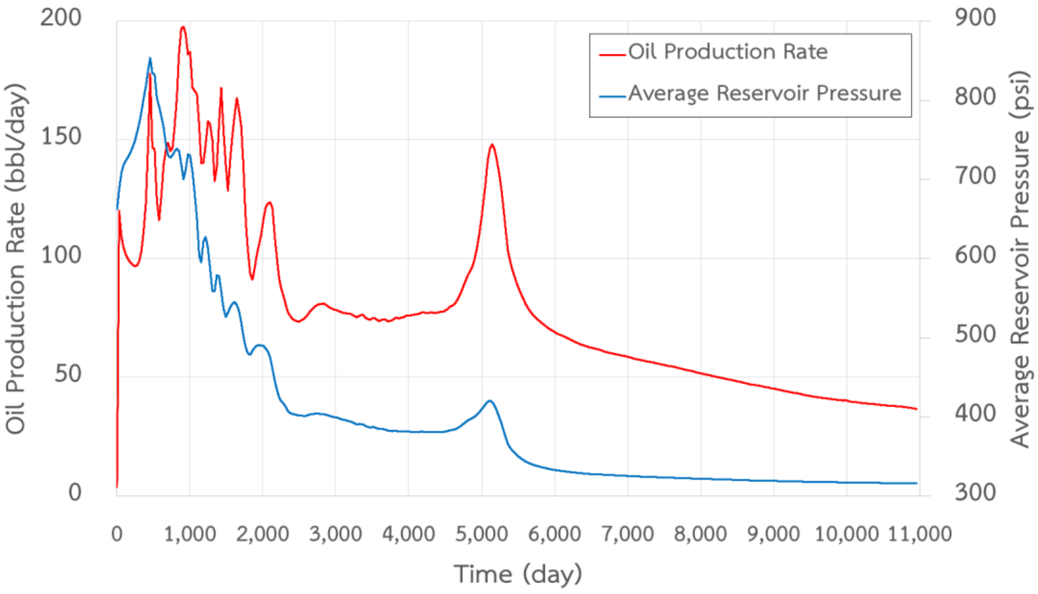


Figure 5.1 Oil production rate and average reservoir pressure from ISC process in VI2HP configuration as a function of time

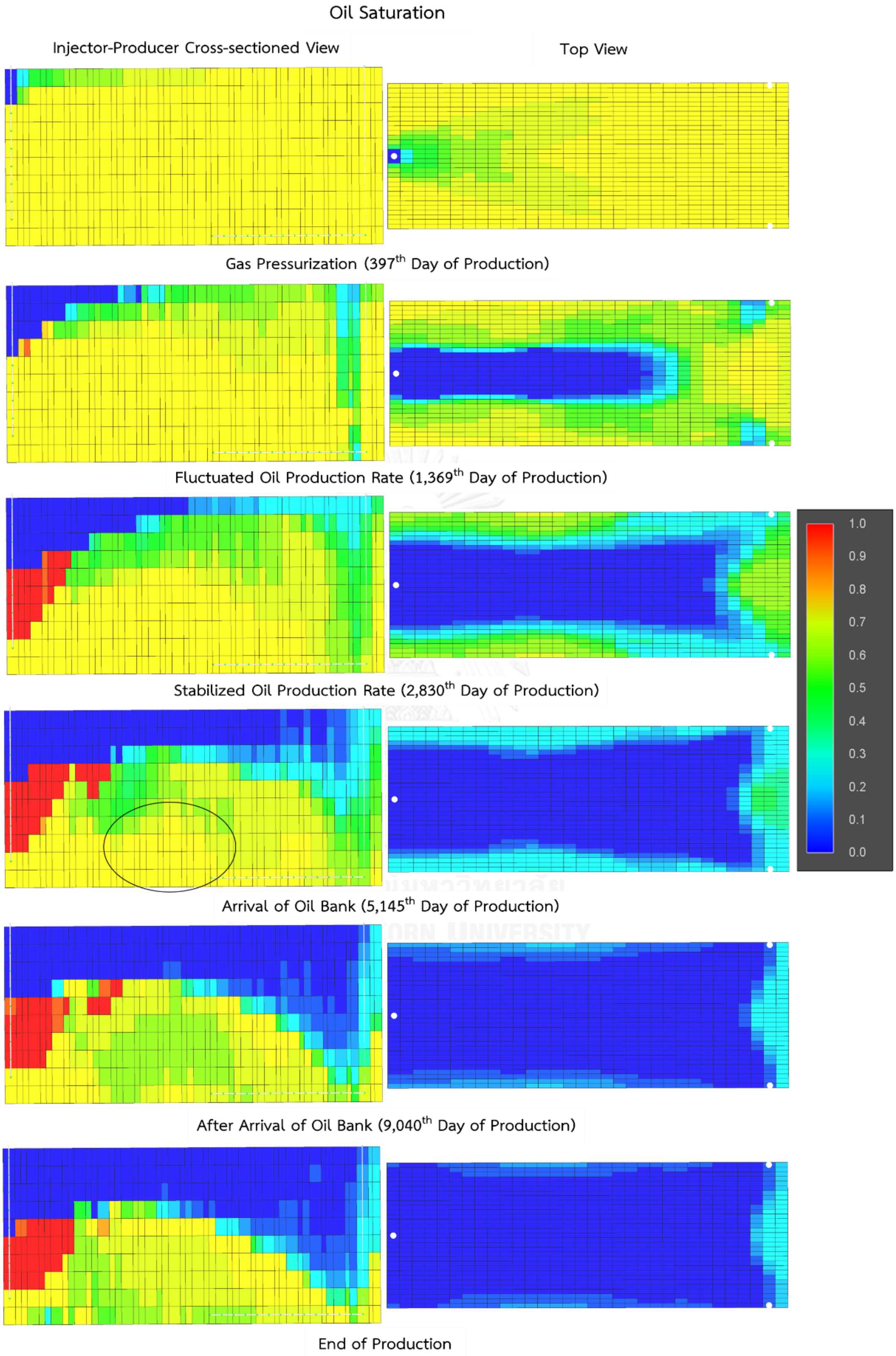
In order to explain oil recovery mechanisms occurred during the in-situ combustion process, oil saturation profiles in each period in both side and top views are illustrated in Figure 5.2 to assist the explanation. In the first period, it can be observed from reservoir pressure that there is an increment of pressure in this period. Oil is mainly driven to production wells by means of provided pressure from injected air. From Figure 5.2, it can be observed that oil saturation profile at day 397th is decreased in certain areas of reservoir but not at very high degree. In this period, air is heated and it is also observed that a great reduction of oil is found only at the top of vertical injection well where most air preferably enters into the reservoir. In this period, injected air tends to move upward due to its gravity and is induced downward due to horizontal production wells. Adjacent to the production well oil saturation is still high.

The second period can be described by arrival of injected air together with products from combustion process. It can be observed at the production day of 1,369th that oil saturation adjacent to injection well is greatly reduced in larger extend compared to the first period and moreover, there is also location with very high oil saturation. This is an evidence that combustion front is already occurred. At elevated temperature at combustion front, all liquids turn into gas as well as solid form (coke). High oil saturation is a combination of coke deposition together with light oil that is vaporized and condensed back again into oil phase when connate water is all vaporized and travelled forward to production well as steam phase. Gas breakthrough is occurred at heel side of horizontal production wells and reservoir pressure is decreased. From the figure, it can be observed that gas breakthrough is not fully developed on horizontal section of production well. However, it can be observed that oil saturation in the area where gas pass through is greatly reduced to blue scale which is very low. This also confirms the effect from combustion gases that carry heat to lower the residual oil saturation in this area. Within the same time of gas breakthrough, oil that obtains heat from combustion can also be produced from the toe side of production wells as can be observed from yellow color zone. Fluctuation of oil production is due to arrival of different gasses that will be described later on.

After combustion front is generated and fire front is maintained, all generated gases are flooded out together with injected air. It can be observed at day 2,830th that larger area with low oil saturation is observed around both production wells compared to the previous period. In this period injected gas reaches production wells mainly on and oil is still produced at the toe side. Oil production rate is stable maintained with a small reduction of reservoir pressure. This period is sustained until around day 4,500th before an arrival of oil bank from combustion front.

In this fourth period, large oil bank with high oil saturation arrives at the toe side of production as can be observed in the circle at day 5,145th. This oil bank is pushed by injected air that tends to by-pass the oil bank. From the figures at day 9,040th, oil lobes with high oil saturations can be observed. This explains the period after an arrival of oil bank and this can be confirmed by increment of gas production rate after day 5,000th as illustrated in Figure 5.3. At the end of production, it can be observed that there are still oil lobes with high saturation but with smaller sizes. As displacing fluid is much lighter than displaced fluid, the displacement mechanism is therefore inefficient and oil production rate declines during this period.

From Figure 5.3 it can also be observed that there is also fluctuation of gas production in second period. At day 1,369th which is the period that oil production rate is fluctuated, arrival of several gases including, Carbon Dioxide, Nitrogen, Oxygen, and steam is shown in Figure 5.4. It can be observed that Nitrogen which is inert gas that does not participate the combustion reaction arrives at high quantity at production wells. Carbon Dioxide is also observed in this period as combustion is already occurred and Carbon Dioxide is one of the products from combustion. Small amount of steam also appears at this period as steam is also a product but since it turns back to water phase, its saturation is quite small further away from combustion front. The late arrival of Oxygen can be explained that it is consumed at the combustion front and hence only the excess amount can travel beyond the combustion front. According to different time that gases arrive to production well, the gas production rate fluctuates and this results in fluctuation of oil production rate.



Gas Pressurization (397th Day of Production)

Fluctuated Oil Production Rate (1,369th Day of Production)

Stabilized Oil Production Rate (2,830th Day of Production)

Arrival of Oil Bank (5,145th Day of Production)

After Arrival of Oil Bank (9,040th Day of Production)

End of Production

Figure 5.2 Oil saturation of dry combustion in VI2HP configuration at selected times

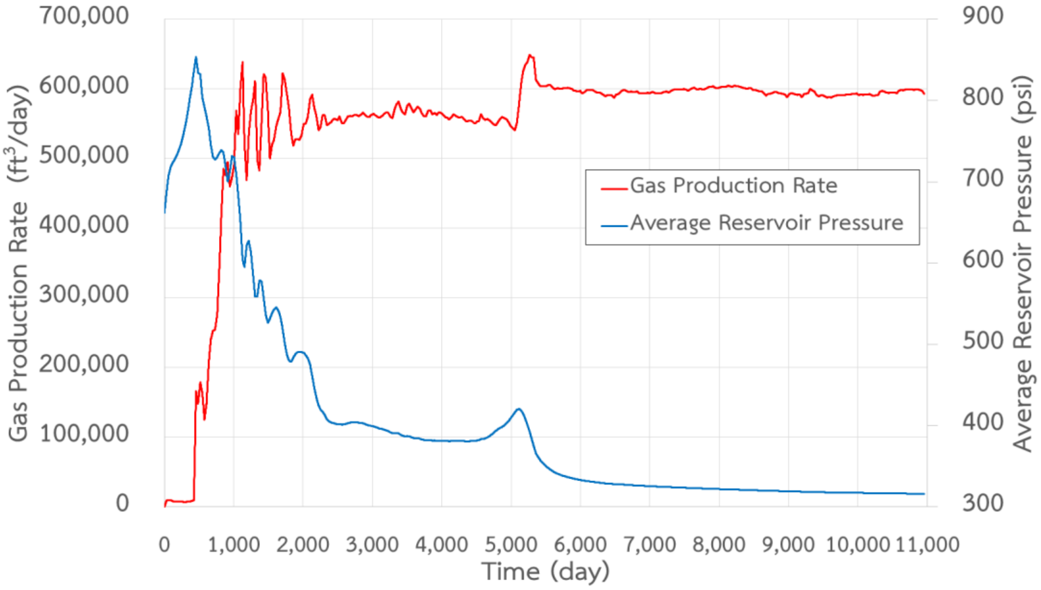


Figure 5.3 Gas production and average reservoir pressure from dry combustion process in VIH2P configuration as a function of time

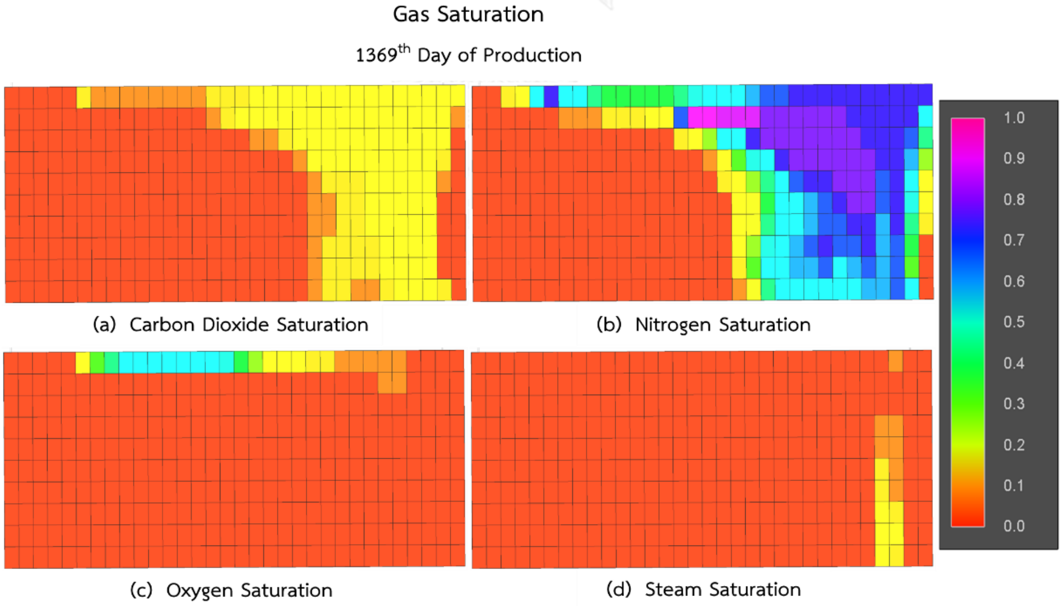


Figure 5.4 Gas saturation profiles of VI2HP configuration at day 1,369th illustrating a) Carbon Dioxide, b) Nitrogen, c) Oxygen and d) steam

After 5 years of heating period, combustion front is expected to occur near injection well from combustion reaction between oxygen in injected air and reservoir fluid. From temperature profiles shown in Figure 5.5, it can be obviously seen that the combustion front is formed on top layers which as injected air tends to flow upward due to low density compared to oil. Location of combustion is settled around the highest temperature in the profile which is represented by yellow color. Beyond the fire front high temperature is a result from combusted gases which are products from combustion reaction. The fire front propagates along the reservoir with the same direction of injected air. Comparing the location of fire front at the end of production, it can be seen that fire front propagates slowly and there is still significant amount of heat of from combustion that is not used yet to reduce oil viscosity or other oil recovery mechanisms.

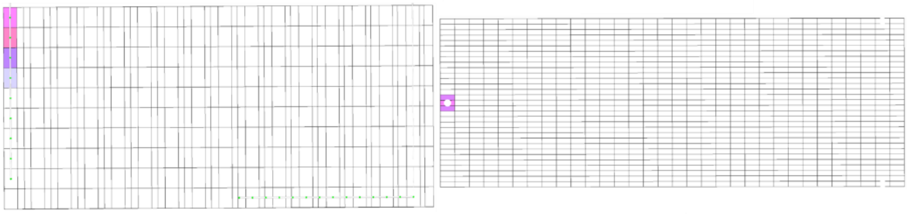
Since the main purpose of thermal recovery is to reduce oil viscosity, the profile of oil viscosity profile is therefore displayed. From oil viscosity profile illustrated in Figure 5.6, oil viscosity in most part of reservoir is decreased below 100 cP at the end of production period. As oil viscosity is a function of temperature, high reduction of oil viscosity is therefore observed around location of fire front.

To confirm the appearance of fire front, coke deposition can also be used. Coke is a product from cyclization which results in solid hydrocarbon at very high temperature. According to Figure 5.7, coke is formed and deposited near wellbore of vertical injection well and slightly moves further with the same direction of injected oxygen. Comparing Figure 5.5, it also confirms that fire front only travel for a short distance over production period.

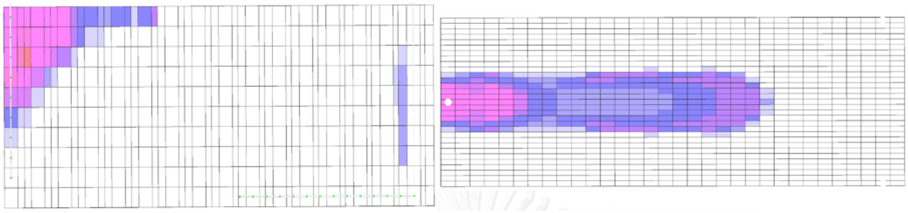
Temperature (°F)

Injector-Producer Cross-sectioned View

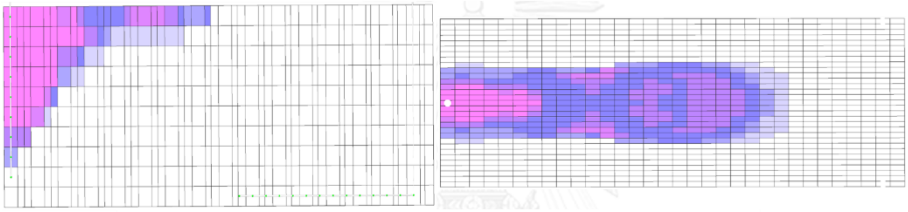
Top View



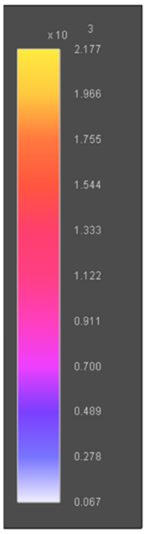
Gas Pressurization (397th Day of Production)

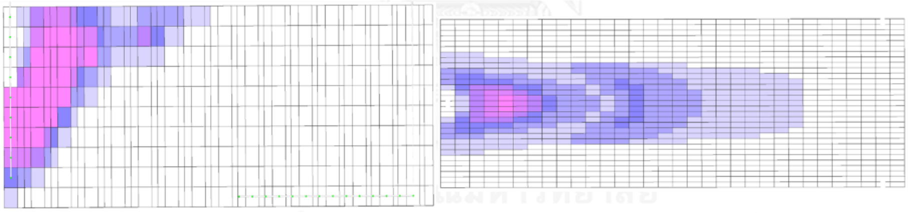


Fluctuated Oil Production Rate (1,369th Day of Production)

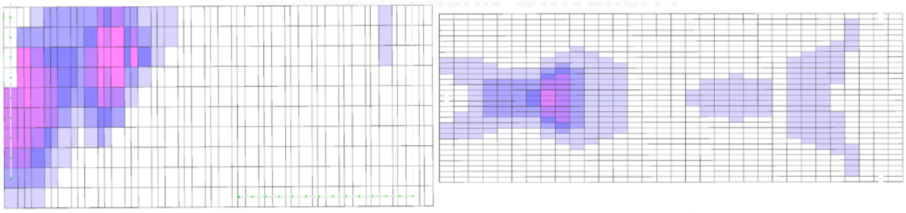


End of Heating Period (1,827th Day of Production)

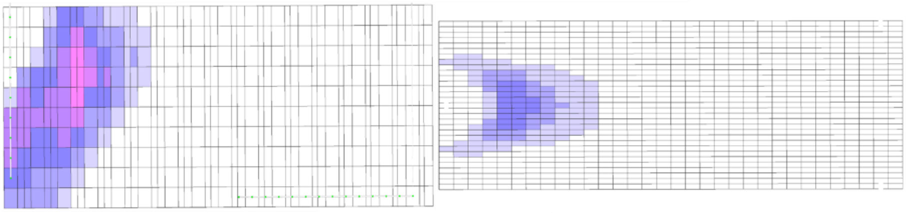




Stabilized Oil Production Rate (2,830th Day of Production)

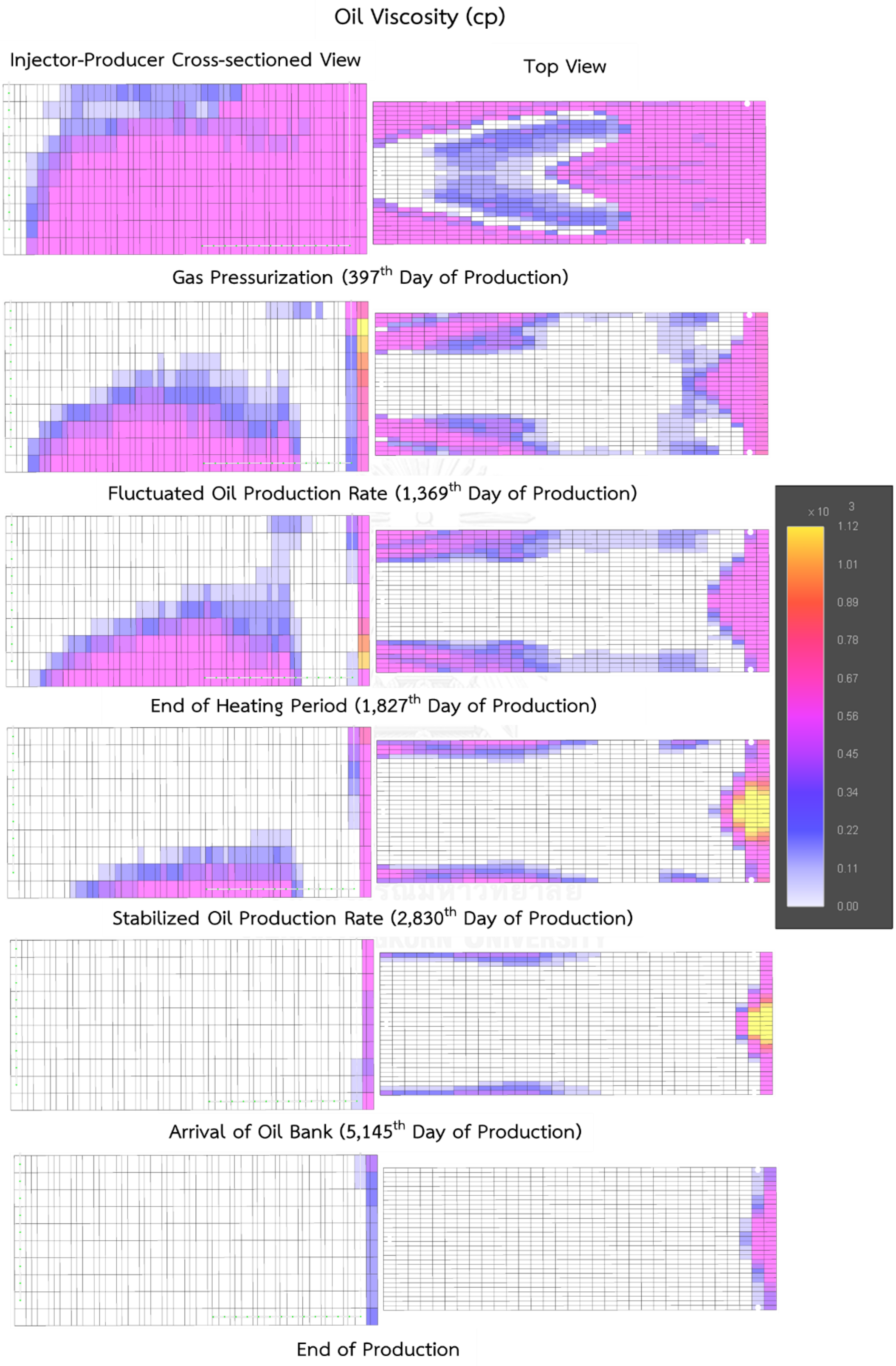


Arrival of Oil Bank (5,145th Day of Production)



End of Production

Figure 5.5 Temperature profiles in VI2HP configuration at selected times



Oil Viscosity (cp)

Injector-Producer Cross-sectioned View

Top View

Gas Pressurization (397th Day of Production)

Fluctuated Oil Production Rate (1,369th Day of Production)

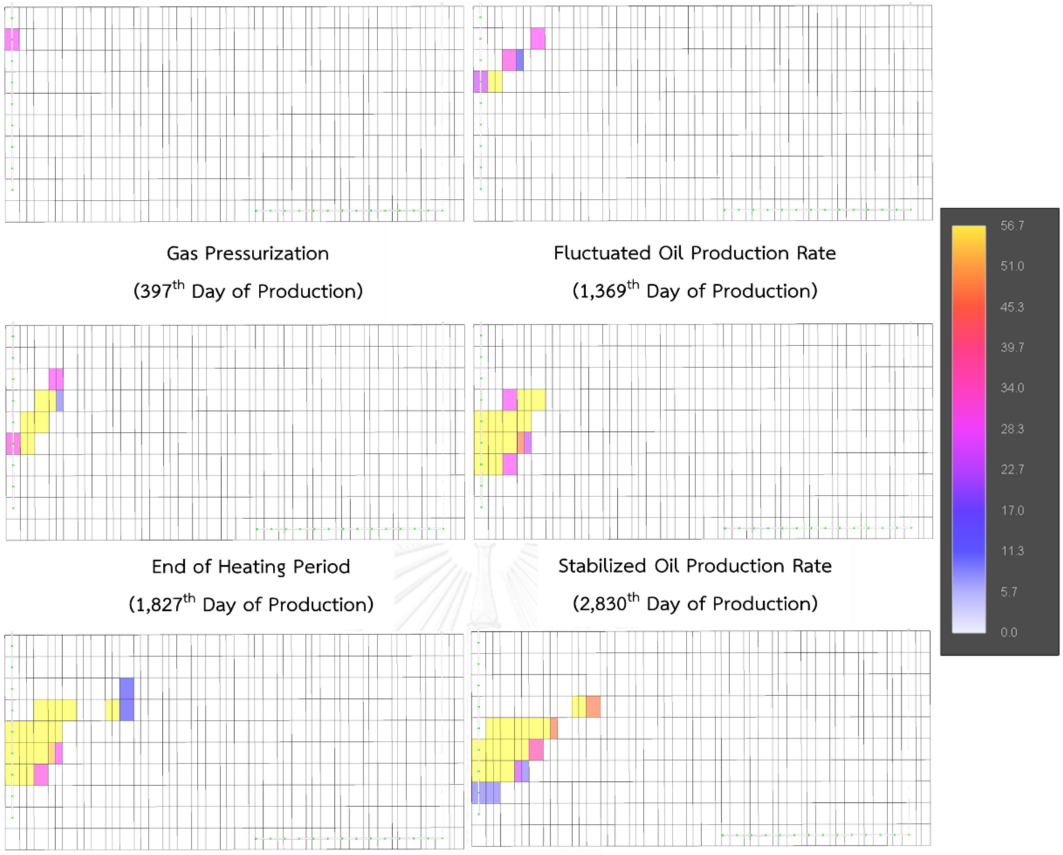
End of Heating Period (1,827th Day of Production)

Stabilized Oil Production Rate (2,830th Day of Production)

Arrival of Oil Bank (5,145th Day of Production)

End of Production

Figure 5.6 Oil viscosity profiles in VI2HP configuration at selected times



Coke Deposition (lb/ft^3)

Injector-Producer Cross-sectioned View

Gas Pressurization

(397th Day of Production)

Fluctuated Oil Production Rate

(1,369th Day of Production)

End of Heating Period

(1,827th Day of Production)

Stabilized Oil Production Rate

(2,830th Day of Production)

Arrival of Oil Bank

(5,145th Day of Production)

End of Production

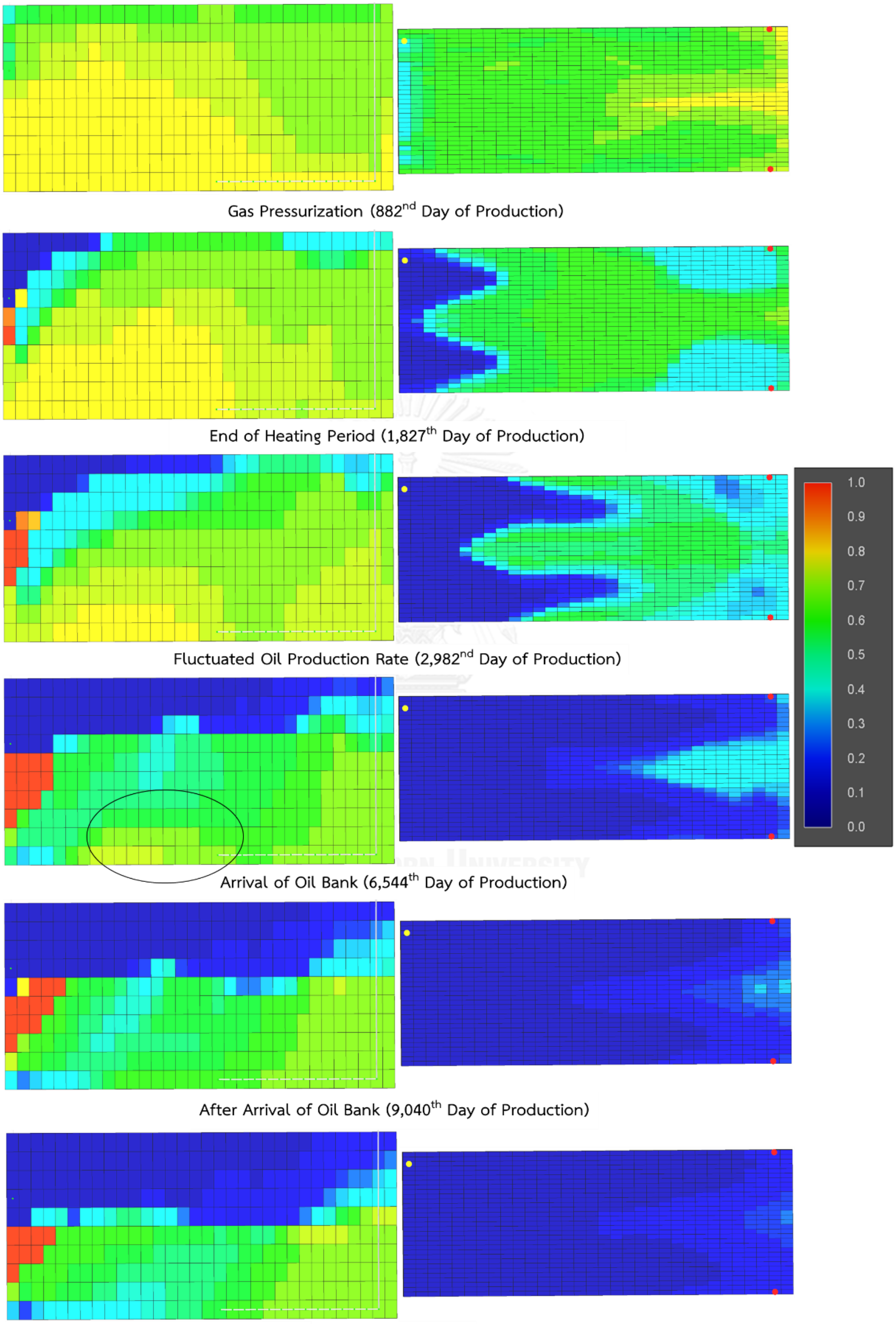
Figure 5.7 Coke deposition profiles in VI2HP configuration at selected times

In case of HI2HP configuration, gas pressurization is also occurred but oil production rate is not as high as in case of VI2HP configuration. Gas breakthrough increases gradually over time after gas pressurization so that oil production rate is less fluctuated compared to VI2HP configuration. Arrival of oil bank in HI2HP is later than VI2HP and the peak of oil bank is smaller. However, oil production rate of HI2HP is higher after arrival of oil bank. Oil saturation profiles at different periods are illustrated in Figure 5.8 while oil production rate and reservoir pressure as a function of time for HI2HP well configuration is shown in Figure 5.9.

