Downhole Water Drainage from a Gas Reservoir for Water Dumpflood in an Underlying Oil Reservoir

Mr. Htet Myet Zin Naing

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การระบายน้ำจากแหล่งกักเก็บก๊าซธรรมชาติเพื่อการแทนที่ด้วยน้ำในแหล่งกักเก็บน้ำมันชั้นล่าง

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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By	Mr. Htet Myet Zin Naing
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Thesis Advisor	Assistant Professor SUWAT ATHICHANAGORN, Ph.D.

Accepted by the FACULTY OF ENGINEERING, Chulalongkorn University in Partial Fulfillment of the Requirement for the Master of Engineering

Dean of the FACULTY OF ENGINEERING
(Professor SUPOT TEACHAVORASINSKUN, D.Eng.)

THESIS COMMITTEE

Chairman
(Assistant Professor JIRAWAT CHEWAROUNGROAJ, Ph.D.)
Thesis Advisor
(Assistant Professor SUWAT ATHICHANAGORN, Ph.D.)
External Examiner
(Monrawee Pancharoen, Ph.D.)

เท็ท เมียต ชิน แนง : การระบายน้ำจากแหล่งกักเก็บก๊าซธรรมชาติเพื่อการแทนที่ด้วยน้ำในแหล่งกักเก็บน้ำมันชั้นล่าง. (Downhole Water Drainage from a Gas Reservoir for Water Dumpflood in an Underlying Oil Reservoir) อ.ที่ปรึกษาหลัก : ผศ. ดร.สุวัฒน์ อธิชนากร

สำหรับหลุมเจาะในแหล่งเก็บก๊าซธรรมชาติที่ขับเคลื่อนด้วยน้ำด้านล่างการไหลของน้ำเข้าสู่หลุมนำไปสู่การผลิตน้ำในปริมาณมาก ซึ่งทำให้การผลิตก๊าซธรรมชาติลดลง หากแหล่งเก็บก๊าซธรรมชาติมีแหล่ง กักเก็บน้ำมันอยู่ด้านล่าง วิธีที่เรียกว่า "Downhole Water Drain for Water Dumpflood" (DWDDF) สามารถช่วยระบายน้ำออกจากชั้นน้ำที่อยู่ใต้แหล่งกักเก็บก๊าซธรรมชาติและไหลลงสู่แหล่งกักเก็บน้ำมันเพื่อใช้ในกระบวนการแทนที่ด้วยน้ำ เทคนิค DWDDF สามารถช่วยเพิ่มการผลิตก๊าซธรรมชาติจากแหล่งเก็บก๊าซด้านบนและการผลิตน้ำมันจากแหล่งกักเก็บน้ำมันด้านล่างได้ในเวลาเดียวกัน ในการศึกษานี้ แบบจำลองแหล่งเก็บอย่างง่ายซึ่งมีสมบัติของหินและของเหลวทั่วไปที่พบในประเทศไทยได้ถูกสร้างขึ้นโดยใช้แบบจำลองแหล่งกักเก็บเชิงตัวเลข ECLIPSE100 เพื่อประเมินประสิทธิภาพการผลิตแบบจากชั้นล่างขึ้นบนและแบบ DWDDF

การศึกษาการจำลองแบ่งออกเป็นสองส่วน: ตัวแปรที่เกี่ยวข้องกับการผลิตและคุณสมบัติของแหล่ง กักเก็บ สำหรับการประเมินตัวแปรที่เกี่ยวข้องกับการผลิต ผลของแบบจำลองแสดงให้เห็นว่ากรณีที่ดีที่สุดของ DWDDF ผลิตปริมาณเทียบเท่าน้ำมัน (BOE) เพิ่มขึ้น 16.47% และน้ำน้อยลง 94.04% เมื่อเทียบกับกรณีที่ดีที่สุดของการผลิตแบบจากชั้นล่างขึ้นบน ในการเปรียบเทียบระหว่างการผลิตแบบจากชั้น ล่างขึ้นบนและ DWDDF สำหรับคุณสมบัติของแหล่งกักเก็บที่แตกต่างกัน พบว่าความหนาของแหล่งกักเก็บก๊าซธรรมชาติและความหนาของชั้นน้ำเป็นปัจจัยสำคัญที่ส่งผลต่อค่า BOE เนื่องจากเกี่ยวข้องกับปริมาณของก๊าซและน้ำที่ไหลผ่าน นอกจากนี้ การบังคับใช้ DWDDF จะมีประสิทธิภาพมากขึ้นเมื่อนำไปใช้ในแหล่งกักเก็บก๊าซธรรมชาติที่มีความสามารถในการซึมผ่านในแนวนอนที่ดีและ kv/kh ratio ที่ต่ำกว่า

สาขาวิชา	วิศวกรรมทรัพยากรธรณีและปิโตรเลียม	ลายมือชื่อนิสิต ....
ปีการศึกษา	2564	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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KEYWORD: DOWNHOLE WATER DRAIN FOR WATER DUMPFLOOD, DOWNHOLE WATER DRAIN, WATER DUMPFLOOD, WATER CONING, WATER CROSSFLOW, GAS CROSSFLOW

Htet Myet Zin Naing : Downhole Water Drainage from a Gas Reservoir for Water Dumpflood in an Underlying Oil Reservoir. Advisor: Asst. Prof. SUWAT ATHICHANAGORN, Ph.D.

For wells drilled in a bottom water-drive gas reservoir, water coning may lead to a considerable amount of water production which diminishes the gas recovery. If the gas reservoir has an oil reservoir underneath, a method called “Downhole Water Drain for Water Dumpflood” (DWDDF) can be performed to drain water from the aquifer underneath the gas reservoir and dump it into the oil reservoir to perform waterflooding. DWDDF technique can help increase gas production from the upper gas reservoir and oil production from the lower reservoir at the same time. In this study, a simple reservoir model having common rock and fluid properties found in Thailand was constructed using ECLIPSE100 numerical reservoir simulator in order to evaluate the performance of the conventional bottom-up production scenario and the proposed strategy of the DWDDF scheme.

The simulation study was divided into two parts: operating parameters and reservoir parameters. For the assessment of the operating parameter, results demonstrate that the best case of DWDDF produces 16.47% more barrels of oil equivalent (BOE) and 94.04% less water production when compared with the best case of the bottom-up scenario. Comparing between bottom-up and DWDDF schemes for different reservoir properties, it was found that gas reservoir thickness and column height of aquifer are key factors affecting BOE recovery as it is related to the amount of gas and water crossflows. Furthermore, the applicability of DWDDF is more effective when it is applied in a gas reservoir with good horizontal permeability and a lower kv/kh ratio.

Field of Study:	Georesources and Petroleum Engineering	Student's Signature ....
Academic Year:	2021	Advisor's Signature ....

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Last but not least, this thesis is dedicated to my dearest parents: U Thein Oo and Daw Pyone Pyone Naing. This endeavour would not have been possible without their love and warm-hearted support for my studies, thank you very much.

Htet Myet Zin Naing

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LIST OF ABBREVIATIONS

API	American Petroleum Institute
BHP	Bottom hole pressure
BOE	Barrel of oil equivalent
cP	Centipoise
˚F	Degree Fahrenheit
ft.	Feet
GIIP	Gas initially in place
GOR	Gas to oil ratio
ID	Internal diameter
mD	Millidarcy
MMSCF	Million standard cubic feet
psia	Pound force per square inch absolute
PVT	Pressure volume temperature
RB/STB	Reservoir barrel per stock tank barrel
SCAL	Special core analysis
SCF	Standard cubic feet
STB	Stock tank barrel
THP	Tubing head pressure
VFP	Vertical flow performance
VLP	Vertical lift performance
WGR	Water to gas ratio

NOMENCLATURES

B_g	Gas formation volume factor, bbl/MSCF
B_w	Water formation volume factor, RB/STB
FL	Frictional loss, psi/BWPD
h_g	Column height of gas zone, ft
h_w	Column height of water zone, ft
k_h	Horizontal permeability, mD
k_{rg}	Relative permeability to gas
k_{ro}	Relative permeability to oil
k_{rw}	Relative permeability to water
k_v	Vertical permeability, mD
n_g	Corey exponent for gas
n_o	Corey exponent for oil
n_w	Corey exponent for water
p_{eo}	Boundary pressure in oil zone, psig
p_{ew}	Boundary pressure in water zone, psig
S_{gcr}	Critical gas saturation
S_{gi}	Initial gas saturation
S_{org}	Residual oil saturation to gas
S_{wcr}	Critical water saturation
S_{wi}	Initial water saturation
S_{win}	Minimum water saturation

CHAPTER 1

INTRODUCTION

1.1 Introduction and Problem Statement

Many natural gas producing wells around the globe are dealt with liquid loading problem since the early time of petroleum industry. Liquid loading is a crucial problem in gas wells because not only gas production can be reduced but also liquid loading can kill the well by accumulating water in the wellbore. Gas reservoirs associated with aquifers experience lower gas recovery compared to volumetric gas reservoirs due to liquid loading problems. Liquid loading is mainly caused by excessive water production because of water-coning toward the perforation of the gas-producing well. As the gas is produced, the fluid pressure around the wellbore is reduced and creating a differential pressure at the vicinity of the well that tends to deform gas-water contact (GWC) into a bell shape. Thus, the water invades toward the well, leading to reduced ultimate gas recovery as large packets of gas would be left behind the encroaching waterfront. In addition, water coning in gas wells incur a considerable amount of water production at the surface. Produced water needs to be disposed of in environmentally acceptable ways, creating higher operating costs.

The problem of liquid loading can be moderated by reducing the strength of the water aquifer. One of the techniques to alleviate water coning toward wellbore is the Downhole Water Drain (DWD). This innovative technique allows to drain water from the water zone (water source) underneath the gas reservoir to a lower reservoir (water sink) by perforating both the water source and the water sink. In the case that the lower reservoir is an oil reservoir, water from the water source can be used for the purpose of water dumpflood. Water dumpflood is the technique in which downhole water is dumped into the low-pressured oil reservoir in order to maintain the reservoir pressure with the aid of natural crossflow. Thus, no additional injection well is required. As a consequence, there is no extra cost for the injection operation. Therefore, the water dumpflood technique can help increase oil production at a low cost.

In this thesis, the concepts of DWD and water dumpflood are combined to study the applicability and effectiveness of both production techniques. A simple representative system of reservoirs to implement the above-mentioned concept is necessary to include bottom water drive gas reservoir at a shallower depth (upper gas reservoir) and oil reservoir at a deeper location (lower oil reservoir). DWD technique can help reduce water coning in the upper gas reservoir. At the same time, water from the aquifer is drained (due to DWD technique) to the lower oil reservoir, similar to water dumpflood technique. Therefore, this innovative technique is named as Downhole Water Drain for Water Dumpflood (DWDDF). This proposed method requires the well to be perforated in three intervals: upper gas reservoir, aquifer and lower oil reservoir. In addition, gas zone completion and water zone completion are required to be isolated by installing a packer inside the casing. Then, gas can be produced to the surface and water can be dumped into the lower oil reservoir from the aquifer underneath the gas reservoir simultaneously. Oil from the repressurized lower oil reservoir can be put on production from production wells. Therefore, DWDDF technique not only increase gas recovery by reducing water production in the upper gas reservoir but also increase oil recovery in the lower oil reservoir.

In this study, the performance of the proposed method is investigated by using ECLIPSE100 numerical reservoir simulator. The generic reservoir model is created by using general rock and fluid properties for the upper gas reservoir and aquifer whereas typical fluid properties from fields in the Gulf of Thailand for lower oil reservoir. Thus, this study is mainly focused on the investigation of suitable reservoir parameters to apply Downhole Water Drain for Water Dumpflood technique. Prior to performing study on reservoir parameters, operational parameters were investigated such as well locations, perforation intervals for proposed three zones (gas-, aquifer-, oil-zone), and appropriate time to operate dumpflood in order to have an optimum condition. After that reservoir parameters were varied in order to determine a broad range of reservoir characteristics to implement the proposed method. The studied parameter for this section includes horizontal permeability, kv/kh ratio, thickness of gas column and thickness of water column in the upper gas reservoir.

1.2 Objectives

1. To investigate the performance and applicability of the “Downhole Water Drain for Water Dumpflood” technique compared to conventional production technique (natural depletion)
2. To determine the appropriate operational and general reservoir conditions that make “Downhole Water Drain for Water Dumpflood” fruitful.

1.3 Outline of methodology

A black oil simulator of Schlumberger Simulation Launcher (ECLISPE100) was used to create a numerical reservoir model and investigate the performance of the conventional production technique and proposed production strategy. The outline of the methodology is as follows:

1. Construct the generic rectangular shape reservoir model using Cartesian coordinates. It includes two homogeneous reservoirs separated by a shale layer: the upper reservoir is the bottom water-drive reservoir, and the lower reservoir is the oil reservoir.
2. Set up three production wells for a conventional bottom-up production scenario, and two production wells and one dumping well for the proposed production strategy of downhole water drain for water dumpflood (DWDDF) scheme in order to conduct operating parameters and reservoir parameters studies.
3. Perform simulation for the bottom-up scenario in order to investigate the effect of (a) well locations for two wells aside from the middle well, and (b) perforation interval of the oil column. Next, the selected well location is used to study the effect of the perforation interval of the gas column.
4. Conduct simulation for DWDDF scheme to examine the well locations for two production wells assuming the other operating conditions as 60% for oil, gas, and water perforation intervals and

dumpflooding at the end of plateau rate. Then, the selected well location is used to find out the effect of the following operating parameters:

    a. Perforation interval of the oil column
    b. Perforation interval of the gas column
    c. Perforation interval of the water column
    d. Starting time for water dumpflood

5. The selected best operating condition of each production technique is employed at each of the following reservoir conditions in order to investigate the applicability of the proposed method.
    a. Horizontal permeability of the gas reservoir
    b. kv/kh ratio of the gas reservoir
    c. Thickness of the gas column
    d. Thickness of the water column

1.4 Outline of thesis

There are six chapters in this thesis consisting of:

Chapter 1 describes the liquid loading and water coning problems found in gas wells with conventional production techniques and the general concept of the proposed production strategy. It also states the objectives, the outline of thesis and the expected usefulness getting from this research study.

Chapter 2 provides brief descriptions of previously published works of literature and methods related to mitigating water coning problems in gas wells located in the bottom water-drive reservoir as well as the oil production improvement option using water dumpflood.

Chapter 3 includes fundamental theories and concepts related to the study.

Chapter 4 presents the details of the numerical reservoir model construction in ECLIPSE100. It also provides details of the thesis methodology.

Chapter 5 highlights the simulation results from various operating conditions and reservoir conditions of bottom-up and DWDDF production techniques. Moreover, obtained results and new findings from this simulation study are analyzed and discussed in this segment.

Chapter 6 is composed of conclusions of this research and recommendations for further study.

1.5 Expected Usefulness

This study is aimed to provide a comprehensive explanation about “Downhole Water Drain for Water Dumpflood” technique. The explanations are stated by comparing the proposed method with the conventional oil and gas production technique. Additional expected consequences of this thesis are as follows:

1. The outcomes of the thesis are expected to bring a better insight regarding the “Downhole Water Drain for Water Dumpflood” technique
2. The results of the study are anticipated to bring perception in case of choosing suitable reservoir parameters/conditions to operate the “Downhole Water Drain for Water Dumpflood” technique.
3. This academic study is envisaged to be a general guideline regarding the “Downhole Water Drain for Water Dumpflood” technique in the case of determining operating conditions.

CHAPTER 2

LITERATURE REVIEW

In this chapter, relevant studies on the water coning mechanism and various methods for reducing water coning in the water-drive reservoir are described. In addition, investigations related to water dump-flood in oil reservoirs are also reviewed and summarized.

Armenta & Wojtanowicz [1] conducted a study to qualify water coning mechanisms in gas wells. They developed a combination study of numerical simulation and analytical models in order to analyze the major reasons that trigger off a substantial increase in water production. The authors concluded that early water breakthrough and increasing water-gas ratio (WGR) may result from water coning due to the combined effects of increased vertical permeability, non-Darcy flow due to high gas flow velocity, and lower density of perforation.

Arcaro and Basssiouni [2] performed a technical and economic feasibility study of the co-production process for the Eugene Island field. The co-production method is one of the improved gas recovery methods for moderate-strong water drive gas reservoir, in which existing wells in the watered-out area of the reservoir are converted to higher rate water producers. The authors suggested that the co-production technique can enhance gas recovery for water drive gas reservoir in three ways by (1) producing water to the surface to lower the reservoir pressure and allowing remaining gas to expand, (2) producing water from watered-out well to slow the advance of water shock front and (3) lowering the reservoir pressure in the swept zone would allow the previously trapped immobile gas to mobile. They chose 10,300-ft sand in Eugene Island Block 305 to study the applicability of the co-production technique. The authors made a comparative study between conventional production and co-production for the subject reservoir by using volumetric analysis, the material balance approach and a layered tank model based on the material balance equation (MBE). According to simulation results, the co-production method is predicted to give 83% of gas recovery while conventional production can only provide 62% of the recovery. After that, economic analysis is conducted by varying gas prices ($0.5 to $5/ Mcf) to compare the profitability of each production process. The authors suggested that the co-production process is a fruitful option to apply this reservoir. Finally, the authors advised that co-production can certainly enhance gas recovery and it is profitable to apply in many other water drive gas reservoirs. However, these reservoirs should meet the general screening criteria of this technique and it is necessary to perform economic analysis for potential reservoirs in order to determine whether coproduction is also economically feasible for these reservoirs or not. Lastly, the authors recommended that it would be achieved the greatest economic potential if co-production is set up in reservoirs not yet watered out.

Armenta & Wojtanowicz [3] proposed dual completions with the downhole water sink (DWS) method to increase gas recovery in the bottom-water gas reservoir. The authors evaluated that efficacy of the well with the DWS technique is significantly better than conventional well from the perspective of gas production performance. Numerical simulation is used in this study and the performance of DWS well is comparatively studied with outcomes of both conventional well and downhole gas water separator (DGWS) well. According to the results, 2.6 times gas recovery is increased in the tight reservoir with low pressure by applying a dual completion system compared to conventional wells. Results show that it is important to have a full perforation in a low permeability reservoir to bring the highest recovery whereas gas recovery is insensitive to perforation larger than 30% in higher permeability reservoirs for the study of conventional wells. Besides, DWS wells show the highest recovery over conventional wells and the authors suggested that the reservoir with permeability less than 10mD and subnormal pressure is the best candidate to apply DWS. The authors stated that completion length also plays a major role in DWS wells. In this study, DGWS and DWS gave similar final gas recovery, however, the production time of DGWS is 35% lengthier than DWS. Moreover, less water is produced in DWS well compared to DGWS.

Radwan [4] investigated the feasibility of the downhole gas-water separation (DGWS) technique in order to improve gas recovery in the bottom water drive gas reservoir. The concept of DGWS is the separation of gas and water inside the well and separated water is injected into the same aquifer. By taking advantage of the large gravity difference between gas and water, the DGWS technique is achieved by allowing the occurrence of natural separation between water and gas in the casing-tubing annulus. The naturally separated gas flows to the surface whereas the separated water is re-injected by installed bypass tools or downhole pumps. Results show that DGWS can always achieve higher gas recovery efficiency than conventional wells and full gas column perforation can provide the highest recovery in DGWS well. Lower reservoir pressure with smaller permeability (less than 10mD) is the best condition to operate DGWS technology. The author concluded that DGWS can increase 333% of the gas recovery in the low-pressure reservoir (1500 psia) with 1mD permeability.

Wojtanowicz and Xu [5] conducted a study to reduce formation water production during oil production from bottom water drive oil reservoir by applying a new completion method. The proposed completion method comes up with three sets of completion throughout the well; one completion in the oil zone to produce oil and another two sets of perforations are located within the upper and deeper locations of the water column to accommodate water loop equipment. The water loop equipment is separated by a packer from the oil completion and it involves a submersible pump, the upper perforation (water sink) and the lower perforation (water source). The concept is that water is allowed to drain from the sink into pump suction and it is reinjected into the deeper location of the water zone (source). This idea not only increases oil recovery together with the reduction of water production but also gives a solution to solve environmental problems regarding the disposal of produced formation water. The numerical simulation study was conducted and the results reveal that the downhole water loop method can effectively hold down the dynamic shape of OWC in the vicinity of the well and it would increase two to four times of oil production rate with minimum water cut compared to the conventional completions. The degree of effectiveness of this method is improved under the following conditions;

1. When strong water drive obstructs the oil production through water coning,
2. When the lateral departure of discharge (injection) section of the water loop is deviated enough to set water source below and aside from the water sink and
3. When the aquifer is thick enough to provide adequate lateral departure for the discharge section (water source) without having excessive hole curvature of the well in the water column.

Jin and Wojtanowicz [6] initiated an attempt to develop the nodal analysis model to apply it for DWL well in order to produce oil from the bottom water drive oil reservoir. In this investigation, three design parameters are focused on, which are the depths of the three well completions, oil production rate (top rate) and drainage/injection rate (bottom rate). The authors made an investigation regarding the operational range of DWL for a subject reservoir and conducted a comparative study between the conventional production technique and DWL technique. The completion of DWL wells involves top oil completion within the oil column, water sink completion below OWC and injection completion at the deeper location of the same water column. Submersible pumps are installed in both top oil completion and water sink completion, the former is used to produce oil and the latter is applied to inject drained water to a deeper location of the same aquifer. Top rate, bottom rate and drainage/injection spacing (D/I spacing) are selected operational parameters to study by using a simulator. Results show that DWL wells can produce higher oil rates with lower water cut whereas conventional wells produce a constant liquid rate, higher water cut leads to less oil produced. In DWL wells, higher D/I spacing can significantly achieve a higher oil rate together with reducing water cut. In addition, it is interesting to know that greater D/I spacing can increase the critical oil production rate. However, they found out that there is an optimum value for D/I spacing, no more improvement would be found if the D/I spacing value is higher than the optimum value. Two times increase in water drainage would provide an 80% increase in oil production at optimum D/I spacing. Water-free oil production can exist for each DWL system and this favourable condition comes together with the combination of top production rate, drainage-injection rate and D/I spacing. At particular D/I spacing, it is necessary to achieve synchronized increases in production and drainage rates together, as a result, this can bring an effective increase in oil production. This implies that increasing oil production alone could not bring a favourable condition since it would result in higher water cut. The fruitful fact is that DWL wells can effectively perform even with small D/I spacing, which means this technique has the possibility to achieve a favourable condition if it is also operated in the thin aquifer. Lastly, the authors proposed that nodal analysis can be applied in DWL wells to design D/I spacing and determine what would be the required number of ESP to equip in the particular system.

Kamonkhantikul [7] conducted a study to determine suitable operating and reservoir conditions for the downhole water drain (DWD) method. In the DWD method, the well is perforated at the water zone underneath the gas reservoir to drain water into the partially depleted gas reservoir. This method not only reduces the water coning problem but also increases gas recovery from both reservoirs. The strength of the aquifer becomes less strong when water from the aquifer drains into the lower gas reservoir. Thus, more gas from the bottom water-drive gas reservoir can produce with less water production as water coning toward the upper gas reservoir is mitigated. Besides, the additional benefit is that draining water into the pressure-depleted gas reservoir at a deeper location can induce gas reservoir repressurization, and it can bring more gas production. According to the results, gas recovery is slightly improved and water production reduces moderately in the case of a lower initial production rate for commingled production. For bottom-up production, all the studied operational parameters induce a small impact on gas recovery. Both production scenarios show gas recovery efficiency is fairly improved when gas zone perforation interval becomes longer, however, water production is significantly increased. For DWD, gas recovery is slightly increased at longer gas and water perforation intervals. Then, the author selected the best cases from each production scenario to study reservoir parameters. Results show that water column thickness can moderately impact gas recovery for commingled production, however, its impact is small on DWD and bottom-up production. Lower gas reservoir thickness can considerably affect commingled production, fairly affect bottom-up production and slightly affect DWD. The author explained that vertical permeability has a strong impact on bottom-up and commingled production while having no impact on DWD. On the other hand, horizontal permeability induces a small impact on DWD, strong impacts on commingled production and moderate impacts on bottom-up production. Results show that under the same reservoir condition, DWD has better gas recovery and lower water production compared with both bottom-up and commingled production.

Ogolo et al. [8] conducted a simulation study to investigate the feasibility of improved gas recovery by injecting CO2 gas at the gas-water contact (GWC) to control water influx. CO2 can separate the gas zone and water zone by occupying a space between them since water is denser than CO2 and CO2 is denser than methane. Besides, CO2 can displace natural gas by expanding and it can increase and maintain reservoir pressure simultaneously. Even if water influx has happened at some point, the zone which is invaded by water is the CO2 zone; thus, the gas zone would not be invaded by water. In fact, this technique can transform the water drive mechanism into a full or partial volumetric drive mechanism. In addition, CO2 can dissolve in water – the solubility of CO2 in water is increasing together with pressure and decreasing together with increasing salinity of water and temperature. One thing to note is that the solubility of CO2 in water is greater than in methane, as a consequence, CO2 breakthrough can be delayed because of its higher solubility in water. However, CO2 can contaminate natural gas because both of them can be miscible in some conditions. The authors studied two different conditions: conventional gas production for 30 years and gas production together with CO2 injection for 30 years. Three producers were arbitrarily placed surrounded by seven injectors (peripheral flood pattern). Simulation results show that recovery of 17% and 11% increase at two producers after 30 years of CO2 injection together with natural gas production compared with the case without CO2 injection. However, there is a 12% recovery decrease at one producer for the case with CO2 injection, authors reported that the problem at this producer has not been found yet. As a whole field result, 4% of condensate recovery is increased and about 60% of water influx is reduced by injecting CO2. This proposed method not only improves the recovery efficiency of natural gas but also increases cumulative condensate production. However, the total CO2 injection time and flood pattern in this study can be relatively expensive in terms of operation cost, which might not be economically favourable.

Buranatavonsom [9] introduced a method called Downhole Water Dump Flood (DWDF) to solve the problem of water coning in a strong bottom-water drive gas reservoir. He conducted a comparative study between the conventional gas production method and DWDF by varying the perforation interval of the gas reservoir. He created a reservoir model, which is composed of a bottom water-drive gas reservoir (upper reservoir) and a lower oil reservoir. There are two wells in this investigation, one well is connected to both upper and lower reservoirs and another well is connected to the lower reservoir only. Results show that gas perforation interval of 50% is the optimum condition. The difference between DWDF and conventional gas production is that the DWDF method requires to perforate into the aquifer to drain water from there to the lower oil reservoir. The authors studied the DWDF method by creating a water perforation interval of 50% (from the bottom of the aquifer) and he studied the different cases of perforation interval for the gas zone to find out the optimum conditions for gas production from the upper reservoir and oil production from the lower reservoir. In order to find out the best condition from the perspective of the production optimization point, the cumulative gas and oil production were combined into a single unit, which is the barrel of oil equivalent (BOE). Simulation results show that an 80% gas perforation interval is the optimum condition. According to the results, the author concluded that DWDF is not only able to reduce water production but also able to increase gas recovery. The author also suggested that gas perforation is a key factor in this method, it can directly affect total gas and water production. And also, DWDF can perform better than the conventional method when the gas perforation is more than 50%. Last but not least, DWDF can increase by 21% of oil recovery over the conventional method.