Oil Saturation

X-Z (24th Y-Plane) Cross-sectioned View

Top View



Gas Pressurization (882nd Day of Production)

End of Heating Period (1,827th Day of Production)

Fluctuated Oil Production Rate (2,982nd Day of Production)

Arrival of Oil Bank (6,544th Day of Production)

After Arrival of Oil Bank (9,040th Day of Production)

End of Production

Figure 5.8 Oil saturation of dry combustion in HI2HP configuration at selected times

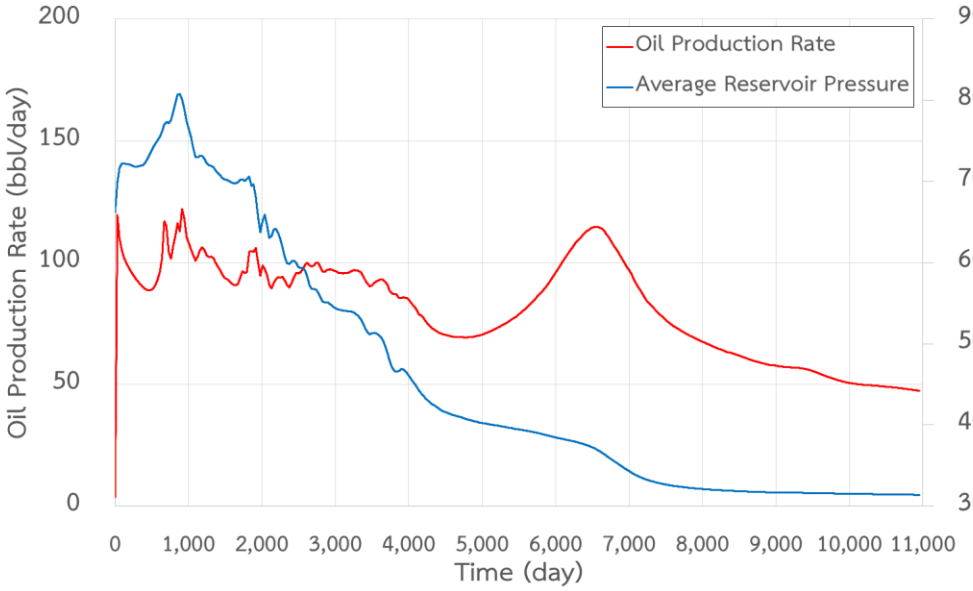


Figure 5.9 Oil production rate and average reservoir pressure from ISC process in HI2HP configuration as a function of time

From Figure 5.9, reservoir pressure dictates the gas pressurization process up to the production day around 1,000th. Fluctuation of oil production rates can be explained as same as in case of vertical wells that several gases may arrive to production wells in different period. From the figure at day 1,827th day which is the end of heating period, it can be observed that low oil saturation already exists around the injection well as well as high oil saturation below injection well. This is an evidence of appearance of combustion front. Nevertheless, from top view it can be observed that fire front appears in two lobes. As air is injected from horizontal well at certain horizontal depth, gas enters formation with more difficulty in first period. Moreover, oil is drained from the reservoir from two sides and this therefore, induces gas to enter formation with different abilities at different locations and the closer to the production well, the higher the total amount of injected air. More evidences on appearance of fire front in HI2HP is explained later in this section. Another different from VI2HP is that, gas breakthrough occurs in the middle of horizontal section. This can be explained that the depth of injection is located closer to production well and injected air hence, is earlier induced to flow downward.

Arrival of oil bank still occurs at the toe side of the production well as can be seen from difference between production days 6,544th and 9,040th. At the end of production, it can be observed that majority is of oil is remained at the heel side of production well. At this location injected air cannot arrive as it is induced earlier by the closer location of horizontal injection well compared to vertical injection well. Comparison of oil production rates obtained from VI2HP and HI2HP is shown in Figure 5.10.

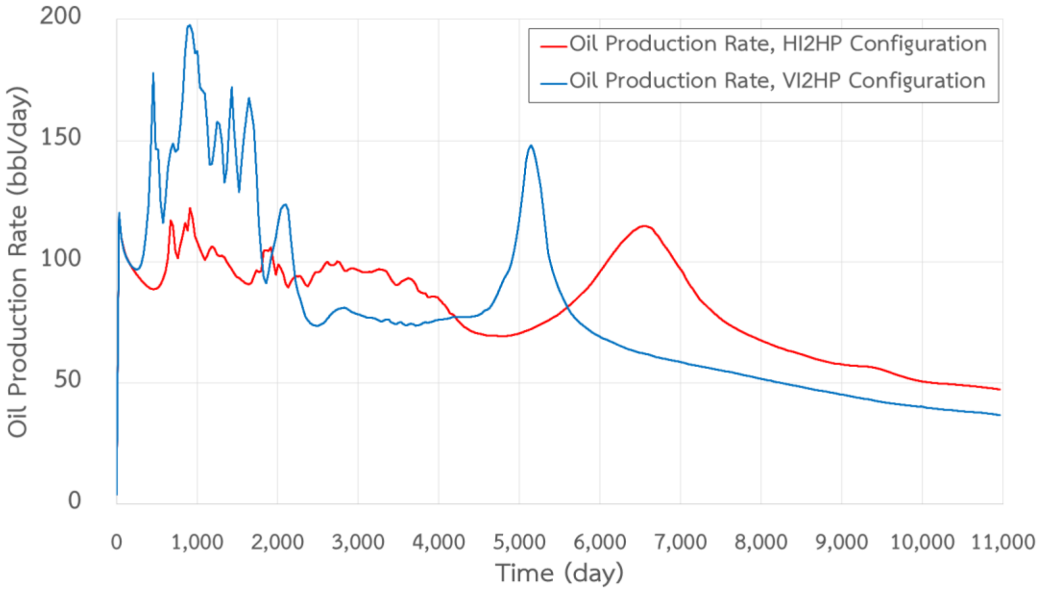


Figure 5.10 Comparison of oil production rates between VI2HP and HI2HP configuration

From Figure 5.10, it can be seen that VI2HP configuration gives higher oil production rate at early years of production and also yields earlier arrival of oil bank compared to HI2HP. As horizontal well is longer than vertical well in this study, injection rate is therefore higher than case of vertical well to balance well exposure. Nevertheless, as horizontal well is located at only one certain depth which is around middle depth of reservoir, total amount of injected air is therefore relatively low compared to vertical well that has part of well located at shallower location. From

Figure 5.11, it can be seen that desired air injection rate can be attained at faster time in case of VI2HP compared to HI2HP. This results in high oil production rate in first period of production in case of vertical injection well as can be seen in Figure 5.10.

From approximately day 2,000th when desired air injection rate is already attained in case of HI2HP, oil production rate is higher than that of VI2HP. This also corresponds to higher amount of gas production in case of HI2HP as can be observed in Figure 5.12.

Although horizontal injection well is not favorable in terms of amount of injected gas in first period, it yields more benefit on forming of oil bank in latter stage. The difference in oil production rate during the arrival of oil bank from these two configurations is due to different shape of combustion front. Temperature profile which is good evidences for detecting location of fire front of HI2HP is shown in Figure 5.13.

Fire front occurred in HI2HP configuration forms a shape with two lopes, one at toe side and one at heal side. As gas is injected throughout the whole horizontal section but preference is found closer to locations of production wells, air is therefore more injected at toe and heel sides. This results in generating of two fire fronts. As fire front is split in two, they therefore travel at lower speed, resulting in late arrival of oil bank. However, forming two fire fronts also results in better sweep efficiency which consecutively causes higher in oil production rate at arrival of oil bank.

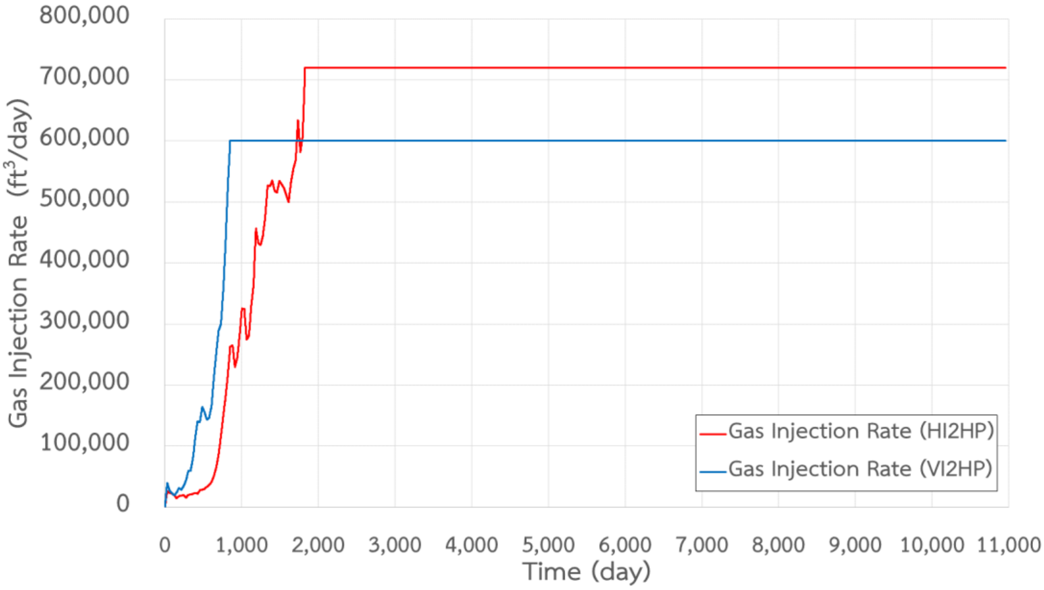


Figure 5.11 Comparison of gas injection rates between VI2HP and HI2HP configuration as a function of time

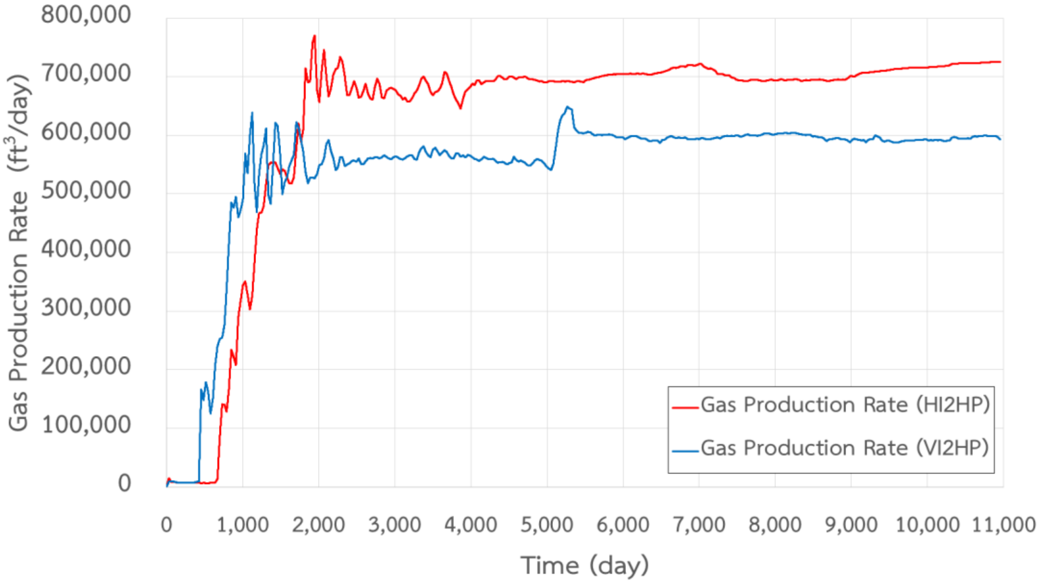


Figure 5.12 Comparison of gas production rates between VI2HP and HI2HP configuration as a function of time

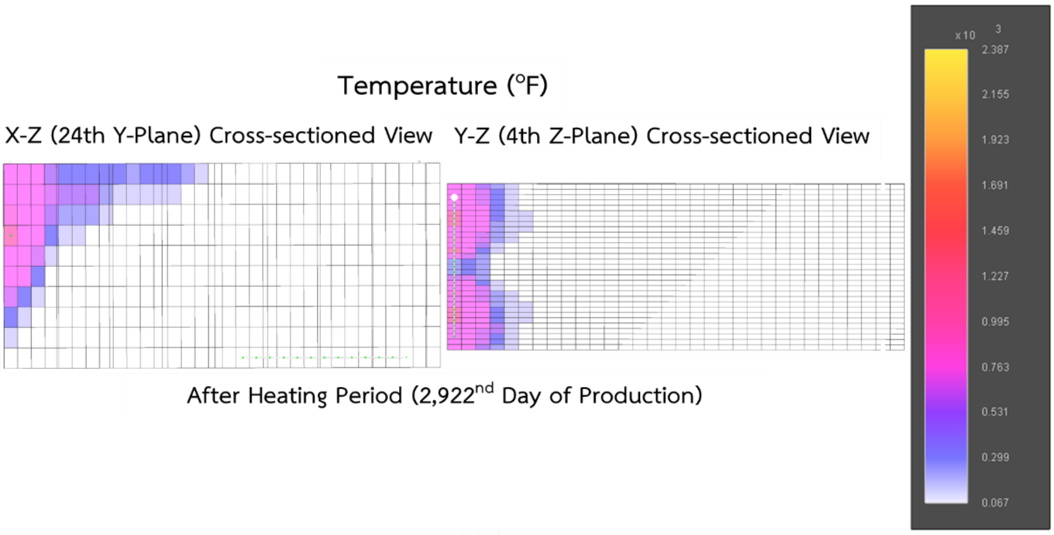


Figure 5.13 Temperature profiles of dry combustion in HI2HP configuration at 2,922nd day of production

In this section, oil recovery mechanisms from dry combustion process in both VI2HP and HI2HP are explained. Oil recovery mechanisms in both cases occur in different periods. Gas pressurization takes place from the start when combustion front does not occur yet. Gas breakthrough causes fluctuation in oil and gas production rates in the following periods which are from injected air as well as products from combustion including Carbon Dioxide and steam. Arrival of different gases at different periods results in fluctuation of gas and oil production. Oil bank in both cases breakthrough at toe side of production wells. Due to fixed depth of horizontal well in case of HI2HP, gas encounters more difficulty to enter formation and shape of fire front is induced into 2 lopes whereas only single fire front is developed in case of VI2HP. At the end of production, there are many locations of reservoir remains high in oil saturation. Nevertheless, majority of oil production is contributed by heat from combustion that causes reduction in oil viscosity.

5.1.2 Selection of Operating Air Injection Rate, Oxygen Concentration and Horizontal Injection well depth

Dry combustion with THAI configuration is first simulated with various oxygen concentration, air injection rate and horizontal injection well depth (for only horizontal well injection) to obtain the best operating parameters on both VI2HP and HI2HP configurations. Dry combustion performed in VI2HP consists of one vertical injection well at the middle left side of the reservoir model and the two horizontal production wells are drilled at both corners at right side of the reservoir with direction of horizontal section turning to opposite corners parallel to y direction. In case of HI2HP, one horizontal injection well is used instead of vertical injection well and the well is drilled with horizontal section located at different depth parallel with x direction. Maximum air injection rate and liquid production rate are intentionally kept constant until the end of production. Oil recovery factor and energy consumed are concerned and used to compare effectiveness of dry combustion combined with THAI for each case. Energy consumed is defined as enthalpy used to produce one unit volume of oil. Process with low enthalpy consumed is therefore more efficient than ones with higher enthalpy consumed.

Oxygen concentration is an essential operating parameter affecting efficiency of in-situ combustion since heat of combustion is lower is case of inadequate amount of Oxygen compared to high amount of Oxygen. However, overabundant amount of Oxygen leads to combustion in unwanted area including burning of production wells.

For VI2HP configuration, only Oxygen concentration and air injection rate are varied. Results from varying different Oxygen concentrations together with air injection rates in VI2HP configuration are shown in Figures 5.14 and Table 5.1 summarizes oil recovery factor, total energy consumed and energy consumed per barrel of oil from the whole cases in this section.

Table 5.1 Summary of oil recovery factor, total energy consumed and energy consumed per barrel of oil of dry combustion in VI2HP configuration

Air Injection Rate (CU-FT/day)	Oxygen Concentration (%)	Oil Recovery Factor (%)	Cumulative Injected Enthalpy (MMBtu)	Energy Consumed per Barrel of Oil (MMbtu/bbl)
480000	40	20.62	9,160	0.0199
	60	26.65	8,021	0.0135
	80	33.03	6,914	0.0094
600000	40	21.23	10,740	0.0227
	60	31.93	9,434	0.0132
	80	38.93	8,305	0.0096
720000	40	22.85	12,238	0.0240
	60	37.53	10,765	0.0129
	80	32.92	9,543	0.0130

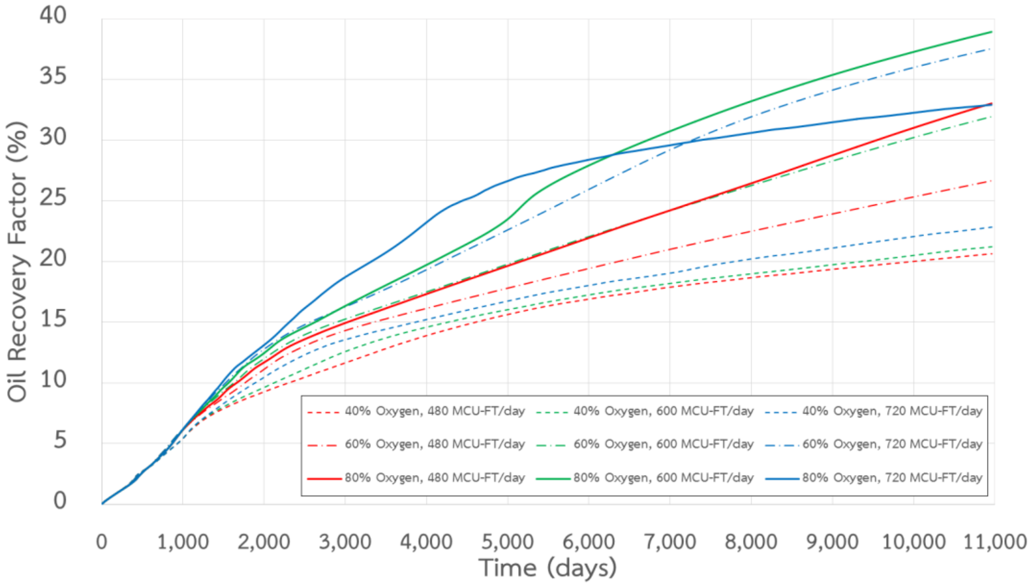


Figure 5.14 Oil recovery factors for cases with different Oxygen concentration and air injection rate as a function of time in VI2HP configuration

From Figure 5.14 it can be obviously seen that Oxygen concentration has more impact to the process comparing to air injection rate as can be seen from changing of color from red to green and to blue for every type of line. Difference in oil recovery factor between three values of maximum air injection rate is quite small at low Oxygen concentration (dot lines) because the increment of injected Oxygen by increasing air injection rate is quite low. Amount of Oxygen is increased but not as high as cases that Oxygen concentration is increased. The difference from changing air injection rates is more obvious at higher oxygen concentration since amount of injected Oxygen is dramatically increased (dash lines and solid lines). Combustion reaction rate is increased from adding amount of Oxygen and the heat of combustion is also increased. So that amount of heat carried in combustion front is increased and recovery factor is significantly increased.

However, extreme amount of Oxygen can give negative feedback. In an extreme case of 80 percent Oxygen concentration and 720,000 ft^3/day of air injection rate oil recovery factor is lowered at late time because the combustion occurs at production well, resulting in very low rate of oil recovery. Nevertheless, this case is not expected in real operation since burning around production well could cause damage to physical system as well as safety to health issues. The temperature profile of aforementioned case is shown in Figure 5.15. Comparison of oil recovery factors at the end of production from whole cases are shown in Figure 5.16.

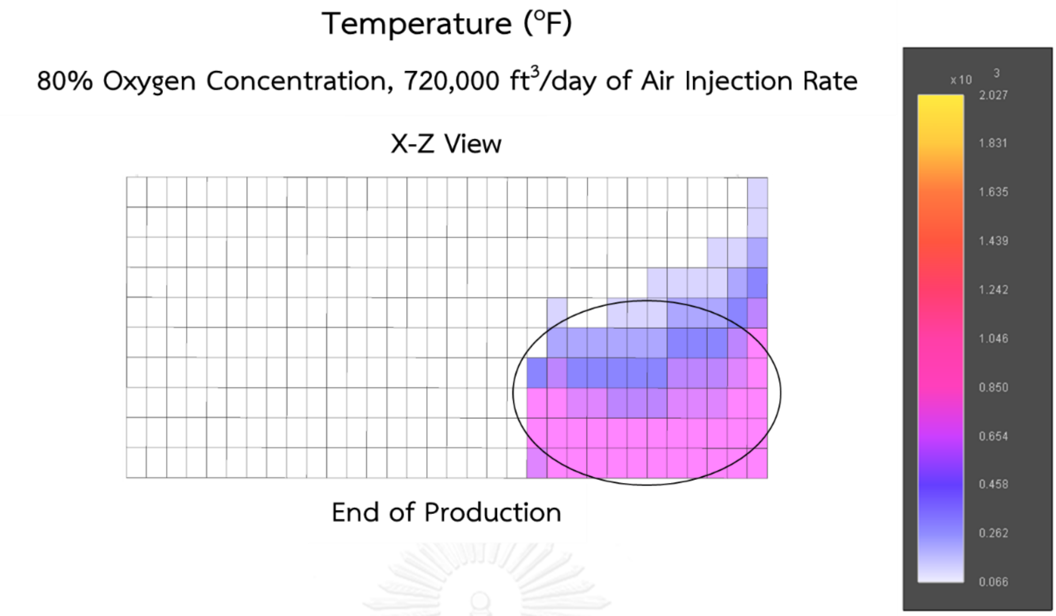


Figure 5.15 Temperature profile of dry combustion performed in VI2HP configuration where the combustion occurred at production wells

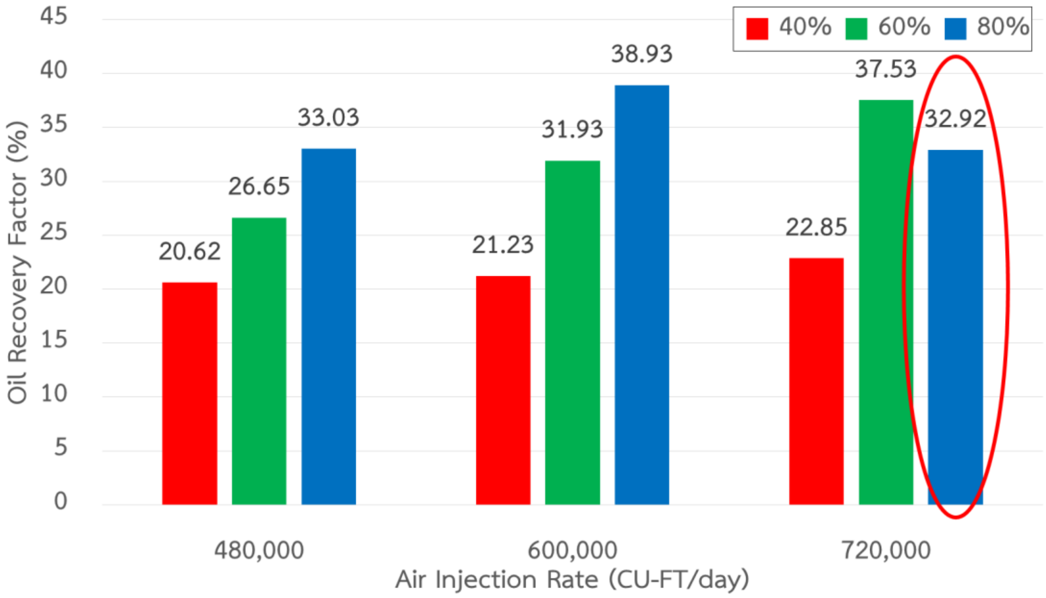


Figure 5.16 Comparison of oil recovery factors at the end of production from dry combustion performed in VI2HP configuration

According to Figure 5.16, it is obvious that Oxygen concentration in air is more sensitive to effectiveness of dry combustion in THAI compared to air injection rate.

From the figure, it also shows that the optimal case that yields the highest oil recovery factor is 80 percent Oxygen concentration and 600,000 ft^3/day of air injection rate. This case yields approximately 38.93 percent of oil recovery factor. As explained previously, the case of 80 percent of Oxygen concentration and 720,000 ft^3/day of air injection rate yields lower recovery factor because combustion occurs at production well from overabundant amount of Oxygen.

On the other hand, oil recovery factor is not the only parameter which can judge the thermal oil recovery process performance. Another factor needed to be considered is energy consumed in the process. Figure 5.17 and Figure 5.18 compare total energy consumed and energy consumed per barrel of oil at the end of production for the whole cases.

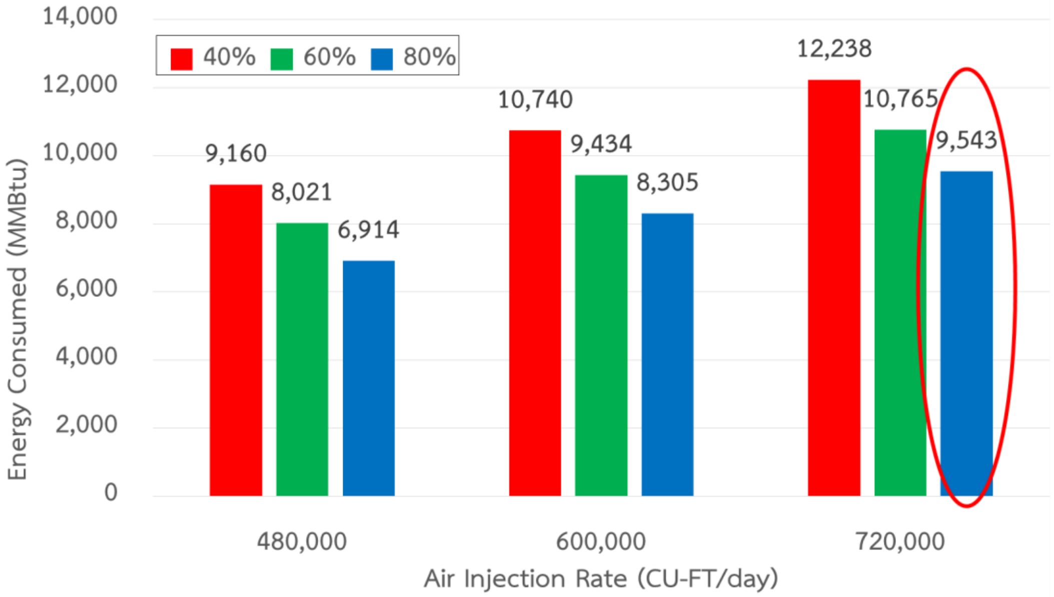


Figure 5.17 Summary of energy consumed at the end of production from dry cases in VI2HP configuration

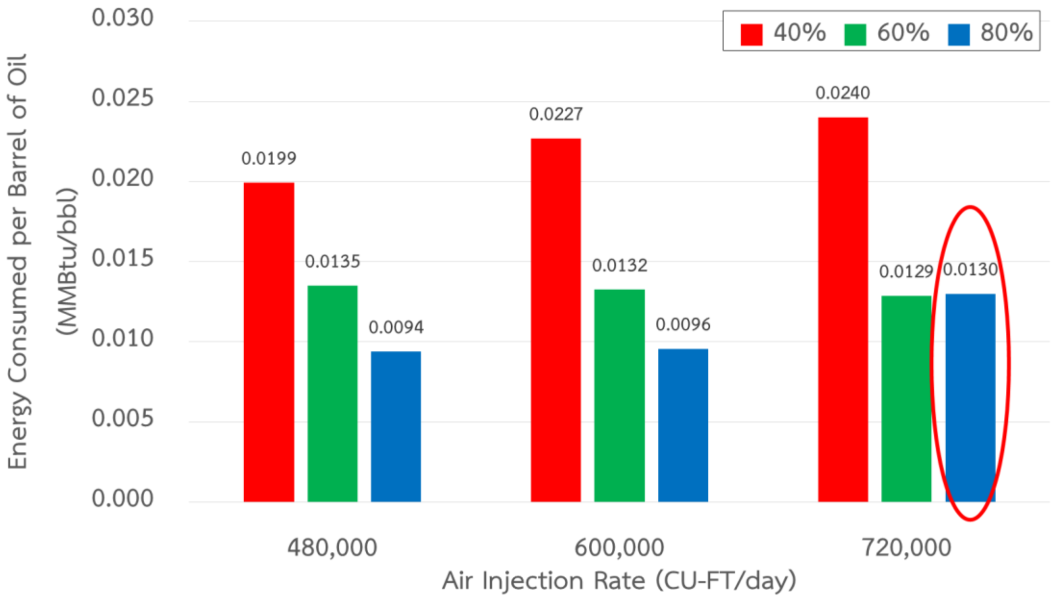


Figure 5.18 Summary of energy consumed per barrel of oil at the end of production from dry cases in VI2HP configuration

Since the time used to inject energy into reservoir is only first 5 years for all cases, the difference in amount of energy injected depends also on Oxygen concentration and air injection rate. From Figure 5.17, it can be seen that injected Nitrogen is the main component which carries the most energy into reservoir. The reason are that energy consumed is increased as increment of increasing air injection rate which both amount of Nitrogen and Oxygen injected are increased but energy consumed is decreased due to increased Oxygen concentration in injected air. Nevertheless, the purpose that energy is needed to be injected in the process is to facilitate the occurrence of combustion front in the reservoir. So that energy consumed in the process is required only for the combustion front to occur and the energy injection is not required after fire front is formed since heat of combustion is primarily utilized to heat oil in the reservoir. If the amount of energy consumed is enough to generate fire front, increasing Nitrogen to provide energy is not essential and Oxygen concentration should be increased instead in order to improve recovery of oil.

From Figure 5.18, the case that consumes the lowest energy to produce one barrel of oil is 80 percent of Oxygen with 600,000 ft^3/day of air injection rate. It can be concluded that the best case judged by energy consumed per barrel of oil is the same case as the best one determined by oil recovery factor because the amount of energy consumed is low enough to generate fire front and the amount of injected Oxygen is not excessive to burn production well. Even though the case of 80 percent of Oxygen concentration with 480,000 ft^3/day yields almost the same energy consumed per barrel of oil but this case yields lower oil recovery than the selected best case. So that the best operating parameters for dry combustion in VI2HP configuration are 80 percent of Oxygen concentration and 600,000 ft^3/day of air injection rate which yields the best oil recovery factor and also consumes reasonable energy to produce one barrel of oil.

Similar to VI2HP configuration, Oxygen concentration and air injection rate are operating parameters required to be adjusted in HI2HP configuration as well. Another operating parameter involved in HI2HP configuration is horizontal injection well depth. Injected gas breakthrough time is expected to be shortened if horizontal injection well depth is shallow. Results of different Oxygen concentrations together with air injection rates and horizontal injection well depths in HI2HP configuration are shown in Figure 5.19 to Figure 5.21 and Table 5.2 and Table 5.3 summarizes oil recovery factor, total energy consumed and energy consumed per barrel of oil from the whole cases in this section.

Table 5.2 Summary of oil recovery factor, total energy consumed and energy consumed per barrel of oil of dry combustion in HI2HP configuration

Air Injection Rate (ft^3/day)	Oxygen Concentration (%)	Horizontal Injection Well Depth (FT)	Oil Recovery Factor (%)	Energy Consumed (MMBtu)	Energy Consumed per Barrel of Oil (MMBtu/bbl)
480,000	40	1,500	22.59	7,891	0.0157
		1,510	19.65	6,679	0.0152
		1,520	18.45	6,518	0.0158
	60	1,500	26.17	7,089	0.0121
		1,510	24.03	5,897	0.0110
		1,520	23.04	5,322	0.0104
	80	1,500	31.77	5,986	0.0085
		1,510	32.62	5,417	0.0074
		1,520	32.24	4,937	0.0069
600,000	40	1,500	24.57	9,458	0.0173
		1,510	22.33	7,496	0.0151
		1,520	21.23	7,343	0.0155
	60	1,500	31.17	8,532	0.0123
		1,510	32.18	6,317	0.0088
		1,520	32.63	5,703	0.0078
	80	1,500	38.12	6,877	0.0081
		1,510	39.86	5,878	0.0066
		1,520	36.31	5,148	0.0064

Table 5.3 Summary of oil recovery factor, total energy consumed and energy consumed per barrel of oil of dry combustion in HI2HP configuration (Continued)

Air Injection Rate (ft^3/day)	Oxygen Concentration (%)	Horizontal Injection Well Depth (FT)	Oil Recovery Factor (%)	Energy Consumed (MMBtu)	Energy Consumed per Barrel of Oil (MMBtu/bbl)
720,000	40	1,500	27.36	10,789	0.0177
		1,510	26.17	8,055	0.0138
		1,520	25.97	7,966	0.0138
	60	1,500	37.79	9,845	0.0117
		1,510	39.98	6,383	0.0072
		1,520	35.28	5,705	0.0073
	80	1,500	38.19	7,692	0.0090
		1,510	46.13	6,173	0.0060
		1,520	42.81	5,185	0.0054

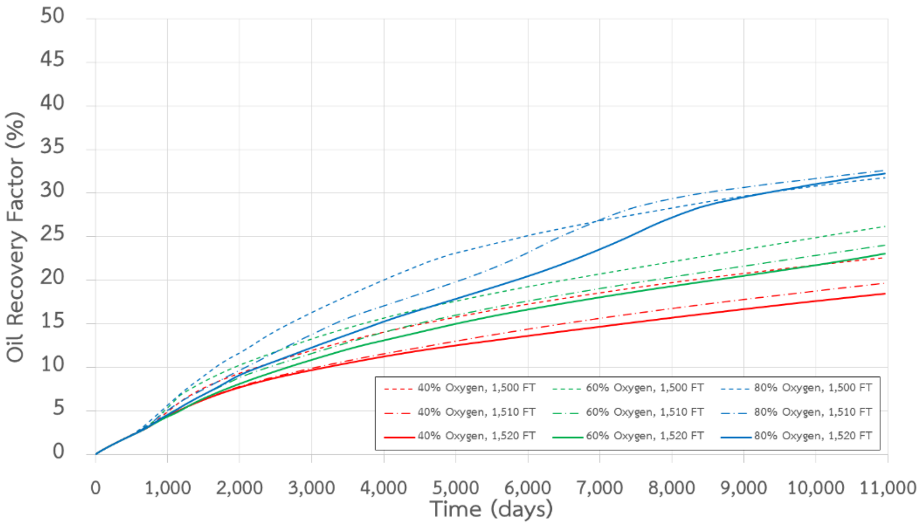


Figure 5.19 Oil recovery factors for cases with different Oxygen concentration and horizontal injection well depth as a function of time in HI2HP configuration with 480,000 ft^3/day of air injection rate

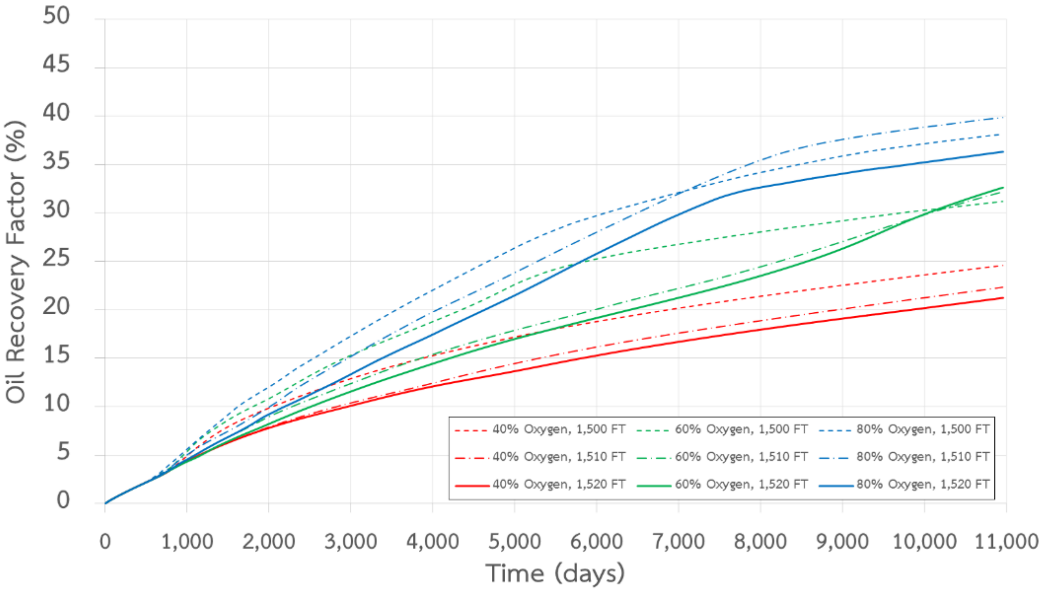


Figure 5.20 Oil recovery factors for cases with different Oxygen concentration and horizontal injection well depth as a function of time in HI2HP configuration with 600,000 ft^3/day of air injection rate

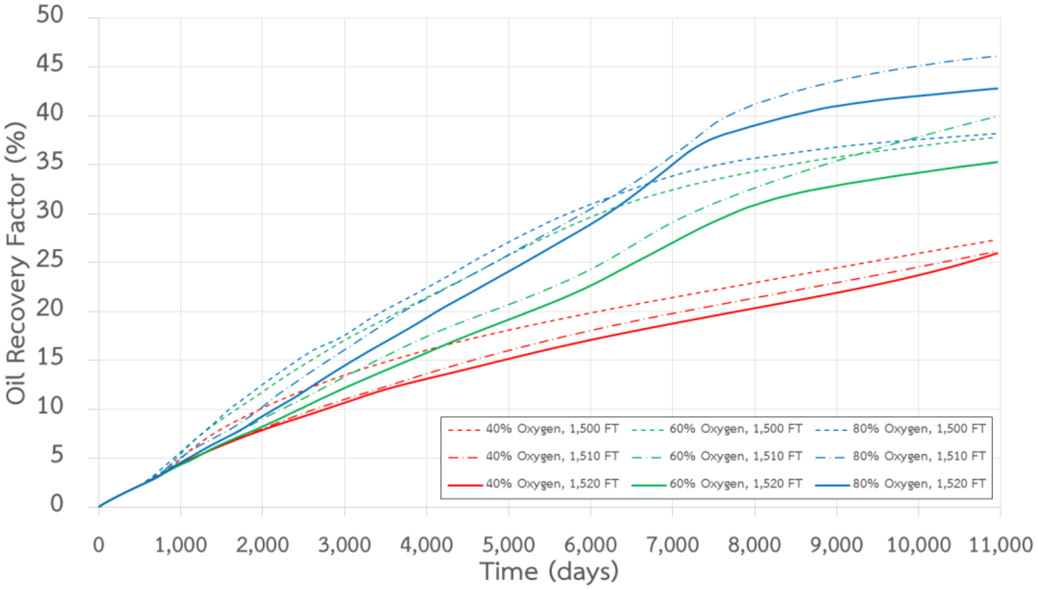


Figure 5.21 Oil recovery factors for cases with different Oxygen concentration and horizontal injection well depth as a function of time in HI2HP configuration with 720,000 ft^3/day of air injection rate

According to Figure 5.19, Figure 5.20 and Figure 5.21, it can be seen that oil recovery factor is increased slightly by increment of increasing air injection rate. So that even though the well configuration is changed into HI2HP, effect of air injection rate is less important comparing to Oxygen concentration and horizontal injection well depth. By increasing Oxygen concentration, oil recovery factor is significantly increased but combustion at production is occurred at high Oxygen concentration in the same way that happens in VI2HP configuration. In case of decreasing horizontal injection well depth, oil recovery factor is increased since total amount of injected gas is better at shallow depth. Fire front is occurred earlier from higher amount of injected gas during heating period so that amount of recovered oil is increased. However, gas breakthrough time is shortened and probability that combustion will occur at production well is increased. Comparison of oil recovery factors at the end of production from whole cases in HI2HP configuration are shown in Figure 5.22 to Figure 5.24.

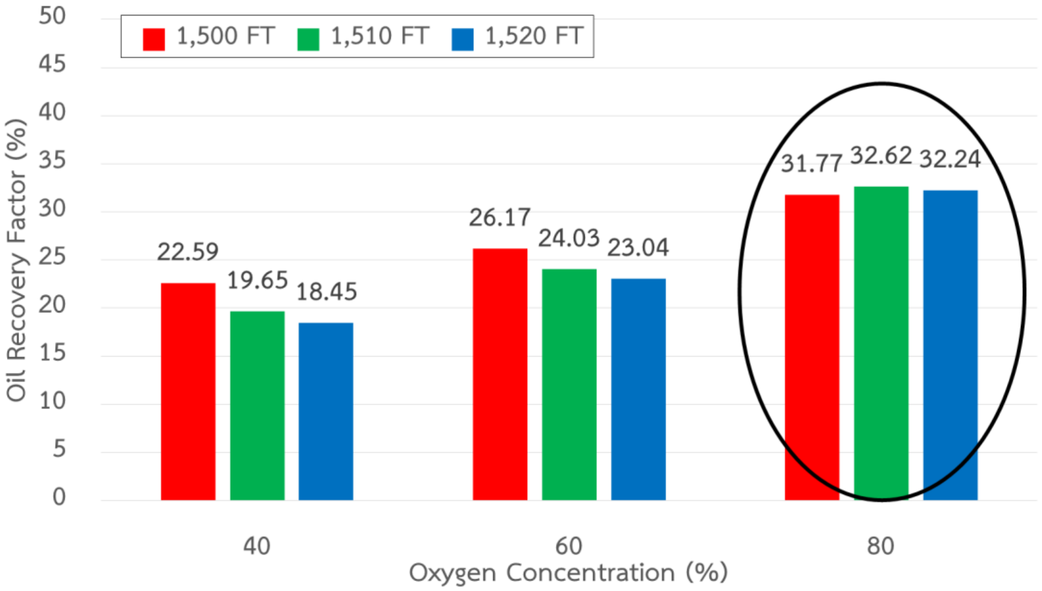


Figure 5.22 Summary of oil recovery factor at the end of production from dry cases in HI2HP configuration with 480,000 ft^3/day of air injection rate

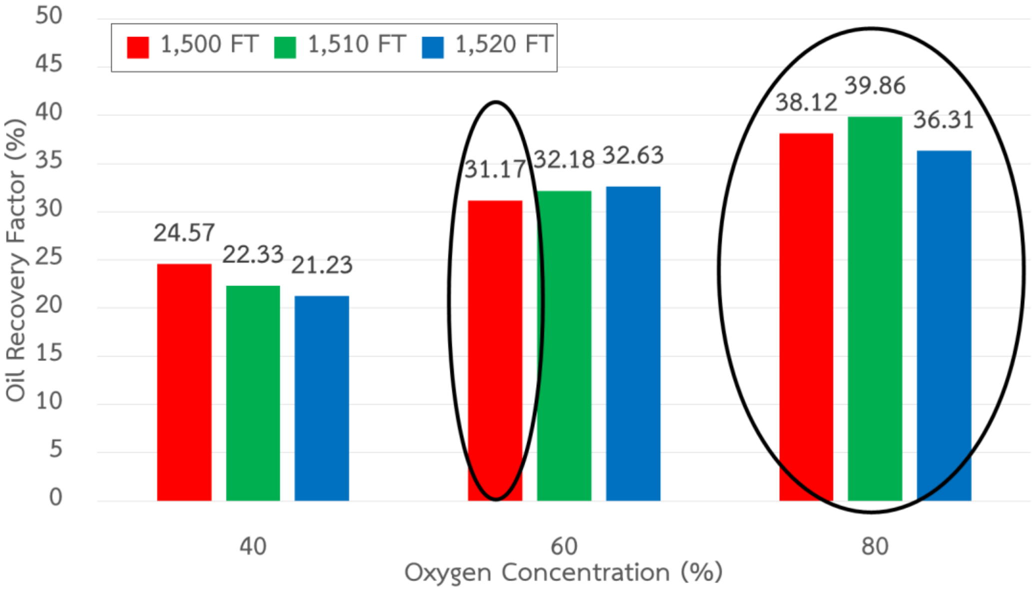


Figure 5.23 Summary of oil recovery factor at the end of production from dry cases in HI2HP configuration with 600,000 ft^3/day of air injection rate

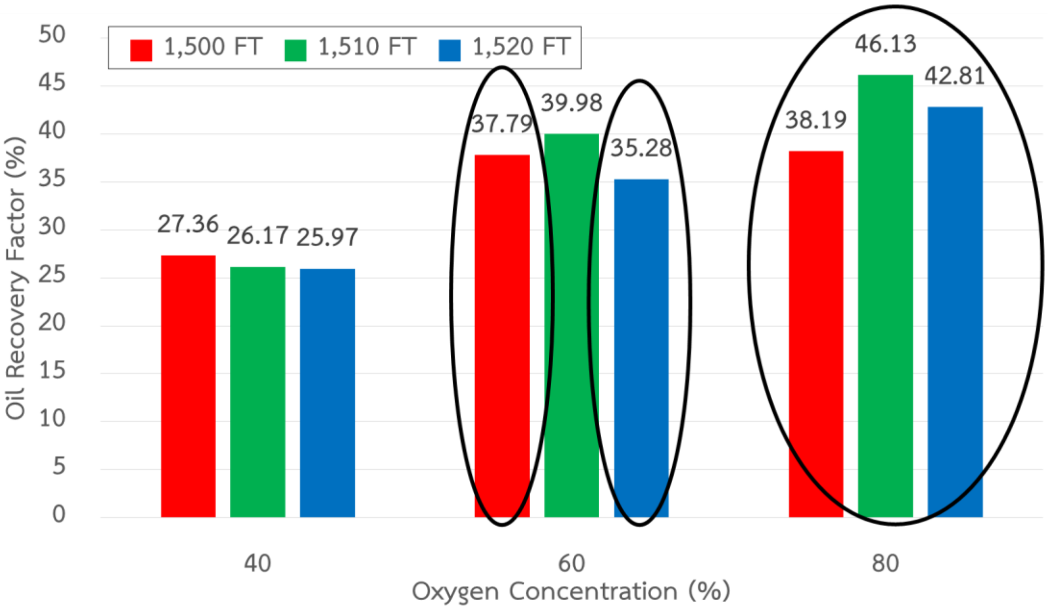


Figure 5.24 Summary of oil recovery factor at the end of production from dry cases in HI2HP configuration with 720,000 ft^3/day of air injection rate

From Figure 5.22, at low air injection rate, injection at deeper location encounters problem of total amount of injected gas, resulting in lowering of oil recovery factor. However, to compensate with this problem, higher Oxygen content accelerates appearance of fire front and deeper location of injection well increases heating area as most produced gas will flow to upper layers as explained in section 5.1.1. Similar effects can also be observed as shown in Figure 5.23 in cases of higher injection rate of 600,000 ft^3/day. Reverse trend occur at lower Oxygen percent of 60. From Figure 5.24, mostly similar results also occur in the highest air injection rate except some cases encounter burning of production wells due to too much Oxygen content together with too deep horizontal injection well.

The best operating condition for dry combustion in HI2HP configuration are 60 percent of Oxygen concentration, 720,000 ft^3/day of air injection rate and 1,510 ft of horizontal injection well. As explained previously, there are some cases that yield higher oil recovery factor but these cases which are circled have combustion around production wells.

Comparisons of total energy consumed in HI2HP configuration for different three air injection rates are illustrates in Figure 5.25 to Figure 5.27.

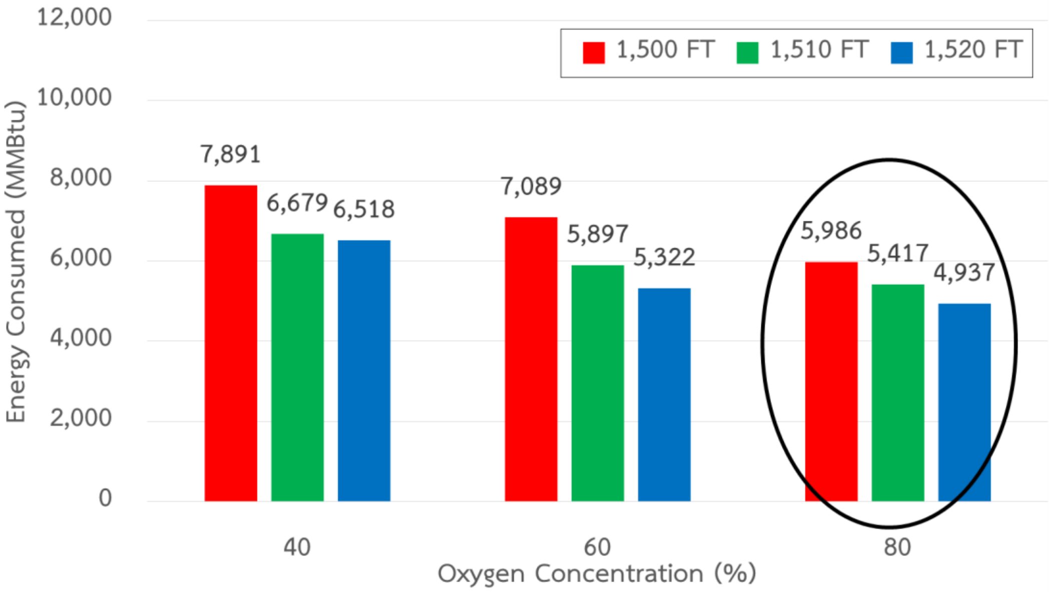


Figure 5.25 Comparison of total energy consumed at the end of production from dry combustion in HI2HP configuration with 480,000 ft^3/day of air injection rate

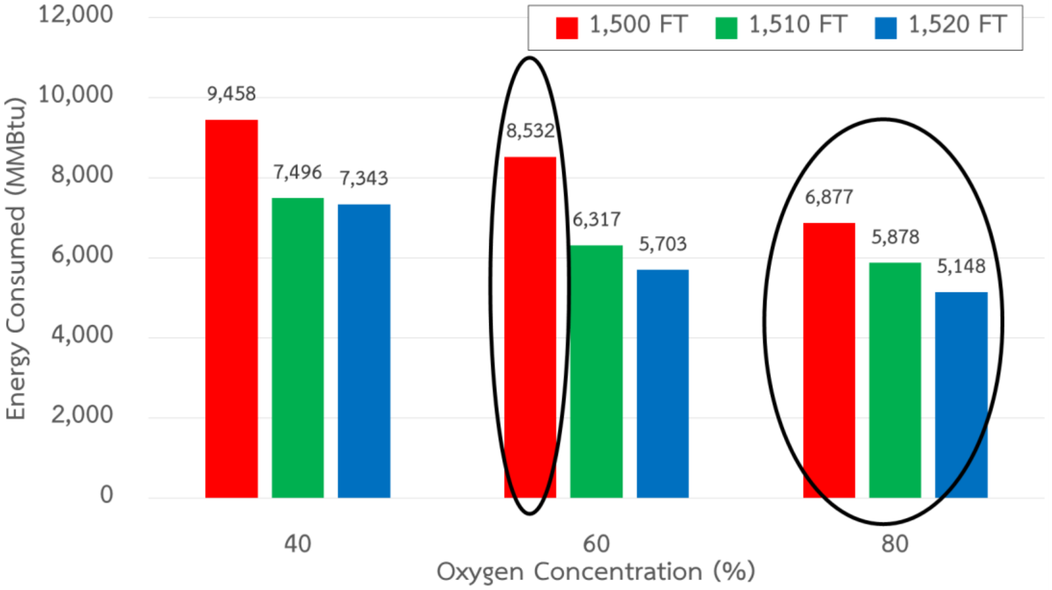


Figure 5.26 Comparison of total energy consumed at the end of production from dry combustion in HI2HP configuration with 600,000 ft^3/day of air injection rate

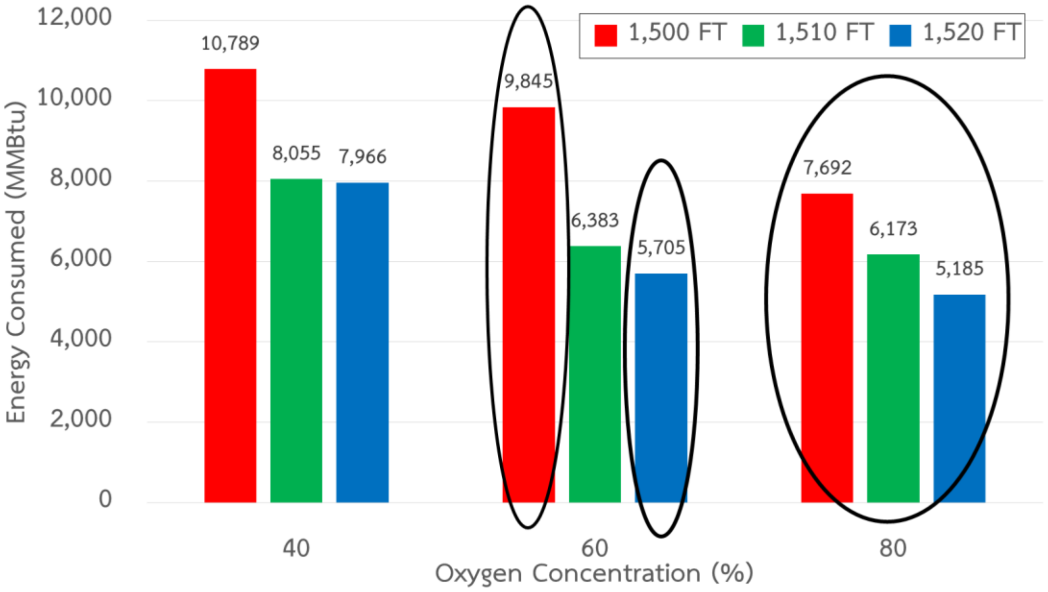


Figure 5.27 Comparison of total energy consumed at the end of production from dry combustion in HI2HP configuration with 720,000 ft^3/day of air injection rate

Effects of changing Oxygen concentration and air injection rate in HI2HP configuration are as same as in VI2HP configuration. In case of increasing horizontal injection depth, since amount of injected hot air is decreased when the depth is increased due to higher reservoir pressure and hence, less total amount of injected gas, energy consumed in the process is also decrease. Comparisons of energy consumed per barrel of oil for different three injection rates are shown in Figure 5.28 to Figure 5.30.

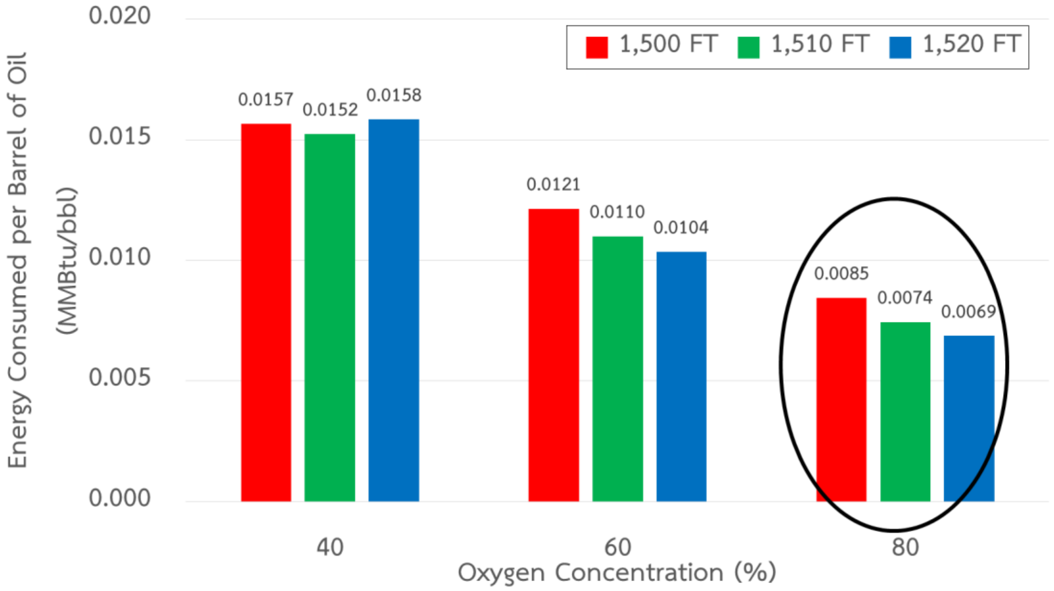


Figure 5.28 Comparison of energy consumed per barrel of oil at the end of production from dry combustion in HI2HP configuration with 480,000 ft^3/day of air injection rate

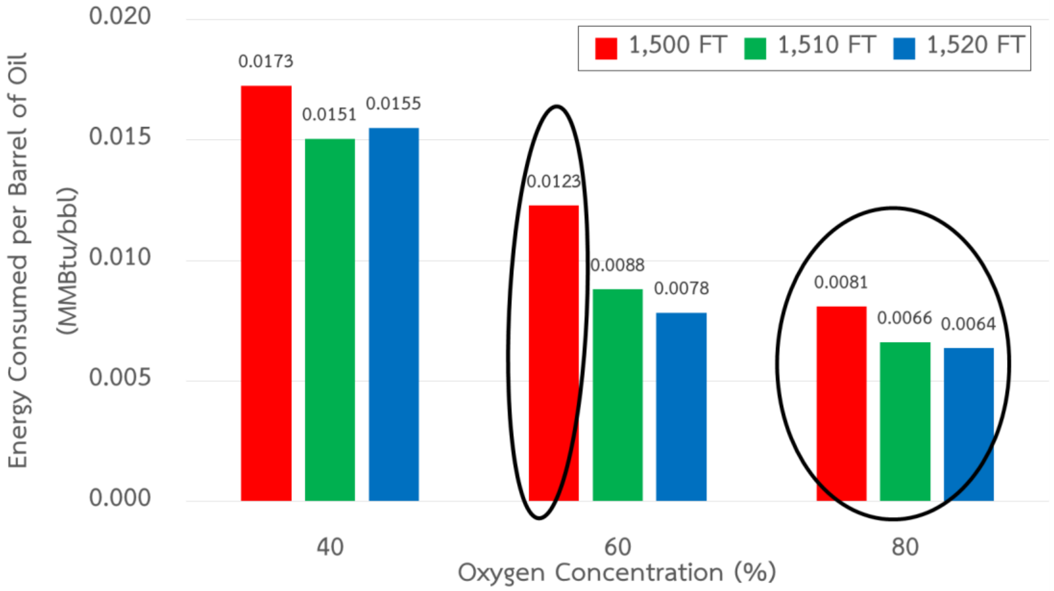


Figure 5.29 Comparison of energy consumed per barrel of oil at the end of production from dry combustion in HI2HP configuration with 600,000 ft^3/day of air injection rate

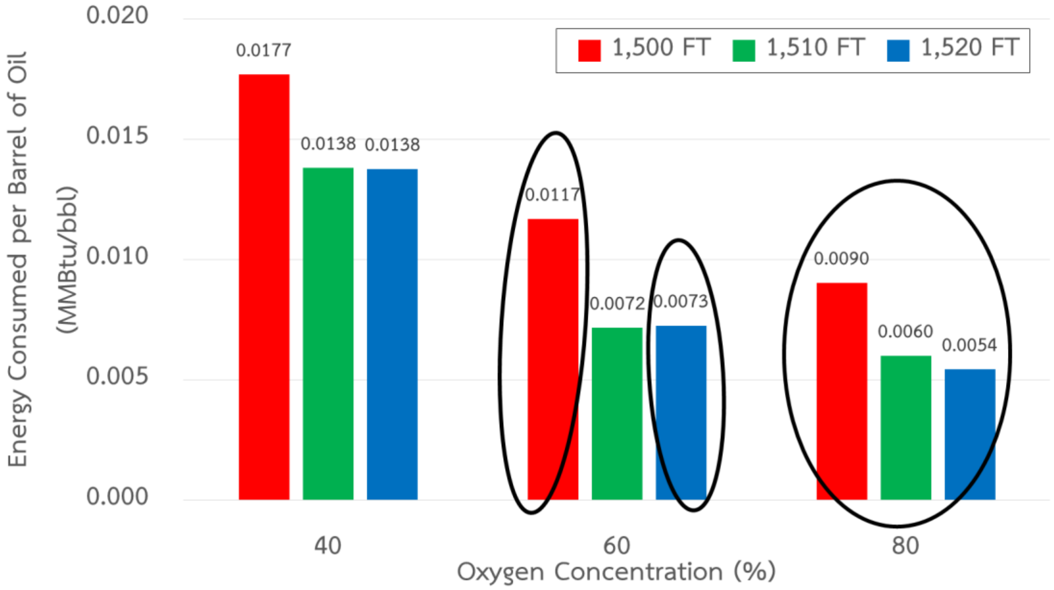


Figure 5.30 Comparison of energy consumed per barrel of oil at the end of production from dry combustion in HI2HP configuration with 720,000 ft^3/day of air injection rate

Operating conditions which give the best energy consumption is as same as the case that give the highest oil recovery factor which is 60 percent of Oxygen concentration, 720,000 ft^3/day of air injection rate and 1,510 ft of horizontal injection well. Some cases may yield better energy consumed but burning at production well occurs and these cases must be avoided.

It can be concluded that Oxygen content is important design parameter for in-situ combustion. As fire front must be generated, enrichment of Oxygen is required and increasing Oxygen through increment of Oxygen concentration is more efficient than increase of air injection rate. Depth of injection well for HI2HP is also another concerned parameter. Deeper location is punished by lowered total amount of injected air as well as high Oxygen breakthrough can cause burning at production wells. However, at appropriate Oxygen content and air injection rate, deeper location can obtain benefit from larger contact between generated fire front and reservoir oil especially at the lower part where it is hardly in contact with generated gas from combustion.

In this section, two sets of operating conditions which are 80 percent of Oxygen concentration and 600,000 ft^3/day for VI2HP configuration and 60 percent of Oxygen concentration, 720,000 ft^3/day of air injection rate and 1,510 ft of horizontal injection well in HI2HP configuration are selected for the following sections where wet combustion is combined.

5.2 Wet In-situ Combustion Base Case

After dry combustion is performed in reservoir model and the best operating parameters for each well configuration are selected, wet combustion combined with THAI configuration is performed by co-injecting water with air after heating period with various values of operating parameters including water injection rate and time to start wet combustion in order to determine optimal values of these two parameters. With these values increment of air injection rate is performed to validate the best air injection rate obtained from dry combustion process. Oil recovery factor is used for discussion of effectiveness of the process.

5.2.1 Oil Recovery Mechanisms in Wet Combustion Process

Oil recovery mechanisms by mean of wet combustion are altered because of injected water and hence, they are explained again in this section. VI2HP case is selected for explanation first and the case of HI2HP configuration will be discussed later on. Operating parameters used in representative cases are 5 years of time to initiate wet combustion and 200 bbl/day of water injection rate in VI2HP configuration and 10 years of time to start wet combustion and 200 bbl/day of water injection rate in HI2HP configuration.

Oil production rate and average reservoir pressure as a function of production time in VI2HP configuration are illustrated in Figure 5.31. From the figure, oil production rate before 1,827 days of production which is prior to wet combustion remains the same as in dry combustion. After water is injected into the reservoir, oil production rate can be separated into 3 periods consisting of 1) fluctuation and rapid increment of oil production rate (1,827th to 3,200th day), 2) small increment of oil production rate (3,200th to 4,100th day) and 3) steady oil production rate before the end of production period (4,100th day to 10,958th day).

Fluctuation of oil production rate between day 1,827th and 2,800th occurred from arrival of different gases as same as in case of dry combustion. However, it can be observed from the figure that average reservoir pressure is increased around day 2,200th due to injected water which becomes pressure support to the reservoir. During this high reservoir pressure period, sudden reduction of reservoir pressure occurs twice which are around day 3,000th and 3,800th.