Shizawi et al. [10] presented a successful field implementation of the dumpflooding process to improve oil recovery in a small satellite field of W-field, managed by Petroleum Development Oman (PDO). The authors stated that this satellite field was suggested to perform the waterflooding process due to its pressure depletion. However, there were some concerns about performing waterflooding in this small field is economically favourable or not. Thus, the dumpflood process came into consideration to improve oil production as an economically viable option because it does not require many surface facilities to inject water and additional injectors. In this field implementation, the water zone at the deeper location was perforated and produced water from this zone was injected into the upper oil reservoir by ESP. There are two main reservoirs in this field, which are H and A. The field contains 18 wells and two of them have been abandoned. In the dumpflood well, the lower water zone and upper oil zone are isolated by a Pod system, a retrievable ESP packer is installed above the oil zone and SSD is installed against the upper oil zone to discharge fluid. Pressure response and improved oil production has been seen at surrounding producers after 10 months of the dumpflood operation. They said that fracture pressure is reached after 10 months of injection and the H-zone was stopped to inject water. The authors concluded that the benefits of pressure response and oil gain in the range of 40% have occurred by dumpflooding in W-field.

According to these previous studies, the bottom water-drive gas reservoir with the water coning problem can be solved by several production techniques that can improve gas recovery and reduce unwanted water production. There is one study that describes applying the downhole water dump flood technique in the multi-layered system (consisting of the bottom water-drive gas reservoir and underlying oil reservoir located at a deeper location) not only increases gas recovery from the bottom water-drive gas reservoir but also improves oil recovery from the oil reservoir. Nevertheless, none of the literature has investigated the effect of well location, the effect of perforation interval of oil and water columns, and the effect of starting time to implement dumpflood for the downhole water drain for water dumpflood (DWDDF) scheme. Besides, there is no research investigation relating to a study on various reservoir parameters regarding the DWDDF scheme. Hence, this study is aimed to investigate the appropriate operating condition and suitable reservoir conditions for the DWDDF scheme.

CHAPTER 3

THEORY AND CONCEPT

Water production in gas wells is more sensitive compared to oil wells. Excessive water production not only reduces the gas recovery efficiency but also shortens the production life. Once a lot of water accumulates at bottom of the gas well, gas in the reservoir is unable to flow into the well, resulting in the liquid loading problem. Water coning is a crucial reason for excessive water production in gas wells and it can be caused by differential pressure due to gas production when the perforation of the well is close to gas-water contact (GWC).

Fluid flow distribution around the wellbore is dominated by three forces, which are capillary force, viscous force, and gravity force. Typically, capillary force is neglected in coning. Viscous force is related to the pressure gradient of associated fluid while gravity force is associated with fluid density differences and related to the vertical direction. Coning can occur when the viscous force around the wellbore is greater than the gravitational force.

The simplest way to reduce water coning in gas wells is not to produce the gas higher than the critical production rate. Once the gas well is producing gas over the critical production rate, the cone vicinity to the well starts to deform and aquifer water breakthrough into the perforation can incur. There are various methods to estimate the critical production rate for the oil-water system. Only a few of these methods can be used for both gas-water system and oil-water system. The method proposed by Chaney et al. [11] in 1956 can be used to estimate the critical flow rate for both gas and oil. Equation 3-1 was developed by Chaney et al. [11] in order to determine the critical flow rate for gas wells, in which they suggested critical production rate curves are required to determine hypothetical rates (Q_{curve}). In fact, Q_{curve} is the corrected value to account for the actual properties of reservoir rock and fluid.

$$Q_{gc} = 0.5288 \times 10^{-4} \left[\frac{k_g(\rho_w - \rho_g)}{\mu_g B_g} \right] Q_{curve} \tag{3-1}$$

where

Q_{gc} = critical gas flow rate, MSCF/D

k_g = effective gas permeability, md

ρ_w = density of water, lb/ft^3

ρ_g = density of gas, lb/ft^3

μ_g = viscosity of gas, cp

B_g = gas formation volume factor, bbl/MSCF

Q_{curve} = hypothetical rates

This study is focused on not only investigating solving the problem of water encroachment toward gas well perforation by dumping downhole water from the water zone underneath the gas reservoir but also examining the benefit of water dumpflood in the oil reservoir. The concept of water dumpflood is the process of allowing water to flow naturally from the water-bearing reservoir into the oil reservoir by creating a flow communication in the well. In fact, it is necessary for the water zone to have higher pressure compared to the oil reservoir. Hence, water from the water zone (high-pressure zone) can flow naturally into the oil reservoir (low-pressure zone). Water dumpflood is famous for lower capital and operating costs compared to waterflooding. In addition, it has a positive impact on the environment regarding the disposal of water. Davies [12] proposed that the rate at which fluid flows from one zone to another zone is a constant value if the reservoir static pressures in both zones are maintained. The author described the equation for fluid transfer based on the injectivity of injected zone, the productivity of the water source, friction loss in the casing and the difference between reservoirs' static pressures.

$$q_w\left[\frac{1}{I}+\frac{1}{J}+FL\right]=p_{ew}-p_{eo}=\text{constant} \tag{3-2}$$

where

q_w =water producing rate, BWPD

I =injectivity index, BWPD / psi

J =productivity index, BWPD / psi

FL =frictional loss, psi / BWPD

p_{ew} =boundary pressure in water zone, psig

p_{eo} =boundary pressure in oil zone, psig

As the water dumpflood is similar to waterflooding in terms of injecting water into the oil reservoir, it is good to understand the relationship between injection rate and injection pressure. In this study, water from the bottom water-drive reservoir is dumpflooded into the underlying oil reservoir. Therefore, the aquifer pressure and its size are important parameters for the downhole water dumpflood operation since these properties are related to the amount of water dumped. The relationship between injection rate and injection pressure in the radial flow system can be expressed in mathematical form as follows:

$$p_{inj} - \overline{p_R} = 141.2 \frac{q_{inj} B_w \mu_w}{k k_{rw} h} \left[\ln\left(\frac{r_e}{r_w} \right) - 0.75 + s \right] \tag{3-3}$$

where

p_{inj} = well injection pressure, psi

$\overline{p_R}$ = average reservoir pressure, psi

q_{inj} = water injection rate, bbl/D

B_w = water formation volume factor, RB/STB

μ_w = water viscosity, cp

k = absolute permeability, mD

k_{rw} = relative permeability to water

h = reservoir thickness, ft.

r_e = well's drainage radius, ft.

r_w = wellbore radius, ft.

s = skin

CHAPTER 4

METHODOLOGY

As the objectives of this research are to investigate the performance of the "Downhole Water Drain for Water Dumpflood" (DWDDF) technique by varying different operational parameters and to analyze the suitable reservoir conditions for the application of the proposed technique, a hypothetical reservoir model is built using general rock and fluid properties. A numerical reservoir simulator of ECLIPSE100 was used to accomplish this task. Generally, the simulation study is divided into two sections: Bottom-up production and DWDDF. All steps of each production method are clearly expressed in this chapter.

4.1 Reservoir model

The generic reservoir model is constructed as a rectangular shape using Cartesian coordinates. This hypothetical model consists of two homogeneous reservoirs: upper bottom water-drive gas reservoir and lower oil reservoir separated by a shale layer. The top depths of the bottom water-drive gas reservoir and oil reservoir are 6,000 ft and 8,000 ft, respectively. For the base case of this study, the upper zone consists of 15 feet of gas column and 15 feet of water underneath; the shale layer separating the upper and lower zone is1970 ft, and the lower oil reservoir is 100 ft thick. The length and width of both reservoirs are 3150 ft and 750 ft, respectively. The reservoir model is created by using 63x15x41 grid cells in the direction of x, y, and z, respectively. Thus, each grid size in both x- and y-direction is 50 ft. Since there are 41 grids in the z-direction, the grid arrangement of each zone is 10 grids of the gas zone, 20 cells of water zone, 1 block of shale layer and 10 layers of oil zone. The details of the reservoir model are summarized in Table 4.2, and the constructed hypothetical reservoir model is illustrated in Figures 4.1-4.3.

Table 4.1 Dimensions of the hypothetical reservoir model.

Property	Bottom water-drive gas reservoir		Oil Reservoir	Unit
	Gas Zone	Water Zone		
Top depth	6000	6015	8000	ft
Thickness	15	15	100	ft
Dimension in X, Y, Z directions	3150 x 750 x 15	3150 x 750 x 15	3150 x 750 x 100	ft
Number of cells in X, Y, Z directions	63 x 15 x 10	63 x 15 x 20	63 x 15 x 10	-
Grid Size in X, Y, Z directions	50 x 50 x 1.5	50 x 50 x 0.75	50 x 50 x 10	ft

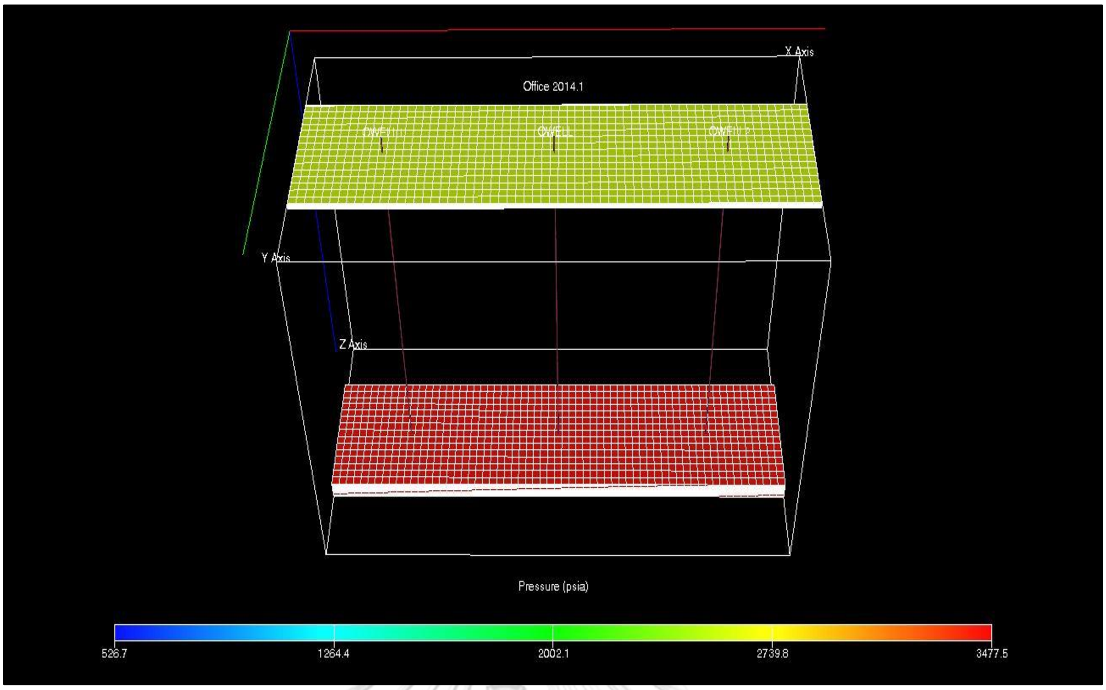


Figure 4.1 3-D view of bottom water-drive reservoir and lower oil reservoir.

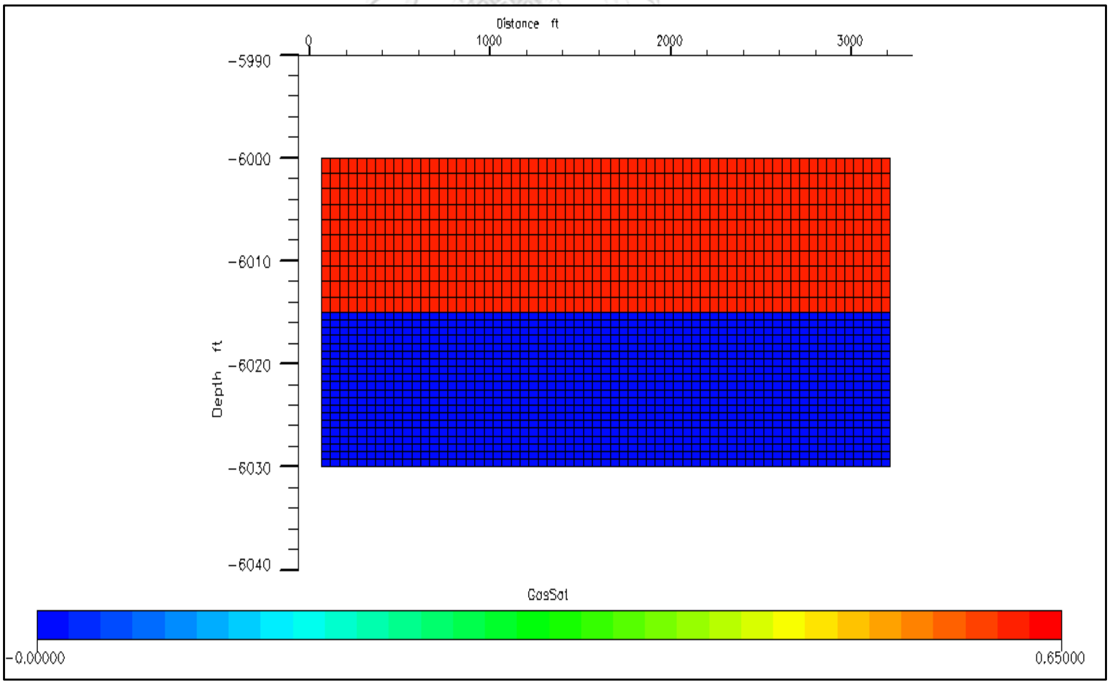


Figure 4.2 Side view of bottom water-drive reservoir.

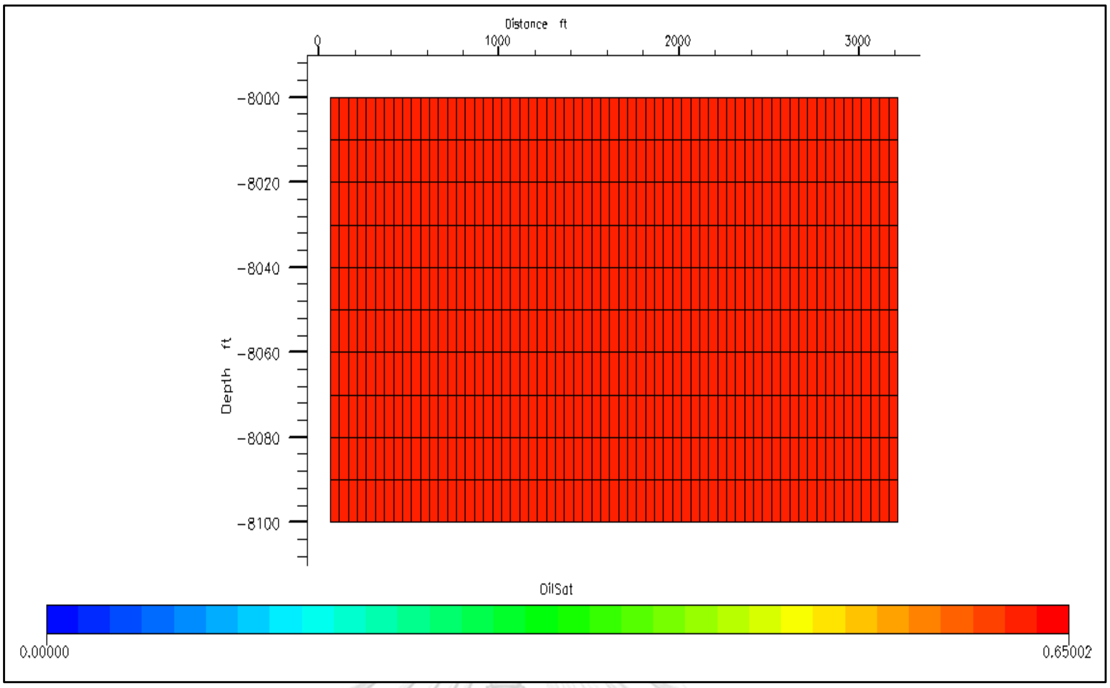


Figure 4.3 Side view of lower oil reservoir.

Since this study is aimed to investigate the proper reservoir condition to apply the DWD technique in bottom-water drive gas reservoir together and water dumpflood in oil reservoir at a deeper location isolated by a shale layer, the hypothetical model is built by using general rock and fluid properties. The general rock and fluid properties of each reservoir used in this study are shown in Table 4.2.

Table 4.2 Physical properties of generic reservoir model.

Property	Bottom water-drive gas reservoir		Oil Reservoir	Unit
	Gas Zone	Water Zone		
Porosity	0.2	0.2	0.2	fraction
Horizontal Permeability	15	15	100	mD
Vertical Permeability	1.5	1.5	10	mD
Initial water saturation	0.35	1	0.35	fraction
Initial gas saturation	0.65	0	0	fraction
Initial oil saturation	0	0	0.65	fraction

4.2 PVT Section

Since this study is aimed to evaluate the applicability of downhole water drain from bottom water drive gas reservoir into a lower oil reservoir, it is necessary to define three fluids (gas, oil and water) in the PVT section. In this study, reservoir rock type is assumed as consolidated sandstone. For the oil reservoir properties, oil gravity, gas gravity, gas-oil ratio (GOR) and reservoir temperature are taken from the previous study of Anansupak [13], which is the study of viability study of the water dump-flood technique in the Gulf of Thailand. ECLIPSE100 calculates the required fluid and rock properties at different pressure and temperature conditions by using in-house correlations. A normal hydrostatic pressure gradient of 0.433 psi/ft is used to calculate for both water drive-gas reservoir and oil reservoir. Rock and fluid properties for the two reservoirs are summarized in Table 4.2 while PVT properties are illustrated in Figures 4.4-4.7.

Table 4.3 Rock and fluid properties of generic reservoir model.

Reservoir	Property	Value	Unit
Upper gas reservoir	Gas gravity	0.6	-
	Reservoir temperature	180	°F
	Reservoir pressure	2598	psia
	Reference Pressure (P_{ref})	2598	psia
	Water FVF at P_{ref}	1.015824	RB/STB
	Water compressibility	3.03E-06	psi^{-1}
	Water viscosity at P_{ref}	0.349905	cp
	Rock compressibility	1.53E-06	psi^{-1}
Lower oil reservoir	Oil gravity	35	°API
	Gas gravity	0.85	-
	Reservoir Temperature	200	°F
	Reservoir pressure	3464	psia
	Solution gas oil ratio	200	SCF/STB
	Bubble point pressure	960.21	psia
	Reference Pressure (P_{ref})	3464	psia
	Water FVF at P_{ref}	1.021051	RB/STB
	Water compressibility	3.07E-06	psi^{-1}
	Water viscosity at P_{ref}	0.3093396	cp
	Rock compressibility	1.53E-06	psi^{-1}

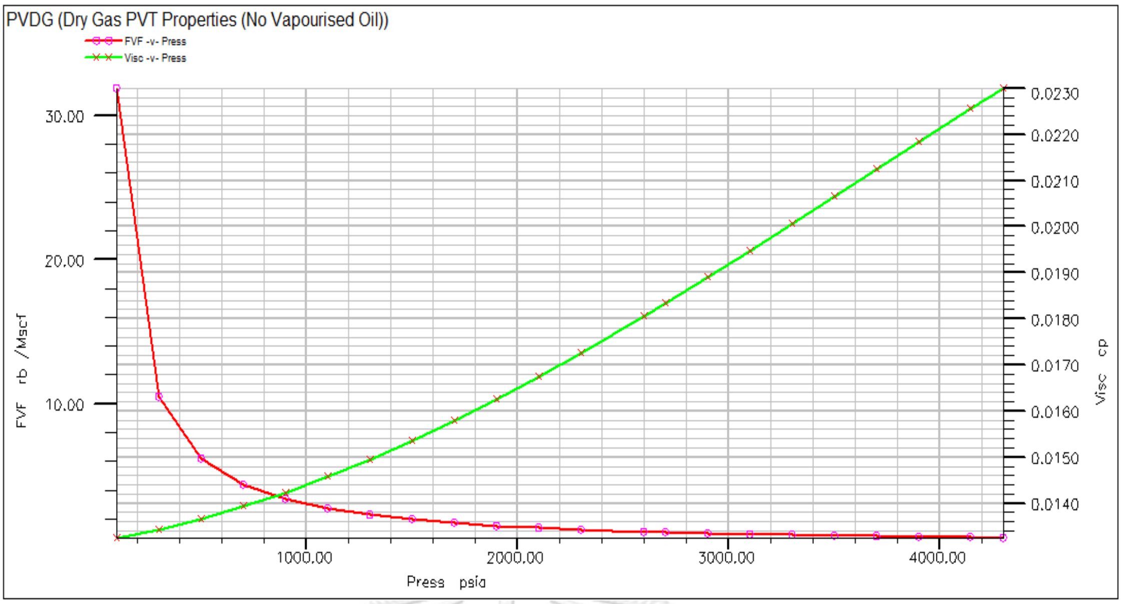


Figure 4.4 Gas Formation volume factor and gas viscosity for bottom water-drive gas reservoir.

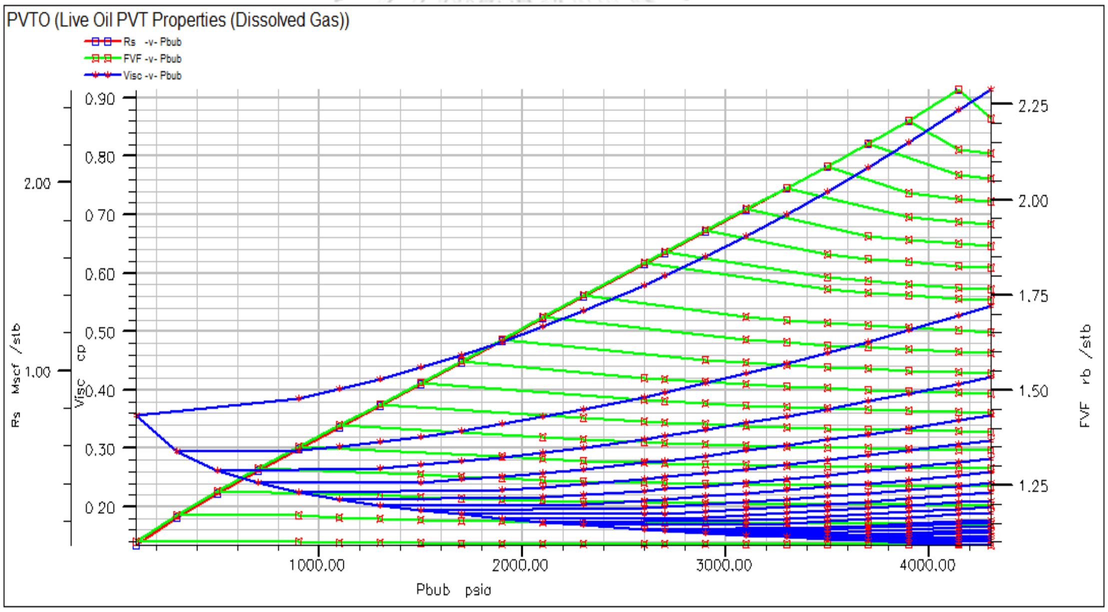


Figure 4.5 Live oil PVT properties for bottom water-drive gas reservoir.

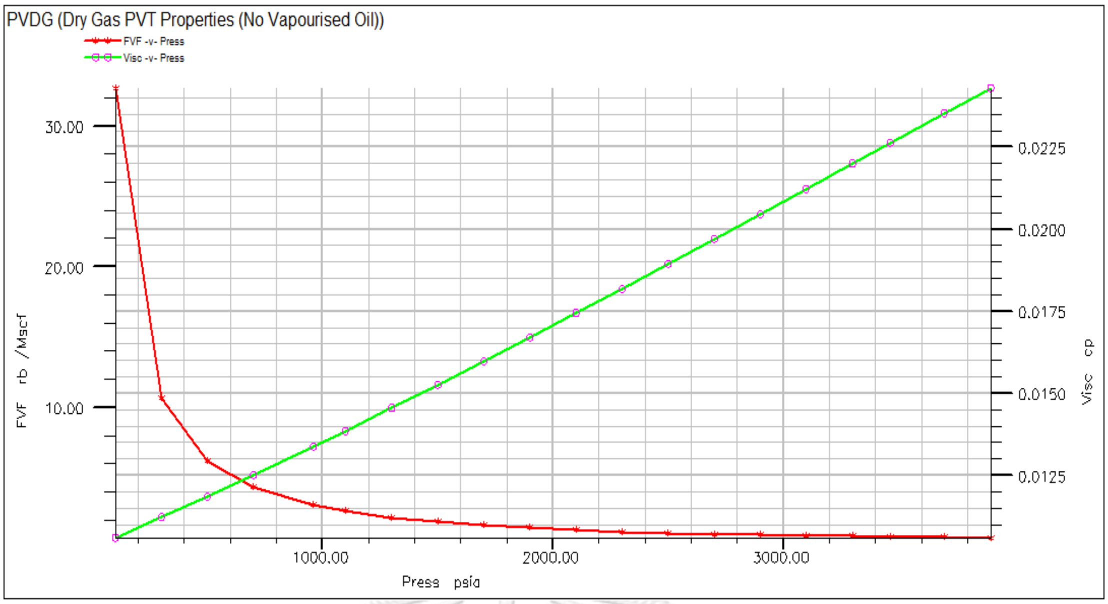


Figure 4.6 Gas Formation volume factor and gas viscosity for lower oil reservoir.

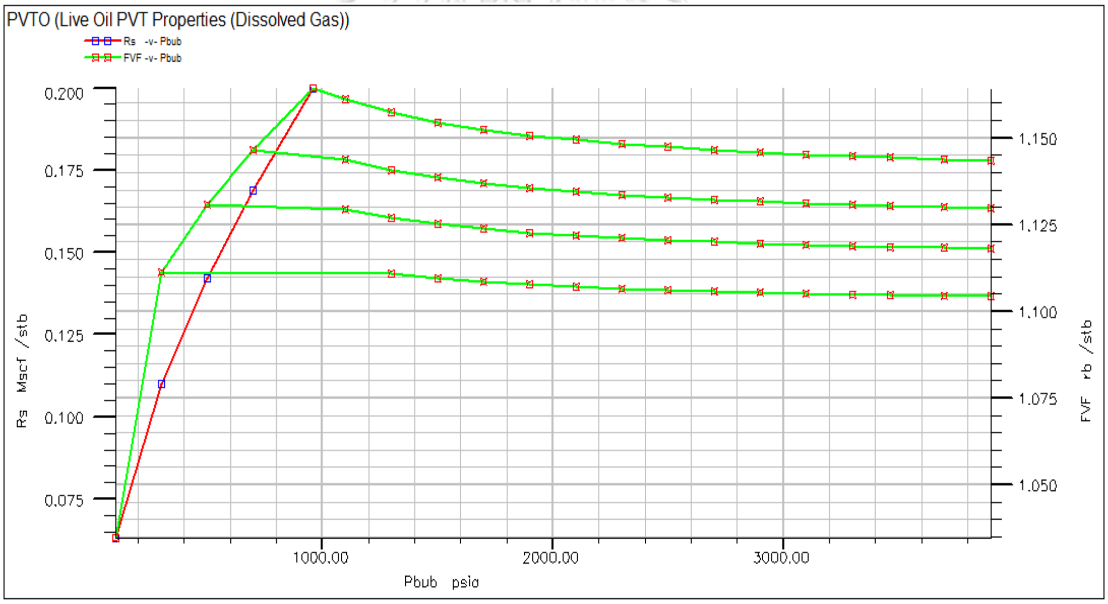


Figure 4.7 Live oil PVT properties for lower oil reservoir.

4.3 Special Core Analysis (SCAL) Section

In this study, Corey’s relative permeability correlation is assumed to generate required relative permeability curves using input parameters. Input parameters to generate relative permeability curves are taken from the previous study of Anansupak [13]. Both bottom water-drive gas reservoir (upper reservoir) and lower oil reservoir (lower reservoir) share the same set of input parameters, thus, both reservoirs possess the same oil-water and oil-gas relative permeability curves. Capillary pressure is neglected in this study. Table 4.4 shows the input parameters and values of these parameters to generate relative permeability curves using Corey correlation. Figures 4.8-4.9 illustrate relative permeability curves generated by Corey correlation.

Table 4.4 Parameters used in Corey correlation.

Parameter	Value
Corey exponent for water (n_w)	2.5
Corey exponent for gas (n_g)	2.5
Corey exponent for oil (n_o)	2.5
Minimum water saturation (S_{wmin})	0.35
Critical water saturation (S_{wcr})	0.35
Initial water saturation (S_{wi})	0.35
Relative permeability to water at S_{orw}	0.4
Relative permeability to oil at S_{wc}	0.8
Critical gas saturation (S_{gcr})	0.05
Initial gas saturation (S_{gi})	0.05
Residual oil saturation to gas (S_{org})	0.37
Relative permeability to oil at S_{gc}	0.8
Relative permeability to gas at S_{org}	0.4

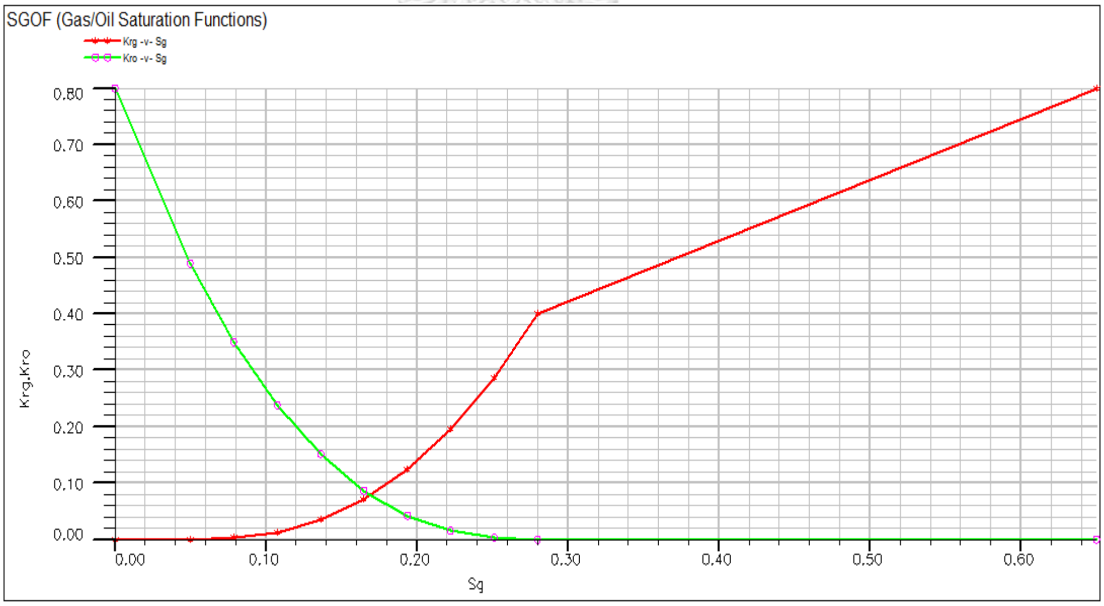


Figure 4.8 Relative permeability to gas and oil for upper gas reservoir and lower oil reservoir.

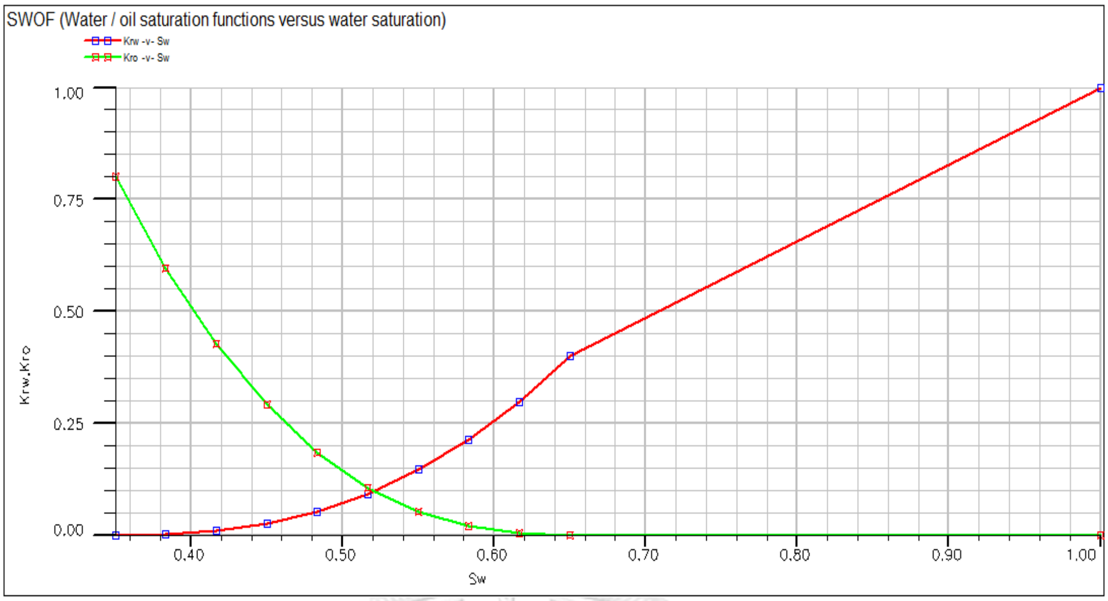


Figure 4.9 Relative permeability to water and oil for upper gas reservoir and lower oil reservoir.

4.4 Wellbore model and production control

There are two production scenarios in this simulation study: bottom-up production and Downhole Water Drain for Water Dumpflood (DWDDF). In fact, bottom-up production in this study is natural depletion, which is created to make a comparative study with DWDDF. There are three vertical wells for both cases to fulfil the objectives of this investigation. The wellbore diameter of all three wells is 6-1/8 inches with tubing ID of 2.441 inches and tubing roughness of 0.0006 inches. As the minimum tubing head pressure is specified as production control for gas production, a vertical flow performance table (VFP) needs to be generated for gas production from the upper reservoir. The same table will be used for three vertical wells. In this case, various gas flow rates, tubing head pressures (THP) and water-gas ratios (WGR) are used to generate the VFP table using Grey’s correlation. For oil production from the bottom reservoir, the minimum bottomhole pressure is specified for production control since pump is assumed to be installed. Thus, there is no need for VFP table. For the case of DWDDF, a VFP table is needed to determine the pressure loss in the tubing connecting the upper and lower reservoirs. In this case, various liquid flow rates and bottomhole pressures of the upper reservoir are varied to construct the VFP table using Petroleum Expert 2 correlation. In total, two vertical flow performance tables (VFP) are generated from PROSPER software and then exported to ECLIPSE.

For both scenarios, the minimum THP for gas production is specified at 300 psia, and the economic limit is 500 MSCF/day. For oil production, the minimum bottom hole pressure (BHP) is defined at 500 psia, which is a typical value used for abandonment conditions, and the economic limit of oil production is 50 STB/day while the maximum water cut is constrained at 90%. The simulation runs will stop once the production condition reaches one of these controlled values.

4.5 Production Scenarios

In this section, a detailed production schedule for bottom-up production and DWDDF scheme is discussed.

The first well is located in the middle of both reservoirs. In the case of bottom-up production, this well is used to produce fluids from the lower oil reservoir first and then the upper gas reservoir. In the case of DWDDF, this well is additionally perforated into the water zone when it is used to produce gas from the upper reservoir. The purpose of additional perforation is to drain and dump water into the lower oil zone (by creating two completion systems in the same well). For the other two wells, they are located on each side of the reservoir. In the case of bottom-up production, these two wells are used to produce fluids from the lower oil reservoir first and then the upper gas reservoir. In the case of Downhole Water Drain for Water Dumpflood, they are used to produce fluids from the lower oil reservoir only.

For bottom-up production, the lower oil reservoir is completed in all three wells to put on production in the first place. As this case is natural depletion, the three wells are produced until the specified oil production constraints. Then, the lower oil reservoir is isolated by installing a plug or packer above the top of the oil reservoir. After that, all three wells are perforated into the upper gas reservoir in order to produce gas. This completion operation is assumed to take 30 days; thus, it can be noted as gas wells are scheduled to be put on production 30 days after the end of oil production. Since this is natural depletion, gas production will be ended once the production rate is lower than the defined economic rate. Locations of the two wells aside from the middle one and perforation intervals of the lower oil reservoir and upper gas reservoir for the three wells are proposed to be investigated in the bottom-up production case.

For DWDDF scheme, the oil reservoir is produced using the natural drive mechanism plus the water being dumped from the upper reservoir. Three wells are initially used for oil production (except for the case that dumpflood is started since the first day of production). Locations of the two wells aside from the middle one and perforation intervals of the oil reservoir for the three wells were studied. To start DWDDF process, the middle well is perforated into the gas zone for gas production and into the water zone to drain water into the lower oil reservoir. Prior to gas zone perforation, a plug or packer can be installed inside the wellbore in order to prevent downward gas flow that may come from gas inside the tubing. Therefore, gas is produced to surface from gas column while water from the water column is dumped into the lower oil reservoir. During DWDDF, only the two wells aside the middle one produce fluids from the oil zone. Perforation interval of the gas column, perforation interval of the water column, and starting time for DWDDF process will be investigated to maximize hydrocarbon recovery.

4.6 Methodology

1. Build base reservoir model using ECLISPE100. The hypothetical model contains an upper bottom-water drive gas reservoir, a shale layer, and a lower oil reservoir.
2. Perform simulation to determine the best operating conditions for two scenarios:

a. For bottom-up production, this study investigates the best

   (i) locations for the two wells aside from the middle one since they affect the drainage area and flow geometry of the fluids towards the wells (3 sets of locations as shown in Figure 4.10). Note that the dark blue location indicates the middle well location which is fixed while the other well locations are varied to red locations (I-1=6, I-2=58), yellow locations (I-1=11, I-2=53), and green locations (I-1=16, I-2=48) and all well locations in the J direction are fixed at the 8th grid (J=8).

   (ii) perforation interval in the oil reservoir since secondary gas cap may form and affect oil production (80%, 60%, 40% from bottom depth) as summarized in Table 4.5.

   (iii) perforation interval in the gas reservoir since it has impact on water coning (80%, 60%, 40% from top depth) as summarized in Table 4.6.

   Since the upper and lower reservoirs are not commingled, we can determine the best conditions for the oil reservoir first (3 locations x 3 perforation intervals) and then choose the best case to run another 3 cases for gas perforation intervals. Thus, the total number of cases in the bottom-up scenario is 12 cases.

b. For Downhole Water Drain for Water Dumpflood, this study investigates the best

   (i) locations for the two wells aside from the middle one since they affect the drainage area and flow geometry of the displacing and displaced fluids towards the wells (3 sets of locations as shown in Figure 4.10).

   (ii) perforation interval in the oil reservoir since secondary gas cap may form and affect oil production (80%, 60%, 40% from bottom depth)

   (iii) perforation interval of the gas column since it has impact on water coning (80%, 60%, 40% from top depth)

   (iv) perforation interval in the water column since it has impact on water coning (80%, 60%, 40% from bottom depth)

   (v) starting time for water dumpflood (first day of oil production, the end plateau rate, economic oil production rate)

   After the best well locations (assuming 60% for oil, gas, and water perforation intervals and dumpflooding at the end of plateau rate) are determined in terms of the highest BOE (barrel of oil equivalent) which includes (1) gas production from the gas zone and (2) oil and gas production from the lower zone, they are fixed for the remaining investigations. The number of remaining cases is 81 cases (3 gas perforation intervals x 3 water perforation intervals x 3 oil perforation intervals x 3 starting times for water dumpflood) as summarized in Table 4.7. Thus, the total of cases in this scenario is 84.

3. Perform simulation for cases with different reservoir parameters to see the applicability of the proposed method by comparing performance of the bottom-up scenario and DWDDF scheme. Due to time limitation, the best operating conditions obtained for each scenario in Step 2 are used in this set of

simulation runs. Barrel of oil equivalent (BOE) is used as a criterion to determine the best operating conditions for each production scenario. Thus, cumulative oil and gas production from the lower oil reservoir and cumulative gas production from the upper gas reservoir are added in term of BOE. According to BP statistical review of world energy (2021), one barrel of oil is equivalent to 6000 SCF. Even though the operating conditions determined in Step 2 may not "truely" be the best for these cases, it provides us some idea which range of reservoir conditions are suitable or not suitable for DWDDF scheme, which is the purpose of this section, i.e., investigating the applicability of the proposed method rather than determining the best operating conditions for each case. Reservoir parameters to be investigated are listed as follows:

a. horizontal permeability of the gas reservoir since it affects pressure drawdown and how fluids move into the well (15, 50, 100 mD)
b. kv/kh ratio of the gas reservoir due to its impact on vertical moment of fluids into the well (0.01, 0.1, 0.5)
c. thickness of gas column due to its effect on flow geometry (15, 30, 60)
d. thickness of water column as its strength affects water coning (15, 30, 60)

There are 81 cases for each production scenario (3 horizontal permeabilities x 3 kv/kh ratio x 3 gas thicknesses x 3 water thicknesses) as summarized in Table 4.8. Thus, the total number of cases is 162.

4. Analyze results and summarize important findings. Note that the total number of cases for the analysis is 258.

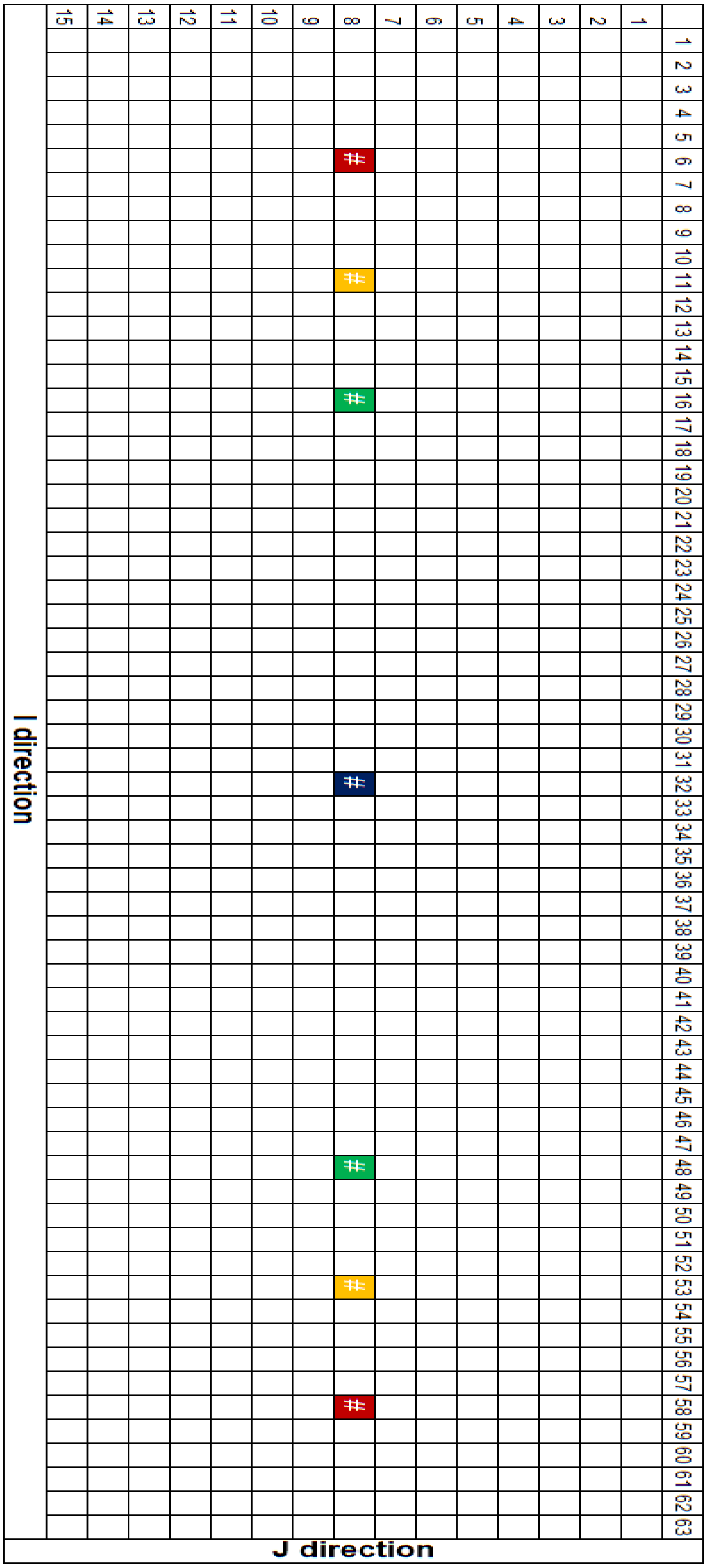


Figure 4.10 Varied set of well location.

Table 4.5 Varied operational parameters for bottom-up scenario. (Note that: Perforation interval is specified from bottom depth)

Bottom-up scenario (Conventional Oil Production)				
	Oil Well Location		Perforation Interval	
	I Location	I Location	Percent	ft.
	6	58	80%	80
			60%	60
			40%	40
	11	53	80%	80
			60%	60
			40%	40
	16	48	80%	80
			60%	60
			40%	40

Table 4.6 Varied operational parameter for bottom-up scenario. (Note that: Perforation interval is specified from the top depth)

Bottom-up scenario (Conventional Gas Production)		
	Perforation Interval	
	Percent	ft.
	80%	12
	60%	9
	40%	6

Table 4.7 Varied operational parameters for DWDDF scheme.

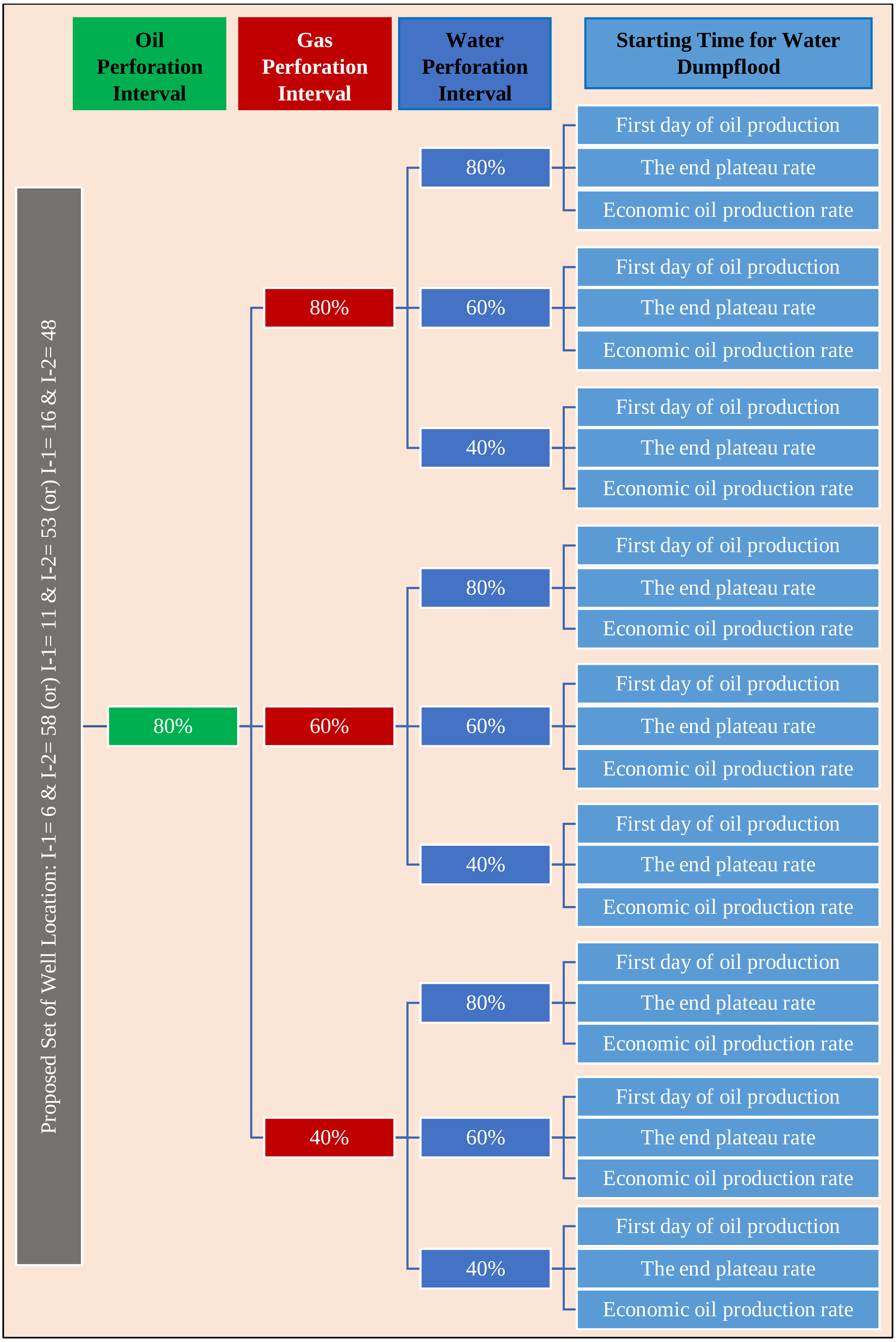
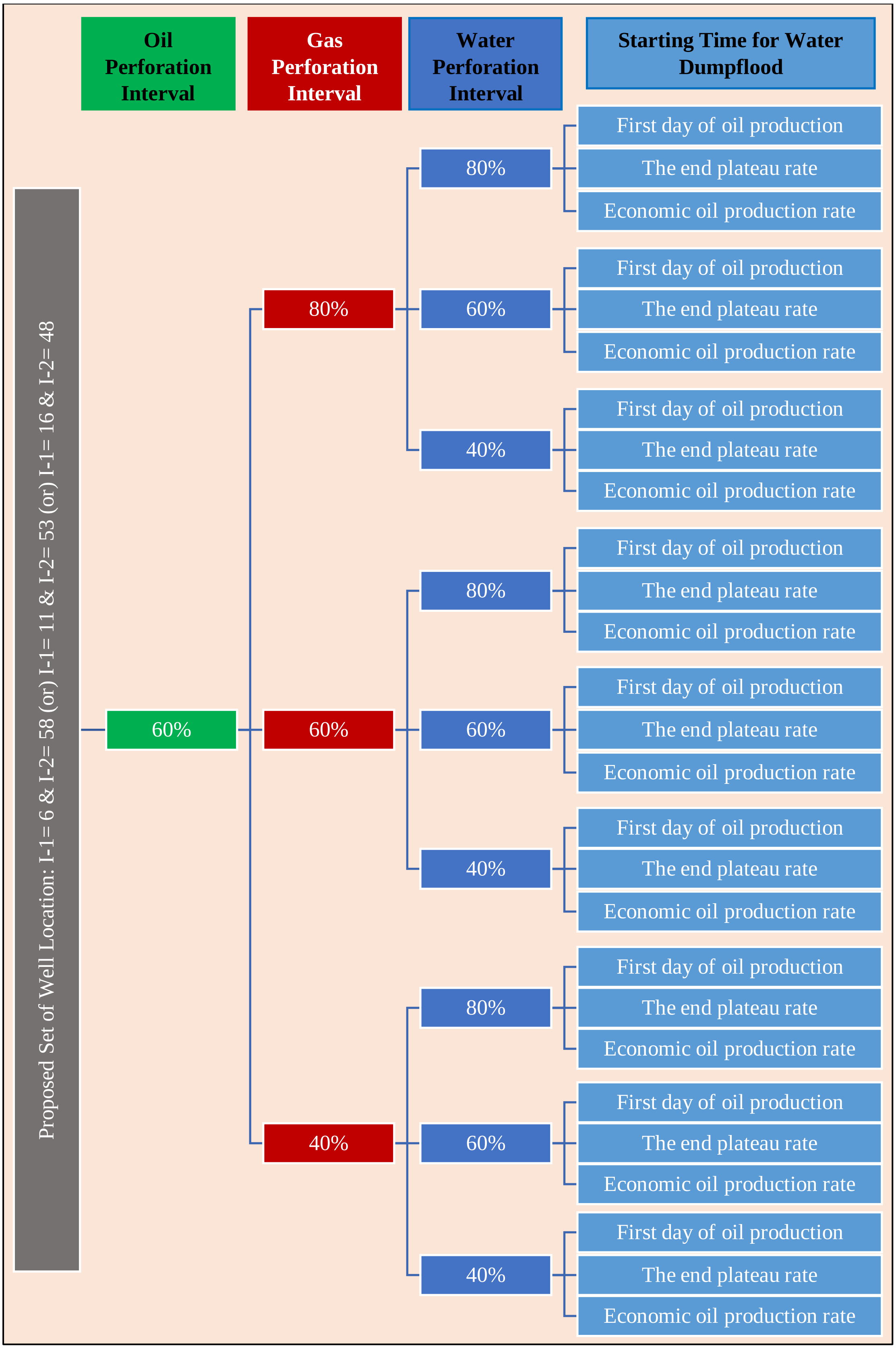


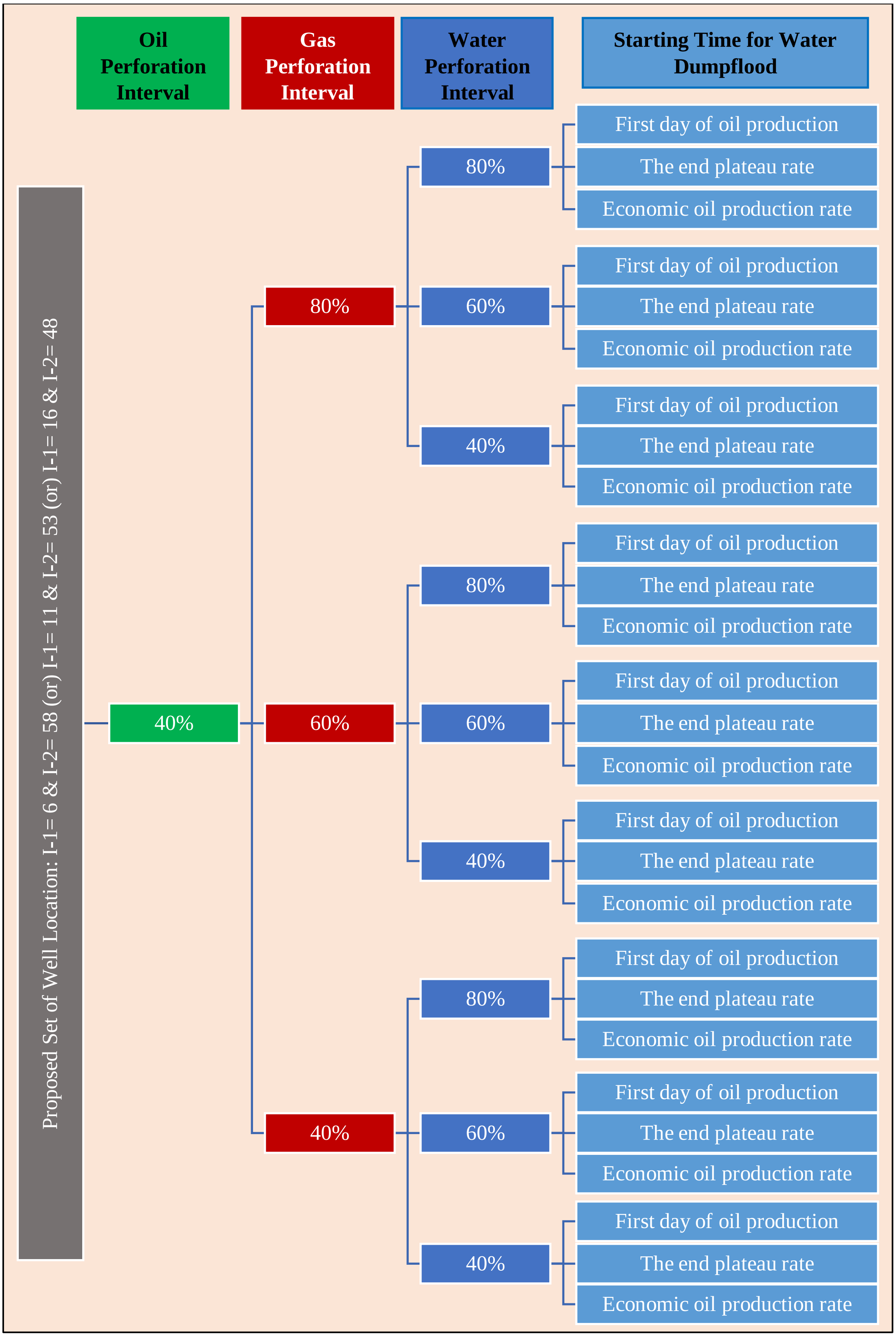
Table 4.7 Varied operational parameters for DWDDF scheme (continued).