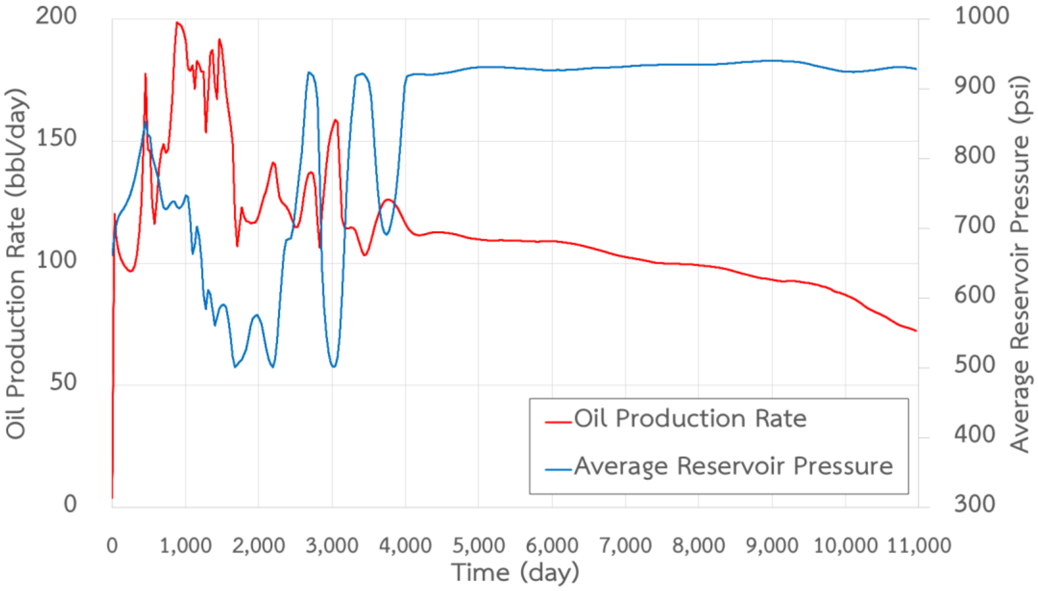


Figure 5.31 Oil production rate and average reservoir pressure from wet combustion process in VI2HP configuration as a function of time

In order to explain oil recovery mechanisms during the period where reservoir pressure suddenly drops, gas production rate together with air injection rate are illustrated in Figure 5.37.

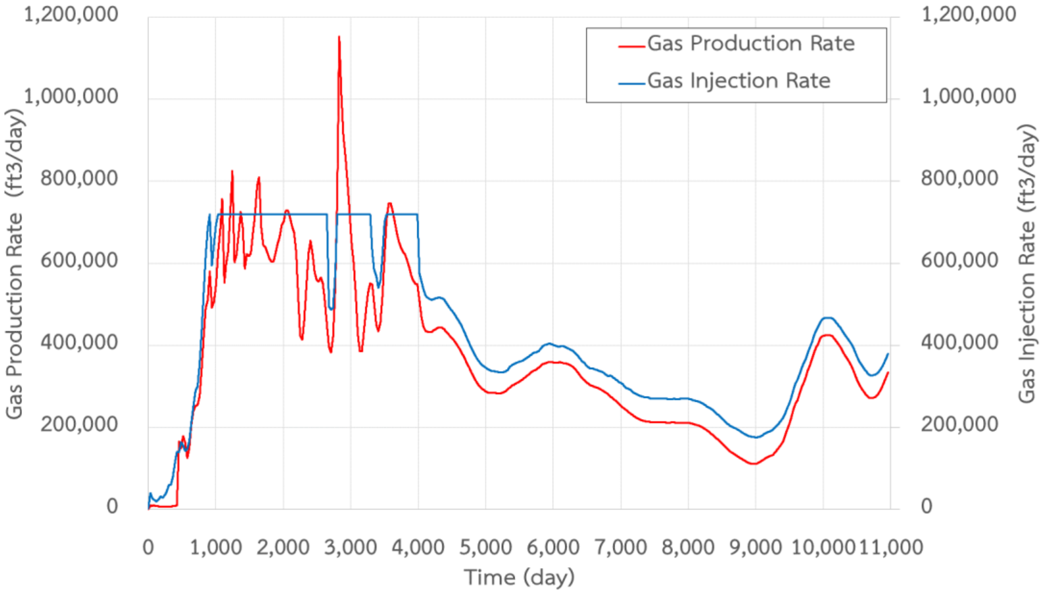


Figure 5.32 Gas injection and production rates from wet combustion process in VI2HP configuration as a function of time

From Figure 5.32, it can be observed that at around year 3,000th and 3,800th gas production rate is quite high especially at year 3,000th. The evidence of steam saturation profile in Figure 5.33 explains that this high gas production is responsible by generated in-situ steam. As water is injected after the end of heating period, this water turns into steam and travels together with injected air which is mainly Nitrogen as Oxygen is consumed at the combustion front. Breakthrough of steam which is compressible gas therefore, results in releasing of reservoir pressure and consequently a drop of reservoir pressure. As water is co-injected with air, part of water will quench the combustion front and this results in a breakthrough of Oxygen. From Figure 5.34, it can be explained that second drop of reservoir pressure at around day 3,800th is responsible by Oxygen from injected air.

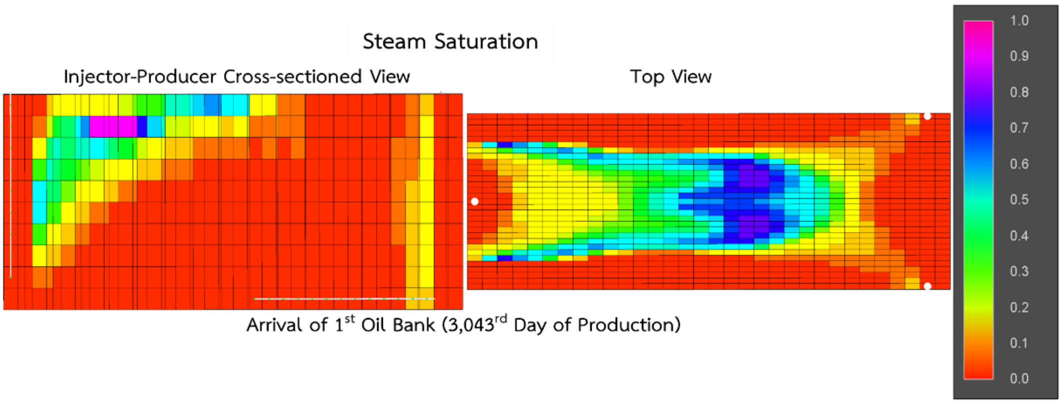


Figure 5.33 Steam saturation of wet combustion in VI2HP configuration at 3,043rd day of production

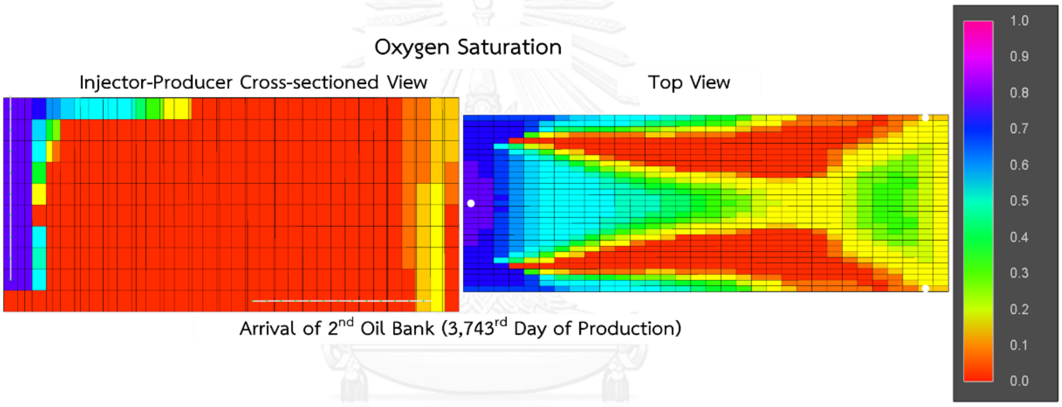


Figure 5.34 Oxygen saturation of wet combustion in VI2HP configuration at 3,743rd day of production

After day 4,000th reservoir pressure is maintained at maximum value of which is due to the constraint of injection well. Injected gas cannot be achieved at desire gas injection rate as well as water production rate illustrated in Figure 5.35. As there are many phases produced at production well, this reduces flow ability of reservoir and hence, injecting fluids is controlled by maximum bottomhole pressure instead of desired injection rate. From Figure 5.35 is can be observed that water injection rate starts to increase around day 10,000th again. This can be explained that once combustion front is totally quenched, water will not change to vapor phase and will remain as only liquid phase. Comparison of locations of water in Figure 5.36 can explain this phenomenon.

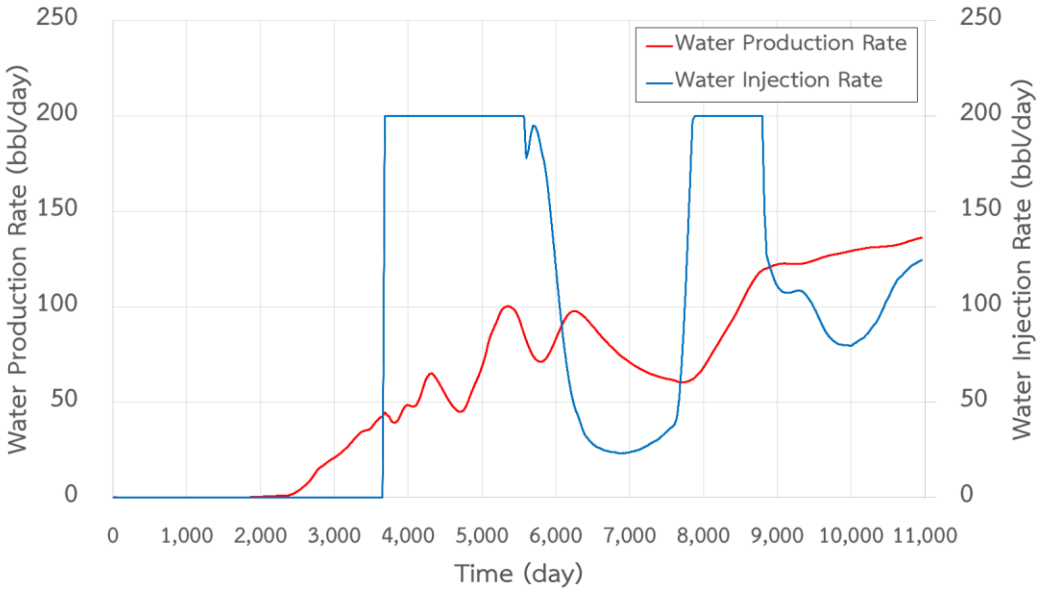


Figure 5.35 Water injection and production rates from wet combustion process in VI2HP configuration as a function of time

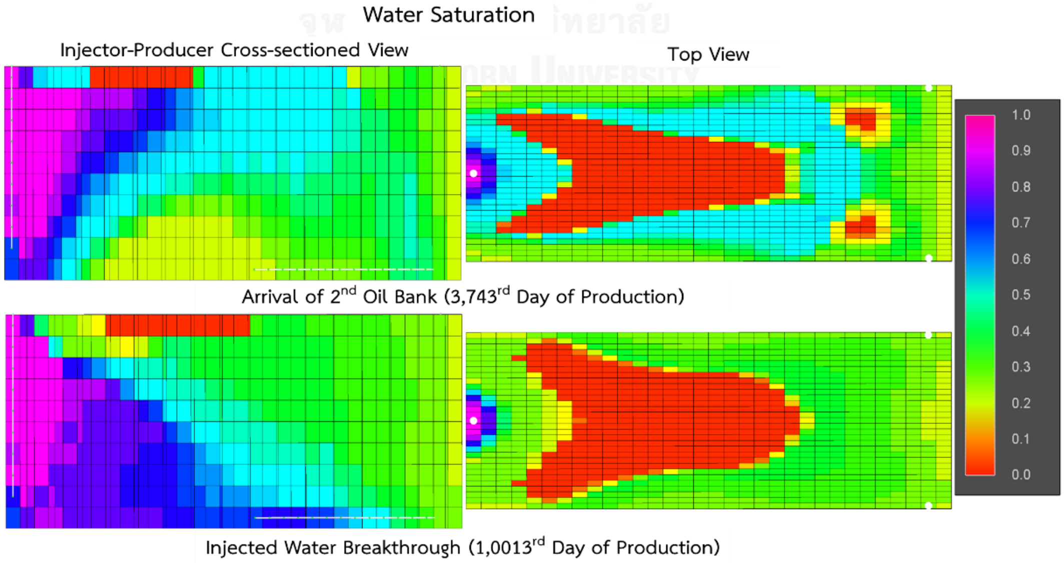
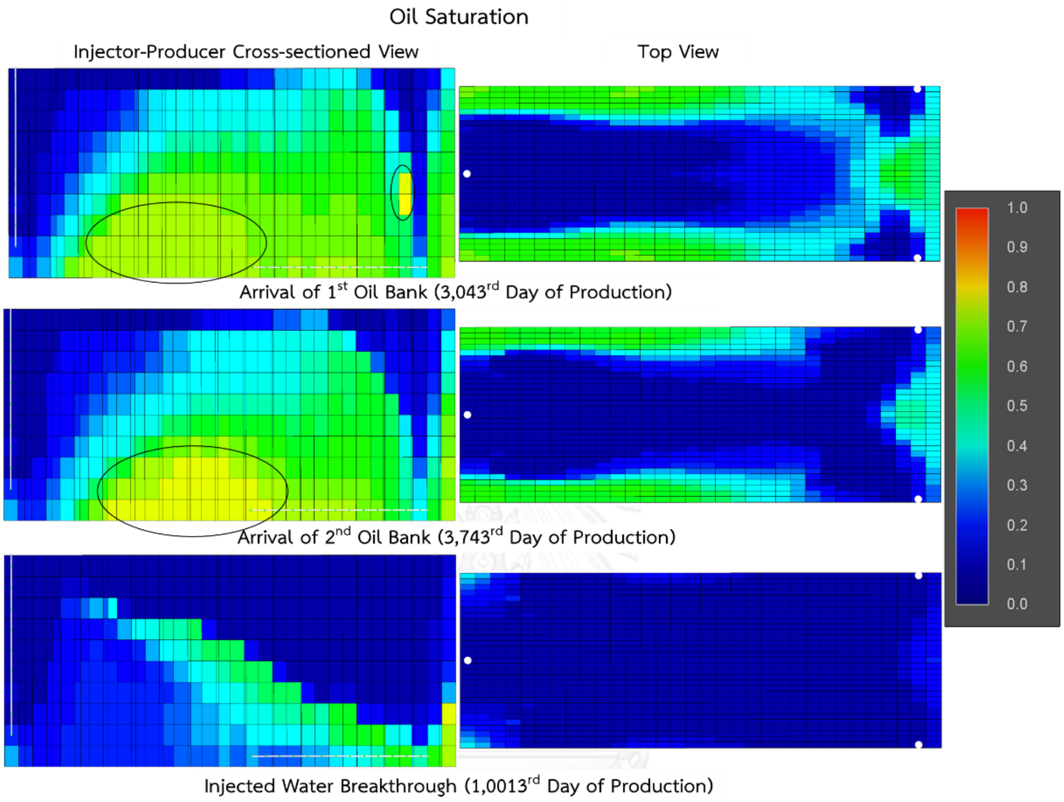


Figure 5.36 Water saturation of wet combustion in VI2HP configuration at 3,743rd and 1,0013rd day of production

According to arrival of different fluids at different times, oil production rates also changes with time. Figure 5.37 illustrates oil saturation at different times.



Arrival of 1st Oil Bank (3,043rd Day of Production)

Arrival of 2nd Oil Bank (3,743rd Day of Production)

Injected Water Breakthrough (1,0013rd Day of Production)

Figure 5.37 Oil saturation of wet combustion in VI2HP configuration at selected times

From Figure 5.37 it can be observed that at around day 3,000th, oil is produced at both toe and heel sides. As steam on top of reservoir carries heat, it therefore can push small part of oil down to heel side of production well. Moreover, another oil bank also reaches production well at the toe side. Around day 3,800th oil bank arrives to production well mainly at toe side and after injected water floods out, only small part of oil remains trapped between upper region that has been pushed by steam and lower region being pushed by water.

Injection of water in wet combustion results in disappearing of fire front to create steam zone. Oil is pushed into production wells in two different ways which are from hot steam pushing oil from top to bottom direction into heel side of the well and from hot water pushing heating oil at the bottom of reservoir to toe side of production well.

In case of HI2HP configuration, oil production rate and average pressure profile are shown in Figure 5.38. Similar to VI2HP configuration, since water is injected after 3,653 days of production these profiles are the same as in dry combustion explained in section 5.1.1. Oil production rate after water injection can be divided into 4 periods which are 1) fluctuation and two significant increments of oil production rate (3,653rd to 5,400th day) 2) a significant increment of oil production rate (5,400th to 6,200th day) 3) a gradual increment of oil production rate (6,200th to 9,000th day) and 4) steady rate of oil production before the end of production period (9,000th to 10,958th day). Oil saturation profile of wet combustion in HI2HP configuration as shown in Figure 5.39 is used to assist in explanation of changes in oil production rate as well.

In the first period, there are small fluctuations and a small increment in oil production rate before day 4,600th due to arrival of excessive injected Oxygen. After 4,600 days of production, oil production rate is increased from the effect of in-situ steam. According to oil saturation profile at day 4,900th, oil is produced mainly from toe side of the horizontal production well. After 4,900 days until 5,400th day of production, oil production rate is decreased due to arrival of water.

After day 5,400th of production, oil production rate is increased from oil flowing from upper part to heel side of the production well from gas flooding. From oil saturation profile at day 5,752nd, additional amount of oil appears from upper part and is pushed down to the middle part of production well by injected air and combustion gases. Oil production rate is decreased after day 5,752nd from water breakthrough at toe side of the horizontal production well.

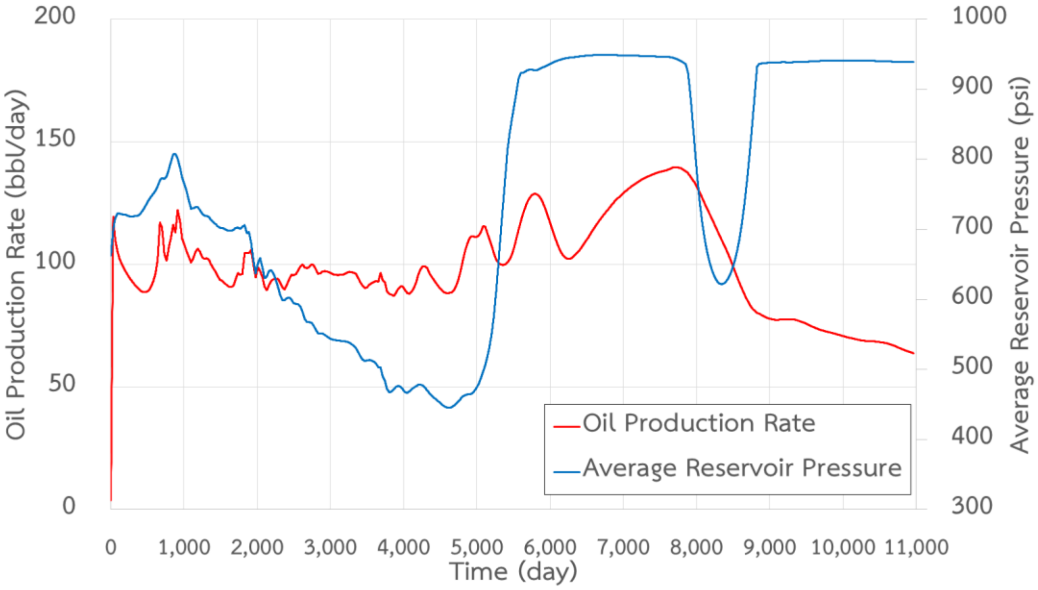
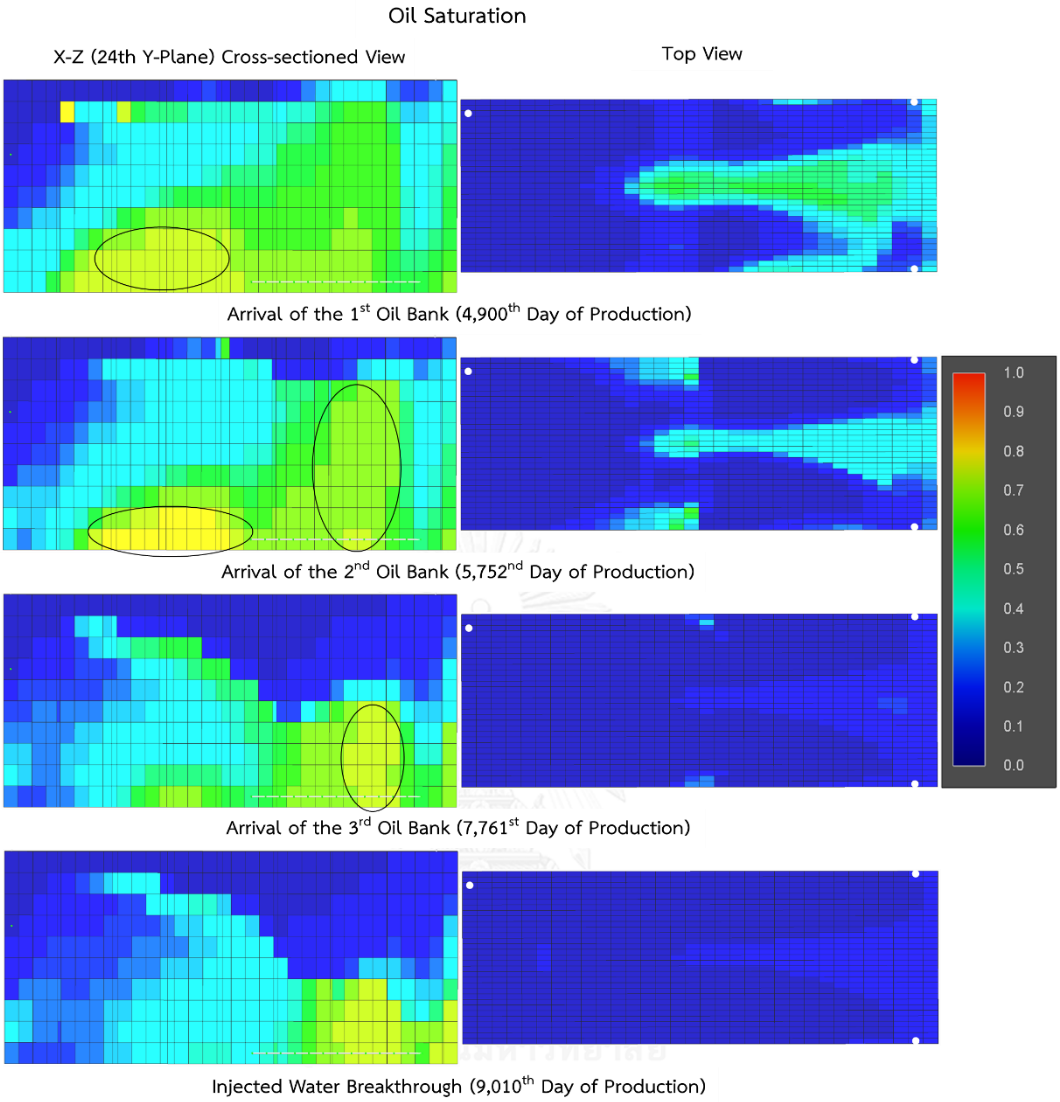


Figure 5.38 Oil production rate and average reservoir pressure from wet combustion process in HI2HP configuration as a function of time

At the third period that starts after 6,200 days of production, oil production rate is raised from oil coming from upper part to middle part by gas flooding and oil coming to toe side by injected water. According to oil saturation profile at day 7,761st, oil still can be produced from circled regions until injected water, which does not change its phase to steam, arrives at toe side of production wells and gas breakthrough at heel side of production wells as can be seen from gas production rate in Figure 5.39. From Figure 5.40 gas injection and production rates declines both for certain period due to arrival of large oil bank. Due to flow ability of oil that is increased at production wells, it is more difficult to inject gas and this results in a great reduction of amount of air injected at injection well. Once oil bank is flooded out, a sharp increment of gas injection and production rates is observed. However, gas production rate is higher than air injection rate due to generation of steam from injected water. Comparison between water production rate and oil production rate as shown in Figure 5.41 confirms the explanation that water production is increased from condensed water and injected water when oil production rate is reduced.


Oil Saturation

X-Z (24th Y-Plane) Cross-sectioned View

Top View

Arrival of the 1st Oil Bank (4,900th Day of Production)

Arrival of the 2nd Oil Bank (5,752nd Day of Production)

Arrival of the 3rd Oil Bank (7,761st Day of Production)

Injected Water Breakthrough (9,010th Day of Production)

Figure 5.39 Oil saturation of wet combustion in HI2HP configuration at selected times

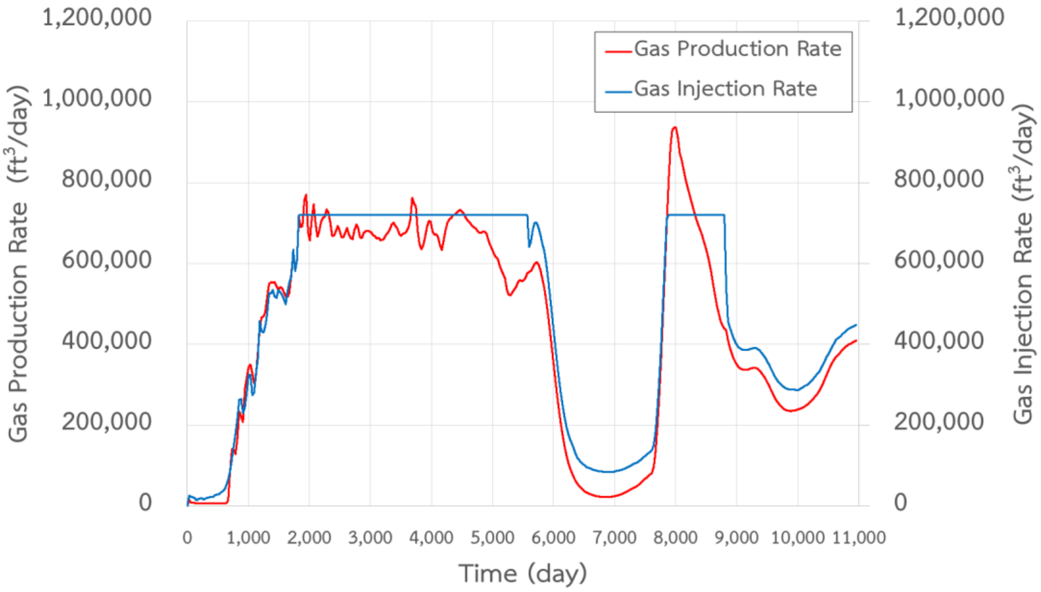


Figure 5.40 Gas injection and production rate from wet combustion process in HI2HP configuration as a function of time

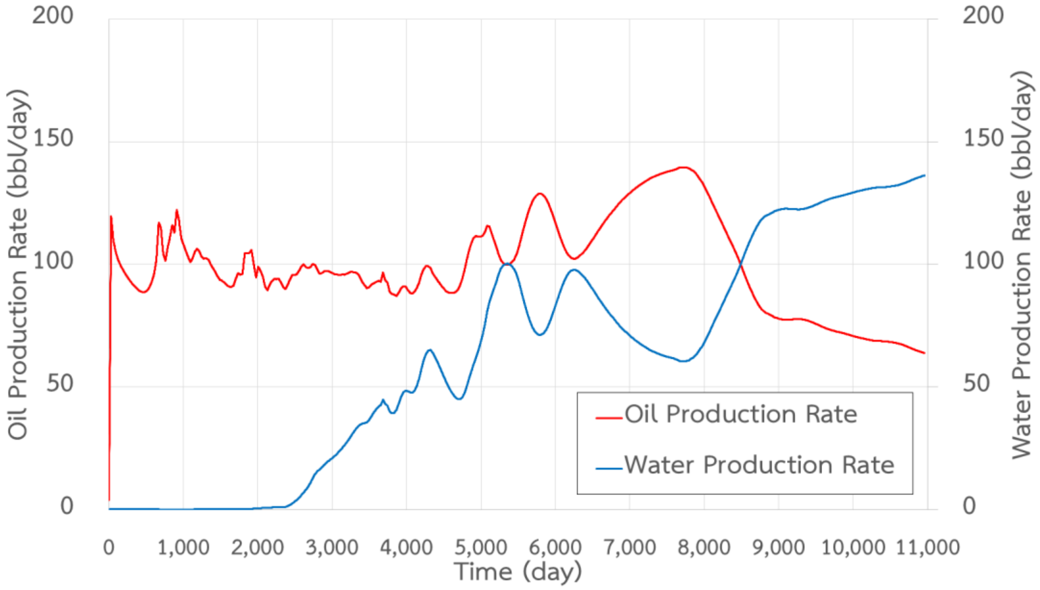


Figure 5.41 Oil and water production rate from wet combustion process in HI2HP configuration as a function of time

After injected water breakthrough occurs, oil production rate is dramatically decreased into steady rate until the end of production. From oil saturation profile at day 9,010th and water saturation profile at the same day as shown in Figure 5.42, it can be obviously seen that water arrives at toe side of production well and water is mainly produced from this side. However, oil still can be produced at steady rate from middle part of production well which is not trapped yet.

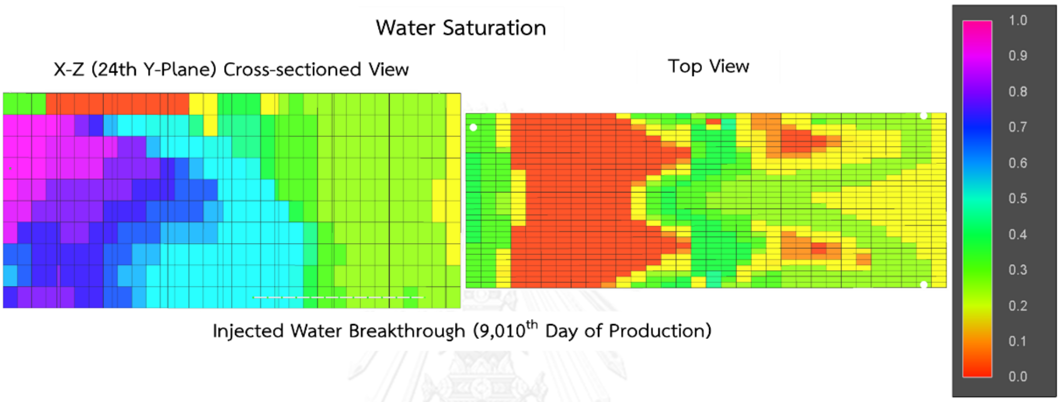


Figure 5.42 Water saturation of wet combustion in HI2HP configuration at 9,010th day of production

Once water is injected to create the wet combustion, oil recovery mechanisms are altered from dry combustion. Injected water turns into steam that can help dissipating heat remained in burnt zone to recovery more oil in a larger extent. Moreover, water that does not change into steam can push heat oil at bottom zone to the toe side of production wells. These selected two cases show quite obvious differences due to different time to start water injection. An earlier water injection in case of vertical injection well results in higher oil production rate in the first period. As water is injected later in case of horizontal well injector to prevent burning at production well, arrival of oil bank from in-situ steam is shown at very late time.

5.2.2 Selection of Operating Water Injection Rate and Time to Start Wet Combustion

Wet combustion with THAI configuration is simulated in the reservoir model using the best operating parameters determined from dry combustion section. Operating parameters needed to be adjusted in this section are time to start wet combustion, water injection rate and air injection rate. Water is co-injected with air after heating period and the simulator will determine which phase the water becomes during injection. Maximum air and water injection rates and liquid production rate are still intentionally kept constant in this step. Only oil recovery factor is concerned and used to determine effectiveness of wet combustion combined with THAI for each case. The reason is that in this step the energy consumed in the process is constant since water is injected after heating period.

Time to start wet combustion is expected to be an important factor in the process because the heat of combustion occurred in the process is distributed and leaked to overburden and underburden area at different time. Injected water can utilize higher heat of combustion at early times after fire front occurred.