Proposed Set of Well Location: I-1= 6 & I-2= 58 (or) I-1= 11 & I-2= 53 (or) I-1= 16 & I-2= 48

Oil Perforation Interval	Gas Perforation Interval	Water Perforation Interval	Starting Time for Water Dumpflood
60%	80%	80%	First day of oil production
			The end plateau rate
			Economic oil production rate
		60%	First day of oil production
			The end plateau rate
			Economic oil production rate
		40%	First day of oil production
			The end plateau rate
			Economic oil production rate
	60%	80%	First day of oil production
			The end plateau rate
			Economic oil production rate
		60%	First day of oil production
			The end plateau rate
			Economic oil production rate
		40%	First day of oil production
			The end plateau rate
			Economic oil production rate
	40%	80%	First day of oil production
			The end plateau rate
			Economic oil production rate
		60%	First day of oil production
			The end plateau rate
			Economic oil production rate
		40%	First day of oil production
			The end plateau rate
			Economic oil production rate

Table 4.7 Varied operational parameters for DWDDF scheme (continued).



	Oil Perforation Interval	**Gas Perforation Interval**	**Water Perforation Interval**	**Starting Time for Water Dumpflood**
Proposed Set of Well Location: I-1= 6 & I-2= 58 (or) I-1= 11 & I-2= 53 (or) I-1= 16 & I-2= 48	40%	80%	80%	First day of oil production
				The end plateau rate
				Economic oil production rate
			60%	First day of oil production
				The end plateau rate
				Economic oil production rate
			40%	First day of oil production
				The end plateau rate
				Economic oil production rate
		60%	80%	First day of oil production
				The end plateau rate
				Economic oil production rate
			60%	First day of oil production
				The end plateau rate
				Economic oil production rate
			40%	First day of oil production
				The end plateau rate
				Economic oil production rate
		40%	80%	First day of oil production
				The end plateau rate
				Economic oil production rate
			60%	First day of oil production
				The end plateau rate
				Economic oil production rate
			40%	First day of oil production
				The end plateau rate
				Economic oil production rate

Table 4.8 Varied reservoir parameters for best condition of DWDDF scheme.

Reservoir Parameters	Values	Unit
Horizontal Permeabilty	15 (Base Case)	mD
	50	mD
	100	mD
kv/kh	0.01	mD
	0.1 (Base Case)	mD
	0.5	mD
Thickness of Gas Column	15 (Base Case)	ft.
	30	ft.
	60	ft.
Thickness of Water Column	15 (Base Case)	ft.
	30	ft.
	60	ft.

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, simulation results of all the 258 cases, obtained from dynamic reservoir models established using Schlumberger Simulation Launcher ECLIPSE 100 by implementing the methodology in Chapter 4; are analyzed and discussed. Firstly, the production performances for different operating conditions of Bottom-up and Downhole Water Drain for Water Dumpflood (DWDDF) production scenarios are discussed. Then, the best operating condition of each production scenarios is determined in terms of the highest BOE. After that, the selected best operating conditions are implemented at different reservoir conditions to perform a reservoir parameters study for both Bottom-up and DWDDF production scenarios.

Each production scenario of both operating and reservoir conditions studies is discussed individually and then, a discussion upon comparative study between two different production scenarios is also conducted. The following sequences of case studies and their impacts on oil and gas production in terms of BOE and unwanted water production are discussed in this chapter.

(1) Effects from operational parameters for Bottom-up,

(2) Effects from operational parameters for DWDDF,

(3) Effects from reservoir parameters for Bottom-up, and

(4) Effects from reservoir parameters for DWDDF.

5.1 Effects from operational parameters for Bottom-up

Well locations and perforation intervals of oil and gas columns were investigated to find out the best operating condition for the Bottom-up production scenario. In this production scenario, all three wells are used to produce fluids from the lower oil reservoir until depletion first and then separately from the upper gas reservoir. The maximum production rate of each oil well at the lower oil reservoir is controlled at 1000 STB/day. For the gas well at the upper reservoir, the maximum gas production rate is fixed at 6 MMSCF/day.

Simulation results of oil production from the lower oil reservoir show that the impact of oil recovery is negligibly small by varying 3 sets of well locations in this study. Figures 5.1 – 5.3 show oil recovery as a function of well locations at the same condition of oil perforation intervals. The difference between the highest and lowest oil recovery impacted by the different well locations at the 80%, 60% and 40% oil perforation interval are 0.1%, 0.09% and 0.25% respectively. Therefore, oil recovery almost does not vary with well location in this study. On the other hand, oil recovery slightly decreases with increasing perforation intervals of the oil column as shown in Figure 5.4. The difference between the highest and lowest oil recovery impacted by the different oil perforation intervals at the same well locations of red location (I-1=6, I-2=58), yellow location (I-1=11, I-2=53), and green location (I-1=16, I-2=48) are 2.38%, 2.54% and 2.47% respectively. Therefore, the impact on oil recovery is very small in the case of altering well location while moderate impact by varying perforation intervals of oil column. In fact, the subject reservoir in this study is homogeneous and permeability is moderate, therefore, varying the well location induce very small impact on oil recovery. On the other hand, a long perforation interval has a slight negative impact on oil recovery because liberated gas which forms when reservoir pressure falls below the bubble point migrates to the upper part of the reservoir and flows into the upper perforations, impeding oil flow and reducing the drive energy of secondary gas cap.

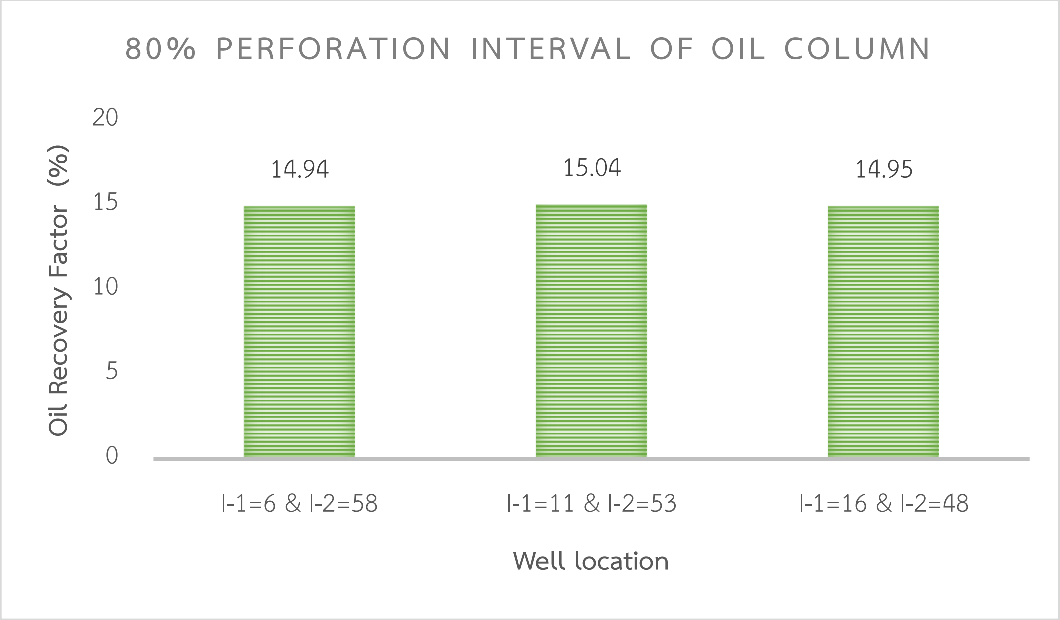


Figure 5.1 Oil recovery for bottom-up production scenario (lower oil reservoir) as a function of well locations at 80% oil perforation interval.

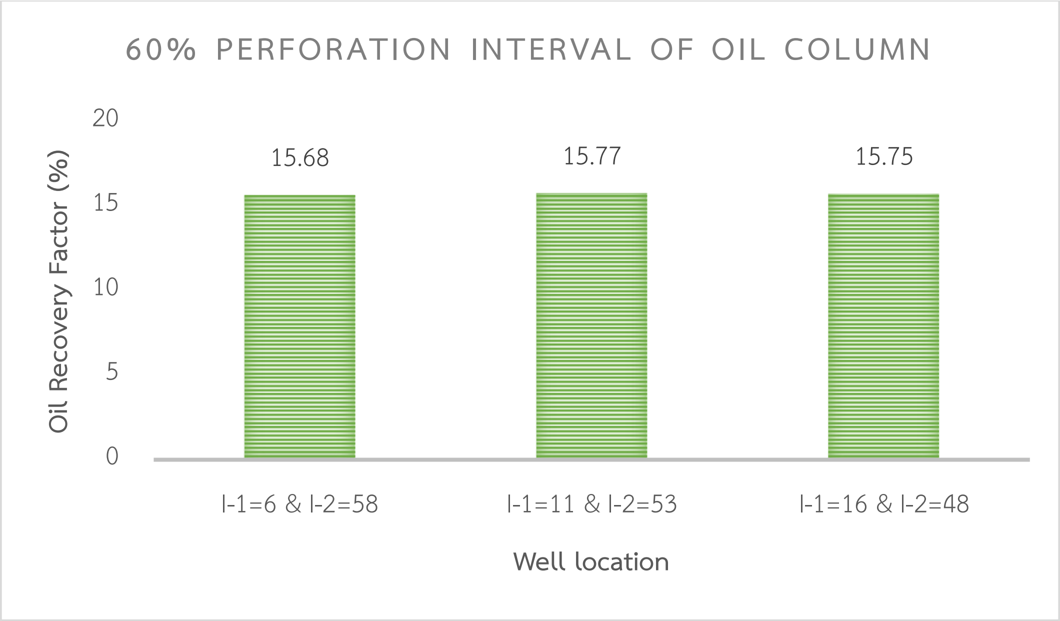


Figure 5.2 Oil recovery for bottom-up production scenario (lower oil reservoir) as a function of well locations at 60% oil perforation interval.

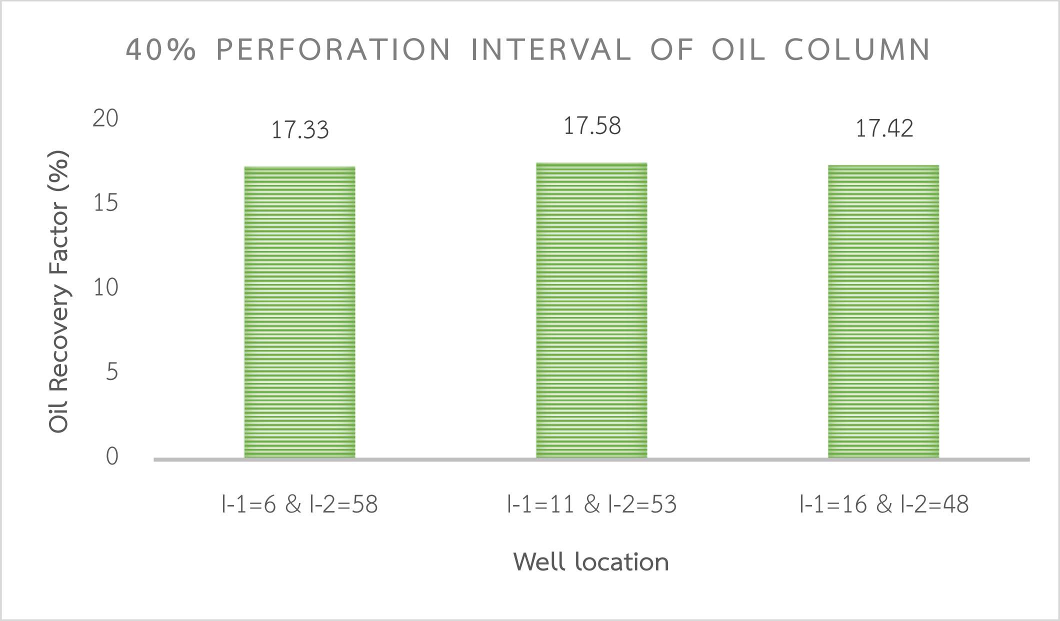


Figure 5.3 Oil recovery for bottom-up production scenario (lower oil reservoir) as a function of well locations at 40% oil perforation interval.

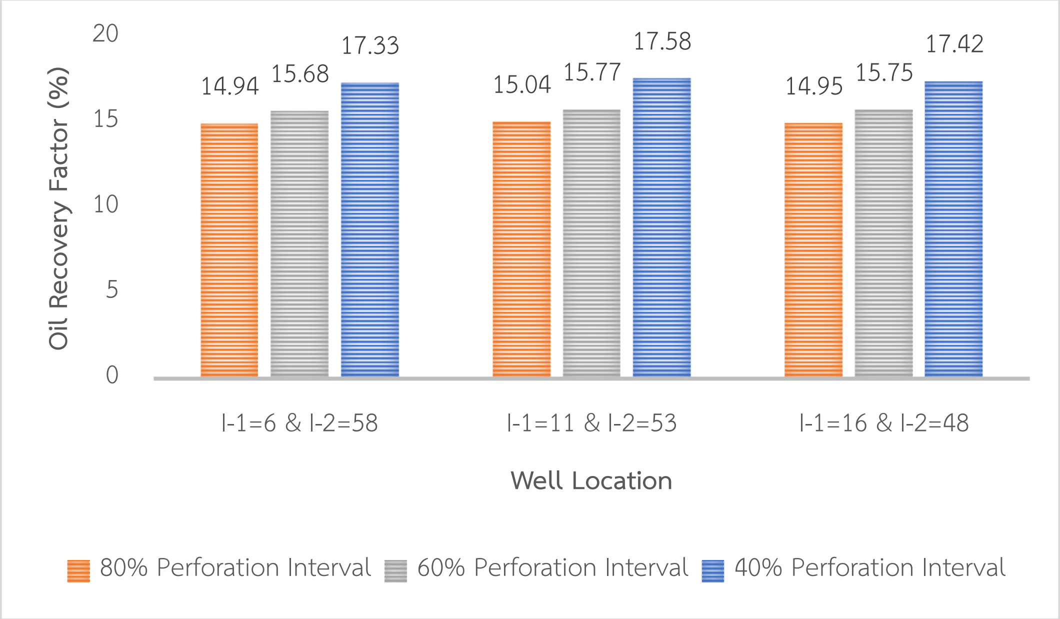


Figure 5.4 Oil recovery factor for bottom-up production scenario (lower oil reservoir) as a function of well locations at various oil perforation interval.

Results from the reservoir simulation runs in terms of cumulative oil production, oil recovery, dissolved gas production, total BOE, water production, production time and plateau production time are summarized in Table 5.1. As the perforation interval of the oil zone was increased from 40% to 60% and 80% from the bottom of the oil reservoir, dissolved gas production increases because as the perforation gets closer to the top layer of the oil reservoir, more liberated gas flows into the upper perforations. Consequently, longer oil perforation intervals reduce the drive energy of the secondary gas cap, and it induces lower oil recovery. Also, the oil perforation interval can impact total BOE as it is mainly affected by cumulative oil production and less contribution from the liberated gas production.

Furthermore, water production of the lower oil reservoir is also associated with the length of oil perforation interval, in fact, water production is mainly due to connate water expansion and water cut is very small. The water production from the oil zone is ranging from 1456 STB to 1719 STB as illustrated in Table 5.2. When the perforation interval of the oil zone is longer, there is less water production at the surface since liberated gas impedes not only oil flow but also water flow into the upper perforations. Regarding production time, the production life of the lower oil reservoir is ranging from 534 days to 1287 days, which is also mainly impacted by the oil perforation interval. 40% oil perforation yields the longest production time, and its plateau time is the shortest resulting from its higher-pressure loss at the sandface compared to the longer ones. However, when the reservoir pressure falls to the bubble point, a longer oil perforation interval induces more liberated gas to flow into the well and lowers the drive energy, and oil production time becomes shorter. Meanwhile shorter oil perforation interval can increase the oil recovery by extending oil production time, resulting from the benefit of secondary gas cap drive energy. In this conventional oil production scenario, oil production in all cases was terminated due to the specified economic limit. Since the effect of well location on oil recovery is very small and its effect on gas recovery is even smaller due to high gas mobility. Hence, the best well location set (I-1=11, I-2=53) is selected for the next step based on the highest total BOE to investigate the effect of gas perforation interval on gas recovery. Among all the scenarios, the case yielding the highest oil recovery of 17.58% (also the highest BOE of 875,854 barrels) is 40% perforation interval of oil zone at well location of (I-1=11, I-2=53) and the case that results in lowest oil recovery of 14.94% (also lowest BOE of 751,488 barrels) is 80% perforation interval of oil zone at well location of (I-1=6, I-2=58).

Table 5.1 Cumulative oil production, oil recovery, dissolved gas production, total BOE for bottom-up production (lower oil reservoir) at various well locations and oil perforation intervals.

Well location	Oil perforation interval	Cumulative oil production	Oil recovery	Dissolved gas production	Total barrel of oil equivalent
	(%)	(STB)	(%)	(MMSCF)	(BOE)
I-1=6 & I-2=58	80	714,366	14.94	223	751,488
	60	749,343	15.68	221	786,120
	40	828,260	17.33	214	863,922
I-1=11 & I-2=53	80	719,088	15.04	224	756,345
	60	753,767	15.77	221	790,570
	40	840,330	17.58	213	875,854
I-1=16 & I-2=48	80	714,594	14.95	223	751,722
	60	752,712	15.75	221	789,496
	40	832,725	17.42	213	868,220

Table 5.2 Water production, production time and plateau production time for bottom-up production (lower oil reservoir) at various well locations and oil perforation intervals.

Well location	Oil perforation interval	Water production	Time	Plateau
	(%)	(STB)	(days)	(days)
I-1=6 & I-2=58	80	1,456	552	78
	60	1,522	728	50
	40	1,699	1287	38
I-1=11 & I-2=53	80	1,456	534	84
	60	1,522	707	54
	40	1,719	1188	38
I-1=16 & I-2=48	80	1,456	552	78
	60	1,529	728	52
	40	1,708	1188	38

Once the conventional oil production is terminated due to the specified economic limit, packer or plug was installed in all three production wells above the top of the oil reservoir. Then, all three wells are perforated into the upper gas reservoir to put on production. This completion operation is assumed to be 30 days long after the end of the oil production. Since the well location (I-1=11, I-2=53) is selected to investigate the effect of gas perforation interval, its total production time of 40% oil perforation scenario is 1188 days. After the completion period of 30 days, all three production wells were put on production from the upper gas reservoir on Day 1218. Simulation results indicate that a longer gas perforation interval helps to moderately increase gas recovery but strikingly increases water production as illustrated in Figure 5.5. Results from the reservoir simulation runs in terms of cumulative gas production, gas recovery, total BOE, water production, production time and plateau production time are summarized in Table 5.3. Gas recovery ranges from 63.28% to 67.54% while water production is from 26,455 STB to 34,973 STB. A longer gas perforation interval can increase gas production as it reduces pressure loss around the well as long as water coning does not cause liquid loading problem in the wells. Note that simulation runs of all gas production scenarios stopped due to the specified economic limit, not liquid loading. Longer gas perforation also induces shorter gas production time and longer plateau production time. Thus, longer perforation interval in the gas zone can increase the gas recovery by extending the plateau rate gas production time. Overall, the case yielding the highest gas recovery of 67.54% with 34,973 STB of water production is 80% gas perforation interval and the case producing the lowest gas recovery of 63.28% with least water of 26,455 STB is 40% gas perforation interval.

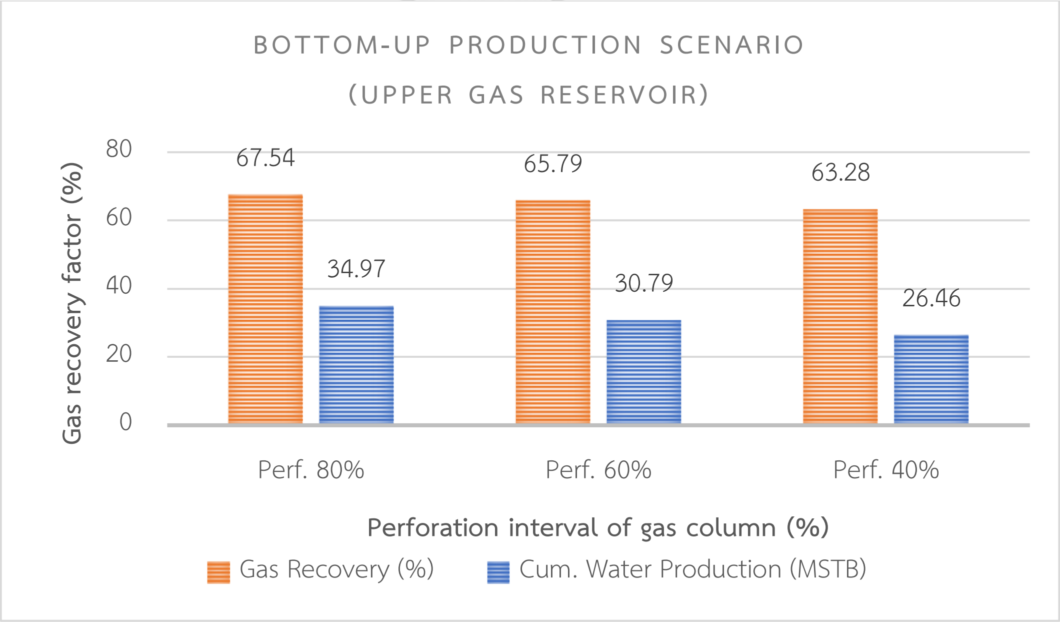


Figure 5.5 Gas recovery and water production for bottom-up production scenario (upper gas reservoir) as a function of oil perforation interval.

Table 5.3 Cumulative gas production, gas recovery, BOE, water production, production time and plateau production time for bottom-up production (upper gas reservoir) at various gas perforation intervals.

Gas perforation interval	Cumulative gas production	Gas recovery factor	Total barrel of oil equivalent	Water production	Time	Plateau
(%)	(MMSCF)	(%)	(BOE)	(STB)	(days)	(days)
80	491	67.54	81,791	34,973	76	6
60	478	65.79	79,664	30,795	80	4
40	460	63.28	76,630	26,455	88	3

In order to find the best production scenario, gas production was converted to BOE and combined with the total oil and dissolved gas production from the lower oil reservoir in terms of BOE. Simulation results for the total BOE, total water production and total production time (including the completion operation period) from both reservoirs for the bottom-up production scenario are summarized in Table 5.4. Total BOE and total water production from both reservoirs are plotted at different perforation intervals of the gas zone and oil zone as illustrated in Figure 5.6 and Figure 5.7, respectively. Results reveal that BOE recovery ranges from 16.42% to 18.92% and the percent differences between the highest and lowest values of total water production is 23.93%. The case yielding the highest BOE of 957,645 barrels is obtained from perforation intervals of 40% for the oil zone and 80% for the gas zone. However, this scenario produces the highest amount of water of 36,692 barrels since longer gas perforation intervals can increase not only gas production but also water production.

Table 5.4 Total BOE, BOE recovery factor, total water production and total production time for bottom-up production at various oil and gas perforation intervals.

Perforation interval (%)		Total BOE	BOE (Recovery factor)	Total water production	Total time
Oil column	Gas column	(STB)	(%)	(STB)	(days)
80	80	838,136	16.56	36,429	640
	60	836,009	16.52	32,251	644
	40	832,974	16.46	27,911	652
60	80	872,361	17.24	36,495	813
	60	870,234	17.20	32,317	817
	40	867,199	17.14	27,977	825
40	80	957,645	18.92	36,692	1294
	60	955,518	18.88	32,513	1298
	40	952,484	18.82	28,174	1306

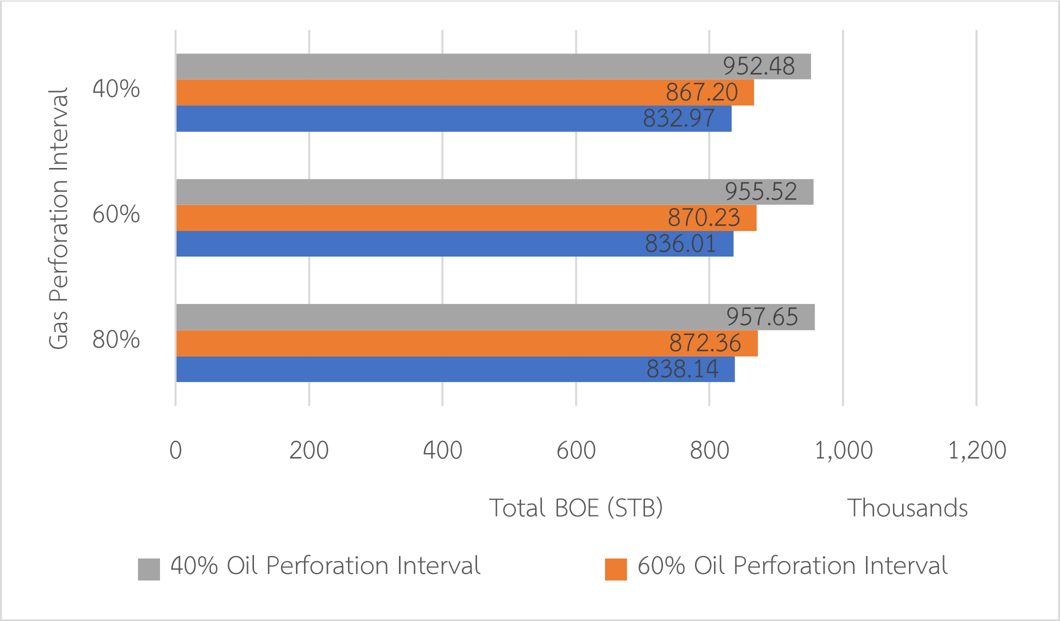


Figure 5.6 Total BOE for bottom-up scenario as a function of perforation intervals of oil and gas zone.

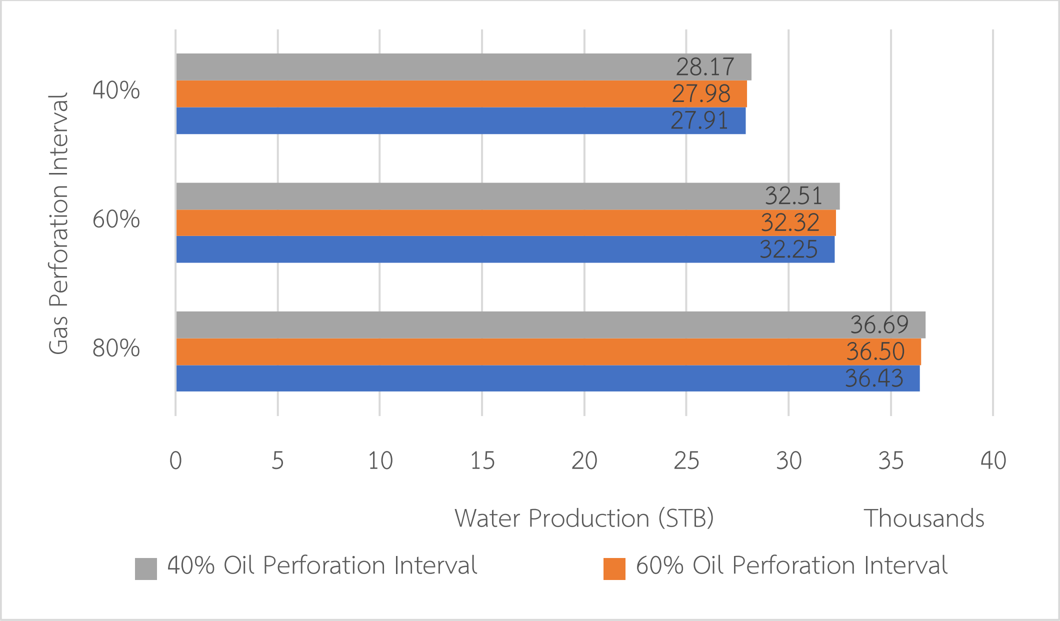


Figure 5.7 Total water production for bottom-up scenario as a function of perforation intervals of oil and gas zone.

5.2 Effects from operational parameters for DWDDF

To find out the best operating condition for DWDDF, several variables were investigated. The well locations, the oil perforation interval of all three wells, the gas perforation interval of the middle well, the perforation interval of the water zone of the middle well and the starting time for DWDDF were varied. Similar to oil production in the bottom-up scenario, the oil reservoir is put on production with the aid of the natural drive mechanism at the early production phase in the DWDDF production scenario. After that, only the middle well is perforated in the gas zone and water zone in order to produce gas separately from the upper gas reservoir and dump water into the lower oil reservoir. Like the bottom-up scenario, the well maximum production rate for the lower oil reservoir and upper bottom water drive gas reservoir is controlled at 1000 STB/day and 6 MMSCF/day, respectively.

Firstly, the best well location is determined by running the three simulation runs, assuming 60% for oil, gas, and water perforation intervals and dumpflooding at the end of the plateau rate. As summarized in Table 5.2, plateau rate oil production time for 60% oil perforation at well location of I-1=6 & I-2=58, I-1=11 & I-2=53 and I-1=16 & I-2=48 are 50 days, 54 days, and 52 days, respectively. Hence, the gas production from the upper gas reservoir and DWDDF started on Day 80, Day 84, and Day 82 of the production stage at the well location of I-1=6 & I-2=58, I-1=11 & I-2=53 and I-1=16 & I-2=48, respectively.

Results from the reservoir simulation runs in terms of total BOE, BOE recovery factor, total water production, total DWDDF production time, and volume of water and gas crossflows at 60% oil, gas, and water perforation intervals but varies with different well location set are summarized in Table 5.5. Similar to bottom-up production, simulation results of the DWDDF production scenario show that the impact of the BOE recovery factor is small by varying 3 sets of well locations in this study. The difference between the highest and lowest oil recovery impacted from the different well locations is 0.29% only. Therefore, BOE recovery almost does not vary with well location in this study.

According to simulation results as summarized in Table 5.5, the case yielding the lowest BOE recovery of 18.88 is obtained from the well location set of I-1=6 & I-2=58, which is the farthest locations from the dumping well, and the amount of water and gas crossflows of this case is also lower than other two cases. The highest amount of water and gas crossflows is obtained from the case with the well location set of I-1=16 & I-2=48, which is the nearest location from the dumping well. Results show that its production time is the shortest among other cases. Although the case with the well location set of I-1=16 & I-2=48 induces the highest amount of water and gas crossflows, its reservoir pressure is still slightly lower than the case with the well location set of I-1=11 & I-2=53 at its late production period. Overall, the case with the well location set of I-1=11 & I-2=53 yields the highest BOE recovery with moderate water production and production time. Although the effect of well location on BOE is small in this investigation, the well location set of I-1=11, I-2=53 was selected for the next step based on the highest total BOE criterion to investigate the effect of various oil, gas, and water perforation intervals and dumpflood starting time on BOE recovery.

Table 5.5 Total BOE, BOE recovery factor, total water production, total DWDDF production time, and volume of water and gas crossflows at 60% oil, gas, and water perforation intervals.

Well location	Total barrel of oil equivalent	BOE (Recovery factor)	Total water production	Time	Water dump volume	Gas crossflow volume
	(BOE)	(%)	(STB)	(days)	(STB)	(MMSCF)
I-1=6 & I-2=58	955,287	18.88	2,173	1233	74,260	40
I-1=11 & I-2=53	970,338	19.17	2,098	1215	75,112	42
I-1=16 & I-2=48	964,873	19.07	1,993	1163	75,193	43

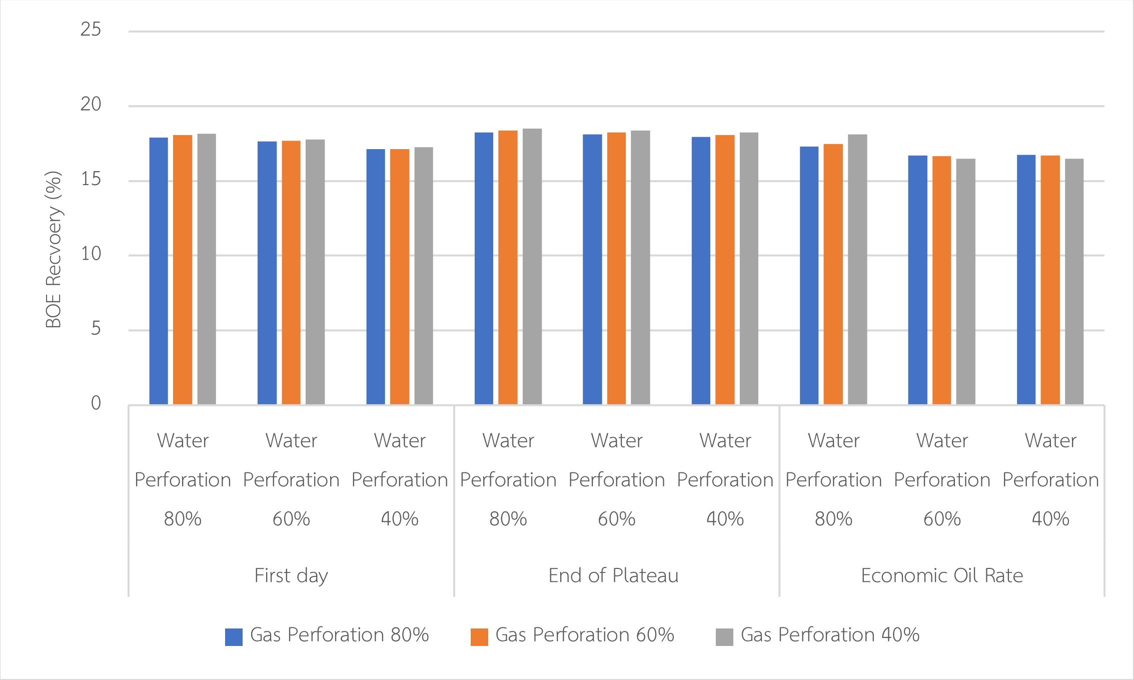
As illustrated in Figures 5.8 – 5.10, varied operational parameters of the DWDDF production scenario have a moderate impact on BOE recovery while significant impact on water production and total production time. The range of BOE recovery in this investigation is from 16.51% to 22.04%. According to simulation results shown in Table 5.6 – 5.8, 40% oil perforation cases yield higher BOE recovery compared to 60% and 80% because of less free gas production, similar to the results of the bottom-up production scenario. In general, cases with shorter gas perforation intervals yield a little higher BOE recovery than longer ones since there is less gas production at the surface, and it causes a higher amount of gas crossflowing from the upper gas reservoir to the lower oil reservoir which helps to improve the oil recovery. Longer water perforation interval cases induce more water to be dumped into the lower oil reservoir. Thus, more oil is displaced for production, resulting in higher BOE recovery. Regarding dumpflood, starting it at the economic oil rate yields the highest BOE recovery for 40% oil perforation cases, which is a BOE recovery of 22.04%. In fact, the lower oil reservoir pressure is lowest at the economic rate condition compared to at the first day of production and the end of plateau rate phases. Thus, when DWDDF is initiated at the economic rate, the large pressure difference between the upper reservoir and lower reservoir causes a higher gas crossflow from the gas reservoir to the oil reservoir, and a high amount of gas cross flows into the lower oil reservoir via the middle well due to lower pressure and facilitates oil flow inside the reservoir. Note that more gas is preferable in this case since free gas is not a problem for 40% perforation of the production well.

On the contrary, gas reduces BOE recovery for 80% oil perforation cases as gas flows into the upper perforation of the oil reservoir. When compared among the three starting times for 80% oil perforation cases, the end of plateau gives the highest BOE recovery due to the highest amount of water cross flowing into the lower oil reservoir as a result of the long dumping time. Starting dumping water on the first day does not yield the highest amount of dumped water as the lower reservoir still has high pressure at the time. For 60% oil perforation, the best starting time swings between the economic rate and the end of plateau due to mixed impacts between the volumes of gas and water cross flowing into the lower reservoir.

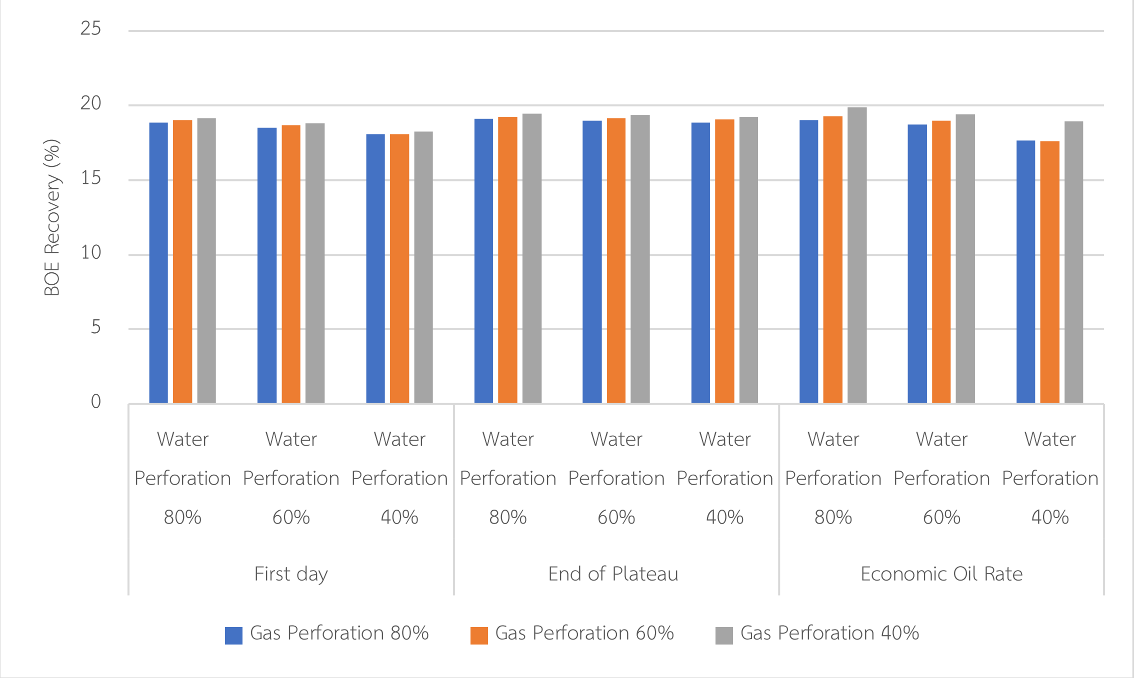
All in all, dumping on the first day could not yield higher BOE recovery compared to other starting times because the lower oil reservoir is still having high pressure. In fact, even a few portions of oil cross flowing from the lower reservoir to the upper reservoir have been found in all cases of dumping on the first day (See Appendix).

Overall, the case yielding the highest total BOE recovery of 22.04% is 40% oil perforation, 80% water perforation, 40% gas perforation, and starting dumpflood at the economic rate. The 40% oil perforation helps reduce the amount of free gas in the reservoir and consequently increases oil production. The 80% water perforation allows more water to be dumped into the oil reservoir while the 40% gas perforation reduces the amount of water flowing up to the gas perforations. Starting dumpflood at the economic rate allows more gas to cross flows into the lower oil reservoir due to the large pressure difference between the two reservoirs.

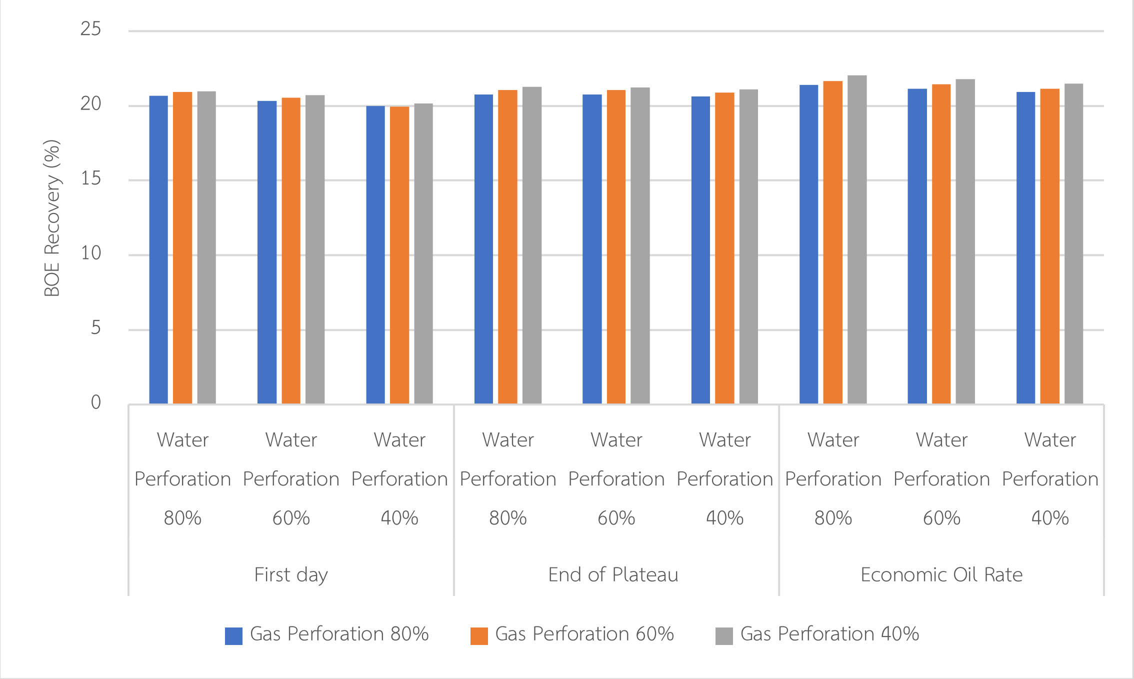
For unwanted water production for the DWDDF production scenario, it ranges from 1,465 STB to 22,921 STB as summarized in Table 5.6 – 5.8, which percent difference is equivalent to 94.62%. Cases in which water dumpflood is started on the first day of oil production show high water production compared to other starting times as illustrated in Figure 5.9. Thus, higher water production is mainly dealt with dumpflood starting time; and most of it comes from the gas well. As the lower oil reservoir still has high pressure at the beginning, the amount of water that can be dumped into the lower reservoir is small. Instead, a large amount of water flows to the surface. In general, cases with shorter water perforation interval yields more water production compared to longer ones and it is more significant in dumping at first day cases. This fact indicates that longer water perforation can reduce the unwanted water production to the surface by dumping it into the lower reservoir. As shown in Figure 5.10, the total production time for DWDDF ranges from 776 days to 2154 days, and the total production period is increased with a decrease in the length of oil perforation interval. In fact, oil production is improved by extending the production period. For the case yielding the highest BOE recovery (40% oil perforation, 80% water perforation, 40% gas perforation, and starting dumpflood at the economic rate), the water production is only 2,188 STB which is among low water production cases. And its total production time is 2082 days, which is also among the longer production period cases.



(a)

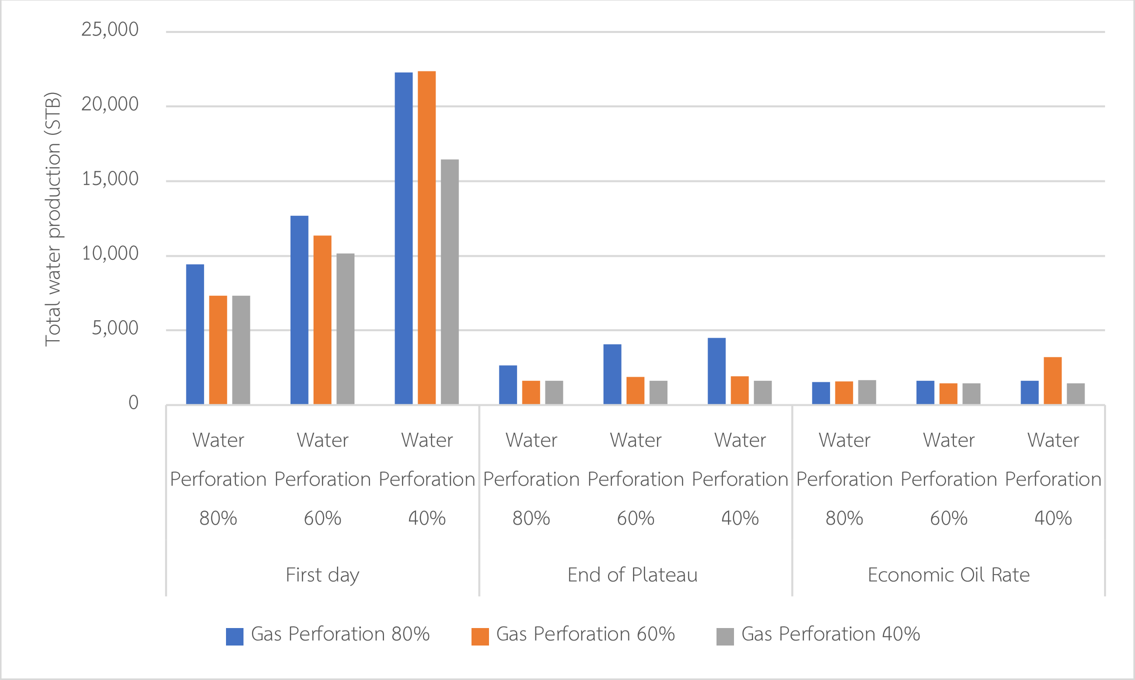


(b)

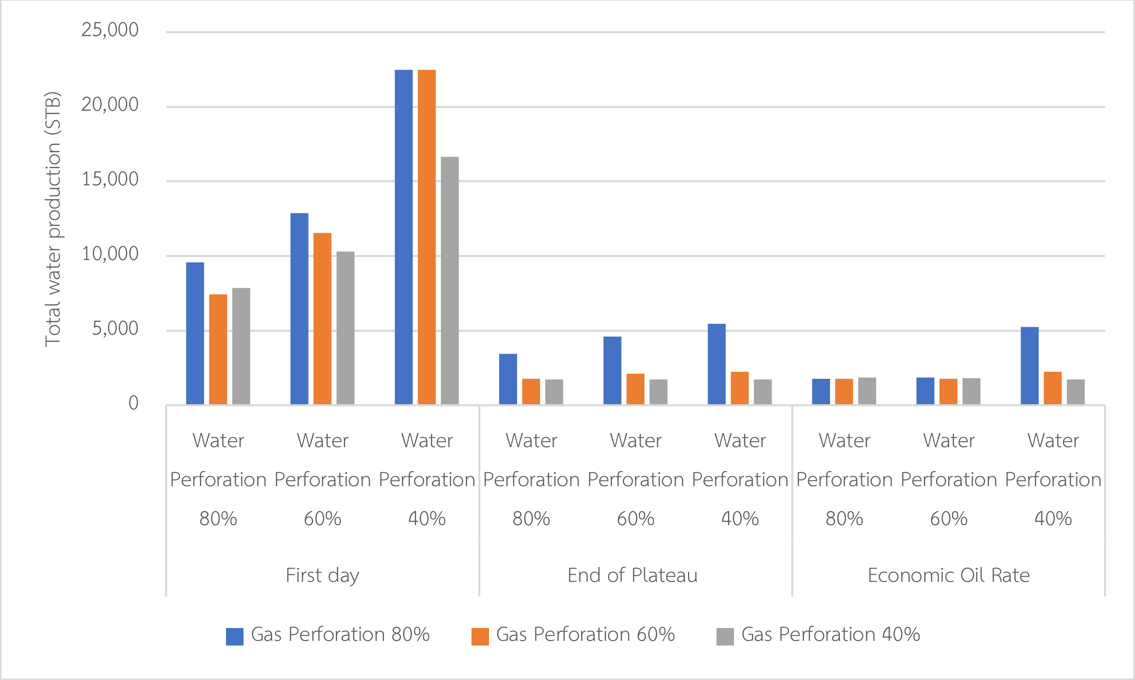


(c)

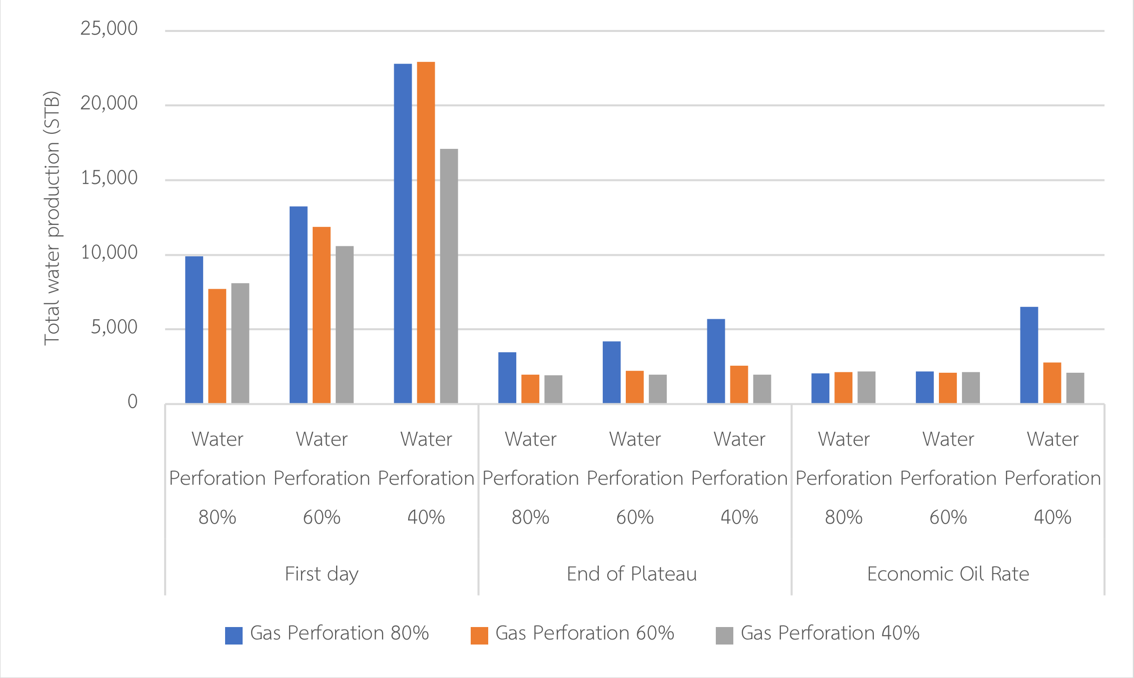
Figure 5.8 BOE recovery for DWDDF at (a) 80% (b) 60% and (c) 40% oil perforation interval for various gas and water perforation intervals as a function of different starting times for water dumpflood.