Time to start wet combustion, water injection rate and air injection rate are varied in both VI2HP and HI2HP configuration. Results from varying different both parameters in VI2HP configuration are shown in Figure 5.43 to Figure 5.47 and Table 5.4

Table 5.4 Summary of oil recovery factor of wet combustion in VI2HP configuration

Time to start wet combustion (Years)	Water Injection Rate (bbl/day)	Oil Recovery Factor (%)
5	120	46.57
	160	52.75
	200	53.77
10	120	46.42
	160	48.16
	200	49.91
15	120	41.80
	160	42.97
	200	44.00

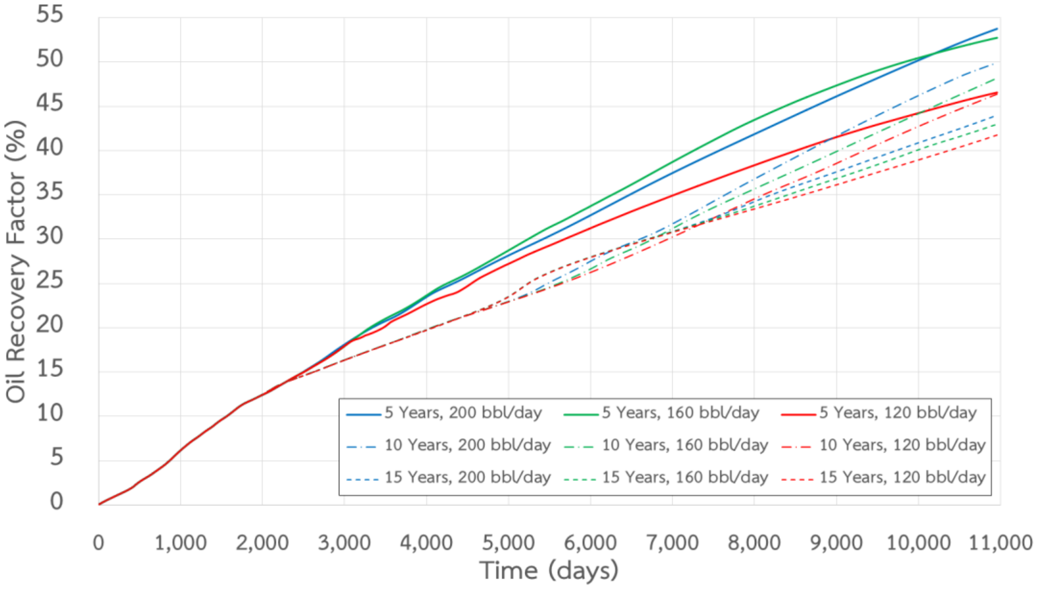


Figure 5.43 Oil recovery factors for wet combustion cases with different time to start wet combustion and water injection rates as a function of time in VI2HP configuration

From Figure 5.43, it can be obviously seen that time to start wet combustion is essential and shows more sensitivity compared to selected range of water injection rate in wet combustion process as can be seen from changing from dot line to dash line and to solid line for every color of line. Difference in oil recovery factor between three values of water injection rates is quite small at late time to start wet combustion because a significant amount of heat of combustion is distributed from combustion front with injected air, combustion flue gas and other reservoir fluid already. So that injected water can utilize heat in the reservoir worse than cases that water is injected at early times. The difference of oil recovery factor due to water injection rates is the highest when water is injected after 5 years of production. If water injection rate is low, the amount of heat occurred in the reservoir that water can utilize is also low. It can be mentioned that the difference between 160 bbl/day and 200 bbl/day of water injection rate when water is injected after 5 years of production is quite low. The reason is that the water injection rate reaches the optimal value and oil recovery factor may be lowered if water injection rate is higher than 200 bbl/day. Overabundant amount of injected water could completely quench the combustion front at very early time and this is considered as unfavorable condition. Graphical summary of oil recovery factors from variation of time to start wet combustion and water injection rate in VI2HP is illustrated in Figure 5.44.

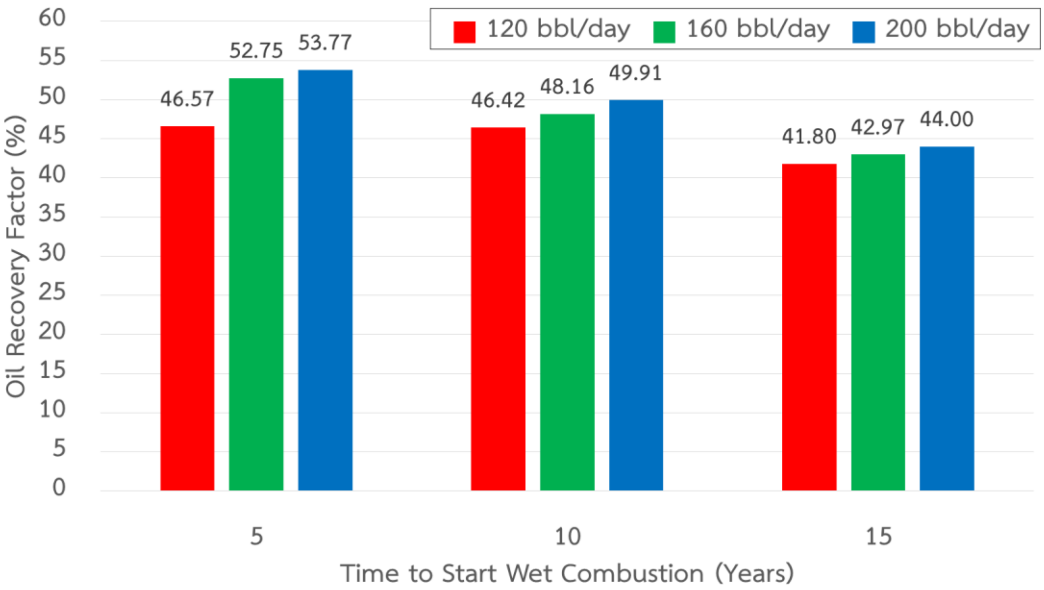


Figure 5.44 Summary of oil recovery factor with different time to start wet combustion and water injection rates at the end of production from wet combustion cases in VI2HP configuration

According to Figure 5.44, it is obvious that time to start wet combustion shows more sensitivities on effectiveness of wet combustion compared to water injection rate. The figure also shows that the optimal case that yields the highest oil recovery factor is 200 bbl/day of water injection rate and water is injected after 5 years of production.

After time to start wet combustion and water injection rate are determined, air injection rate is varied in order to validate the effect to wet combustion. Oil recovery factor, total energy consumed and energy consumed per barrel of oil of this study are summarized in Table 5.5. The results of changing air injection rate are shown in Figure 5.45 to Figure 5.47.

Table 5.5 Summary of oil recovery factor of wet combustion with different air injection rates in VI2HP configuration

Time to start wet combustion (Years)	Water Injection Rate (bbl/day)	Air Injection Rate (ft^3/day)	Oil Recovery Factor (%)	Energy Consumed (MMBtu)	Energy Consumed per Barrel of Oil (MMBtu/bbl)
5	200	600,000	53.77	8,305	0.00693
		720,000	55.32	9,543	0.00774

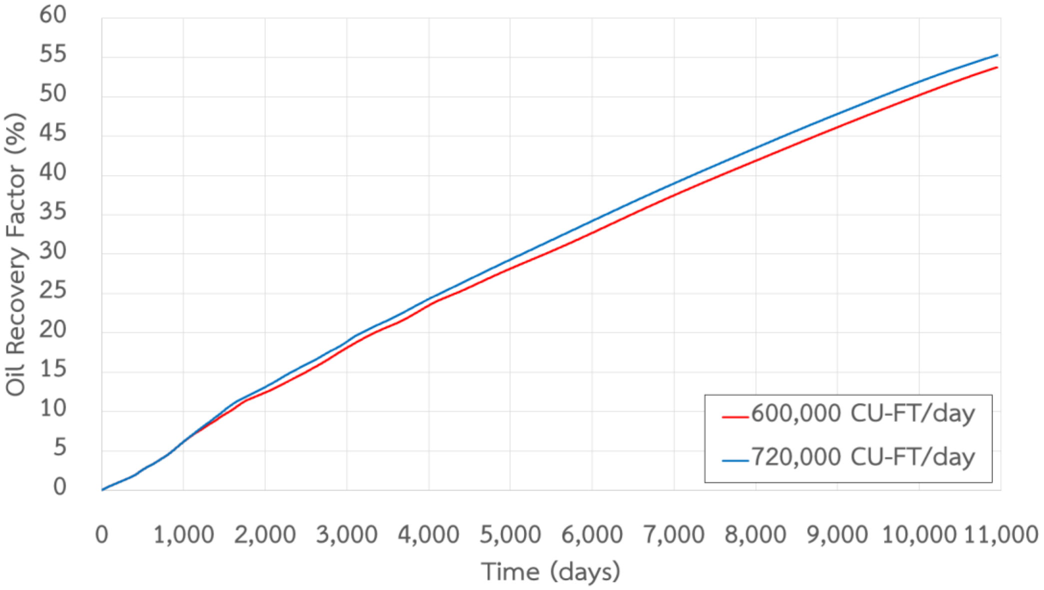


Figure 5.45 Oil recovery factors for cases with different air injection rates as a function of time in VI2HP configuration

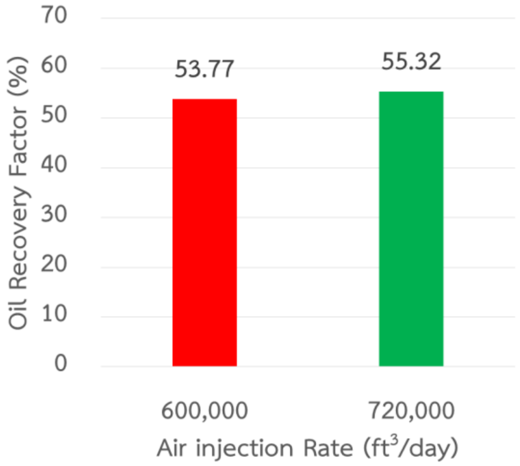


Figure 5.46 Summary of oil recovery factor with different air injection rates at the end of production from wet combustion cases in VI2HP configuration

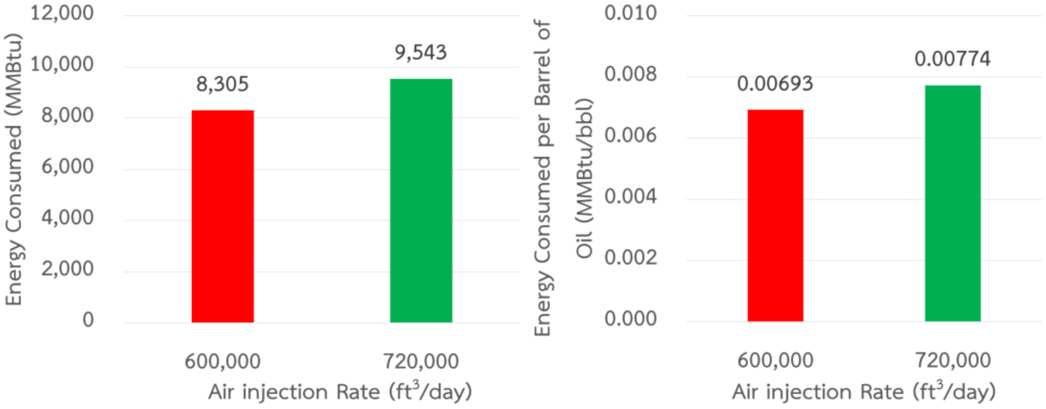


Figure 5.47 Comparison of energy consumed and energy consumed per barrel of oil at the end of production from wet combustion performed in VI2HP configuration

According to Figure 5.45, it can be obviously seen that air injection rate has minor effect to effectiveness of wet combustion. Increasing air injection rate helps wet combustion in terms of increasing heat of combustion, low temperature oxidation and thermal cracking product during dry combustion. So that summary of oil recovery factor as shown in Figure 5.46 results in a slight difference between two values of air injection rate.

Since air injection rate is changed, energy consumed in the process is also altered. From Figure 5.47, it can be seen that energy consumed is increased because of only increased Nitrogen which is discussed in the previous section. So that energy consumed per barrel of oil is increased from both higher amount of oil recovered and energy consumed. It can be concluded that the best parameters for wet combustion in VI2HP configuration are 200 bbl/day of water injection rate, 5 years of time to start wet combustion and 720,000 ft^3/day of air injection rate. Air injection rate of 720,000 ft^3/day is selected because oil recovery factor is significantly increased while energy consumed per barrel of oil is slightly increased. Nevertheless, air injection rate is not increased higher than this value because chance that combustion will occur at production well will be increased as well.

Operating parameters needed to be adjusted in HI2HP configuration are same as in VI2HP configuration. Results of wet combustion cases in this configuration are shown from Figure 5.48 to Figure 5.51 and Table 5.6.

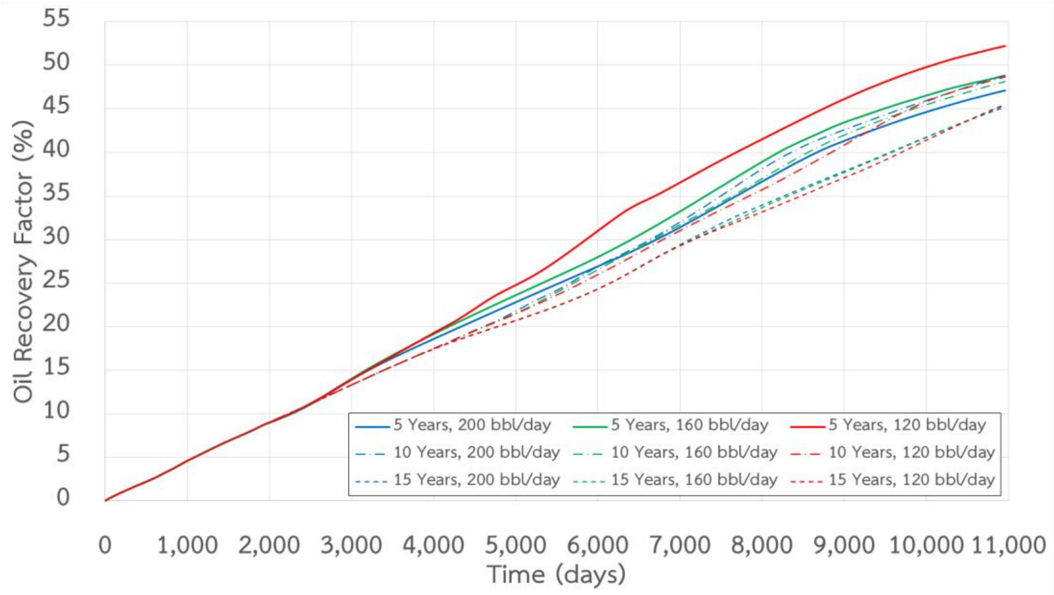


Figure 5.48 Oil recovery factors for wet combustion cases with different time to start wet combustion and water injection rates as a function of time in HI2HP configuration

Table 5.6 Summary of oil recovery factor of wet combustion in HI2HP configuration with various times to start wet combustion and water injection rates

Time to start wet combustion (Years)	Water Injection Rate (bbl/day)	Oil Recovery Factor (%)
5	120	52.23
	160	48.81
	200	47.12
10	120	48.67
	160	48.18
	200	48.89
15	120	45.49
	160	45.46
	200	45.25

From Figure 5.48, it can be seen that the difference of oil recovery factor between three values of water injection rate at 10 and 15 years of time to start wet combustion is similar to VI2HP configuration. However, the difference of oil recovery factor at 5 years of time to start wet combustion is that oil recovery factor is decreased as increment of increasing water injection rate. It can be observed that 120 bbl/day of water injection rate is optimal range of values at 5 years of time to start wet combustion. If the water injection rate is raised further than 120 bbl/day it can cause overabundant amount of water injected that combustion front will be quenched faster than expected and oil recovery factor will be decreased. This can be due to the fact that fire front in this case may be smaller as it is separated into two fronts. Summary of oil recovery factor is shown in Figure 5.49.

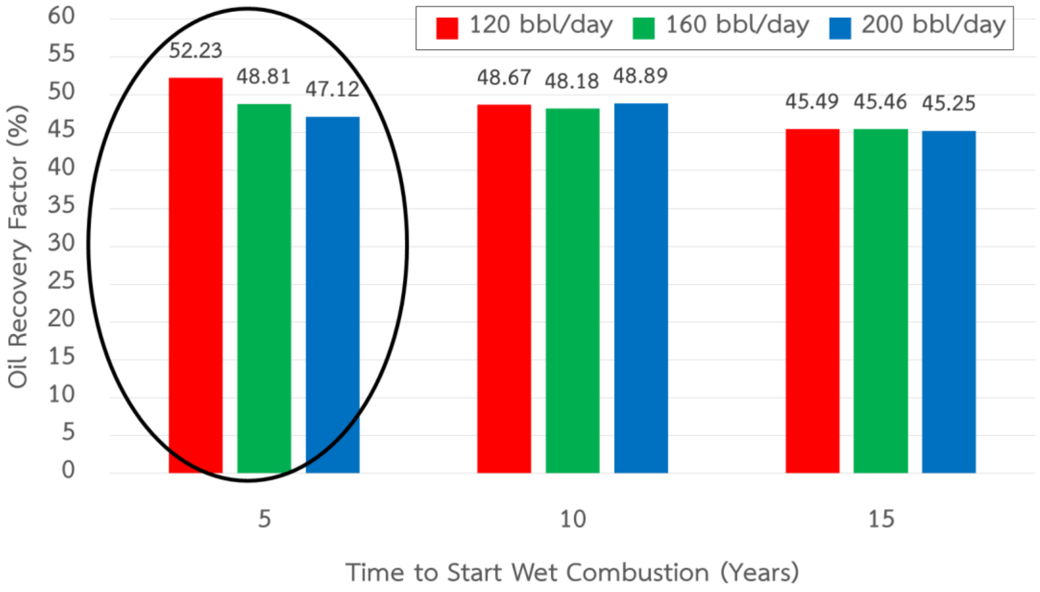


Figure 5.49 Summary of oil recovery factor with different time to start wet combustion and water injection rates at the end of production from wet combustion cases in HI2HP configuration

It can be concluded that set of operating parameters which yields the highest oil recovery is 120 bbl/day of water injection rate and 5 years of time to start wet combustion. Nevertheless, there is combustion occurred around production well which is unwanted condition and cases that combustion occurred at production well are circled in the figure. So that the best parameter that gives the highest oil recovery factor is 200 bbl/day of water injection rate and 10 years of time to start wet combustion. These selected conditions are taken to adjust air injection rate to validate the effect of changing air injection rate as well. The results are showed in Figure 5.50 and Figure 5.51 and Table 5.7.

Table 5.7 Summary of oil recovery factor of wet combustion with different air injection rates in HI2HP configuration

Time to start wet combustion (Years)	Water Injection Rate (bbl/day)	Air Injection Rate (ft^3/day)	Oil Recovery Factor (%)	Energy Consumed (MMbtu)	Energy Consumed per Barrel of Oil (MMbtu/bbl)
10	200	720,000	48.89	6,383	0.00586
		864,000	51.25	6,389	0.00559

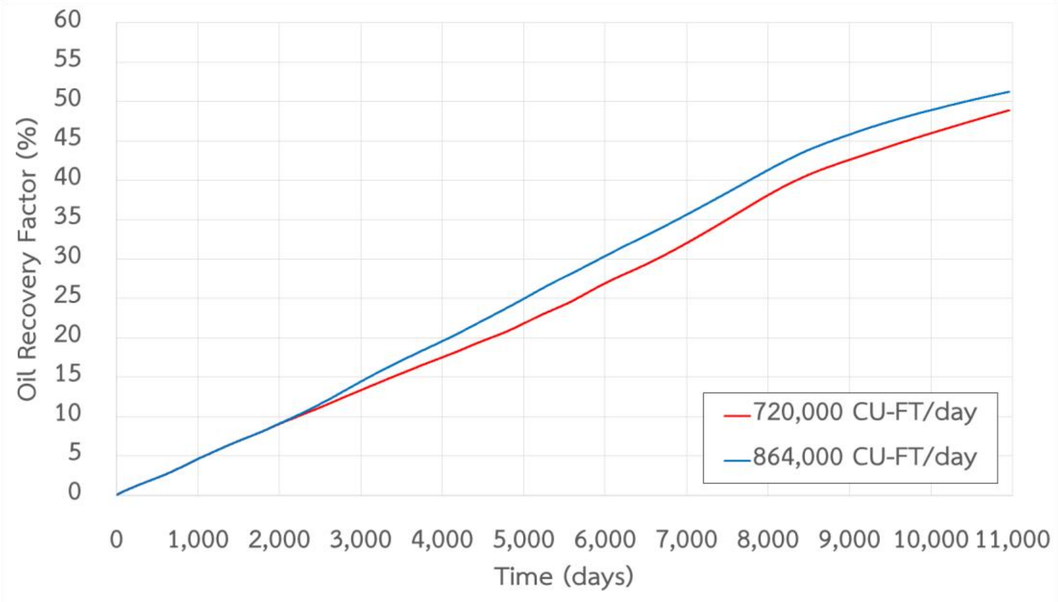


Figure 5.50 Oil recovery factors for cases with different air injection rates as a function of time in HI2HP configuration

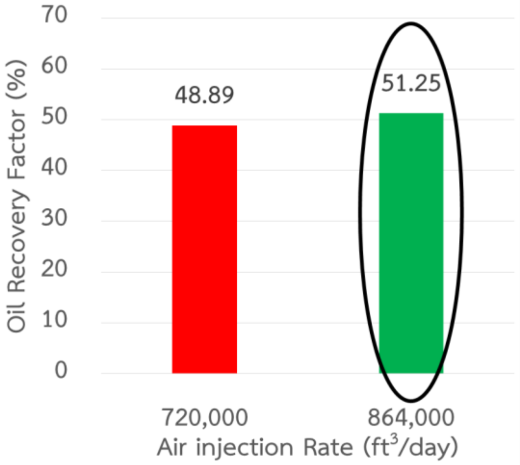


Figure 5.51 Summary of oil recovery factor with different air injection rates at the end of production from wet combustion cases in HI2HP configuration

It can be obviously seen that changing air injection rate has no major effect to wet combustion as same as in VI2HP configuration. Higher oil recovery factor in case of increasing air injection rate is caused by increased oxygen injected that increase heat of combustion in the process. Nevertheless, increasing air injection rate also increases risks that combustion around production well will happen as mentioned in the previous part. The best parameters of wet combustion in HI2HP configuration are 720,000 ft^3/day of air injection rate, 200 bbl/day of water injection rate and 10 years of time to start wet combustion since the combustion occurs around production well as a result of increasing air injection rate.

Comparison between performing wet combustion in different well configurations is shown in Figure 5.52 and Figure 5.53. It can be seen that, the maximum oil recovery by means of using vertical well injector is higher than the case of horizontal injector. This can be explained that wet combustion is performed earlier in case of vertical injector so that injected water can utilize more heat from combustion to recover viscous oil. Sweep efficiency of vertical injector is also better after wet combustion starts due to higher amount of in-situ steam. Moreover, amount of injected water which does not become in-situ steam in HI2HP configuration is higher compared to the case of VI2HP configuration since part of heat may be disappeared to surrounding formations due to later time of co-water injection process.

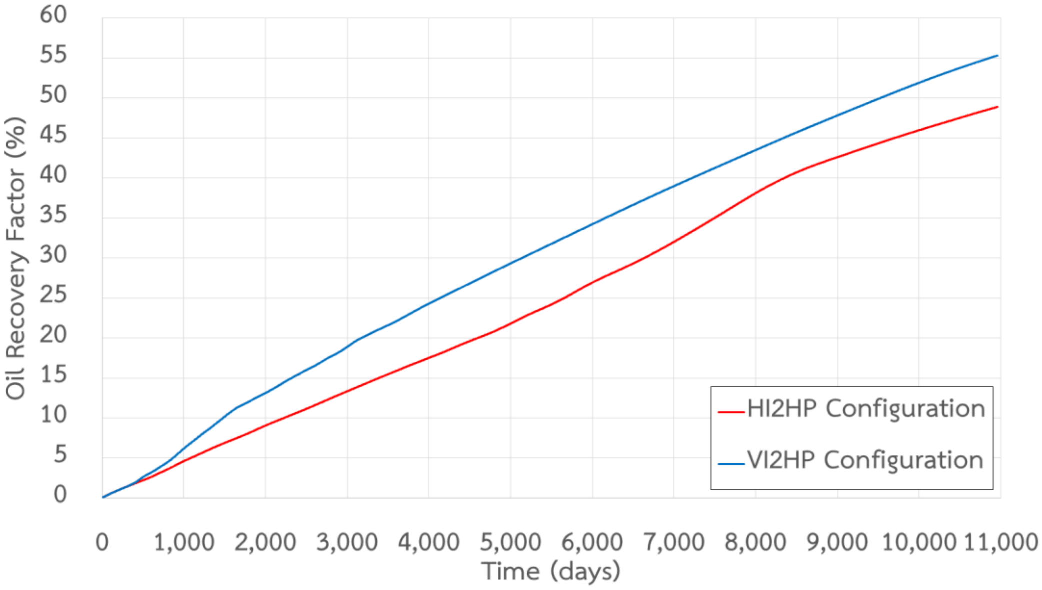


Figure 5.52 Oil recovery factors for wet combustion cases with different well configuration as a function of time

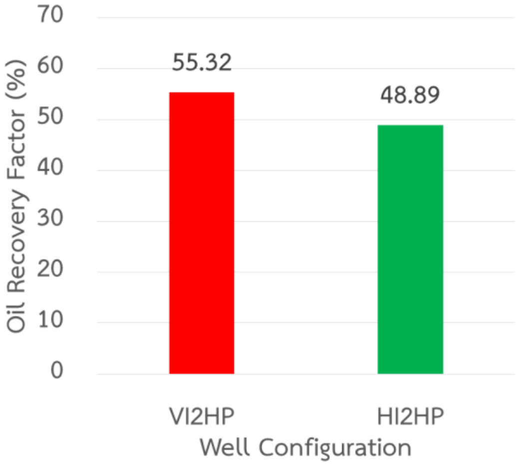


Figure 5.53 Summary of oil recovery factor with different well configuration at the end of production from wet combustion cases

In this section, it can be seen that time to start wet combustion plays more important role in wet combustion process compared to amount of water injected. The early time is required especially for vertical injection well as heat from combustion can be distributed to entire reservoir quickly and at the same time, injected water also provides additional pressure to support drive mechanism. For horizontal well injector, too early water injection may cause early quenching process as fire fronts are smaller and this can reduce effectiveness of wet combustion. Moreover, optimal air injection rate that is obtained from dry combustion can be slightly increased in case of wet combustion as co-injection of water helps retarding air flow ability. So that chance of burning at production well is extended. Vertical injector obtains more benefits compared to horizontal injector in wet combustion because water can be injected earlier so that heat of combustion can be utilized efficiently and heat loss to overburden and underburden area is limited.

From simulation results, two sets of operating conditions which are 200 bbl/day of water injection rate, 5 years of time to start wet combustion and 720,000 ft^3/day for VI2HP configuration and 200 bbl/day of water injection rate, 10 years of time to start wet combustion and 720,000 ft^3/day of air injection rate in HI2HP configuration are selected for the following sections where selected reservoir properties is varied to evaluate their effects.

5.3 Effect of Thermal Properties of Rock Matrix

In this section, reservoir models are constructed to have different thermal properties of rock matrix by changing heat capacity and thermal conductivity in order to study effects of these thermal properties on effectiveness of wet combustion combined with THAI configuration. Summary of thermal properties of reservoir rock with different different thermal properties of rock matrix are summarized in Table 5.8.

Table 5.8 Thermal properties of reservoir rock of three different cases

Case	Thermal Conductivity (Btu/(ft×day×°F))	Heat Capacity (Btu/(ft^3×F))
Base Case	44.00	35.00
Case A	40.98	36.70
Case B	34.94	40.10

For VI2HP configuration, oil recovery factors from different cases with different thermal properties of rock matrix as a function of time are illustrated in Figure 5.54. From the figure it can be seen that oil recovery factor is the highest for Case B in most period prior to the end of production. According to increased heat capacity, after fire front is generated, heat is mainly captured by rock matrix and once water is injected into formation larger amount of steam is generated. Temperature and steam profiles at different times in Figure 5.56 and Figure 5.57 also show that more heat is delivered to a larger extent (with higher advancement) by means of higher steam volume in case B compared to base case. However, as heat carried by steam is also re-absorbed by rock matrix, this results in a drop of trend for both case A and case B before the end of production. Summary of oil recovery factor and energy consumed per barrel of oil are illustrated together in Figure 5.55.

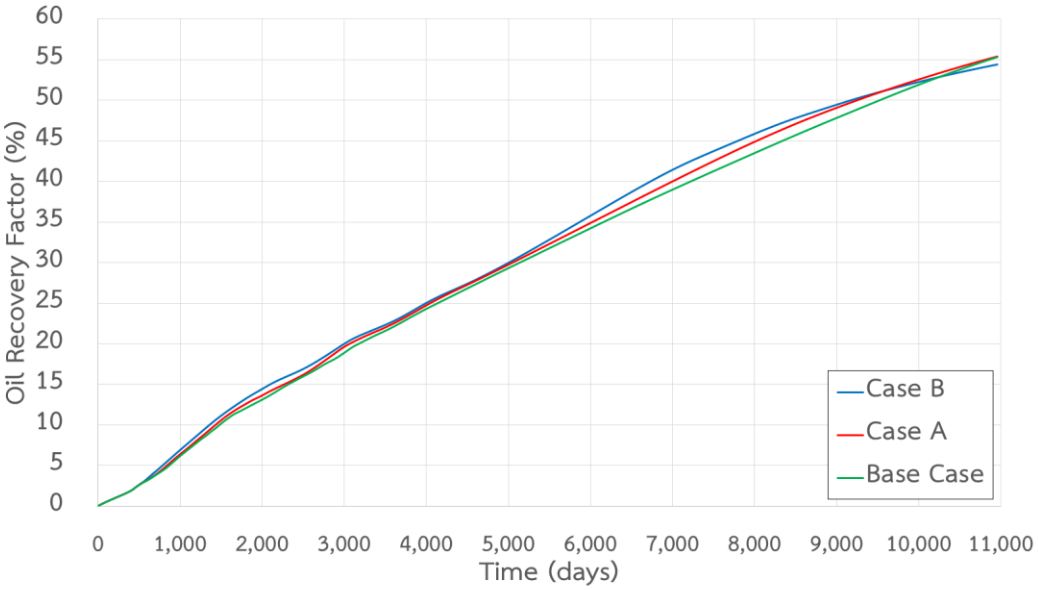


Figure 5.54 Oil recovery factors for wet combustion cases with different thermal properties of rock matrix as a function of time in VI2HP configuration

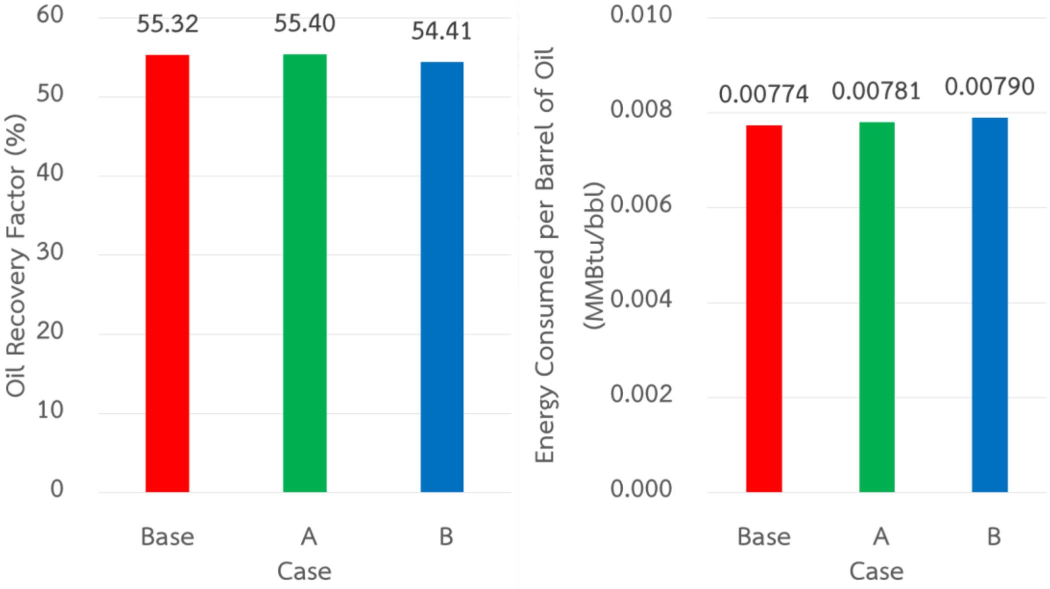


Figure 5.55 Summary of oil recovery factor and energy consumed per barrel of oil with different thermal properties of rock matrix at the end of production from wet combustion cases in VI2HP configuration

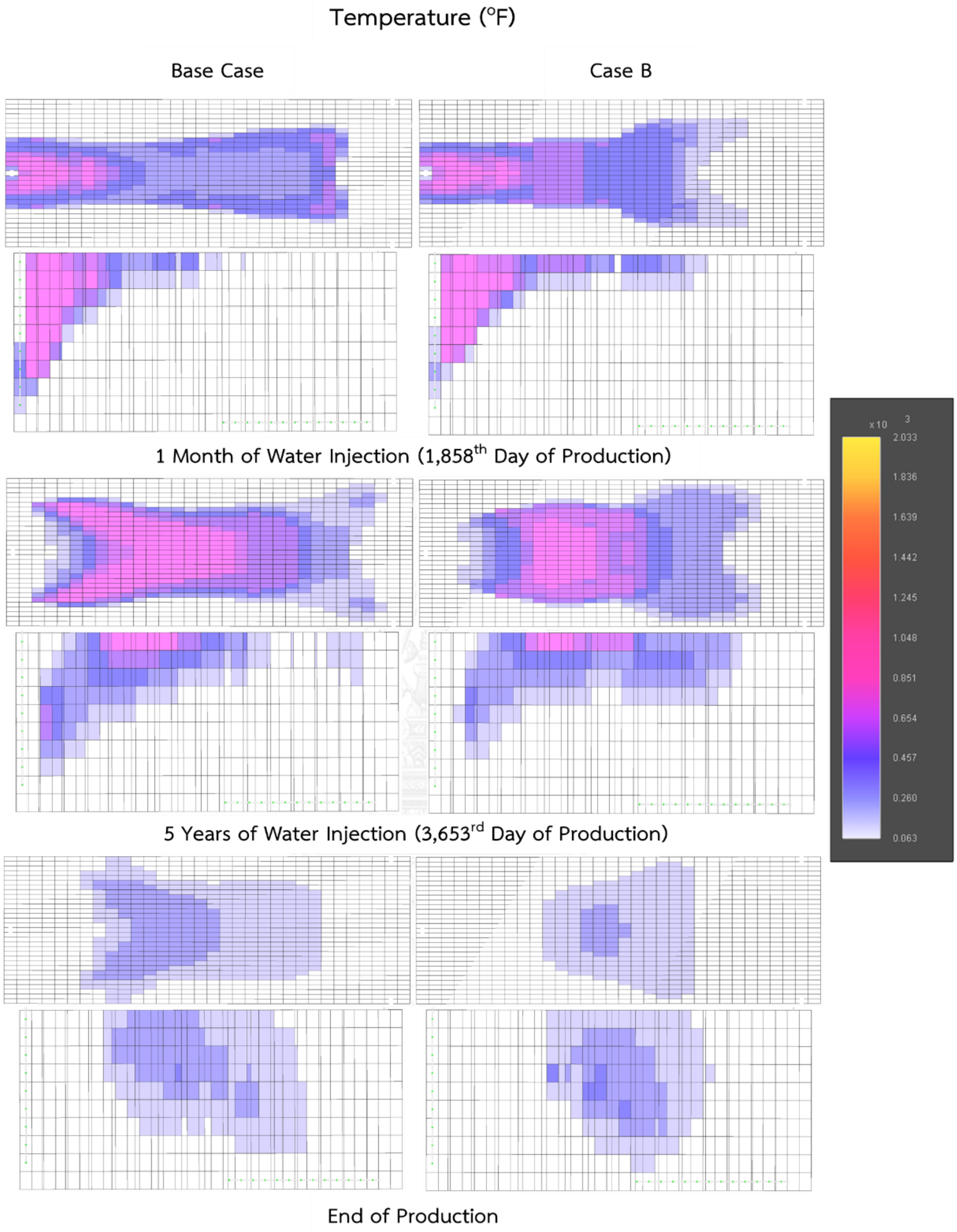


Figure 5.56 Temperature profiles of wet combustion in VI2HP configuration in different thermal properties of rock matrix at selected times

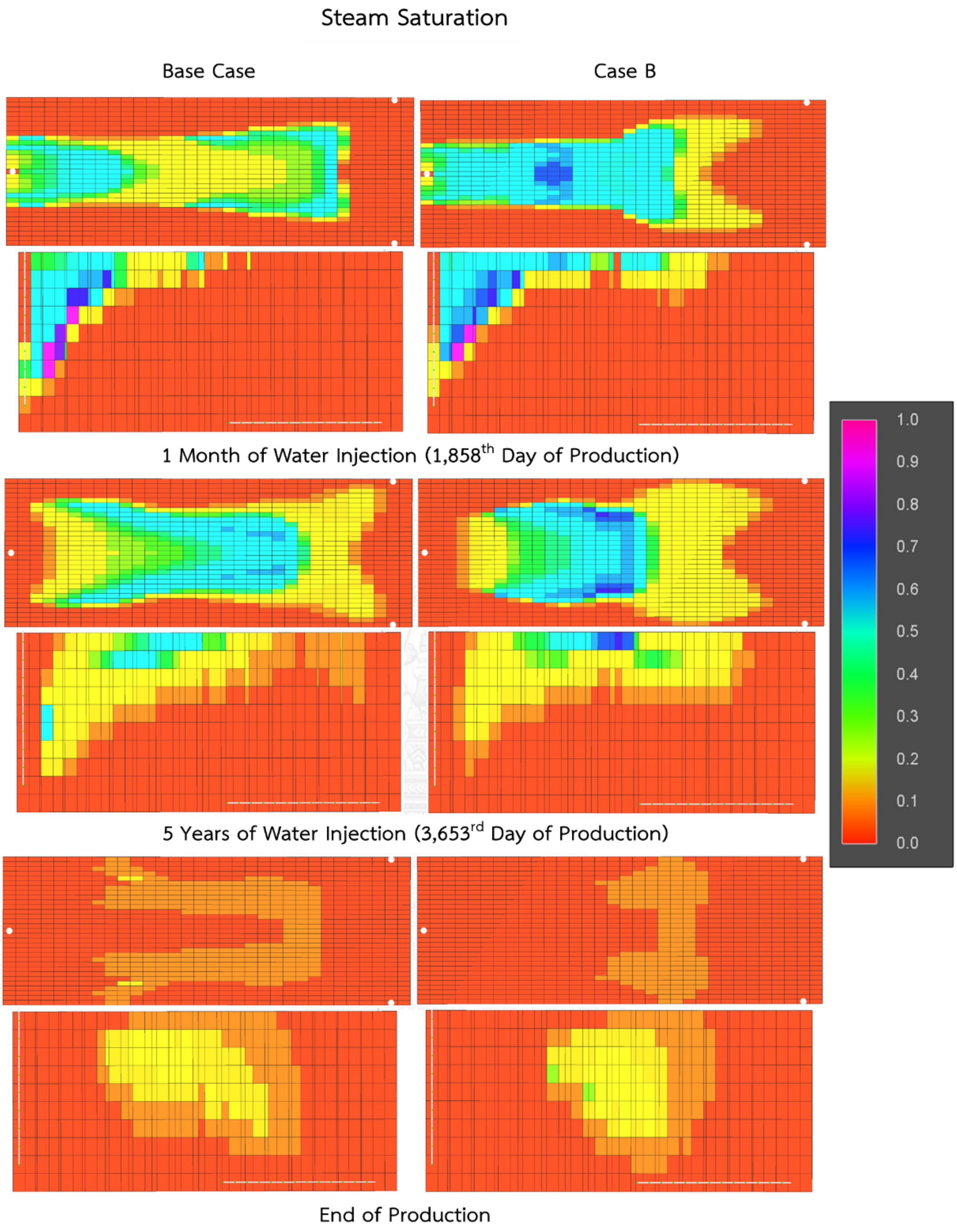


Figure 5.57 Steam saturation profiles of wet combustion in VI2HP configuration in different thermal properties of rock matrix at selected times

From Figure 5.55, it can be seen that changing of thermal properties of rock matrix does not affect much to the ultimate oil recovery as well as energy consumed per barrel of oil. As explained previously, effects of heat capacity yields benefit in terms of generating large amount of steam. However, as heat conductivity is decreased, it can be seen in the later state where generated heat should be delivered to the entire reservoir. Benefits of both result in self-compensation when considering only ultimate oil recovery. Nevertheless, it can be seen that lower differences of thermal properties of rock matrix is more favorable compared to case with higher differences and this can be concluded that heat conductivity slightly dominates heat capacity for wet combustion.

For HI2HP configuration, oil recovery factors from different cases with different thermal properties of rock matrix as a function of time are illustrated in Figure 5.58. From the figure it can be obviously seen that oil recovery factor is decreased with differences of thermal properties of rock matrix. As fire front may propagate slowly due to lower total amount of injected air at fixed depth compared to VI2HP, effect of heat capacity is not pronounced in this case. As time increases, the difference is more obvious which is mainly due to heat conductivity.

Due to higher heat capacity, accumulation of temperature could also result in combustion at production well as can be observed in Figure 5.59 and Figure 5.60. This could be also concluded that high heat capacity and low thermal conductivity are unfavorable for HI2HP when combined with wet combustion.

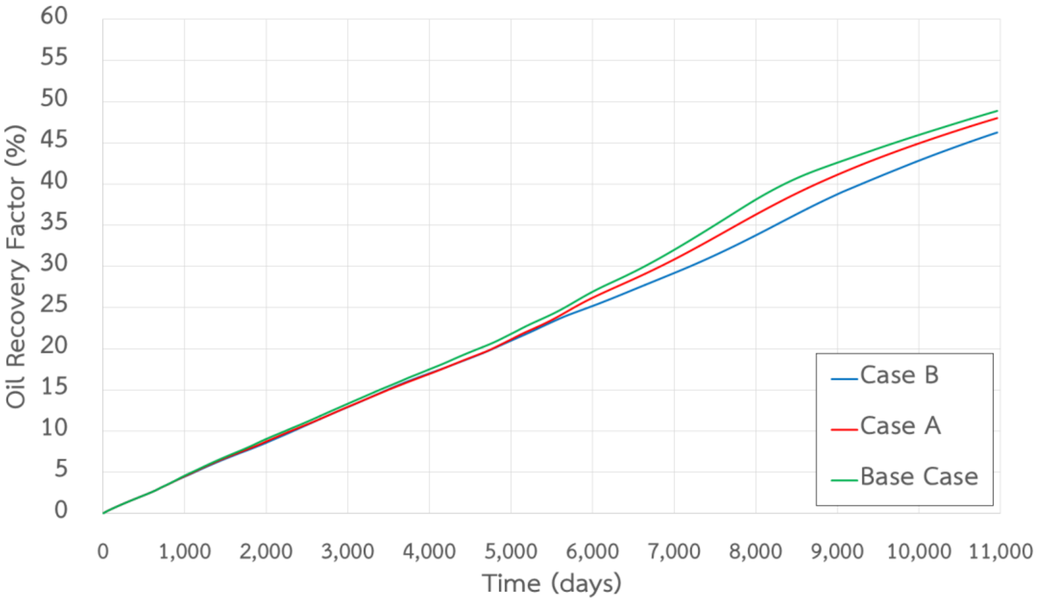


Figure 5.58 Oil recovery factors for wet combustion cases with different thermal properties of rock matrix as a function of time in HI2HP configuration

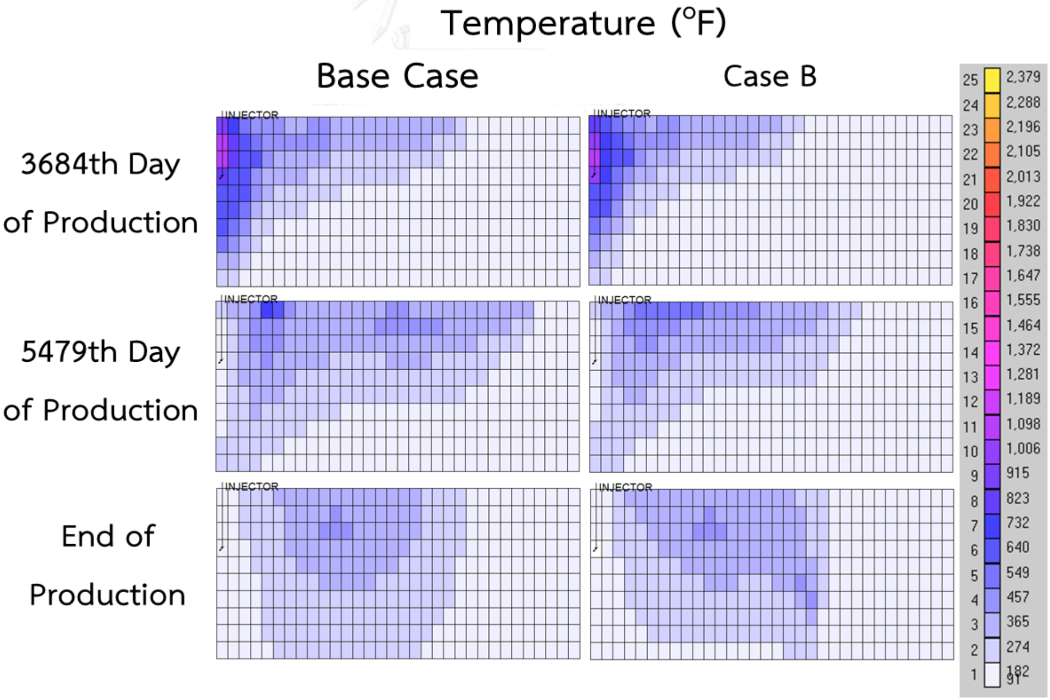


Figure 5.59 Temperature profiles of wet combustion in HI2HP configuration in different thermal properties of rock matrix at selected times

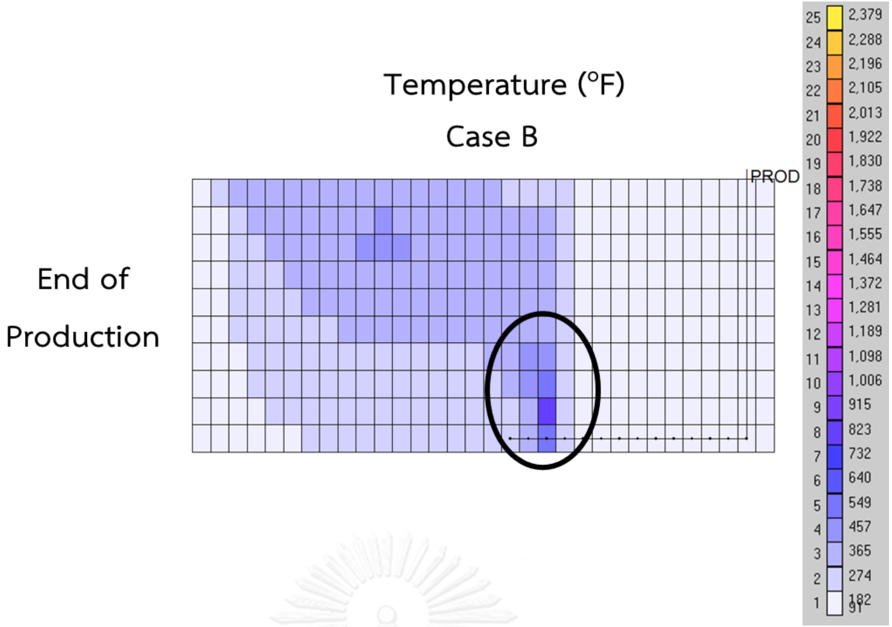


Figure 5.60 Temperature profiles of wet combustion in HI2HP configuration in case B at the end of production which combustion happens at production well

Summary of oil recovery factor and consumed energy consumed per barrel of oil is shown in Figure 5.61. Oil recovery factor decreases with increasing of differences of thermal properties of rock matrix as explained previously. However, a small reduction of energy consumed per barrel of oil in case A compared to base case is due to smaller cumulative amount of gas injected during first 5 years. This lowering of cumulative amount of heated air in first 5 years can be explained by higher heat absorption by rock in case with higher differences of thermal properties of rock matrix and the cooling down gas turns into more viscous gas which consecutively results in lower total amount of injected air.

In this section, effect of different thermal properties of rock matrix is investigated. Increase of heat capacity favors generation of large amount of in-situ steam if fire front is well developed. However, benefit from higher heat capacity is only observed in VI2HP where total amount of injected air is quite high and fire front is well developed. From the results, it can be concluded that heat conductivity plays more important role in controlling effectiveness of wet combustion combined with THAI.

Lower differences is therefore considered as more favorable condition. Nevertheless, lower percent of differences (around 10 percent) is still acceptable especially in case of vertical well injection where benefit of heat capacity slightly dominates drawback from lower heat conductivity.

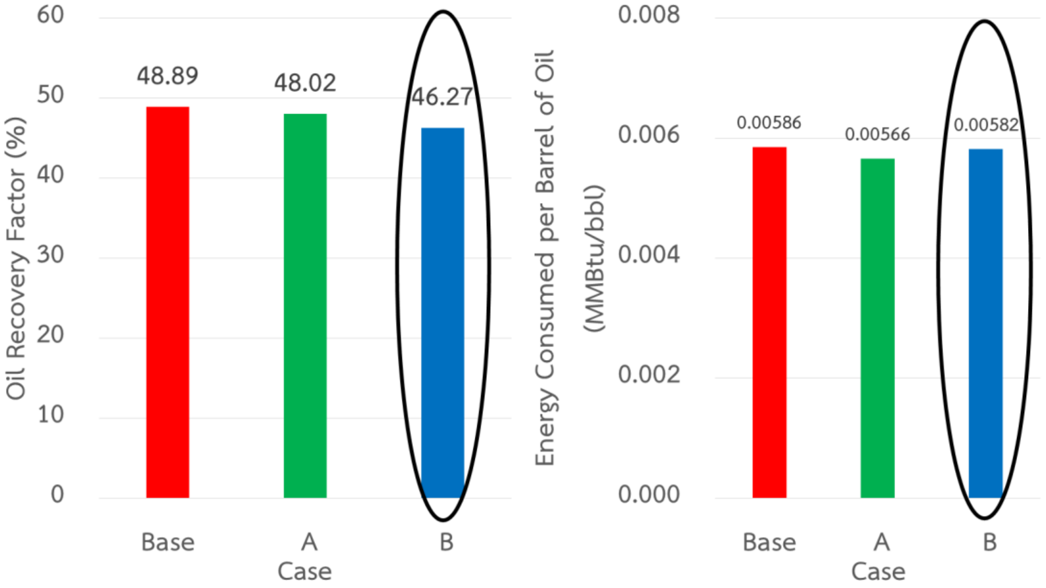


Figure 5.61 Summary of oil recovery factor and energy consumed per barrel of oil with different thermal properties of rock matrix at the end of production from wet combustion cases in HI2HP configuration

5.4 Effect of End-point Saturation

In this section, end-point saturation in relative permeability curves at reservoir temperature (91.11 °F) is varied in order to study its effect while other parameters including shape of relative permeability curves, magnitudes of both relative permeability to oil and to water and end-point saturations of both irreducible water and residual oil at both 560.74°F and 1,500 °F are kept constant. Values of three different end-point saturation sets are summarized in Table 5.9 and constructed relative permeability curve of oil-water system for reservoir model with different sets mentioned earlier are shown in Figure 5.62.

Table 5.9 End point saturations of three different cases at reservoir temperature

Parameters	Case 1			Base Case			Case 2		
Temperature (°F)	91.11	560.74	1500	91.11	560.74	1500	91.11	560.74	1500
Irreducible water saturation (S_{wi})	0.36	0.5	0	0.27	0.5	0	0.18	0.5	0
Residual oil saturation (S_{or})	0.13	0	0	0.2	0	0	0.27	0	0

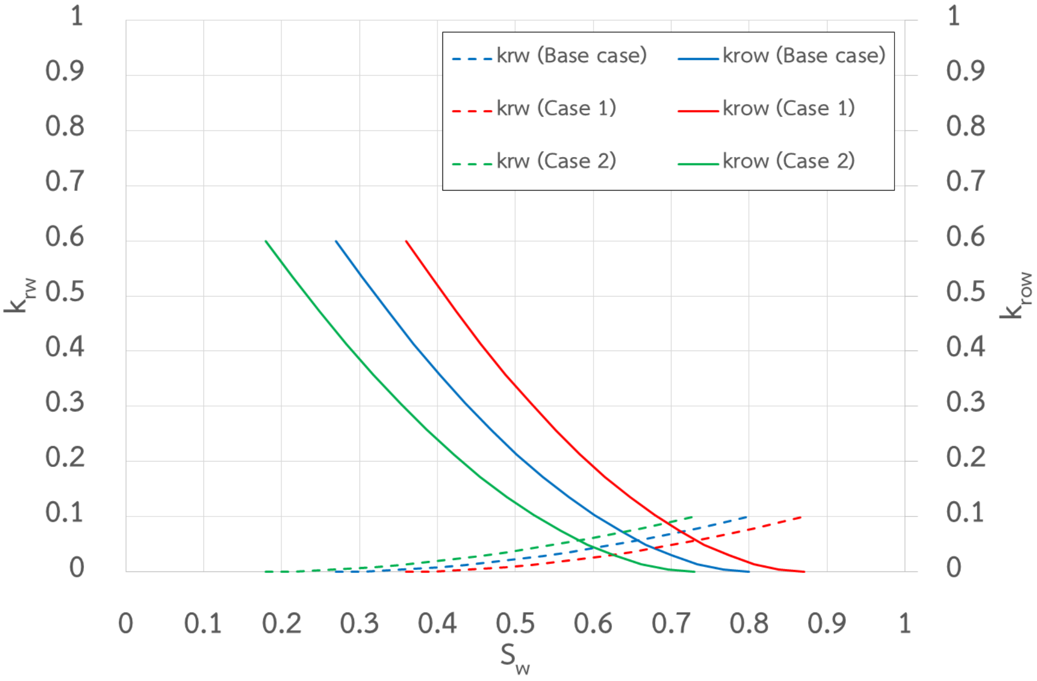


Figure 5.62 Relative permeability curves of oil-water system with different end-point saturations at reservoir temperature as a function of water saturation

The results of oil recovery factor with different irreducible water saturation in both VI2HP and HI2HP configurations are shown in Figure 5.63 and Figure 5.64. It can be obviously seen that at early years of production, oil recovery factor is increased with an increment of irreducible water saturation. As OOIP is decreased according to increased irreducible water saturation, displaceable volume of oil by means of injected fluid is also decreased. Therefore, with the same injection rate of air, higher amount of oil from oil recovery mechanisms is obtained. On the other hand, reduction of irreducible water saturation yields lower oil recovery at early times but oil recovery factor is increased at latter years. It must be noted that increasing of irreducible water saturation can also extend water breakthrough time according to water production as shown in Figure 5.65.

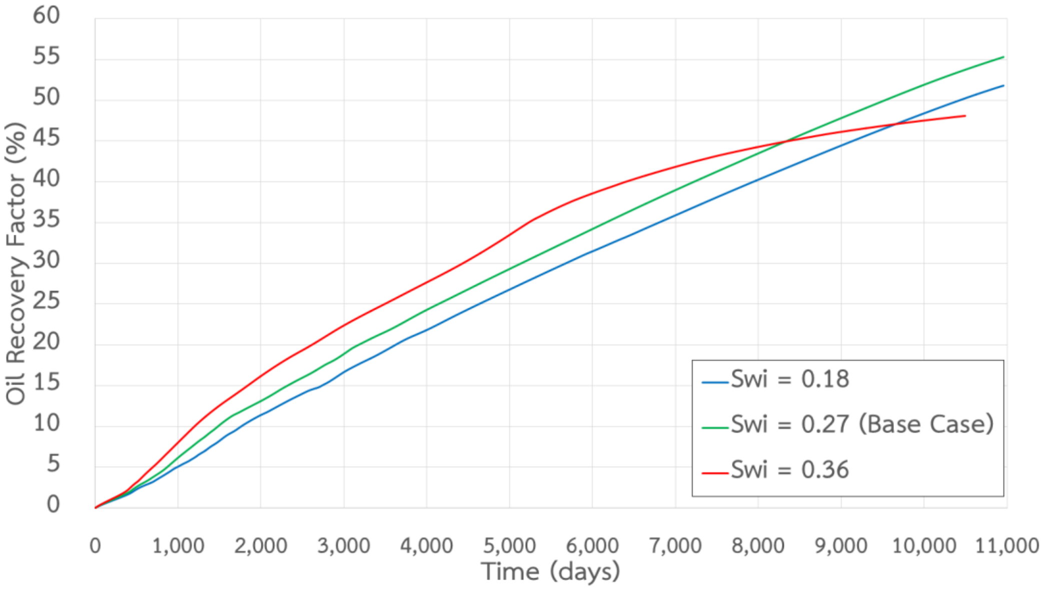


Figure 5.63 Oil recovery factors for wet combustion cases with different irreducible water saturation as a function of time in VI2HP configuration

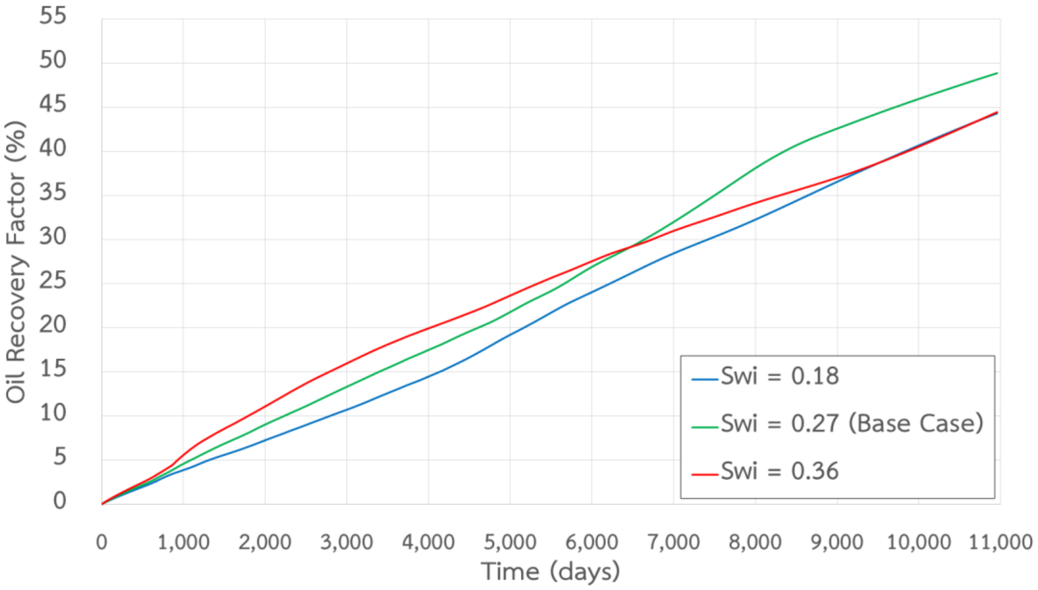


Figure 5.64 Oil recovery factors for wet combustion cases with different irreducible water saturation as a function of time in HI2HP configuration

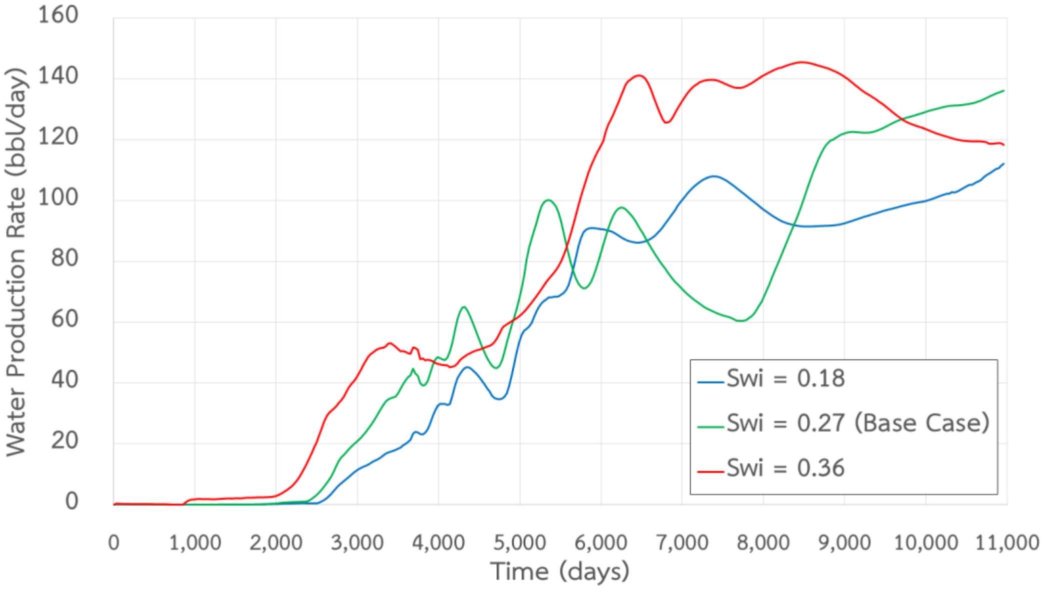


Figure 5.65 Water production rates for wet combustion cases with different irreducible water saturation as a function of time in HI2HP configuration

Steam saturation and temperature profiles of wet combustion of both VI2HP and HI2HP configuration with different cases of end-point saturations are shown in Figure 5.66 to Figure 5.69. It can be observed that injected air and water can displace displaceable fluid with larger volume in the reservoir due when end point saturation is shifted to the right. However, residual water is also increased and therefore it becomes hindrance to steam propagation in wet combustion because the in-situ steam will be held as residual water and worsen the heat transfer.

In case of left-shifted end-point saturation, the oil recovery is lowered because of increased displaceable volume of fluid. Nevertheless, when wet combustion is started, oil recovery is improved due to faster steam propagation according to reduction of irreducible water saturation. Nevertheless, because of increasing in displaceable fluid, oil recovery is still lowered than that of base case. It also can be mentioned that alteration of end-point saturation can change risks that combustion will be happened at production well according to Figure 5.70.