Total water production (STB)
25,000
20,000
15,000
10,000
5,000
0
Water Perforation 80%
Water Perforation 60%
Water Perforation 40%
Water Perforation 80%
Water Perforation 60%
Water Perforation 40%
Water Perforation 80%
Water Perforation 60%
Water Perforation 40%
First day
End of Plateau
Economic Oil Rate
Gas Perforation 80%
Gas Perforation 60%
Gas Perforation 40%

(a)

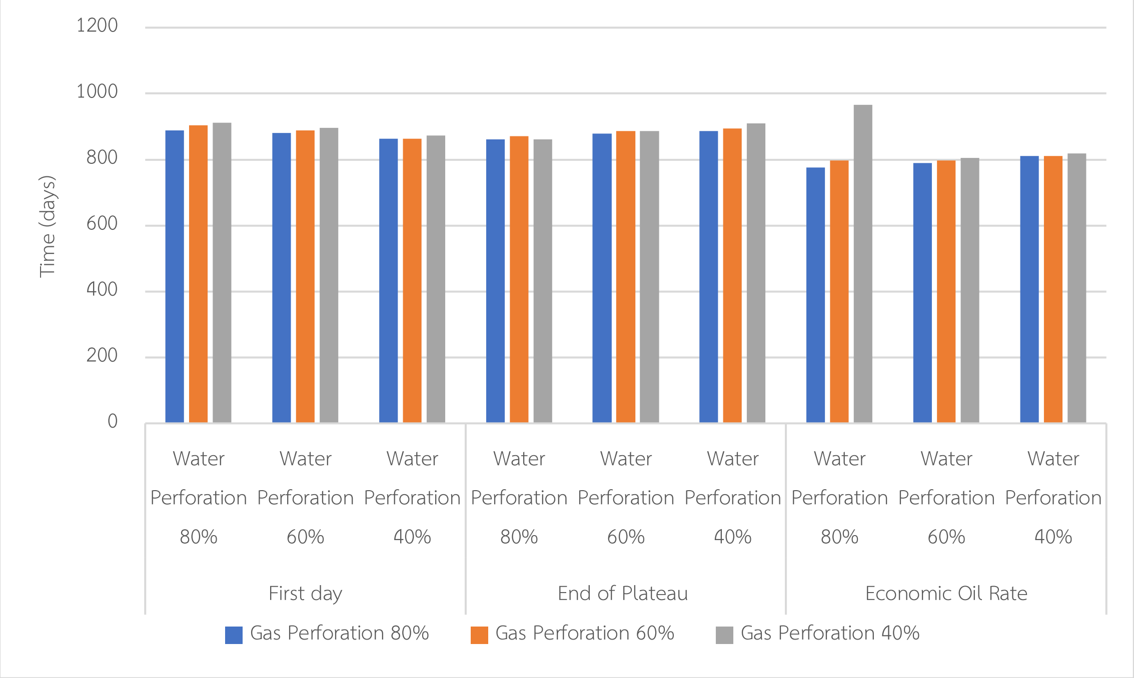

Total water production (STB)
25,000
20,000
15,000
10,000
5,000
0
Water Perforation 80%
Water Perforation 60%
Water Perforation 40%
Water Perforation 80%
Water Perforation 60%
Water Perforation 40%
Water Perforation 80%
Water Perforation 60%
Water Perforation 40%
First day
End of Plateau
Economic Oil Rate
Gas Perforation 80%
Gas Perforation 60%
Gas Perforation 40%

(b)

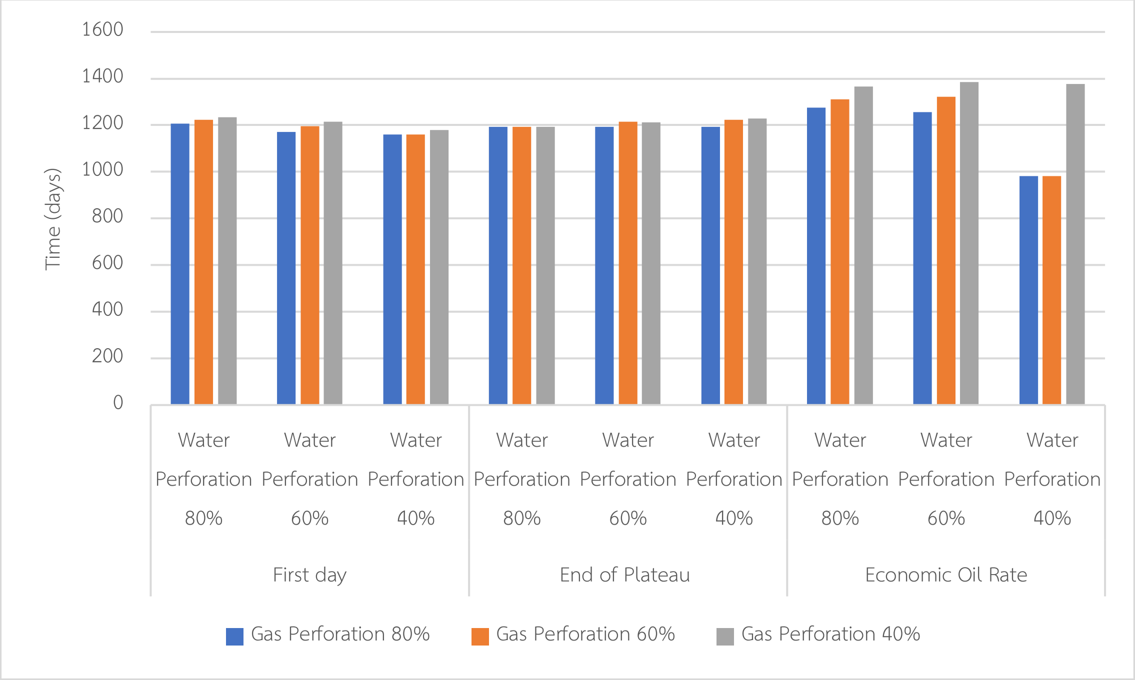


(c)

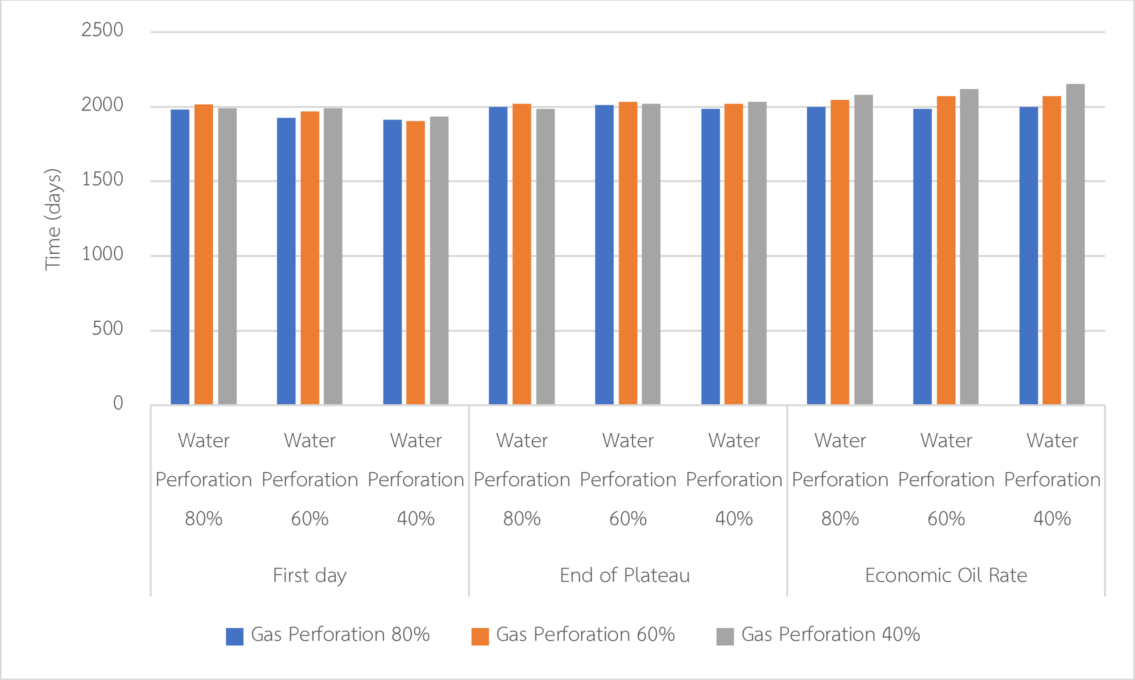
Figure 5.9 Water production for DWDDF at (a) 80% (b) 60% and (c) 40% oil perforation interval for various gas and water perforation intervals as a function of different starting times for water dumpflood.



(a)



(b)



(c)

Figure 5.10 Total production period for DWDDF at (a) 80% (b) 60% and (c) 40% oil perforation interval for various gas and water perforation intervals as a function of different starting times for water dumpflood.

Table 5.6 Total BOE, BOE recovery factor, total water production and total production time for DWDDF at 80% oil perforation interval for various gas and water perforation intervals, and different starting times for water dumpflood.

Perforation interval (%)		Starting time	Total BOE	BOE (Recovery factor)	Total water production	Total time
Gas column	Water column	(days)	(STB)	(%)	(STB)	(days)
80	80	First day	906,598	17.92	9,443	888
	80	End of plateau	923,531	18.25	2,648	862
	80	Economic oil rate	875,286	17.30	1,544	776
	60	First day	892,122	17.63	12,703	880
	60	End of plateau	917,100	18.12	4,070	878
	60	Economic oil rate	846,201	16.72	1,610	790
	40	First day	867,447	17.14	22,294	864
	40	End of plateau	908,922	17.96	4,513	886
	40	Economic oil rate	847,581	16.75	1,610	811
60	80	First day	913,918	18.06	7,313	904
	80	End of plateau	930,286	18.38	1,625	870
	80	Economic oil rate	884,279	17.47	1,573	797
	60	First day	895,832	17.70	11,373	888
	60	End of plateau	923,857	18.26	1,877	886
	60	Economic oil rate	842,732	16.65	1,465	797
	40	First day	867,584	17.14	22,350	864
	40	End of plateau	914,676	18.07	1,908	894
	40	Economic oil rate	846,286	16.72	3,216	811
40	80	First day	918,618	18.15	7,328	912
	80	End of plateau	936,083	18.50	1,628	862
	80	Economic oil rate	917,444	18.13	1,662	966
	60	First day	899,310	17.77	10,167	896
	60	End of plateau	930,968	18.40	1,632	886
	60	Economic oil rate	835,544	16.51	1,463	804
	40	First day	873,361	17.26	16,442	872
	40	End of plateau	922,653	18.23	1,624	910
	40	Economic oil rate	835,513	16.51	1,463	818

Table 5.7 Total BOE, BOE recovery factor, total water production and total production time for DWDDF at 60% oil perforation interval for various gas and water perforation intervals, and different starting times for water dumpflood.

Perforation interval (%)		Starting time	Total BOE	BOE (Recovery factor)	Total water production	Total time
Gas column	Water column	(days)	(STB)	(%)	(STB)	(days)
80	80	First day	954,546	18.86	9,575	1206
	80	End of plateau	966,270	19.09	3,427	1194
	80	Economic oil rate	963,631	19.04	1,755	1275
	60	First day	937,916	18.53	12,860	1170
	60	End of plateau	960,548	18.98	4,594	1194
	60	Economic oil rate	947,957	18.73	1,859	1257
	40	First day	915,750	18.10	22,467	1161
	40	End of plateau	953,922	18.85	5,462	1194
	40	Economic oil rate	892,745	17.64	5,232	982
60	80	First day	963,538	19.04	7,430	1224
	80	End of plateau	973,451	19.24	1,754	1194
	80	Economic oil rate	975,293	19.27	1,791	1311
	60	First day	945,875	18.69	11,525	1197
	60	End of plateau	970,338	19.17	2,098	1215
	60	Economic oil rate	961,481	19.00	1,752	1321
	40	First day	916,151	18.10	22,491	1161
	40	End of plateau	964,844	19.07	2,254	1224
	40	Economic oil rate	891,863	17.62	2,226	983
40	80	First day	969,831	19.16	7,857	1233
	80	End of plateau	983,620	19.44	1,709	1194
	80	Economic oil rate	1,006,124	19.88	1,859	1366
	60	First day	951,064	18.79	10,290	1215
	60	End of plateau	980,286	19.37	1,727	1212
	60	Economic oil rate	981,911	19.40	1,815	1386
	40	First day	923,808	18.26	16,642	1179
	40	End of plateau	973,884	19.24	1,732	1230
	40	Economic oil rate	959,007	18.95	1,749	1376

Table 5.8 Total BOE, BOE recovery factor, total water production and total production time for DWDDF at 40% oil perforation interval for various gas and water perforation intervals, and different starting times for water dumpflood.

Perforation interval (%)		Starting time	Total BOE	BOE (Recovery factor)	Total water production	Total time
Gas column	Water column	(days)	(STB)	(%)	(STB)	(days)
80	80	First day	1,045,674	20.66	9,897	1980
	80	End of plateau	1,051,227	20.77	3,464	1998
	80	Economic oil rate	1,082,975	21.40	2,075	1998
	60	First day	1,029,751	20.35	13,241	1925
	60	End of plateau	1,049,855	20.75	4,183	2010
	60	Economic oil rate	1,068,976	21.12	2,191	1986
	40	First day	1,011,834	19.99	22,787	1914
	40	End of plateau	1,044,395	20.64	5,679	1986
	40	Economic oil rate	1,059,262	20.93	6,521	1998
60	80	First day	1,058,674	20.92	7,709	2016
	80	End of plateau	1,065,770	21.06	1,966	2022
	80	Economic oil rate	1,096,666	21.67	2,122	2046
	60	First day	1,040,573	20.56	11,890	1969
	60	End of plateau	1,064,804	21.04	2,208	2034
	60	Economic oil rate	1,084,885	21.44	2,084	2070
	40	First day	1,010,232	19.96	22,921	1903
	40	End of plateau	1,056,123	20.87	2,574	2022
	40	Economic oil rate	1,068,977	21.12	2,766	2070
40	80	First day	1,061,490	20.98	8,115	1992
	80	End of plateau	1,075,769	21.26	1,935	1986
	80	Economic oil rate	1,115,416	22.04	2,188	2082
	60	First day	1,047,568	20.70	10,594	1992
	60	End of plateau	1,074,972	21.24	1,962	2022
	60	Economic oil rate	1,103,428	21.80	2,149	2118
	40	First day	1,020,842	20.17	17,091	1936
	40	End of plateau	1,068,817	21.12	1,979	2034
	40	Economic oil rate	1,087,602	21.49	2,100	2154

5.3 Comparative study of bottom-up and DWDDF for different operational parameters

As described in the above sections, the highest BOE recovery obtained from the bottom-up production scenario is 18.92% whereas the DWDDF production scenario is 22.04%. Thus, the incremental hydrocarbon production obtained from the DWDDF technique is about 3.12% in terms of BOE recovery. Then, the best operating condition of each production scenario was analyzed and discussed in this section. The simulation results indicate that the total oil production period in the case of DWDDF can be maintained longer than that of conventional production as shown in Figure 5.11 since both water and gas from the upper reservoir cross flow into the lower oil reservoir. Although gas crossflow induces less gas production at the surface from the gas well (lower gas recovery), it helps improve oil recovery of the lower oil reservoir. Also, the DWDDF scenario significantly reduces the amount of unwanted field water production compared to the bottom-up scenario as illustrated in Figure 5.12. Figure 5.13 and 5.14 shows the rate of water being dumped from the gas reservoir into the underlying oil reservoir and the rate of gas cross flow into the oil reservoir from gas reservoir, respectively. Note that the negative values in Figure 5.13 indicate the inflow of water into the lower oil reservoir. These graphical presentations can help to see the movement of water and gas from the water-drive gas reservoir into the oil reservoir clearly. The initial water dumping rate is about 920 STB/day, however, it sharply declines afterwards as the pressure of the underlying oil reservoir becomes higher. Meanwhile, the gas crossflow rate is around 1,670 MSCF in the early times and it rapidly fell as the lower oil reservoir is re-pressurized by both crossflows simultaneously. The interesting fact is that the gas crossflow rate becomes rising again immediately when the gas well dies due to reaching its abandonment rate of 0.5MMSCF/D. As the gas production is immediately stopped due to reaching the economic rate of the well, some amounts of gas are redirected to other ends of the well for dumping into the oil reservoir. However, this occurrence takes for short periods, and the gas crossflow rate becomes steadily declines as the lower oil reservoir pressure becomes higher and the upper reservoir pressure becomes lower.

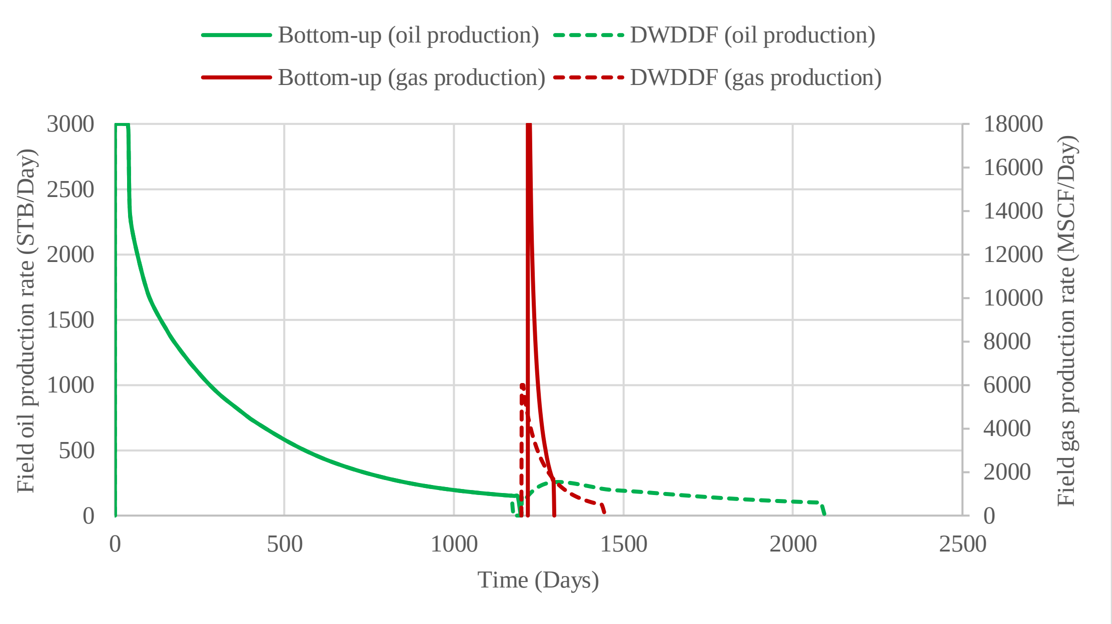


Figure 5.11 Oil and gas production rates for best bottom-up scenario and best DWDDF scenario.

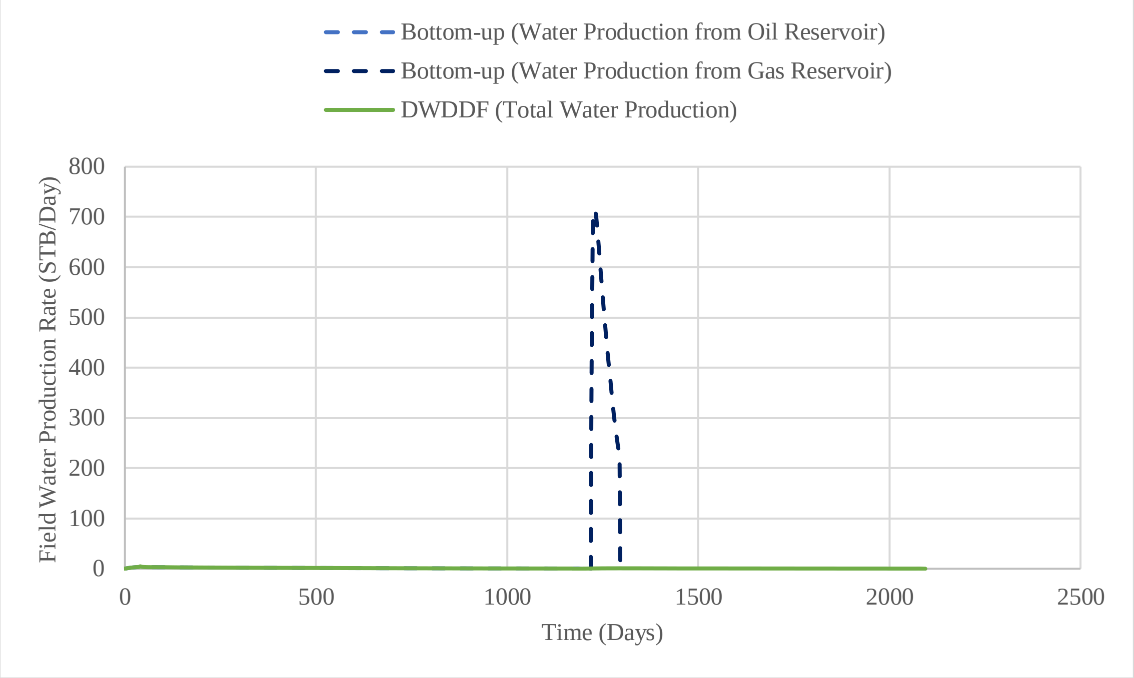


Figure 5.12 Water production rate for best bottom-up scenario and best DWDDF scenario.

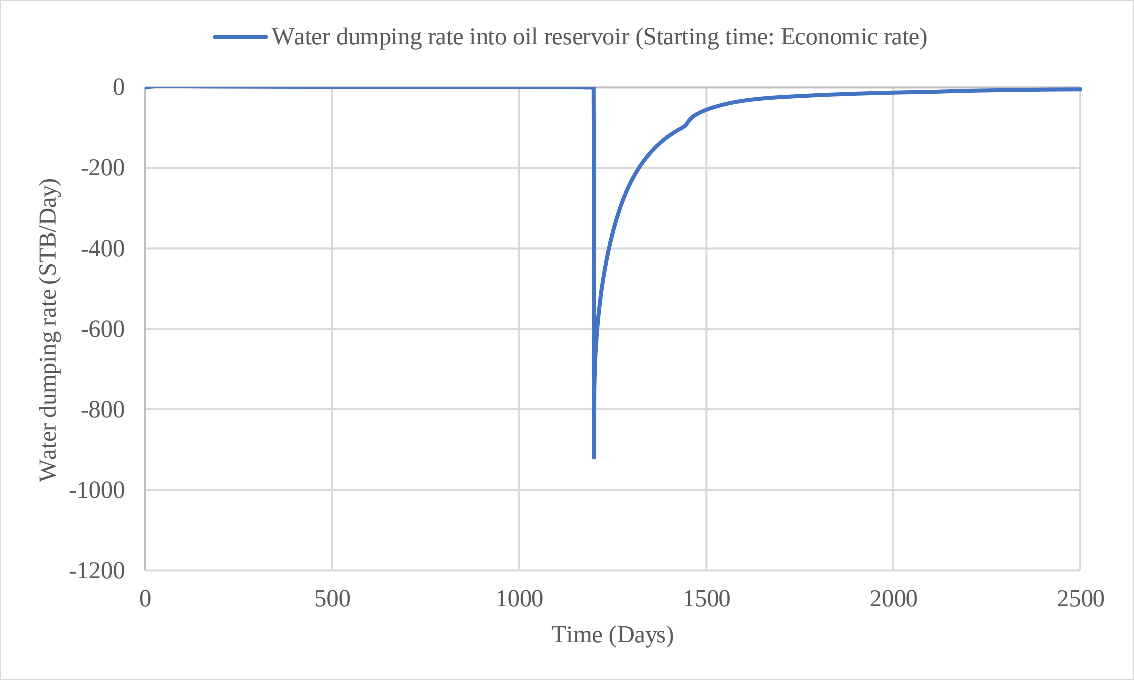


Figure 5.13 Water dumping rate from bottom-water drive gas reservoir to underlying oil reservoir in best DWDDF scenario.

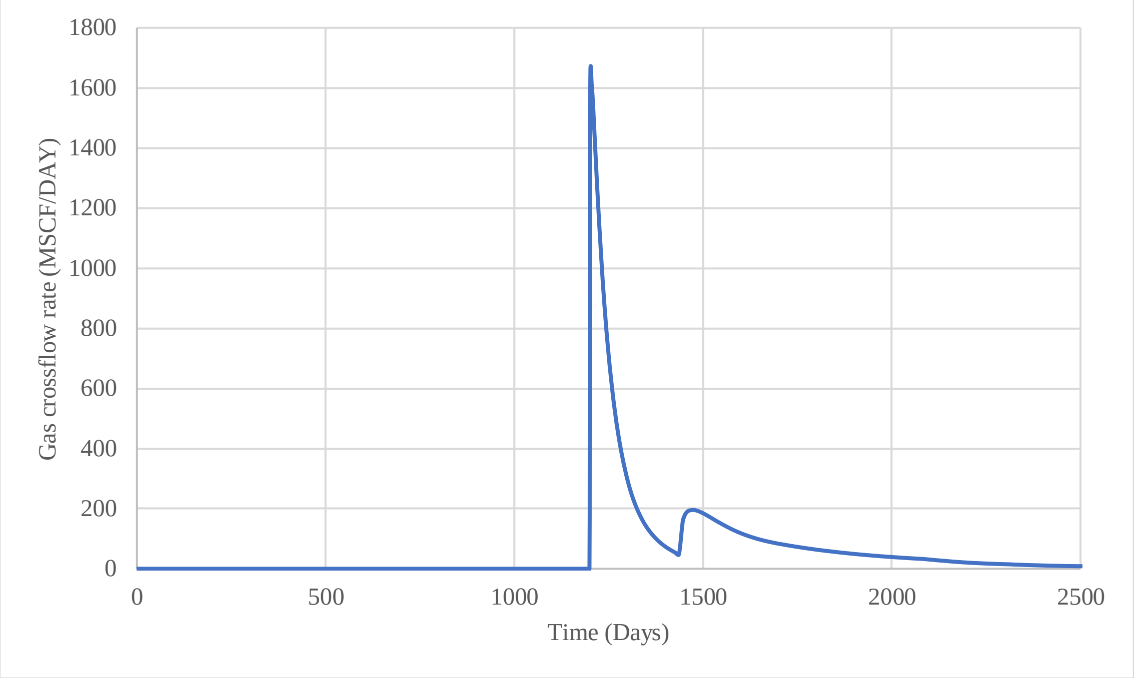


Figure 5.14 Gas crossflow rate from bottom-water drive gas reservoir to underlying oil reservoir in best DWDDF scenario.

As illustrated in Figure 5.15, every DWDDF case can perform better than bottom-up when they have the same oil and gas perforation intervals. Not only total BOE is increased but also unwanted water production is reduced when the DWDDF technique is applied (See Figure 5.16). In fact, hydrocarbon production is improved by extending the total production period in the DWDDF scenario, which implies that production time is extended by re-pressurizing the lower oil reservoir with the aid of both water and gas crossflows. This can be clearly seen in Figure 5.17. According to Figure 5.18, it is obvious to see that the total production time of all DWDDF scenarios is longer than bottom-up.

In order to compare the performance of DWDDF and conventional bottom-up production techniques effectively, the total BOE is used as a key criterion in this section. The best operating condition of each production scenario is selected based on the highest total BOE in order to investigate the effect of reservoir parameters for both production scenarios. For the bottom-up scenario, the highest total BOE is obtained from 40% oil perforation and 80% gas perforation, and this operation condition was chosen to study reservoir parameters. For the DWDDF scenario, the case with the operating condition of 40% oil perforation, 40% gas perforation, 80% water perforation and starting dumpflood at the economic rate was selected to study for the next step. Comparing the best bottom-up scenario and the best DWDDF scenario, DWDDF can increase total BOE by 16.47% from 957,645 to 1,115,416 barrels and reduce water production by 94.04% from 36,692 to 2,188 STB. The production time of DWDDF is 788 days longer than bottom-up production scenario. Therefore, economic analysis needs to be considered for decision making regarding this project. Since this study is focused only on a technical point of view, an economic analysis of the project is neglected in this study.

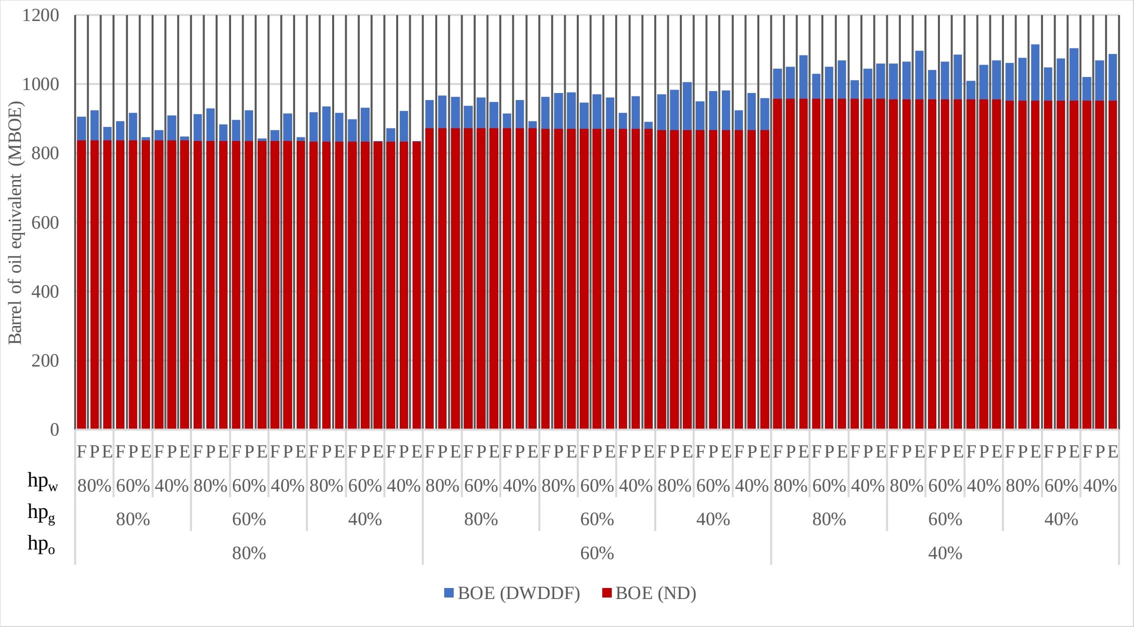


Figure 5.15 Total BOE for Bottom-up production and DWDDF at various oil, gas, and water perforation intervals as a function of different starting times for water dumpflood (Note that hpw, hpg and hpo represent perforation intervals of water, gas and oil, respectively whereas F, P, E stands for dumpflood starting time of first day, end of plateau and economic rate).