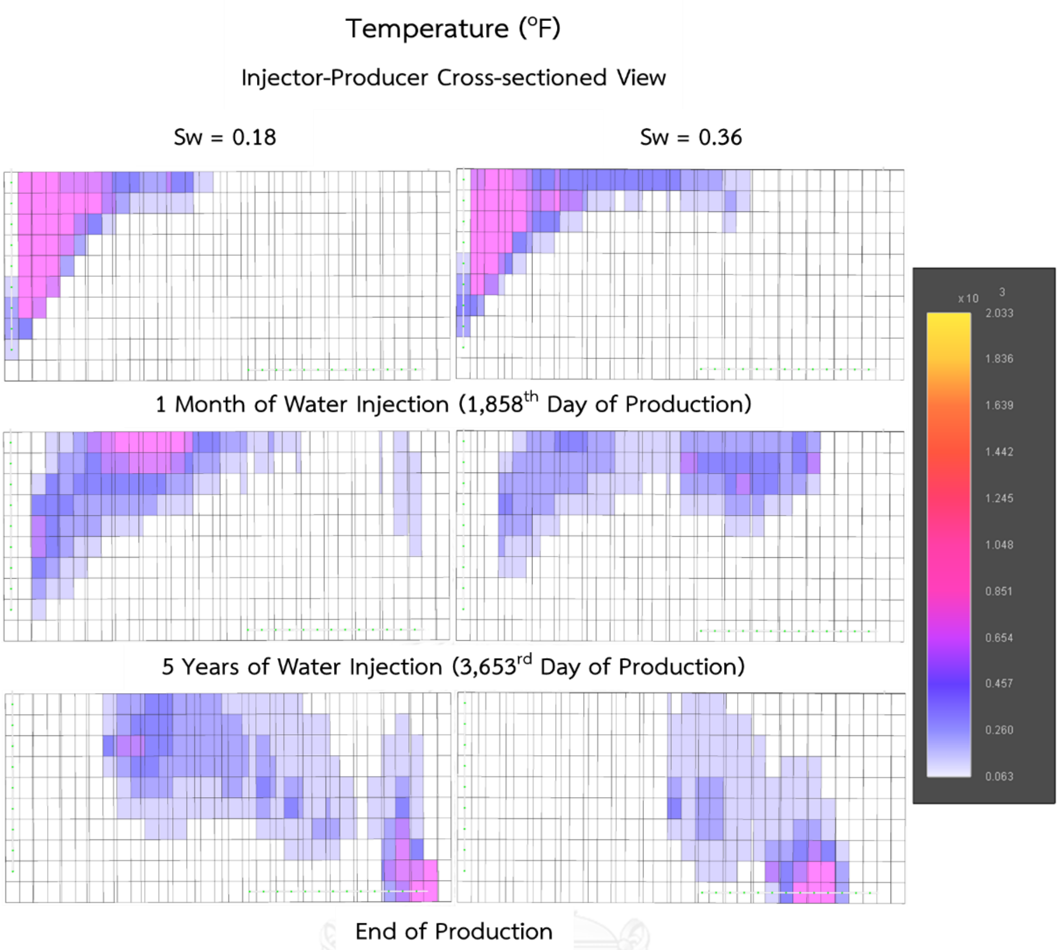


Figure 5.66 Temperature profiles of wet combustion in VI2HP configuration in different end-point saturation at selected times

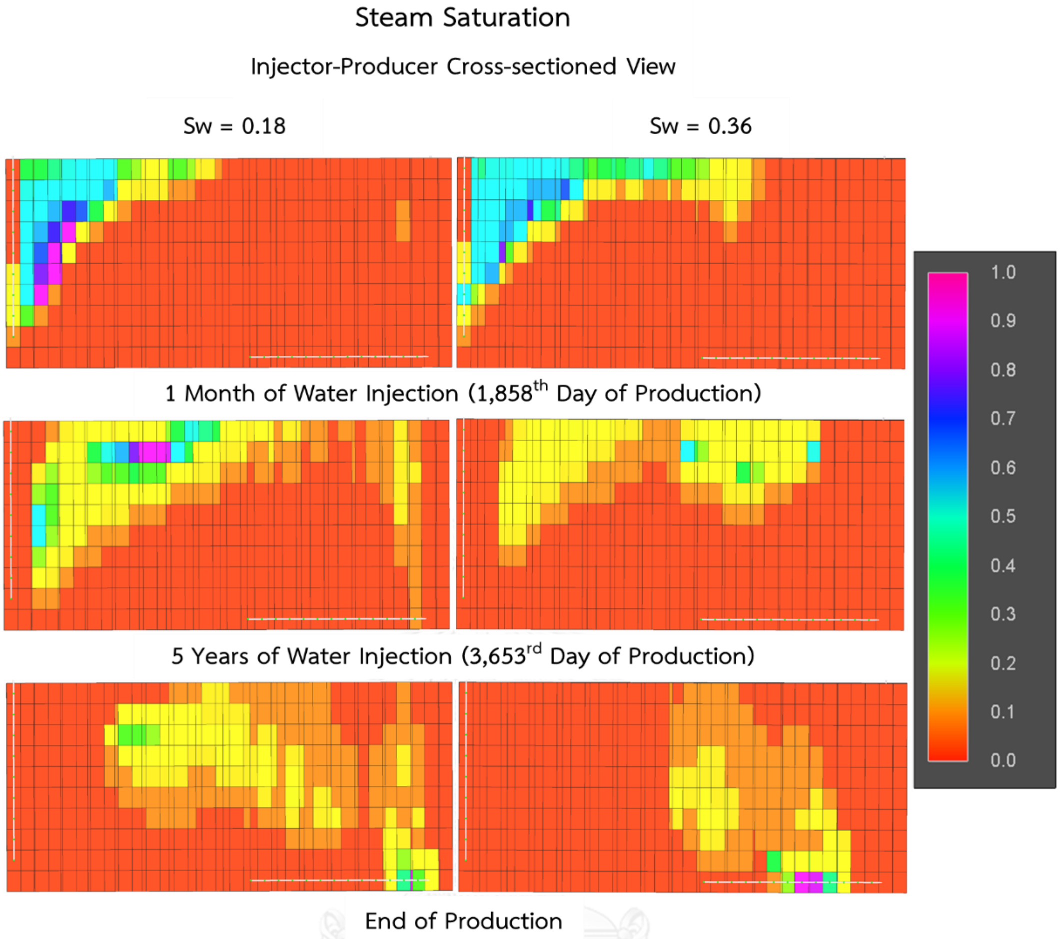
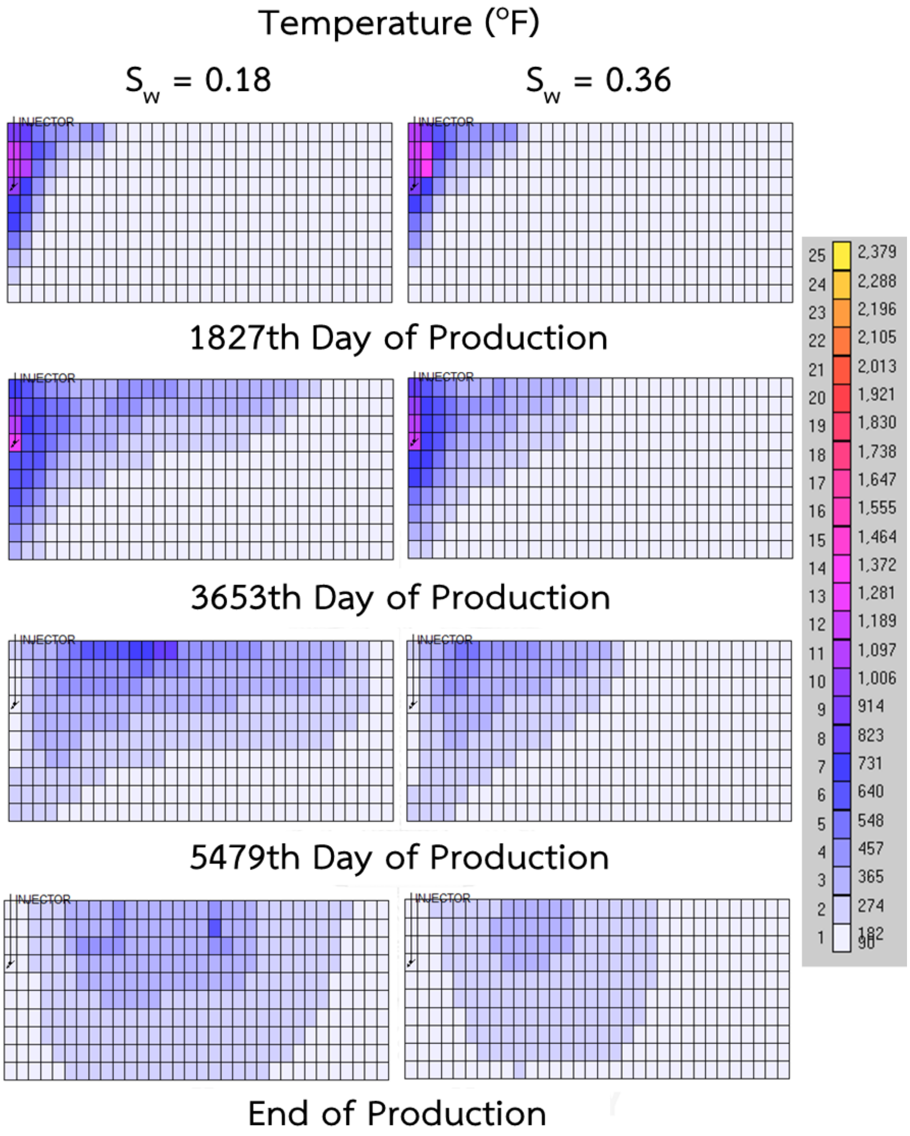


Figure 5.67 Steam saturation profiles of wet combustion in VI2HP configuration in different end-point saturation at selected times



Temperature (°F)

S_w = 0.18 S_w = 0.36

1827th Day of Production

3653th Day of Production

5479th Day of Production

End of Production

Figure 5.68 Temperature profiles of wet combustion in HI2HP configuration in different end-point saturation at selected times

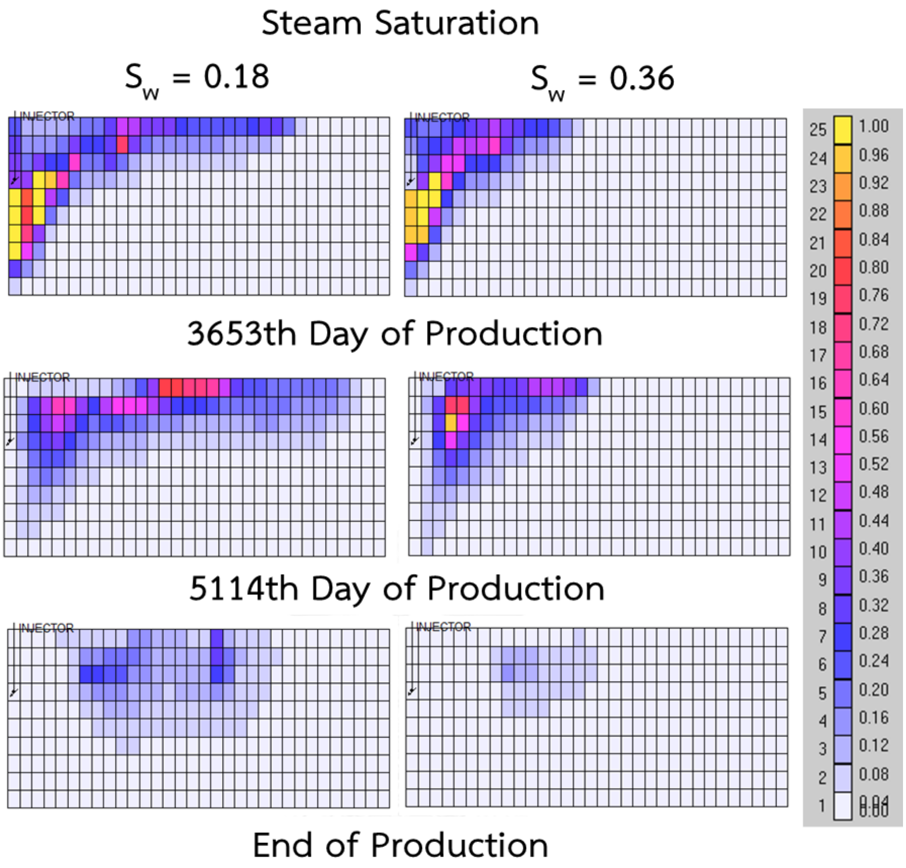
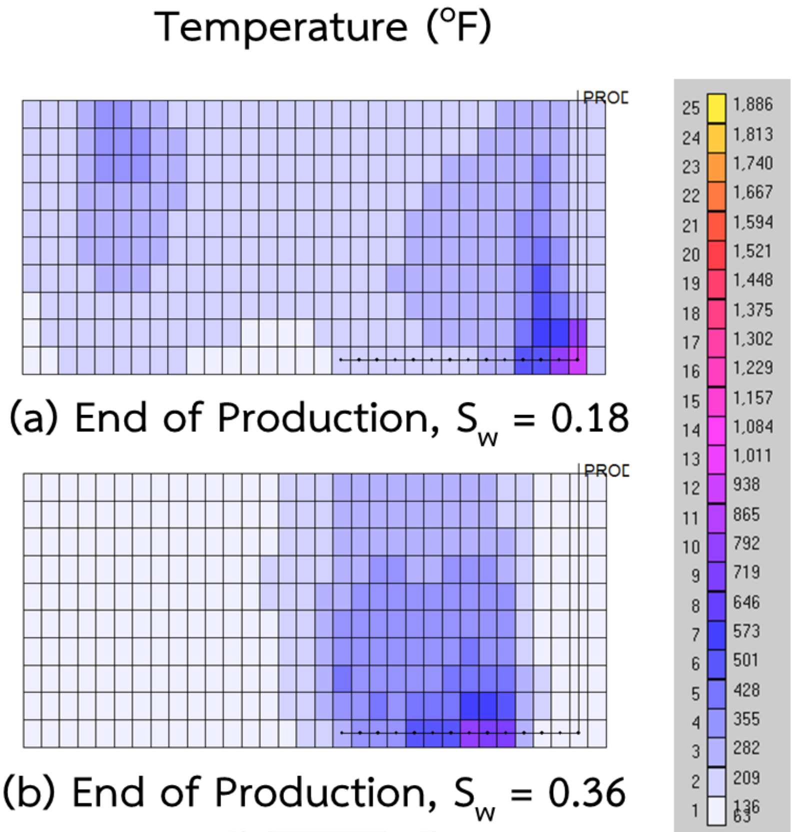


Figure 5.69 Steam saturation profiles of wet combustion in HI2HP configuration in different end-point saturation at selected times



(a) End of Production, $S_w = 0.18$

(b) End of Production, $S_w = 0.36$

Figure 5.70 Temperature profiles of wet combustion in VI2HP configuration in different end-point saturation at the end of production that combustion is occurred at production well

According to summary of oil recovery factor and energy consumed per barrel of oil of wet combustion as shown in Figure 5.71 and Figure 5.72. It can noted that circled cases are the cases that combustion is happened at production well. It can be obviously seen that set of end-point saturation of base case model gives the highest oil recovery factor in both configurations. In terms of energy consumed, decreased irreducible water saturation gives the lowest energy consumed per barrel of oil. As mentioned previously, reduction of irreducible water saturation and at the same time OOIP is increased. Therefore, oil recovery factor of 51.81 percent corresponds to much higher amount of oil in barrel in this case.

From the study in this section, it can be seen that end point saturations of relative permeability curves are important in terms of operation design. Uncertain values of end points could cause fire front to appear at production wells. However, if end point saturations are exactly known it can also be concluded that, high irreducible water saturation will speed up displacement mechanism in early stage due to less displaceable volume. Oil recovery rate is reduced at later time as injected water to create in-situ steam may re-trap in pore space with very high irreducible water saturation. Hence steam propagation occurs slowly. From this study, reservoir with small irreducible water saturation would obtain benefit of steam propagation under appropriate design of operational parameters.

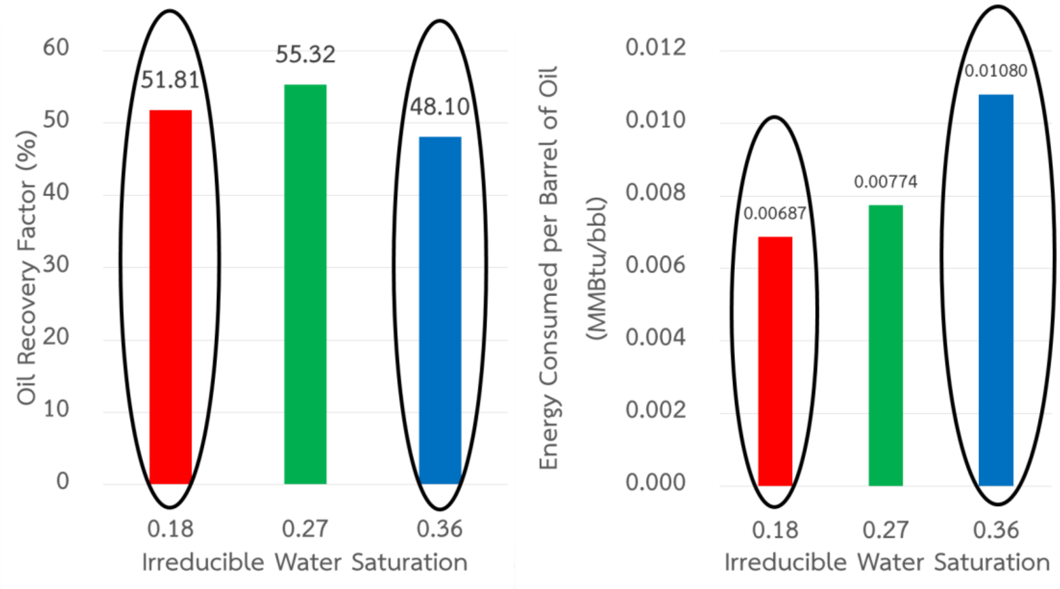


Figure 5.71 Summary of oil recovery factor and energy consumed per barrel of oil with different end-point saturation at the end of production from wet combustion cases in VI2HP configuration

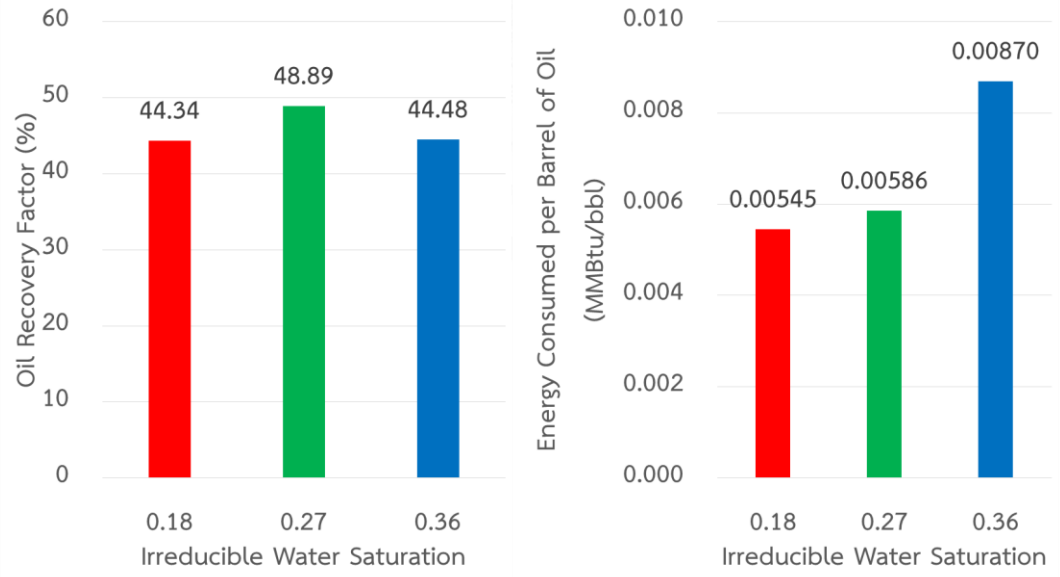


Figure 5.72 Summary of oil recovery factor and energy consumed per barrel of oil with different end-point saturation at the end of production from wet combustion cases in HI2HP configuration

5.5 Effect of Vertical Permeability

In order to study effects of vertical permeability to the combination of THAI configuration and wet combustion, base case reservoir model is constructed with different values of vertical permeability. Horizontal permeability values in all layers of reservoir are remained constant so that the ratio between vertical permeability and horizontal permeability is changed. Two additional values of ratio include 0.1 and 0.01.

Temperature profiles and gas injection rates of wet combustion in VI2HP configuration with different vertical permeability values are shown from Figure 5.73 to Figure 5.75. It can be obviously seen that in case that when k_v/k_h equals to 0.01 the combustion front is not formed due to inadequate amount of heated air injected into reservoir. In this case, injected air can propagate into reservoir via only horizontal direction but cannot override or spread in vertical direction because of greatly reduction of vertical permeability. So that amount of injected air is limited and the combustion front cannot be generated. In case that k_v/k_h equals to 0.1, the result is in between the cases of 0.2 and 0.01. The combustion front is formed but amount of heat from combustion is lowered due to decreased amount of injected air. It also can be mentioned that the combustion is occurred around production well at the end of the production in cases of decreasing vertical permeability as shown in Figure 5.75. The reason is that hot combustion flue gas and steam are accumulated around production well instead of being produced due to decreased vertical permeability and this results in ignition of combustion front.

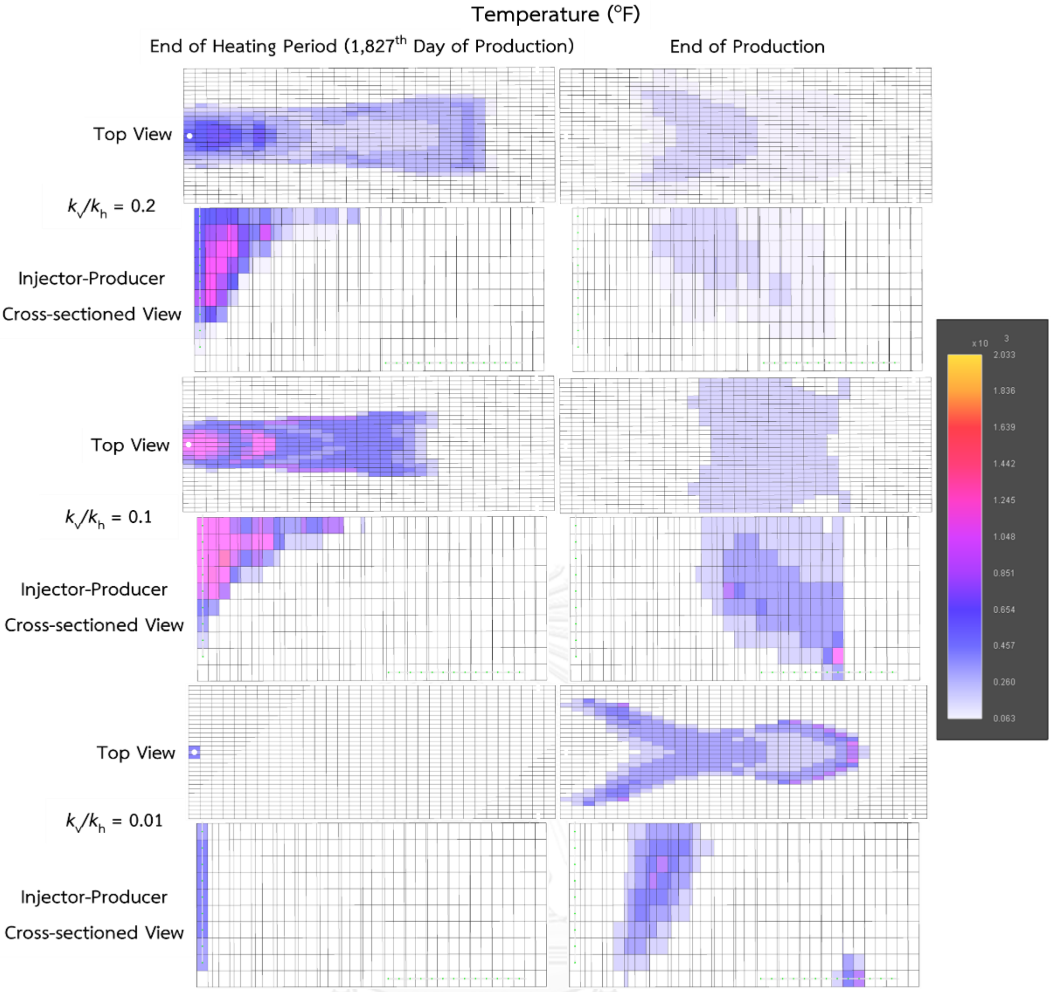


Figure 5.73 Temperature profiles of wet combustion in VI2HP configuration in different k_v/k_h ratio at selected times

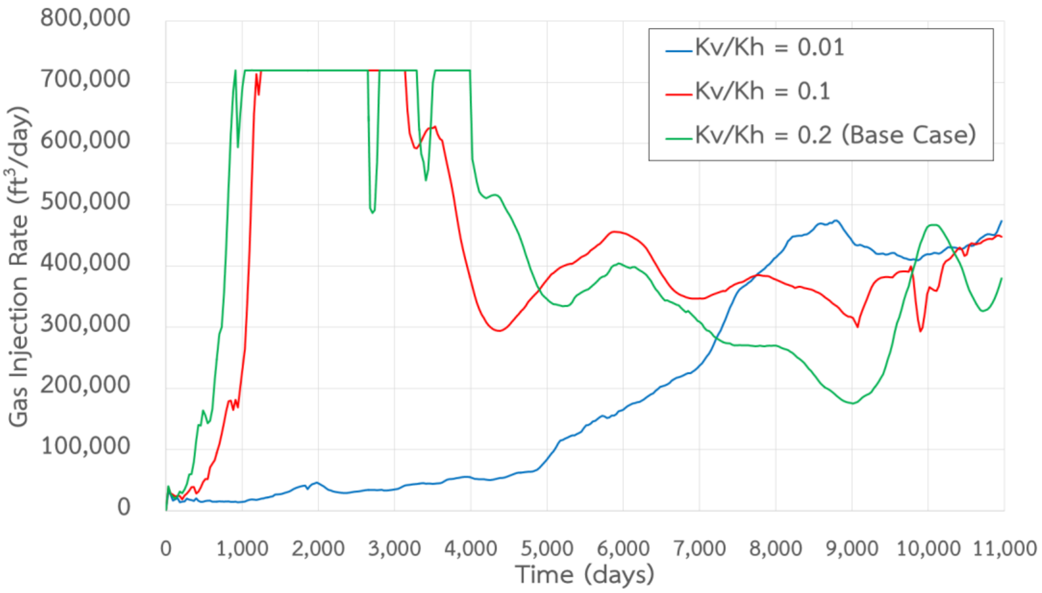
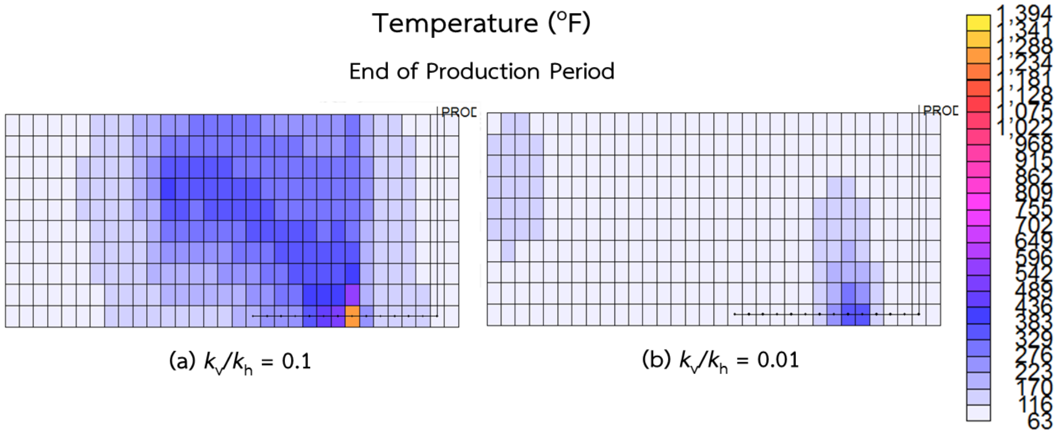


Figure 5.74 Gas injection rates for wet combustion cases with different k_v/k_h ratio as a function of time in VI2HP configuration


Temperature (°F)

End of Production Period

(a) k_v/k_h = 0.1

(b) k_v/k_h = 0.01

Figure 5.75 Temperature profiles of wet combustion in VI2HP configuration in selected k_v/k_h ratio that combustion happens around production well

Summary of oil recovery factors and energy consumed per barrel of oil of wet combustion in VI2HP configuration with different k_v/k_h ratio are shown in Figure 5.76 and Figure 5.77. It can be obviously seen that oil recovery factor is dramatically decreased as vertical/horizontal permeability ratio is decreased due to decreased amount of injected air into the reservoir. Energy consumed is also lowered because amount of heated air injected at the first five years of production is also decreased, leading to failure in attempt to make combustion front in case that k_v/k_h equals to 0.01. It can be concluded that vertical/horizontal permeability ratio give considerably impact to wet combustion in VI2HP in terms of increasing risks that combustion will be happen around production well. It also can be mentioned that circled cases are the cases that combustion is occurred around production well.

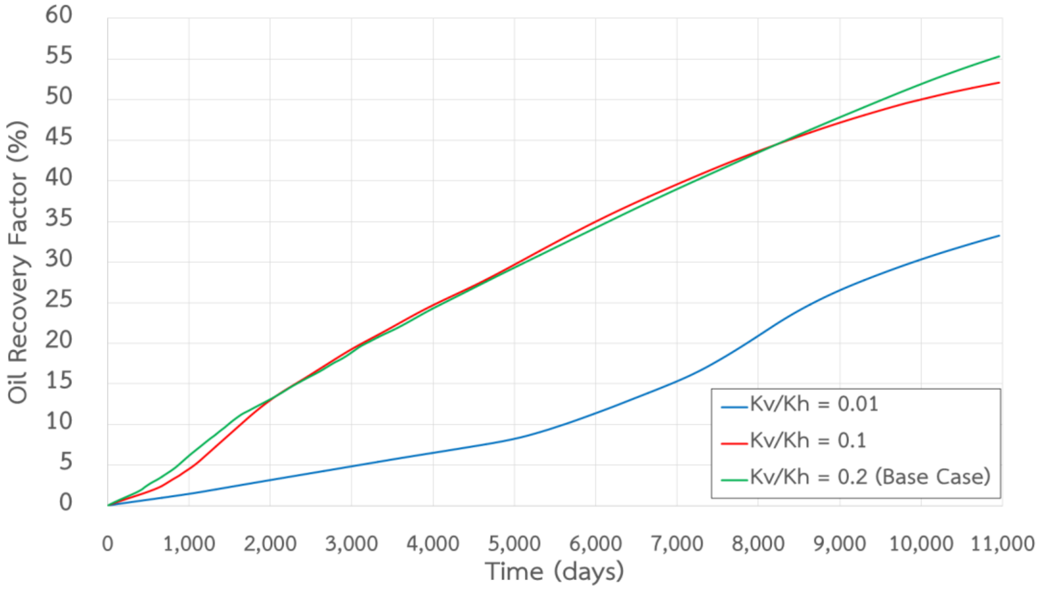


Figure 5.76 Oil recovery factors for wet combustion cases with different k_v/k_h ratio as a function of time in VI2HP configuration

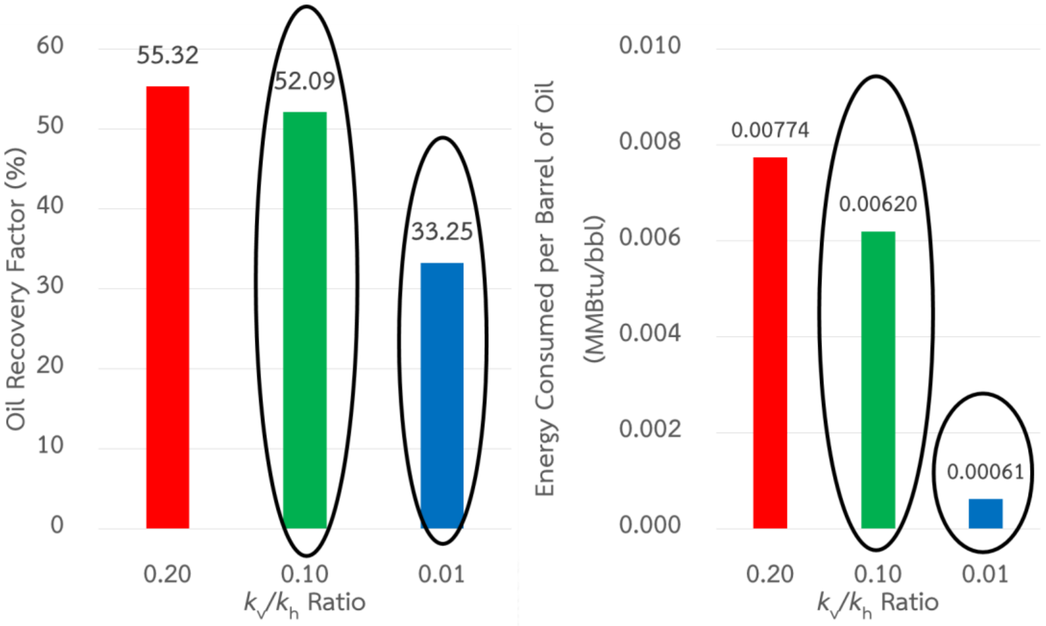


Figure 5.77 Summary of oil recovery factor and energy consumed per barrel of oil with different k_v/k_h ratio at the end of production from wet combustion cases in VI2HP configuration

Similar to VI2HP configuration, temperature profiles and gas injection rates shown in Figure 5.78 and Figure 5.79 follow the same trend. It can be seen that heat of combustion is lowered due to decreased amount of injected air and the combustion front cannot be occurred because amount of heated air is not adequate. The difference of heat occurred in reservoir between values of vertical/horizontal permeability ratio in HI2HP configuration is worse than in VI2HP configuration because air is injected only at single depth. It also can be noted that the combustion is not happened around production well in case of changing vertical/horizontal permeability ratios.

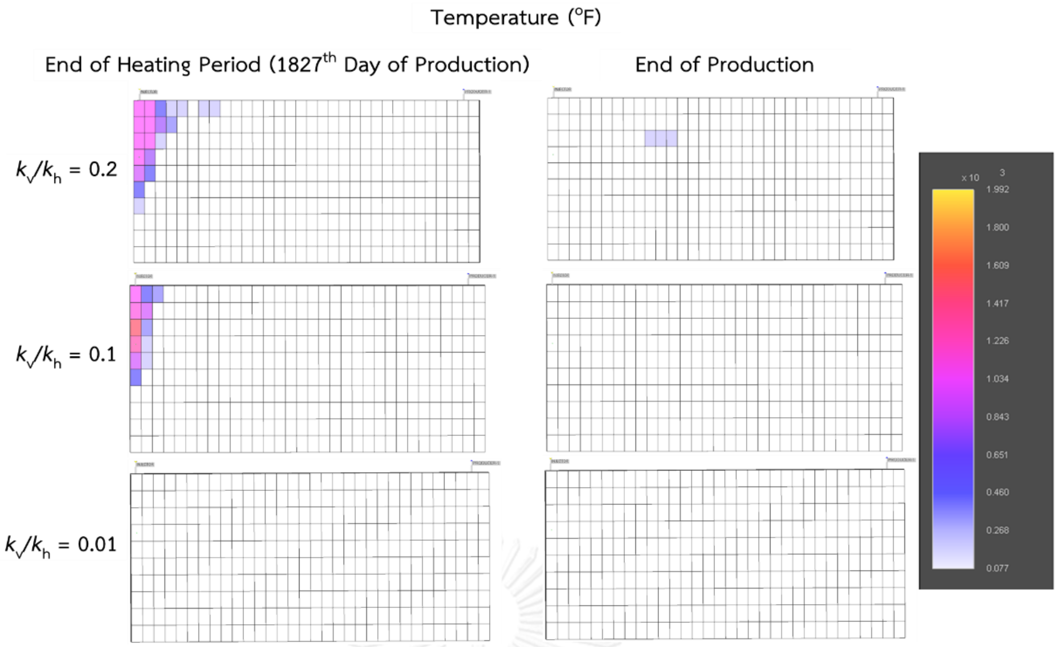


Figure 5.78 Temperature profiles of wet combustion in HI2HP configuration in different k_v/k_h ratio at selected times

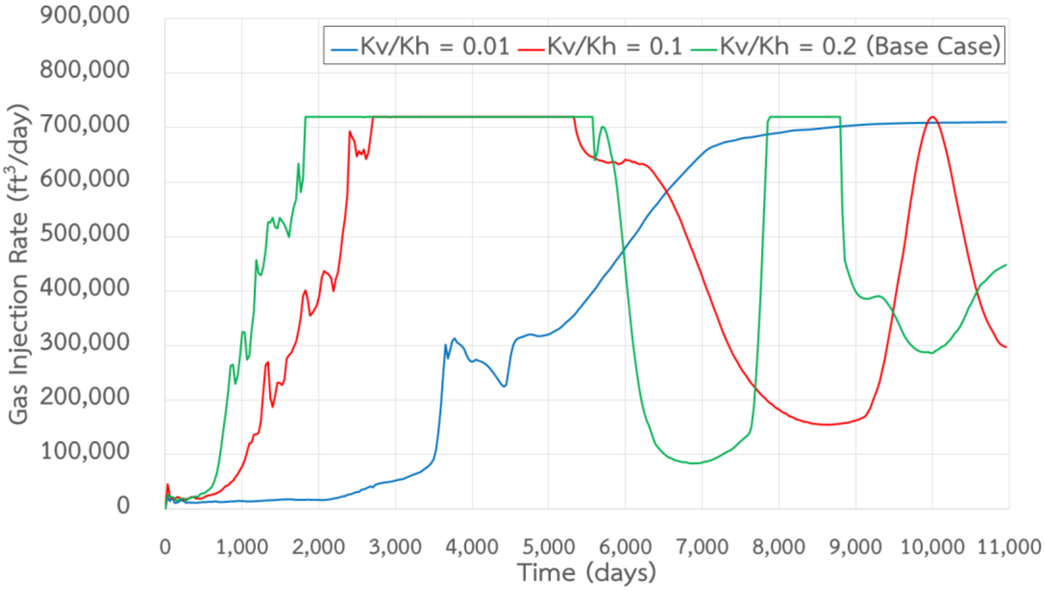


Figure 5.79 Gas injection rates for wet combustion cases with different k_v/k_h ratio as a function of time in HI2HP configuration

Summary of oil recovery factors and energy consumed of wet combustion in HI2HP configuration are shown in Figure 5.80 and Figure 5.81. The results are similar to cases in VI2HP configuration that both oil recovery factor and energy consumed per barrel of oil are decreased due to lowered amount of injected air.

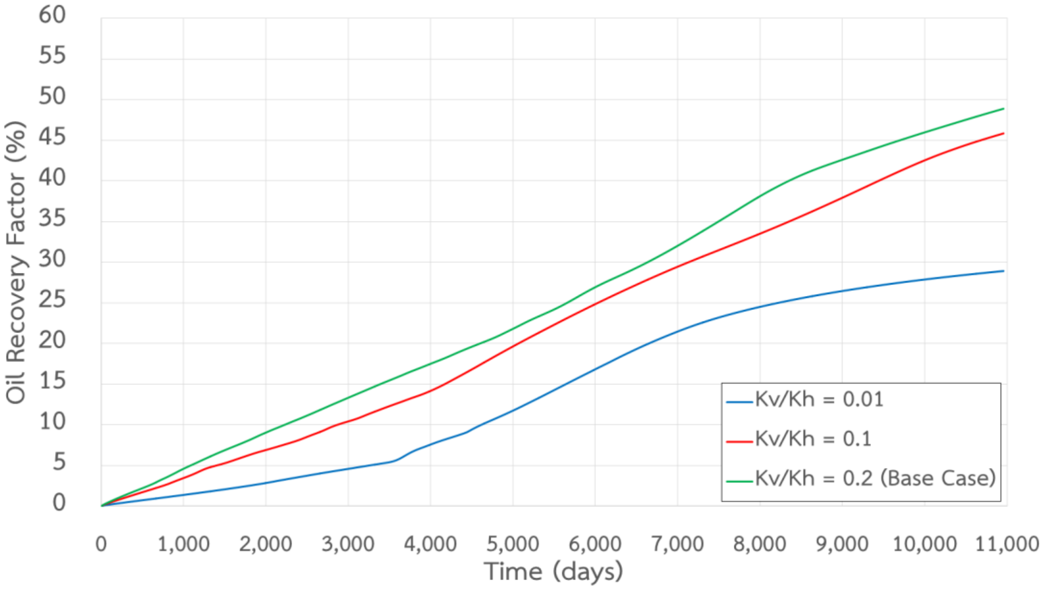


Figure 5.80 Oil recovery factors for wet combustion cases with different k_v/k_h ratio as a function of time in HI2HP configuration

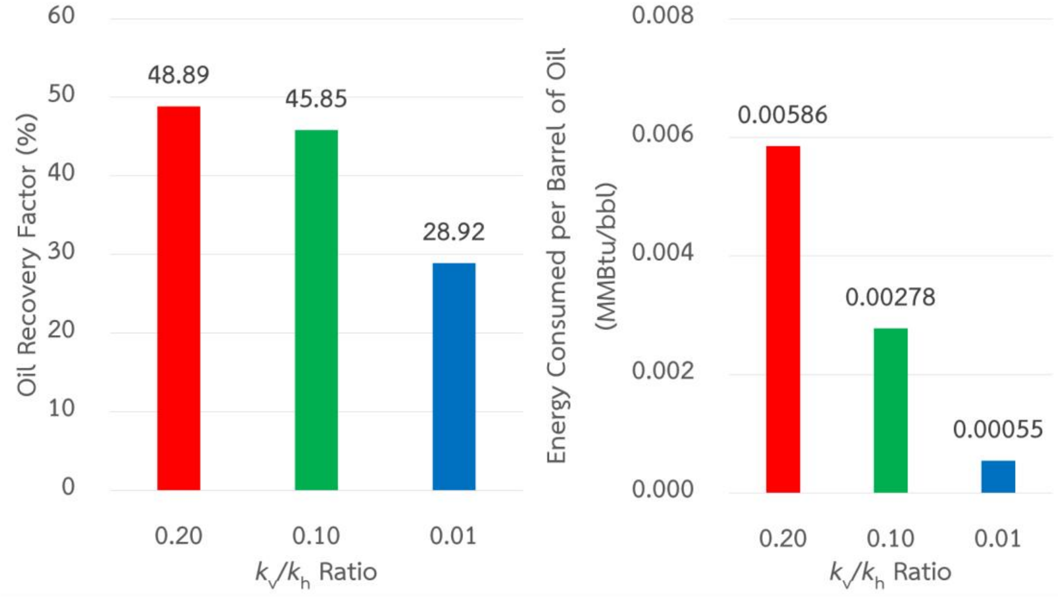


Figure 5.81 Summary of oil recovery factor and energy consumed per barrel of oil with different k_v/k_h ratio at the end of production from wet combustion cases in HI2HP configuration

It can be concluded that vertical permeability has significant impact on the process that it can change total amount of injected air that is the key factor to generate good combustion front. High vertical permeability results in high total amount of injected air as air which enters into reservoir horizontally first can propagate also in vertical direction. Moreover, value of vertical permeability also affects to chances that production well can be burnt and hence, operational parameters must be appropriately designed for specific value of vertical permeability.

CHAPTER VI
CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Results and discussion from the previous chapter shows that performance of THAI combined with wet in-situ combustion process depends on several operating and reservoir parameters. Study of both parameters are useful to be a guideline for applying this combination of techniques into homogenous heavy oil reservoir. Conclusions are summarized below.

1. In dry in-situ combustion in THAI, there are several phases of oil recovery mechanism consisted of gas pressurization in early stage, oil banks generated gases and oil bank that is caused from viscosity reduction. Major part of oil is being produced from viscosity reduction which takes longer period of the total period of production. There are some differences between VI2HP and HI2HP configurations occurred in this part. Vertical injection well has better total amount of injected gas and oil production rates since shallow depth has lower reservoir pressure and gains better oil recovery. Horizontal injection well generates two fire fronts which can sweep better in areal view. However, there is still high amount oil saturation where injected gas cannot push to production wells in both configurations.
2. In determination of operating parameters in dry combustion in THAI, 80 percent of oxygen concentration and 600,000 ft^3/day for VI2HP configuration and 60 percent of oxygen concentration, 720,000 ft^3/day of air injection rate and 1,510 ft of horizontal injection well in HI2HP configuration are two sets of operating parameters that is used to be applied with wet combustion.
3. When wet combustion is combined with THAI, wet combustion can gives additional benefits into the process. Injected water can support reservoir pressure due to its incompressible properties and can pushes oil that its

viscosity is lowered from dry combustion. Injected water is also changed into in-situ steam after contacts with heated reservoir rock and can distribute the heat to reservoir oil. Nevertheless, water injected at late time may not convert to steam as combustion front is quenched and this water will help pushing oil to toe side of production well.

4. The best combination of operating parameters for THAI combined with wet combustion are 200 bbl/day of water injection rate, 5 years of time to start wet combustion and 720,000 ft^3/day for VI2HP configuration and 200 bbl/day of water injection rate, 10 years of time to start wet combustion and 720,000 ft^3/day of air injection rate in HI2HP configuration.
5. Effects of selected reservoir parameters are studied afterward and the first parameter thermal properties of rock matrix. High value of heat capacity corresponds to low heat conductivity. Large amount of in-situ steam is generated by increased heat capacity if fire front is well developed and this can be observed in only VI2HP configuration. Thermal conductivity has more impact to the process compared to heat capacity in terms of controlling effectiveness of wet combustion combined with THAI.
6. From the study of end point saturation, it can be seen that end point saturations of relative permeability curves are important in terms of operation design. Increased irreducible water saturation can accelerates displacement mechanism in early phase from decreased displaceable volume. But oil recovery is lowered at latter phase as water which is injected as in-situ steam may re-trap in pore space therefore steam propagation is slower in higher irreducible water saturation. So that reservoir with lower irreducible water saturation would obtain benefit of steam propagation under appropriate design of operational parameters.
7. Vertical permeability has significant impact on the process as total amount of injected air that is the key factor to generate good combustion front is altered. High total amount of injected air which enters into reservoir

horizontally first then can propagate also in vertical direction can be observed in high vertical permeability.

8. Combustion in production well is the main unfavorable condition in this study. It can be happened either from inappropriate sets of operating parameters which are consisted of high air injection rate and high oxygen concentration or from inappropriate design values of reservoir parameters such as imprecise irreducible water saturation value and low vertical permeability.

6.2 Recommendation

Some recommendation are provided for further study in combination of wet combustion and THAI.

1. Effects of temperature to relative permeability curves should be studied because it is one of the main factor which helps the oil recovery in this combination.
2. Since number of grid blocks is limited due to the license of program used for reservoir simulation, more grid blocks are required in order to study more appropriate well configuration and study effects of laminated shale.
3. Effects of heterogeneity should be studied because the performance of this combination can be determined in a more realistic way.
4. Effect of changing time used in heating period should be studied because it mainly affects appearance of fire front which has essential impact to the outcome of process.

REFERENCES

1. Lapene, A., Castanier, L.M., Debenest, G., Quintard, M.Y., Kamp, A.M., and Corre, B., *Effects of Water on Kinetics of Wet In-Situ Combustion*, in *SPE Western Regional Meeting*. 2009, Society of Petroleum Engineers: San Jose, California, United States.
2. Venkatesan, V.N., Sampath, K., and Otto, J.B., *Oxygen Fireflooding: Determination Of Maximum Water/Oxygen Ratio For Normal Wet Combustion*, in *CIM/SPE International Technical Meeting*. 1990, Society of Petroleum Engineers: Calgary, Alberta, Canada.
3. Bagci, A.S. and Okandan, E., *Dry And Wet Combustion Studies Of Different Api Gravity Crude Oils From Turkish Oil Fields*, in *Annual Technical Meeting*. 1988, Petroleum Society of Canada: Calgary, Alberta, Canada.
4. Joseph, C. and Pusch, W.H., *A Field Comparison of Wet and Dry Combustion.* Journal of Petroleum Technology, 1980. **32**(09): p. 6.
5. Rojas, J.A., Ruiz, J., and Vargas, J., *Numerical Simulation of an EOR Process of Toe to Heel Air Injection (THAI) - Finding the Best Well Pattern*, in *SPE EOR Conference at Oil & Gas West Asia*. 2010, Society of Petroleum Engineers: Muscat, Oman.
6. Xia, T.X., Greaves, M., and Turta, A.T., *Injection Well - Producer Well Combinations in THAI 'Toe-to-Heel Air Injection'*, in *SPE/DOE Improved Oil Recovery Symposium*. 2002, Society of Petroleum Engineers: Tulsa, Oklahoma, United States.
7. Greaves, M. and Xia, T.X., *Simulation Studies of THAI Process*, in *Canadian International Petroleum Conference*. 2000, Petroleum Society of Canada: Calgary, Alberta, Canada.
8. Ramey, H.J., *In Situ Combustion*, in *8th World Petroleum Congress*. 1971, World Petroleum Congress: Moscow, USSR.
9. Green, D.W. and Willhite, G.P., *Enhanced Oil Recovery*. 2003, Richardson, Texas: Society of Petroleum Engineers.

10. Greaves, M., *Upgrading Athabasca Tar Sand Using Toe-to-Heel Air Injection*, in *SPE/CIM International Conference on Horizontal Well Technology*. 2000, Society of Petroleum Engineers: Calgary, Alberta, Canada.
11. Xia, T.X., Greaves, M., and Turta, A., *Main Mechanism for Stability of THAI-"Toe-to-Heel Air Injection"*, in *Canadian International Petroleum Conference*. 2003, Petroleum Society of Canada: Calgary, Alberta, Canada.
12. Belgrave, J.D.M., Moore, R.G., Ursenbach, M.G., and Bennion, D.W., *A Comprehensive Approach to In-Situ Combustion Modeling.* SPE Advanced Technology Series, 1993. **1**(01): p. 10.

APPENDIX

APPENDIX

CMG Builder program is used to create simulation model data for STARS simulator. There are 7 main sections required for the input of both reservoir simulation including I/O Control, Reservoir, Components, Rock-Fluid, Initial Conditions, Numerical and Well and Recurrent and field unit set and single porosity are used in the simulator.

1. I/O Control

1.1 Simulation Results File Writing

1.1.1 Frequency of Simulation Results File Writing – When to write (WSRF)

Date/Time	Information	Writing Frequency
Initial	Well	Every TIME or DATE keywords (TIME)
Initial	Grid	Every TIME or DATE keywords (TIME)
Initial	Sector	Every TIME or DATE keywords (TIME)

1.1.2 Select Variable For Simulation Results File

Variable Description	Status
Net heater rate (CCHLOSS)	Check
Pressure (PRES)	Check
Oil saturation (SO)	Check
Component solid concentration (SOLCONC)	Check (MASS)
Water saturation (SW)	Check
Temperature (TEMP)	Check
Viscosity (VISO)	Check
Component composition in gas phase (Y)	Check

2. Reservoir

2.1 Create Cartesian Grid

Parameter	Value
Grid Type	Cartesian
K Direction	Down
Number of Grid Blocks	32, 31, 10
Block width (I Direction)	32x40
Block width (J Direction)	31x15

2.2 Array Properties

Parameter	Whole Gird	Unit
Grid Top (at Layer 1)	1475	ft
Grid Thickness	10	ft
Porosity	0.3	fraction
Permeability I	1000	md
Permeability J	1000	md
Permeability K	0.2xkh	md

2.3 Thermal Rocktypes

2.3.1 Rock Compressibility

Parameter	Value	Unit
Porosity Reference Pressure	681.98	psi
Formation Compressibility	0.000003	1/psi

2.3.2 Thermal Properties

2.3.2.1 Rock Thermal Properties

Parameter	Value	Unit
Volumetric Heat Capacity	35	Btu/(ft3xF)
T-dependent Coefficient	0	Btu/(ft3xFxF)

2.3.2.2 Thermal Conductivity

Parameter	Value	Unit
Thermal Conductivity Phase Mixing	COMPLEX	
Reservoir Rock	44	Btu/(ftxdayxF)
Water Phase	8.6	Btu/(ftxdayxF)
Oil Phase	1.8	Btu/(ftxdayxF)
Gas Phase	1	Btu/(ftxdayxF)
Solid Phase	72	Btu/(ftxdayxF)

2.3.3 Overburden Heat Loss

Parameter	Value	Unit
Overburden		
Volumetric Heat Capacity	35	Btu/(ft3xF)
Thermal Conductivity	24	Btu/(ftxdayxF)
Underburden		
Volumetric Heat Capacity	35	Btu/(ft3xF)
Thermal Conductivity	24	Btu/(ftxdayxF)

3. Components

3.1 PVT Table Using Correlations

Description	Value	Unit
Reservoir temperature	91.11	
Generate data upto max. pressure of	4351	psi
Bubble point pressure calculation (Generate from GOR value)	80	ft3/bbl
Oil density at STC(14.7 psia, 60 F) (Stock tank oil gravity (API))	12	API
Gas density at STC(14.7 psia, 60 F) (Gas gravity (Air=1))	0.9	fraction
Oil properties (Bubble point, Rs, Bo) correlations	Standing	
Oil compressibility correlation	Glaso	
Dead oil viscosity correlation	Beggs and Robinson	
Live oil viscosity correlation	Beggs and Robinson	
Gas critical properties correlation	Standing	
Set/Update Values of Reservoir Temperature, Fluid Densities in Dataset	Check	

3.2 Water Properties Using Correlations

Description	Value	Unit
Reservoir temperature (TRES)	91.11	F
Reference pressure (REFPW)	681.98	psi
Water salinity	10000	ppm
Set/update values of TRES and REFPW in PVT Region dialog	Check	

3.3 Imex PVT Regions – General Tab

Description	Value	Unit
Water phase density (DENSITY WATER)	62.4	lb/ft3
Undersaturated Co (CO)	1.173e-5	1/psi

3.4 Bubble Point Pressure and Temperature – Region #1

Parameter	Value	Unit
Bubble Pt.	620.955	psi
Temperature	91.11	F

3.5 Component System

Parameter	Value	Unit
Number of oil components	1	
Number of gas components	1	
Molecular Weight Oil, region 1	501.128	lb/lbmole

3.6 Input Optional Data

3.6.1 Oil Viscosity vs. Temperature (at pressure)

Parameter	Value	Unit
Viscosity Table #	1	
Pressure	14.6923	psi

3.6.2 Oil Viscosity Table

Temperature, F	Oil Viscosity, cp
41	1.60E+08
59	235525
77	8736.9
91.11	1740.38
100	808.665
118	249.646
190	22.9131
262	7.88706
334	4.19227
406	2.71591
478	1.9613
550	1.51476
622	1.22385
694	1.02111
766	0.872608
838	0.759618
910	0.671031
982	0.599877
1054	0.541575
1126	0.493003
1198	0.451962
1270	0.41686
1342	0.386522
1414	0.360057
1486	0.336784
1630	0.297792
1774	0.266457
1918	0.240763
2062	0.219337
2206	0.201215
2350	0.185702
2494	0.172281
2638	0.160564
2782	0.150252
2926	0.14111
3070	0.132954
3214	0.125636
3358	0.119035
3502	0.113053
3632	0.108116

3.7 K value table

Parameter	Min Value	Max Value	Unit
Temperature	59	3632	F
Pressure	14.5038	4351	psi

3.8 Process Wizard – Combustion Model

This part of data set can be entered after Well and Recurrent section is completed. “LTO and HTO based on Belgraves Model: JCPT April 1997, and SPE 20250” Option is used as combustion model.

Parameter	Value	Unit
Use 9 point IJ direction formulation (recommended for field scale)	Check	
Enter gross heat of combustion for the entire oil	10358.1	cal/gm
Enter molecular weight for the entire oil	501.128	lb/lbmole
Enter air/fuel ratio for combustion	120	ft3(ST)/lb
Select Components For Burning		
Dead_Oil (Will burn in oil phase?)	Check	
Soln_Gas (Will burn in gas phase?)	Check	
Select Components For Cracking		
Dead_Oil (Will crack?)	Check	

4. Rock-Fluid

4.1 Rock Fluid Properties

Parameter	Option
Rock Wettability	Water Wet
Method For Evaluating 3-Phase KRO	Stone's Second Model

4.2 Relative permeability correlations

Description	Value
SWCON - Endpoint Saturation: Connate Water	0.27
SWCRIT - Endpoint Saturation: Critical Water	0.27
SOIRW - Endpoint Saturation: Irreducible Oil for Water-Oil Table	0.2
SORW - Endpoint Saturation: Residual Oil for Water-Oil Table	0.2
SOIRG - Endpoint Saturation: Irreducible Oil for Gas-Liquid Table	0
SORG - Endpoint Saturation: Residual Oil for Gas-Liquid Table	0
SGCON - Endpoint Saturation: Connate Gas	0.05
SGCRIT - Endpoint Saturation: Critical Gas	0.05
KROCW - Kro at Connate Water	0.6
KRWIRO - Krw at Irreducible Oil	0.1
KRGCL - Krg at Connate Liquid	0.6
KROGCG - Krog at Connate Gas	
Exponent for calculating Krw from KRWIRO	1.8
Exponent for calculating Krow from KROCW	1.8
Exponent for calculating Krog from KROGCG	1.8
Exponent for calculating Krg from KRGCL	1.8

4.3 Relative Permeability Tables

Water-Oil Table			Liquid-Gas Table (Liquid Saturation)		
Sw	krw	krow	Sl	krg	krog
0.27	0	0.6	0.27	0.6	0
0.303125	0.00068	0.534195	0.3125	0.534195	0.00408071
0.33625	0.002368	0.471808	0.355	0.471808	0.0142098
0.369375	0.004914	0.412889	0.3975	0.412889	0.0294818
0.4025	0.008247	0.357488	0.44	0.357488	0.0494815
0.435625	0.012323	0.305662	0.4825	0.305662	0.0739403
0.46875	0.01711	0.257475	0.525	0.257475	0.102661
0.501875	0.022582	0.212996	0.5675	0.212996	0.135491
0.535	0.028718	0.172305	0.61	0.172305	0.172305
0.568125	0.035499	0.135491	0.6525	0.135491	0.212996
0.60125	0.042913	0.102661	0.695	0.102661	0.257475
0.634375	0.050944	0.07394	0.7375	0.0739403	0.305662
0.6675	0.059581	0.049482	0.78	0.0494815	0.357488
0.700625	0.068815	0.029482	0.8225	0.0294818	0.412889
0.73375	0.078635	0.01421	0.865	0.0142098	0.471808
0.766875	0.089032	0.004081	0.9075	0.00408071	0.534195
0.8	0.1	0	0.95	0	0.6

4.4 Relative Permeability End Points

4.4.1 Overwrite Critical Saturation and Endpoints From Tables

Parameter	Option
Irreducible water saturation (SWR or SWCON)	Temperature dependence
Critical water saturation (SWCRIT)	Temperature dependence
Residual oil saturation for water injection (SORW)	Temperature dependence
Irreducible oil saturation for water injection (SOIRW)	Temperature dependence
Critical gas saturation (SGR)	Temperature dependence
Connate gas saturation (SGCON)	Temperature dependence
Relative permeability to water at Sw=1-soirw (KRWIRO)	Temperature dependence
Relative permeability to oil at connate water and zero gas saturation (KROCW)	Temperature dependence
Relative permeability to gas at connate liquid	Temperature dependence

4.4.2 Relative Permeability Temperature Dependence (KRTEMTAB)

4.4.2.1 Option

Parameter	Value
Temperature Intervals	4
Temperature Range	
Minimum	91.11
Maximum	1500

4.4.2.2 Table

TEMP F	SWR	SWCRIT	SORW	SOIRW	SGCRIT	SGCON	KRWIRO	KROCW	KRGCW
91.11	0.27	0.27	0.2	0.2	0.05	0.05	0.1	0.6	0.6
560.74	0.5	0.5	0	0	0	0	0.1	0.6	0.6
1030.37	0.25	0.25	0	0	0	0	0.55	0.8	0.8
1500	0	0	0	0	0	0	1	1	1

5. Initial Conditions

Parameter	Value	Unit
Reference Pressure (REFPRES)	681.98	psi
Reference Depth (REFDEPTH)	1575	ft

6. Numerical

6.1 STARS Numerical – General

Keyword Description	Dataset Value
Maximum Number of Timesteps (MAXSTEPS)	999999
Maximum Time Step Size (DTMAX)	15 day
Minimum Time Step Size (DTMIN)	1e-008 day
First Time Step Size after Well Change (DTWELL)	0.001 day
Isothermal Option (ISOTHERMAL)	OFF
Model Formulation (TFORM)	SXY
Upstream Calculation Option (UPSTREAM)	NLEVEL
Maximum Newton Iterations (NEWTONCYC)	30
Maximum Time Step Cuts (NCUTS)	10
Adaptive Implicit Method (AIM)	Stability Switching Criterion
Linear Solver Pivot Stabilization (PIVOT)	ON
Linear Solver Iterations (ITERMAX)	300
Linear Solver Orthogonalizations (NORTH)	300

6.2 STARS Numerical – Numset

Keyword Description	Dataset Value
Maximum Average Scaled Residual for All Equations (TOTRES)	TIGHT

7. Well and Recurrent

7.1 Injector well

7.1.1 Perforation

Parameter	Value	
	Vertical	Horizontal
Direction	K axis	J axis
Radius	0.1017 ft	0.1017 ft
Perforation start	1, 16, 1	1, 3, 4
Perforation end	1, 16, 9	1, 29, 4

7.1.2 Well Events for Dry Combustion

Name: INJECTOR

Type: INJECTOR MOBWEIGHT IMPLICIT

Date: 2000-01-01

Constraint	Parameter	Limit/Mode	Value	Action
OPERATE	BHP bottom hole pressure	MAX	950 psi	CONT
OPERATE	STG surface gas rate	MAX	480000-720000 ft3/day	CONT

Injected fluid: GAS

Temperature: 572 F

Pressure: 950 psi

Component	Mole Fraction
N2_CO	0.2-0.6
Oxygen	0.4-0.8

Date: 2005-01-01

Constraint	Parameter	Limit/Mode	Value	Action
OPERATE	BHP bottom hole pressure	MAX	950 psi	CONT
OPERATE	STG surface gas rate	MAX	480000-720000 ft3/day	CONT

Injected fluid: GAS

Temperature: 63 F

Pressure: 950 psi

Component	Mole Fraction
N2_CO	0.2-0.6
Oxygen	0.4-0.8

7.1.3 Well Events for Wet Combustion

Date: 2005-01-01/2010-01-01/2015-01-01

Constraint	Parameter	Limit/Mode	Value	Action
OPERATE	BHP bottom hole pressure	MAX	950 psi	CONT
OPERATE	STF surface total phase rate	MAX	128348-128428 bbl/day	CONT

Injected fluid: WATER-GAS

Temperature: 63 F

Pressure: 950 psi

Component	Mole Fraction
Water	0.000935-0.001557
N2_CO	0.399626-0.199689
Oxygen	0.599439-0.798754

7.1.4 Heater Well

Date: 2000-01-01

Heater Well	Status	Max. Tot. Heating Rate (Btu/day)	Wellbore Temperature (F)
INJECTOR (Vertical)	Check	2.45e+006	572
INJECTOR (Horizontal)	Check	2.45e+006	572

Date: 2005-01-01

Heater Well	Status	Max. Tot. Heating Rate (Btu/day)	Wellbore Temperature (F)
INJECTOR (Vertical)	Uncheck	-	-
INJECTOR (Horizontal)	Uncheck	-	-

7.2 Producer well

7.2.1 Perforation

Parameter	Value	
	PRODUCER-1	PRODUCER-1
Direction	I axis	I axis
Radius	0.1017 ft	0.1017 ft
Perforation start	31, 1, 10	31, 31, 10
Perforation end	18, 1, 10	18, 31, 10

7.2.2 Well Events

Name: PRODUCER-1, PRODUCER-2

Type: PRODUCER

Date: 2000-01-01

Constraint	Parameter	Limit/Mode	Value	Action
OPERATE	BHP bottom hole pressure	MIN	300 psi	CONT
OPERATE	STL surface liquid rate	MAX	100 bbl/day	CONT
MONITOR	WCUT water-cut (fraction)		0.9	STOP

VITA

Phummarin Chardpongsathorn was born on August 21st, 1990 in Bangkok, Thailand. He received a Bachelor degree in Chemical Technology from the Department of Chemical Technology, Faculty of Science, Chulalongkorn University in 2013. After obtaining his first degree, he continued his further study in the Master’s degree program in Petroleum Engineering at the Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University since the academic year 2013.