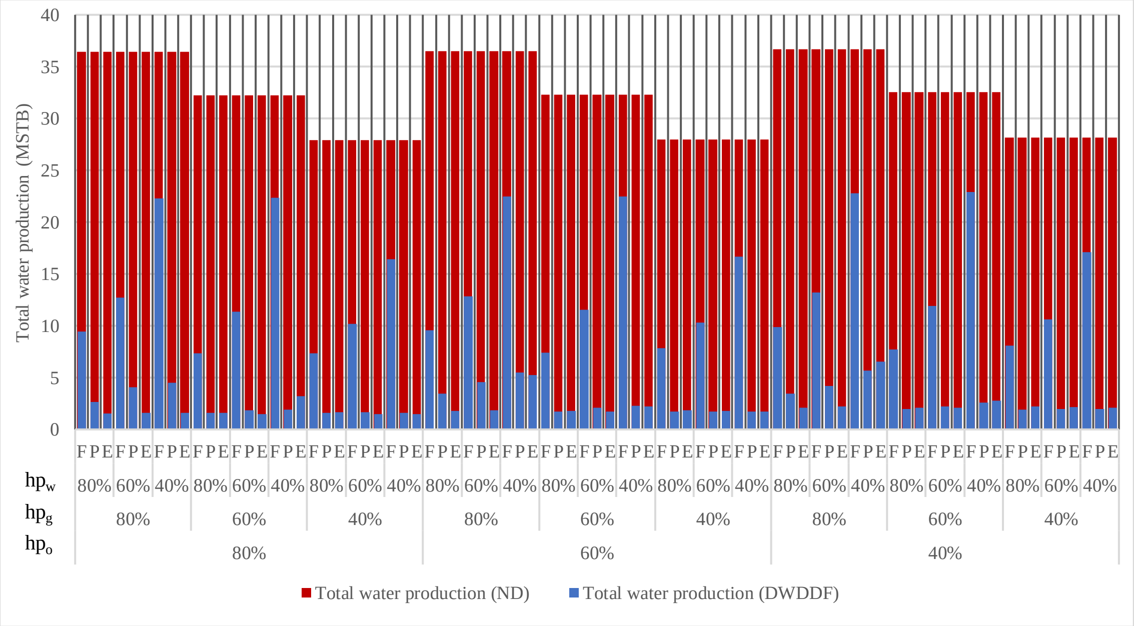


Figure 5.16 Total water production for Bottom-up production and DWDDF at various oil, gas, and water perforation intervals as a function of different starting times for water dumpflood (Note that hpw, hpg and hpo represent perforation intervals of water, gas and oil, respectively whereas F, P, E stands for dumpflood starting time of first day, end of plateau and economic rate).

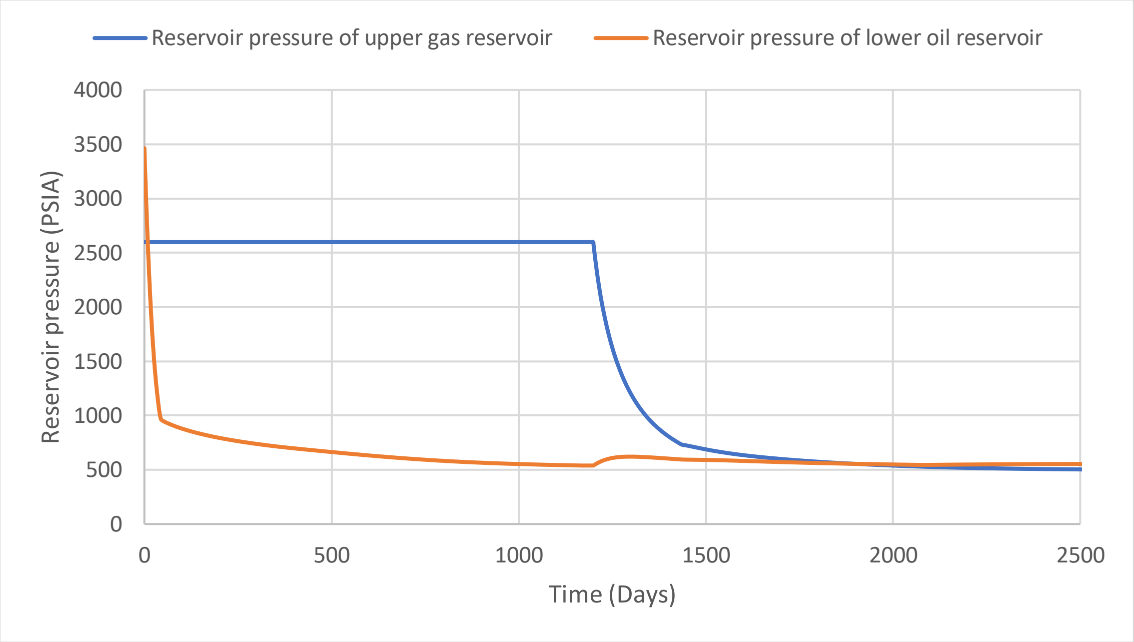


Figure 5.17 Reservoir pressures of bottom-water drive gas reservoir and underlying oil reservoir in DWDDF scenario.

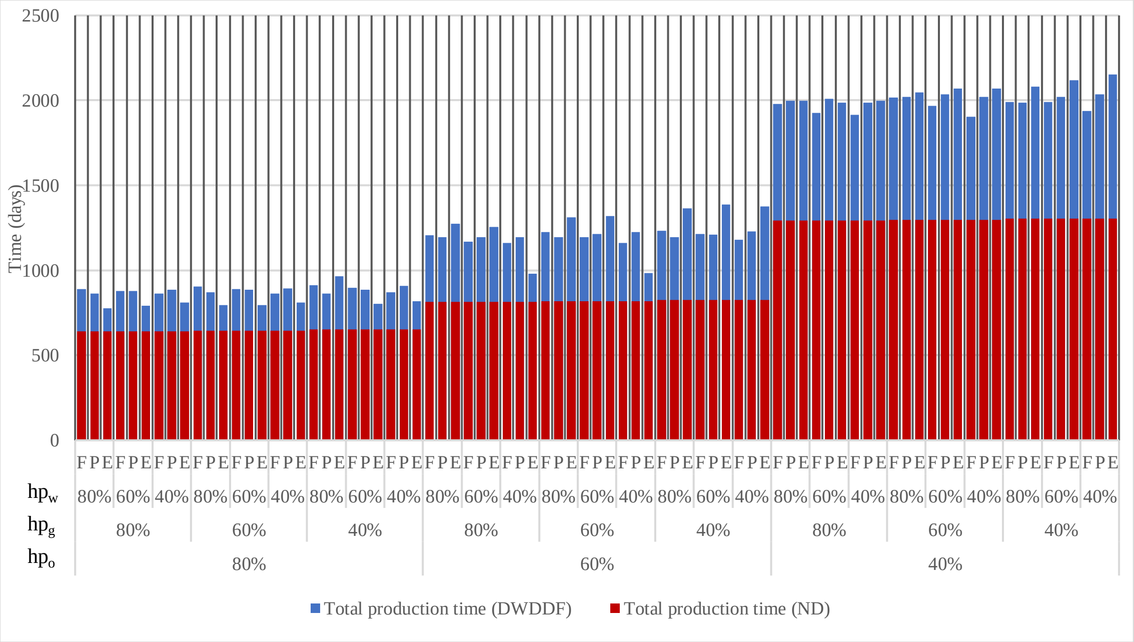


Figure 5.18 Total production time for Bottom-up production and DWDDF at various oil, gas, and water perforation intervals as a function of different starting times for water dumpflood (Note that hpw, hpg and hpo represent perforation intervals of water, gas and oil, respectively whereas F, P, E stands for dumpflood starting time of first day, end of plateau and economic rate).

5.4 Effects from reservoir parameters for Bottom-up

To find out the applicability of the Downhole Water Drain for Water Dumpflood (DWDDF) method, the reservoir parametric study was conducted by comparing the performance of the Bottom-up scenario and the DWDDF scheme. In this section, varied parameters include horizontal permeability of gas reservoir, kv/kh ratio of the gas reservoir, the thickness of gas column and thickness of water column. To investigate the suitable range of the reservoir conditions for the DWDDF technique, the best operating condition of each production method selected in the previous section were used.

To perform the reservoir parametric study for the bottom-up production scenario, the best operating condition of the bottom-up scenario selected from the investigation of the operating parameters (40% oil perforation and 80% gas perforation) was used for the simulation in this section. Since only the reservoir parameters of the upper gas reservoir were varied, there is no impact on the lower oil reservoir in the case of bottom-up production. Because lower oil reservoir and upper gas reservoir bring the production separately as described in the above sections. Therefore, there were no simulation runs associated with the lower oil reservoir in this section.

5.4.1 Investigation of effect of reservoir parameters under horizontal permeability of 15 mD

The simulation results of cases with 15 mD horizontal permeability are shown in Figures 5.19 – 5.21 in terms of gas recovery factor, cumulative water production from gas wells and total gas production time. Results for the bottom-up scenario at horizontal permeability of 15 mD, different kv/kh ratios, and various columns height of gas and water zones are summarized in Table 5.9 in terms of cumulative gas production, gas recovery, BOE, cumulative water production, production time and plateau production time. According to simulation results shown in Figure 5.19, varying the thickness of the water column from 15ft to 60ft when the reservoir possesses kv/kh ratio of 0.01 does not induce any significant changes to gas recovery, but it has little impact on gas well water production. For the 15ft gas reservoir, altering water column height from 15ft to 30ft can increase water production by 1,685 STB (13.24% increment) whereas from 15ft to 60ft can bring more 2,629 STB (19.23% increment) of water production at the surface. At the same gas column thickness, varying water column thickness in the reservoir with a lower kv/kh ratio induces less impact on the amount of water production compared to a higher kv/kh ratio (See Figure 5.20). In fact, water coning can be serious at the reservoir with higher vertical permeability. As the vertical permeability of 0.15 (kv/kh ratio of 0.01) is a very low value, the water production is considerably lower than other cases. Since the water encroachment is considerably small due to lower vertical permeability, it induces the gas recovery to be higher without having significant water inflow to the perforations.

Furthermore, the gas recovery significantly increases with increasing gas reservoir thickness because of two reasons: (1) thicker gas reservoir possesses higher gas initial in place (GIIP) and (2) the reservoir pressure of thicker gas reservoir declines slower than thinner ones as there are more rooms for gas to expand. At all kv/kh ratio values, gas recovery is increasing as the gas reservoir becomes thicker. Besides, the amount of water production was gradually lower as the column height of the gas zone with kv/kh ratio of 0.01 increased because (1) water invasion from GWC to the wellbore is impeded due to lower vertical permeability, and (2) the strength of the aquifer is more strong in the thinner gas reservoir and more active to induce the water encroachment toward the wells.

For reservoir with vertical permeability of 1.5 mD (kv/kh ratio of 0.1), variation of water column thickness has a moderate impact on both gas recovery and water production. In vertical permeability of 1.5 mD cases, results show that the impact on gas recovery by varying water column thickness is more significant in 15 ft gas reservoir compared to 30 ft and 60ft. Gas recovery can increase about 6% when water column thickness is reduced from 60ft to 15ft whereas the increment is only about 2% for both 30ft and 60ft gas reservoirs. Therefore, a decrease in gas recovery due to longer water column thickness is more obvious in a thinner gas reservoir with kv/kh ratio of 0.1. Comparing vertical permeability of 1.5 mD cases and 0.15 mD cases, the impact on gas recovery by varying water column thickness becomes more significant for the cases with vertical permeability of 1.5 mD cases (See Figure 5.19). Therefore, when vertical permeability is higher, the negative impact on gas recovery due to water encroachment becomes more obvious, and less gas recovery can be obtained by producing more water at the surface as the aquifer becomes thicker. This fact is confirmed by Figure 5.20, in which the case with a 15ft gas reservoir with vertical permeability of 1.5 mD produces 34,973 STB of water, which is increased to 50,416 STB (30.63% increment) and 62,164 STB (43.7% increment) when aquifer thickness is varied from 15ft to 30ft, and 15ft to 60ft, respectively. On the contrary, the amount of water production was gradually lower as the thickness of the gas column increased, similar to the case in kv/kh ratio of 0.01.

Results reveal that water column thickness for the aquifer associated with a gas reservoir having vertical permeability of 7.5 mD (kv/kh ratio of 0.5) has more impact on both gas recovery and water production compared to the cases with kv/kh ratio of 0.01 and 0.1. By decreasing water column thickness (from 60ft to 30ft), gas recovery increases from 55.72% to 67.59 (11.87% increment), from 69.85% to 74.57% (4.71% increment) and from 76.94% to 79.21% (2.27% increment) in gas reservoir with thickness of 15ft, 30ft and 60ft, respectively. In addition, decreasing water column thickness for the aquifer associated with a gas reservoir having vertical permeability of 7.5 mD has a more significant impact on water production compared to the 0.15 mD and 1.5 mD cases. Water production is significantly increased with increasing aquifer thickness in all thicknesses of the gas reservoir because the thicker water column is possessing stronger aquifer strength and is capable to produce more water. Moreover, a higher kv/kh ratio induces more water production in gas wells since water coning is more intense where the vertical communication of the reservoir is good. Higher vertical permeability allows more water to flow up to the perforations from the GWC, creating higher hydrostatic pressure inside the well and impeding gas flows. As a result, more water is produced at the surface and gas recovery becomes lower.

Note that all three gas wells died reaching an economic limit, not liquid loading problem in all simulation runs with horizontal permeability of 15 mD. Regarding water gas ratio (WGR), it increases with the increasing kv/kh ratio, and ranges from 1 to 81 STB/MMSCF for the cases with kv/kh ratio of 0.01, from 29 to 311 STB/MMSCF for the cases with kv/kh ratio of 0.1, and from 40 to 424 STB/MMSCF for the cases with kv/kh ratio of 0.5. This fact also confirms that the degree of water coning becomes higher with increasing vertical permeability. Also, WGR increase as water thickness becomes thicker and it decreases as gas thickness becomes thicker. As the water column is thicker, more water from GWC encroach and invades the wellbore, and the well produces higher WGR. In general, when the gas column is thicker, the strength of the aquifer used in this study (water column height of 15, 30, and 60 ft) becomes less active to induce the water encroachment toward the wells. Note that, for the cases with horizontal permeability of 15 mD, all three gas wells died reaching an economic limit, not a liquid loading problem.

As shown in Figure 5.21, total production time is significantly impacted by the gas reservoir thickness. The longer the gas column thickness, the lengthier the total production time was. In fact, the sizeable gas reservoir can produce more gas compared to smaller gas reservoirs. Thus, more production time is required for the larger gas reservoir compared to the smaller gas reservoir at the same operating condition. The highest gas production time of 220 days is obtained from three cases, all of which share the same horizontal permeability (15 mD), kv/kh ratio (0.01) and gas reservoir thickness (60 ft), but different water zone thickness (15, 30 and 60 ft). Also, all these three cases possess higher gas recovery and lower amount of water production among the cases with horizontal permeability of 15mD. Overall, the highest gas recovery of 84.57% is obtained from the case with horizontal permeability of 15 mD, kv/kh ratio of 0.01 and gas reservoir thickness of 60 ft, and water zone thickness of 60 ft, the water production is only 629 STB.

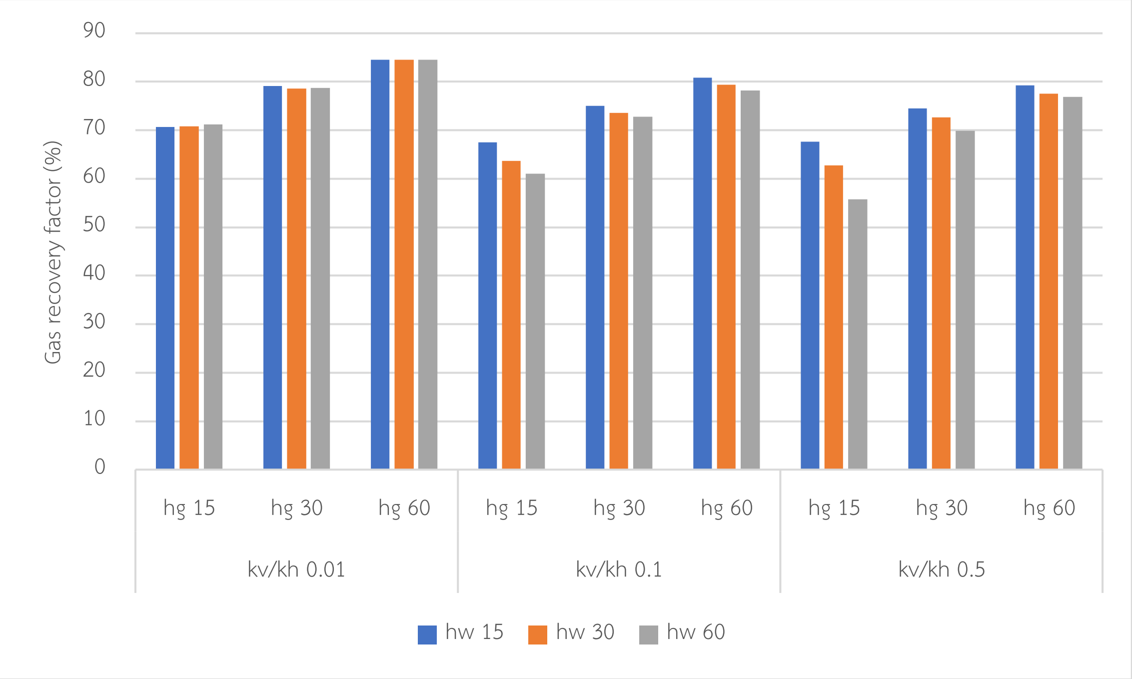


Figure 5.19 Gas recovery at horizontal permeability of 15 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

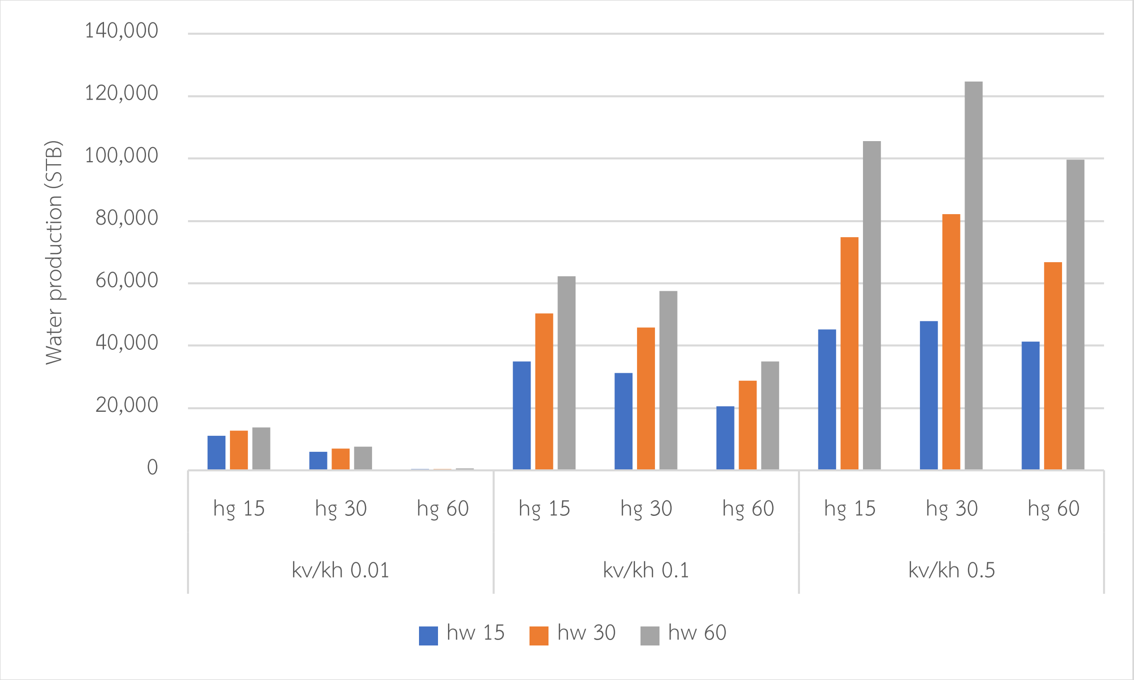


Figure 5.20 Water production at horizontal permeability of 15 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

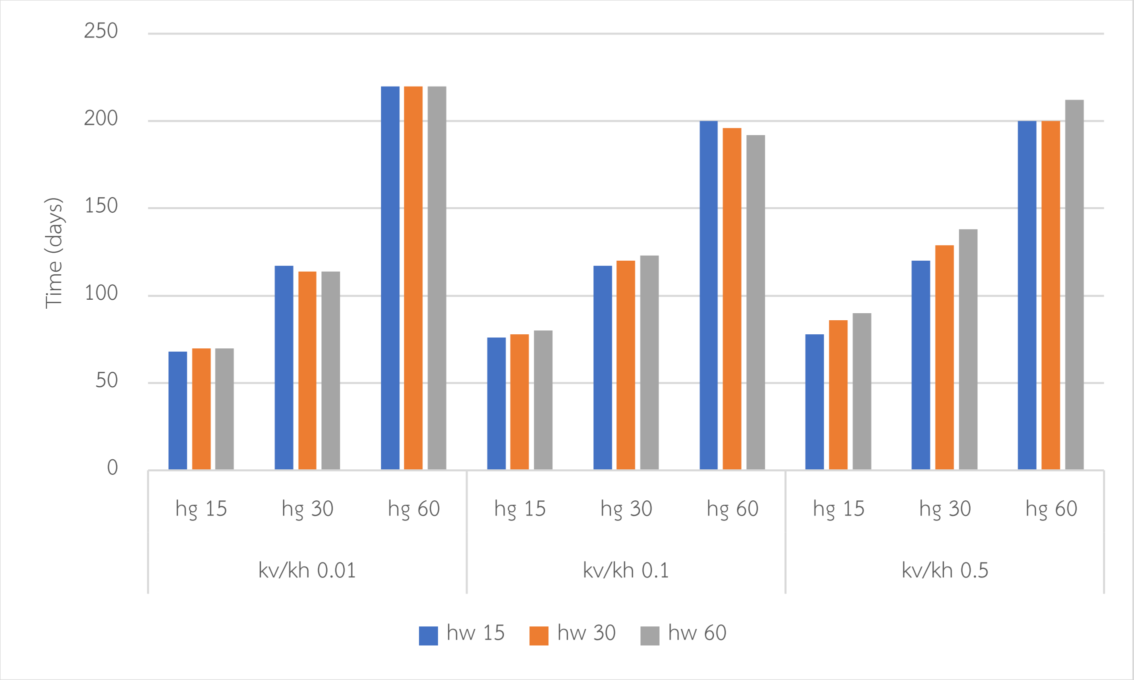


Figure 5.21 Total production period at horizontal permeability of 15 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

Table 5.9 Cumulative gas production, gas recovery, BOE, water production, production time and plateau production time for bottom-up production scenario at horizontal permeability of 15 mD, various kv/kh ratios, different columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Cumulative gas production	Gas recovery factor	Barrel of oil equivalent	Water production	Time	Plateau
	Gas	Water	(MMSCF)	(MMSCF)	(%)	(BOE)	(STB)	(days)	(days)
0.01	15	15	727	514	70.74	85,663	11,044	68	10
		30		515	70.84	85,787	12,729	70	10
		60		517	71.15	86,161	13,672	70	10
	30	15	1,453	1,150	79.16	191,729	5,959	117	36
		30		1,143	78.63	190,428	6,917	114	36
		60		1,144	78.71	190,640	7,574	114	36
	60	15	2,906	2,456	84.49	409,242	333	220	93
		30		2,456	84.50	409,290	484	220	93
		60		2,458	84.57	409,668	629	220	93
0.1	15	15	727	491	67.54	81,791	34,973	76	6
		30		463	63.70	77,137	50,416	78	5
		60		444	61.05	73,931	62,164	80	4.5
	30	15	1,453	1,090	74.98	181,594	31,159	117	30
		30		1,070	73.65	178,365	45,775	120	29
		60		1,058	72.84	176,403	57,598	123	28
	60	15	2,906	2,349	80.81	391,451	20,481	200	90
		30		2,307	79.37	384,482	28,806	196	86
		60		2,274	78.22	378,898	34,906	192	86
0.5	15	15	727	491	67.59	81,850	45,089	78	4
		30		456	62.79	76,039	74,852	86	2
		60		405	55.72	67,479	105,471	90	1.6
	30	15	1,453	1,084	74.57	180,595	47,812	120	28
		30		1,056	72.64	175,925	82,072	129	23
		60		1,015	69.85	169,184	124,714	138	19
	60	15	2,906	2,302	79.21	383,693	41,274	200	86
		30		2,253	77.51	375,472	66,846	200	80
		60		2,236	76.94	372,708	99,702	212	74

5.4.2 Investigation of effect of reservoir parameters under horizontal permeability of 50 mD

Results from the simulation run for a gas reservoir with horizontal permeability of 50 mD are illustrated in Figures 5.22 – 5.24 in terms of gas recovery factor, cumulative water production and total gas production time. Results for the bottom-up scenario at horizontal permeability of 50 mD, different kv/kh ratios, and columns height of gas and water zones are summarized in Table 5.10 in terms of cumulative gas production, gas recovery, BOE, cumulative water production, production time and plateau production time. Similar to the cases with horizontal permeability of 15 mD, varying the thickness of the water column associated with the gas reservoirs having kv/kh ratio of 0.01 does not also generate any significant changes on the gas recovery, but it has little impact on gas well water production. For the 15ft gas reservoir with vertical permeability of 0.5 mD, altering water column height from 15ft to 30ft induces 2,037 STB more water production whereas from 15ft to 60ft can bring 3,271 STB more water production. Similar to the cases with horizontal permeability of 15 mD, the higher kv/kh ratio shows more impact on the amount of water production compared to the lower kv/kh ratio in the case of varying water column thickness at the same condition of reservoir thickness (See Figure 5.23). Because water coning can be more intense when the reservoir possesses higher vertical permeability, and it causes higher water production.

Like horizontal permeability of 15 mD cases, the gas recovery increases with increasing gas reservoir thickness. Also, the amount of water production decreases as the thickness of the gas column increases for all values of kv/kh ratio. According to simulation results, the gas recovery factors of horizontal permeability of 50 mD cases are higher than 15 mD cases at the same condition of three other reservoir parameters. In fact, higher gas recovery can be achieved by higher horizontal permeability, which helps any fluid to flow easier through the porous media and induce a longer plateau rate production period. At the same reservoir condition of kv/kh ratio, gas column thickness, and water column thickness, most cases of horizontal permeability of 50 mD can produce more water compared to 15 mD (horizontal permeability) as the vertical permeability becomes higher; except for some cases with 60 ft gas reservoir. In this study, vertical permeability is calculated based on horizontal permeability, therefore, vertical permeability is increased with horizontal permeability. As the vertical permeability is increased, there are less flow restrictions for water to flow upward from GWC and increase water production. But for some cases with 60 ft gas reservoir, water production of horizontal permeability of 50 mD is lower than 15 mD because the impact on water production due to increasing vertical permeability becomes smaller when gas reservoir thickness is 60 ft.

For reservoir with vertical permeability of 5 mD (kv/kh ratio of 0.1), variation of water column thickness has some impact on gas recovery and moderate impact on water production. In vertical permeability of 5 mD (kv/kh ratio 0.1) cases, results show that gas recovery can increase about 4.52% for 15 ft gas reservoir when water column thickness is reduced from 60ft to 15ft whereas the increment for 30ft and 60ft gas reservoir are only 0.35% and 1.73%, respectively. Thus, a decrease in gas recovery due to longer water column thickness is more obvious in the thinner gas reservoir with kv/kh ratio of 0.1. Nevertheless, comparing vertical permeability of 5 mD cases and 0.5 mD cases, the negative impact on gas recovery by increasing water column thickness becomes more significant for the cases with vertical permeability of 5 mD cases (See Figures 5.22). According to Figure 5.23, it is clear to see that the amount of water production increases with not only increasing water column height but also rising kv/kh ratio. The negative impact on gas recovery due to increasing water production as a result of water encroachment is significantly due to higher vertical permeability.

Results reveal that water column thickness for the aquifer associated with a gas reservoir having vertical permeability of 25 mD (kv/kh ratio of 0.5) has more impact on both gas recovery and water production compared to the cases with kv/kh ratio of 0.01 and 0.1. By decreasing water column thickness (from 60ft to 30ft), gas recovery increases from 64.28% to 74.22 (9.94% increment), from 75.35% to 77.97% (2.63% increment) and from 79.2% to 81.66% (2.46% increment) in gas reservoir with thickness of 15ft, 30ft and 60ft, respectively. In addition, decreasing water column thickness for the aquifer associated with the gas reservoir having vertical permeability of 25 mD has a more significant impact on water production compared to the 0.5 mD and 5 mD cases. The higher kv/kh ratio allows more water to flow up to the perforations from the GWC and impede gas flows. As a result, more water is produced at the surface with lower gas recovery.

For the cases with horizontal permeability of 50 mD, not all cases were reaching the economic limit. For the cases with kv/kh ratio of 0.01, the wells died due to the economic limit, and WGR ranges from 1 STB/MMSCF to 104 STB/MMSCF. The higher WGR values come from the longer water column cases. For the case with kv/kh ratio of 0.1, wells in the cases with 60 ft gas reservoir terminated the production around well production rate of 1 MMSCF/day and the WGR of these cases range from 26 STB/MMSCF to 41 STB/MMSCF. Since WGR values are in the low-value range (not higher than 300 STB/MMSCF), the production rate of 1 MMSCF/day would be the last producible rate from the VLP due to liquid fraction. Therefore, gas wells in this case require more bottom-hole pressure to continue the production until the economic rate because liquid fraction increases the requirement for bottom-hole pressure. In this connection, the gas recovery factor of 60 ft gas reservoir (kv/kh ratio of 0.1) is 80.96%, 81.81%, and 82.69% at 60 ft, 30 ft, and 15 ft of the water column, respectively. Comparing the kv/kh ratio of 0.01 and 0.1 for 60 ft gas reservoirs, premature termination of gas production for kv/kh ratio of 0.1 is due to higher water production (high WGR) compared to kv/kh ratio of 0.01. This information also confirms that the higher kv/kh ratio can lower the gas recovery by producing a higher amount of water because water coning is more intense when there is good vertical communication within the pore spaces. Apart from the 60 ft gas reservoir cases, other cases in kv/kh ratio of 0.1 terminate the production due to reaching the economic limit.

Similar to the kv/kh ratio of 0.1 cases, wells in the cases with 60 ft gas reservoir died at the production rate of 1 MMSCF/day for the case with kv/kh ratio of 0.5. WGR of these cases ranges from 35 STB/MMSCF to 72 STB/MMSCF. In this case, the gas recovery factor of 60 ft gas reservoir (kv/kh ratio 0f 0.5) is 79.20%, 79.98%, and 81.66% at 60 ft, 30 ft, and 15 ft of the water column, respectively. Again, comparing kv/kh ratios of 0.01 and 0.5 for 60 ft gas reservoirs, premature termination of gas production for kv/kh ratio of 0.5 is also due to higher water production (high WGR) compared to kv/kh ratio of 0.01. Therefore, higher kv/kh ratio can have a negative impact on gas recovery by producing a significant amount of water since there is high vertical permeability.

Regarding production time, it is significantly impacted by the gas reservoir thickness. Increasing the column height of the gas zone can extend the production time since the recovery factor of the thicker gas reservoir is always higher than the thinner ones. The highest gas production time of 188 days is obtained from three cases, all of which share the same horizontal permeability (50 mD), kv/kh ratio (0.01) and gas reservoir thickness (60 ft), but different water zone thickness (15, 30, 60 ft). Also, all these three cases possess higher gas recovery and lower amount of water production among the cases with horizontal permeability of 50mD. Overall, the highest gas recovery of 86.69% is obtained from the case with horizontal permeability of 50 mD, kv/kh ratio of 0.01 and gas reservoir thickness of 60 ft, and water zone thickness of 60 ft, the water production is only 639 STB. By comparing the highest gas recovery case from horizontal permeability of 15 mD and 50 mD, it is found that 50 mD case can bring 2.12% more gas recovery with 10 STB less water production than 15 mD. Moreover, the production time of the highest gas recovery case from horizontal permeability of 50 mD is shorter than the one from 15 mD. Therefore, a higher horizontal permeability case can produce more gas with a shorter production time compared to lower ones. In fact, the reservoir with higher horizontal permeability brings a longer plateau rate production period for gas wells compared to the reservoir with lower horizontal permeability. All in all, higher horizontal permeability can increase gas recovery as it helps the fluids to flow easier from pore to pore inside the reservoir and it induces a longer plateau production time and shorter total production time. In general, higher kv/kh ratio allows more water to be produced at the surface since it induces more water to flow up to the perforations from GWC. A thicker gas reservoir can also increase gas recovery since it possesses higher GIIP, and its reservoir pressure declines slower than thinner ones as there are more rooms for gas to expand. In addition, thicker gas reservoirs come up with lower water production compared to thinner ones in this study because the strength of the aquifer is less strong in the thicker gas reservoir. Water production is mainly due to the height of the water column, longer column of water zone induces higher water production compared to shorter ones because the strength of the aquifer is more strong in the thicker water zone.

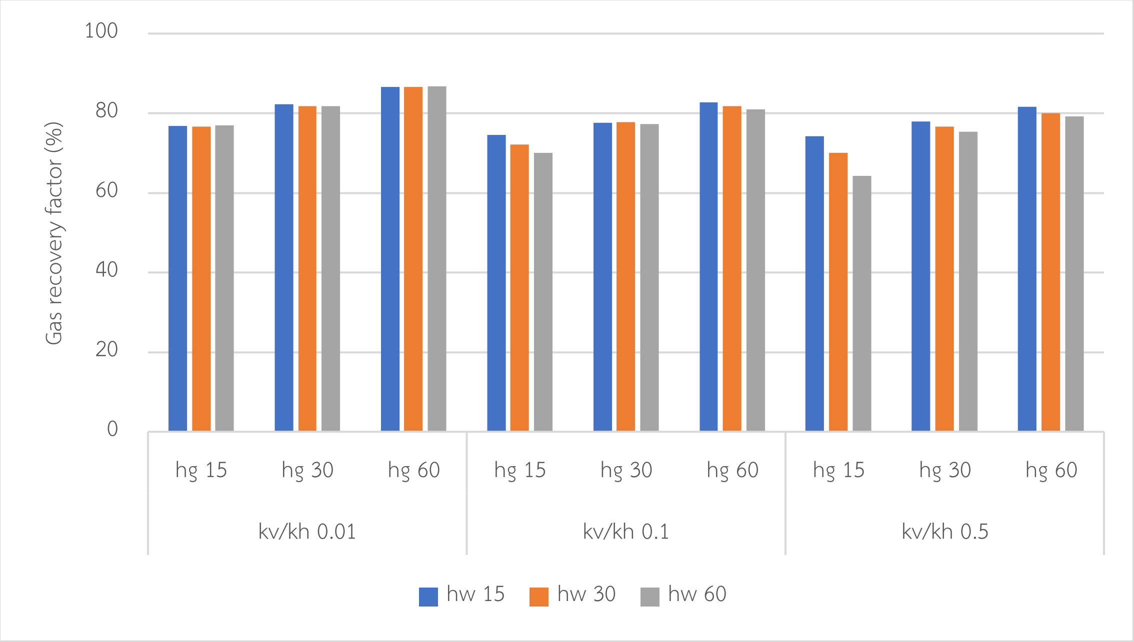


Figure 5.22 Gas recovery at horizontal permeability of 50 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

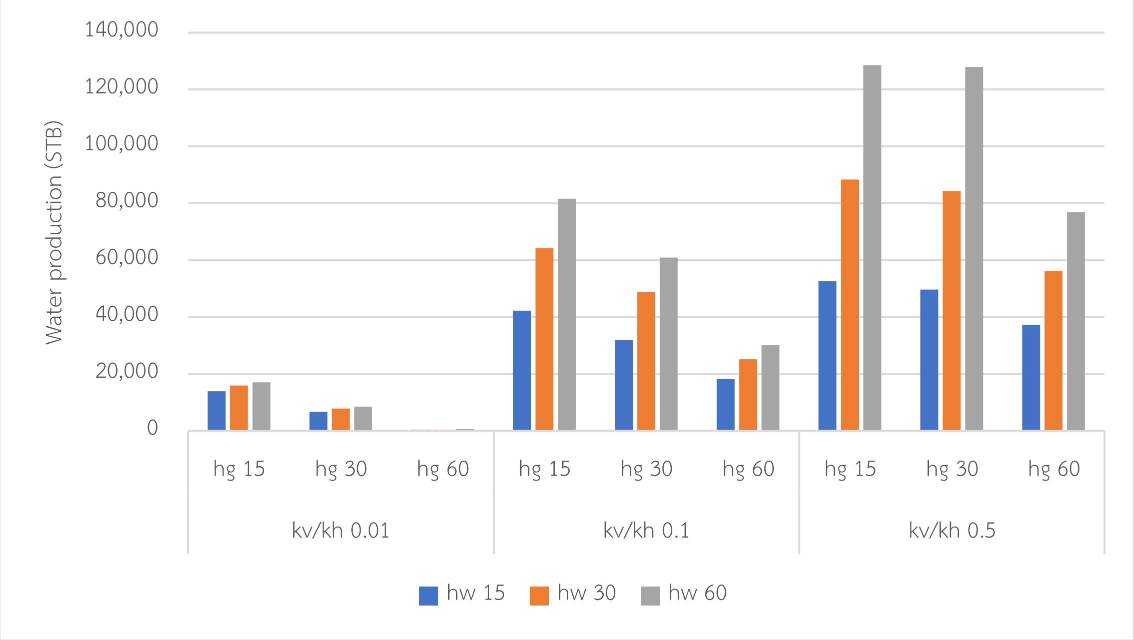


Figure 5.23 Water production at horizontal permeability of 50 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

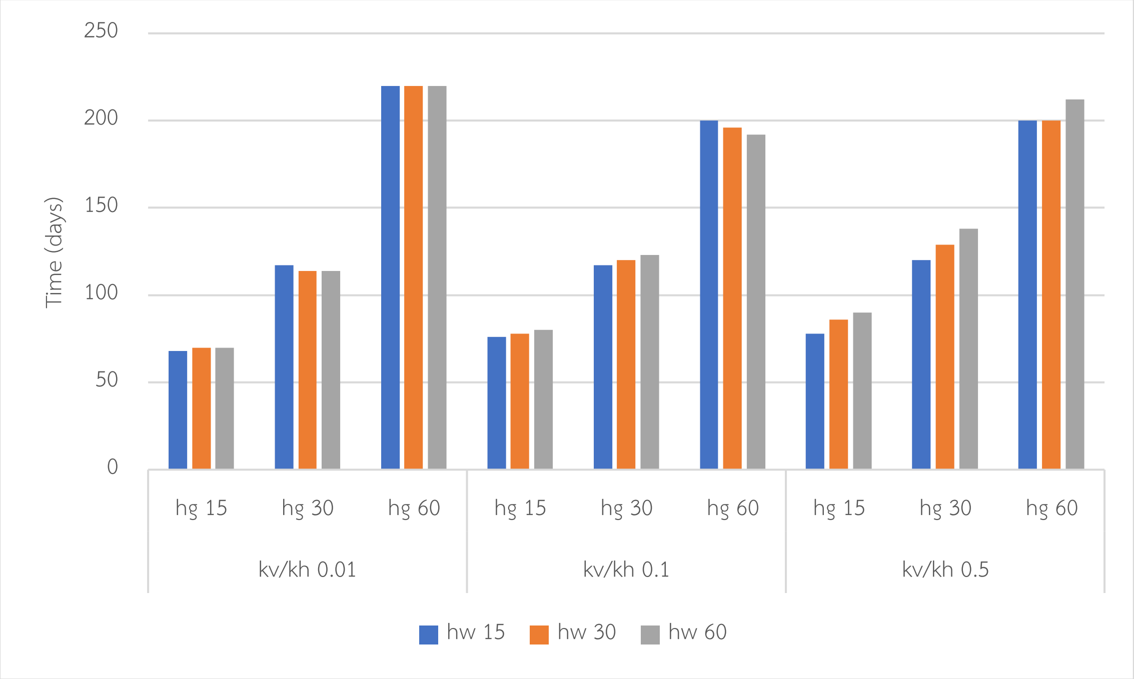


Figure 5.24 Total production period at horizontal permeability of 50 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

Table 5.10 Cumulative gas production, gas recovery, BOE, water production, production time and plateau production time for bottom-up production scenario at horizontal permeability of 50 mD, various kv/kh ratios, different columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Cumulative gas production	Gas recovery factor	Barrel of oil equivalent	Water production	Time	Plateau
	Gas	Water	(MMSCF)	(MMSCF)	(%)	(BOE)	(STB)	(days)	(days)
0.01	15	15	727	558	76.81	93,015	13,891	52	19
		30		556	76.58	92,741	15,928	52	19
		60		559	76.89	93,115	17,162	52	19
	30	15	1,453	1,194	82.19	199,058	6,692	93	50
		30		1,188	81.77	198,039	7,798	90	50
		60		1,189	81.79	198,096	8,508	90	50
	60	15	2,906	2,519	86.65	419,737	320	188	111
		30		2,518	86.65	419,722	467	188	111
		60		2,520	86.69	419,916	639	188	111
0.1	15	15	727	542	74.61	90,345	42,340	58	15
		30		524	72.15	87,376	64,319	62	13
		60		509	70.09	84,878	81,614	64	12
	30	15	1,453	1,128	77.63	188,027	31,872	86	44
		30		1,130	77.74	188,292	48,673	96	40
		60		1,123	77.29	187,185	61,001	99	40
	60	15	2,906	2,403	82.68	400,516	18,132	165	105
		30		2,378	81.81	396,282	25,263	177	102
		60		2,353	80.96	392,148	30,042	162	102
0.5	15	15	727	539	74.22	89,879	52,527	57	14
		30		509	70.04	84,818	88,313	80	10
		60		467	64.28	77,840	128,633	83	7
	30	15	1,453	1,133	77.97	188,846	49,766	93	40
		30		1,114	76.66	185,672	84,408	99	38
		60		1,095	75.35	182,486	128,031	111	32
	60	15	2,906	2,373	81.66	395,552	37,353	168	102
		30		2,325	79.98	387,429	56,185	168	96
		60		2,302	79.20	383,656	76,949	168	93

5.4.3 Investigation of effect of reservoir parameters under horizontal permeability of 100 mD

Results from the simulation run for the gas reservoir with horizontal permeability of 100 mD are illustrated in Figures 5.25 – 5.27 in terms of gas recovery factor, cumulative water production and total gas production time. Results for the bottom-up scenario at horizontal permeability of 100 mD, different kv/kh ratios, and columns height of gas and water zones are summarized in Table 5.11 in terms of cumulative gas production, gas recovery, BOE, and water production, production time and plateau production time. Similar to the cases with horizontal permeability of 15 mD and 50 mD, there are no significant changes to gas recovery by varying the thickness of the water column associated with the gas reservoirs having kv/kh ratio of 0.01, but it has a few impacts on water production. For the 15ft gas reservoir with vertical permeability of 1 mD, increasing the water column height from 15ft to 30ft produces more 2,329 STB water whereas from 15ft to 60ft can bring more 3,784 STB water. Like the cases with horizontal permeability of 15 mD and 50 mD, the amount of water production is significantly increasing with the increasing kv/kh ratio in 100 mD cases. Also, the amount of water production increases more in higher kv/kh ratio cases compared to lower ones when the water column becomes thicker. Therefore, it is obvious to describe that higher kv/kh ratio induces more water production as higher vertical permeability intensifies water coning to happen.

In general, cases with horizontal permeability of 100 mD show that increasing gas reservoir thickness increases the gas recovery but decreases the amount of water production for all values of kv/kh ratio. According to simulation results, gas recovery factors of horizontal permeability of 100 mD cases are significantly higher than 15 mD cases at the same condition of three other reservoir parameters. Meanwhile, gas recovery factors of most of the cases of horizontal permeability of 100 mD are somewhat higher than 50 mD cases at the same condition of three other reservoir parameters, except for one case. Other common reservoir parameters of this exceptional case are kv/kh ratio of 0.5, gas reservoir thickness of 15 ft and water column height of 30 ft. It shows that gas recovery of horizontal permeability of 50 mD is 1.05% higher than 100 mD because gas production of all wells in 100 mD cases was terminated at the higher abandonment rate as it has higher WGR compared to 50 mD cases. Furthermore, it is found that gas recovery increment by increasing horizontal permeability from 15 mD to 50 mD or 100 mD is higher compared to from 50 mD to 100 mD. Therefore, the impact on recovery increment is much more significant when horizontal permeability is varying from 15 mD to 50 mD, and it becomes less when horizontal permeability is increasing beyond 50 mD.

Regarding water production in 15ft gas reservoir, horizontal permeability of 100 mD cases are higher than 15 mD cases at the same reservoir condition of kv/kh ratio and water column height. However, when the gas reservoir becomes thicker, most cases of horizontal permeability of 100 mD are lower water production than 15 mD (horizontal permeability). In these cases, the contribution of gas zone thickness become increases and it decreases the contribution of the vertical permeability. Consequently, horizontal permeability of 100 mD cases are lower in water production compared to 15 mD (horizontal permeability) although it possesses higher vertical permeability. The same concept goes for the pair of horizontal permeability of 100 mD and 50 mD. Comparing at same kv/kh ratio and water column height, water production of horizontal permeability of 100 mD is higher than

50 mD only in most cases with 15 ft gas reservoir where the contribution of vertical permeability is higher than gas zone thickness. In this connection, one case of 15 ft gas reservoir with horizontal permeability of 100 mD shows less water production than 50 mD. This is the same exceptional case as we discussed above regarding comparing the gas recovery of horizontal permeability of 50 mD and 100 mD when other reservoir conditions are fixed (kv/kh ratio of 0.5, gas reservoir thickness of 15 ft and water column height of 30 ft).

For reservoir with vertical permeability of 10 mD (kv/kh ratio of 0.1), variation of water column thickness has some impact on gas recovery and moderate impact on water production like in the cases with vertical permeability of 1.5 mD (horizontal permeability of 15 mD) and 5 mD (horizontal permeability of 50 mD). Comparing vertical permeability of 10 mD cases and 1 mD cases, the negative impact on gas recovery by increasing water column thickness becomes more significant for the cases with vertical permeability of 10 mD cases (See Figures 5.25). According to Figure 5.26, it is clear to see that the amount of water production considerably increases with the rising kv/kh ratio. Water production is slightly increasing with increasing water column height at a low kv/kh ratio while it is substantially rising with rising water column height at a high kv/kh ratio. Therefore, we can conclude that the negative impact on gas recovery due to increasing water production as a result of water encroachment is significantly due to higher vertical permeability.

By decreasing water column thickness (from 60ft to 30ft) in vertical permeability of 50 mD (kv/kh ratio of 0.5), gas recovery increases from 69.76% to 75.70 (6.02% increment), from 77.94% to 78.74% (0.8% increment) and from 82.02% to 83.2% (1.19% increment) in gas reservoir with thickness of 15ft, 30ft and 60ft, respectively. Thus, it is obvious to see that gas recovery of the thinner gas reservoir is mainly affected by the thickness of the water column. Additionally, decreasing water column thickness for the aquifer associated with a gas reservoir having vertical permeability of 50 mD has a more significant impact on the reduction of water production compared to 1 mD and 10 mD cases. Therefore, high vertical permeability can increase water production considerably and it can also lower gas recovery. However, the negative impact on gas recovery due to the high kv/kh ratio becomes less when there is higher horizontal permeability. Therefore, comparing horizontal permeability of 15 mD, 50 mD and 100 mD under the same condition of other reservoir parameters, the highest gas recovery can be seen at 100 mD, followed by 50 mD.

For the cases with horizontal permeability of 100 mD, not all cases were reaching the economic limit. For the cases with kv/kh ratio of 0.01, wells drilled in 15 ft and 60 ft gas reservoirs died due to the economic limit (WGR ranges from 84 to 110 STB/MMSCF for 15 ft gas reservoir and 1 to 2 STB/MMSCF for 30 ft gas reservoir). For 30 ft gas reservoir with kv/kh ratio of 0.01, gas wells terminated production around well production rate of 1 MMSCF/day and WGR ranges from 26 to 32 STB/MMSCF. Since WGR values are in the low-value range (even lower than well dies at the economic rate in 15 ft gas reservoir case), gas wells in this case require more bottom-hole pressure in order to continue the production until the economic rate because its liquid fraction increases the requirement for bottomhole pressure. Similar conditions are also found in the case with kv/kh ratio of 0.1, wells in the cases with 30 ft gas reservoir terminated the production around well production rate of 1 MMSCF/day and the WGR of these cases range from 68 to 123 STB/MMSCF. Therefore, wells were terminated production due to lower bottomhole pressure.

For the kv/kh ratio of 0.5, most of the wells did not reach to specified economic rate, were died around the production rate of 1 MMSCF/day and WGR ranges from 145 to 422 STB/MMSCF for 15 ft gas reservoir, 85 to 179 STB/MMSCF for 30 ft gas reservoir and 26 to 44 STB/MMSCF for 60 ft gas reservoir. It is clear to see that increasing gas column height can lower the WGR values. Also, a lower kv/kh value can lower WGR values and decrease water production. The case yielding the highest WGR value of 422 STB/MMSCF is from horizontal permeability of 100 mD, kv/kh ratio of 0.5, 15 ft gas column thickness and 60 ft water column thickness. However, two wells in this case can produce until the economic rate and only one well terminated production at a production rate of 1.8 MMSCF/day, of which WGR is 384 STB/MMSCF. Therefore, we can conclude that only one well in this case was killed by liquid loading.

Regarding production time for horizontal permeability of 100 mD cases, it is also increasing with increasing gas column height since the recovery factor of the thicker gas reservoir is always higher than the thinner ones. Among all 81 cases, the highest gas recovery of 87.282% is obtained from horizontal permeability of 100 mD, kv/kh ratio of 0.01 and gas reservoir thickness of 60 ft and water zone thickness of 30 ft, the water production is only 311 STB, which is the second lowest water production case among 81 cases. In fact, the second highest gas recovery value is 87.281%, which is only a 0.001% difference from the highest one, but its water production is 116 STB less than the highest gas recovery case. Both cases shared the same reservoir conditions of horizontal permeability, kv/kh ratio and gas reservoir thickness but possess different water zone thicknesses (15 ft and 30 ft). Therefore, it is obvious to see that gas recovery is less impacted by water column thickness when the kv/kh ratio is at a low value (0.01). The total production time of both cases is 180 days, and their plateau rate production period is 114 days. Also, the plateau rate production period of 114 days is the longest among 81 cases. Therefore, higher horizontal permeability can bring higher gas recovery by extending a longer plateau rate period. In general, the total production time of higher permeability cases is shorter than lower ones. All in all, higher horizontal permeability can increase gas recovery as fluids can flow inside the reservoir with less restrictions and it induces a longer plateau production time. Generally, higher kv/kh ratio allows more water to be produced since it induces more water to flow up to the perforations from GWC. A thicker gas reservoir can also increase gas recovery since it possesses higher GIIP, and its reservoir pressure declines slower than thinner ones as there are more rooms for gas to expand. In addition, thicker gas reservoirs come up with lower water production compared to thinner ones in this study because the strength of the aquifer is less strong in the thicker gas reservoir. Water production can also be high due to the height of the water column, longer column of water zone induces higher water production compared to shorter ones because the strength of the aquifer is more strong in the thicker water zone.

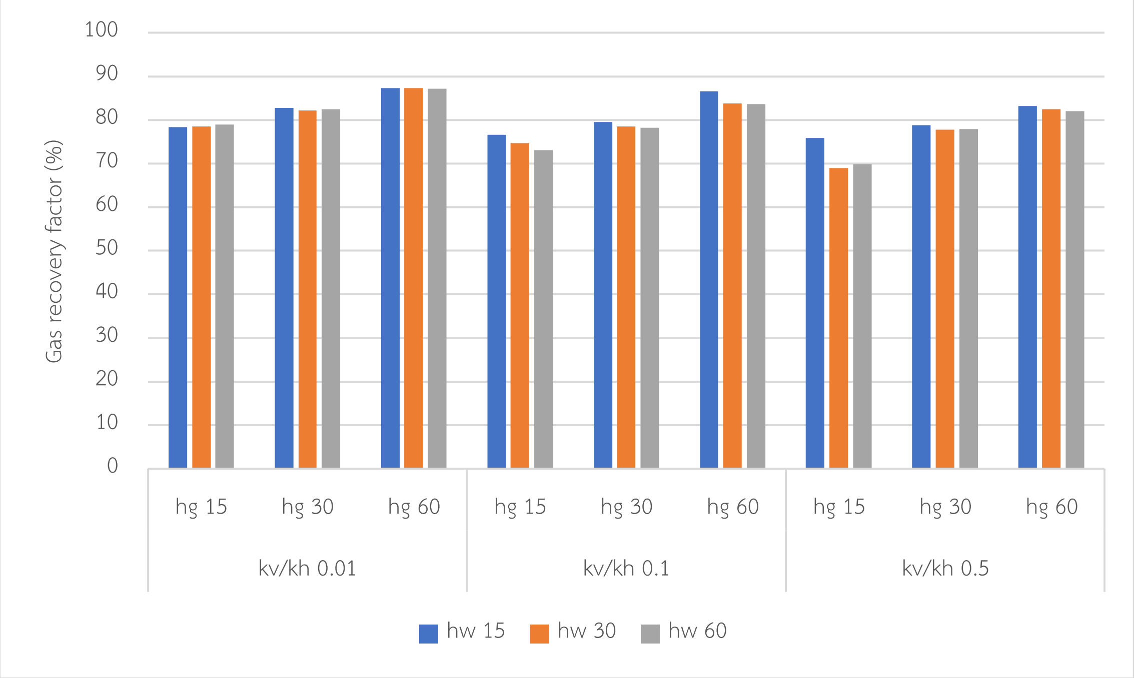


Figure 5.25 Gas recovery at horizontal permeability of 100 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

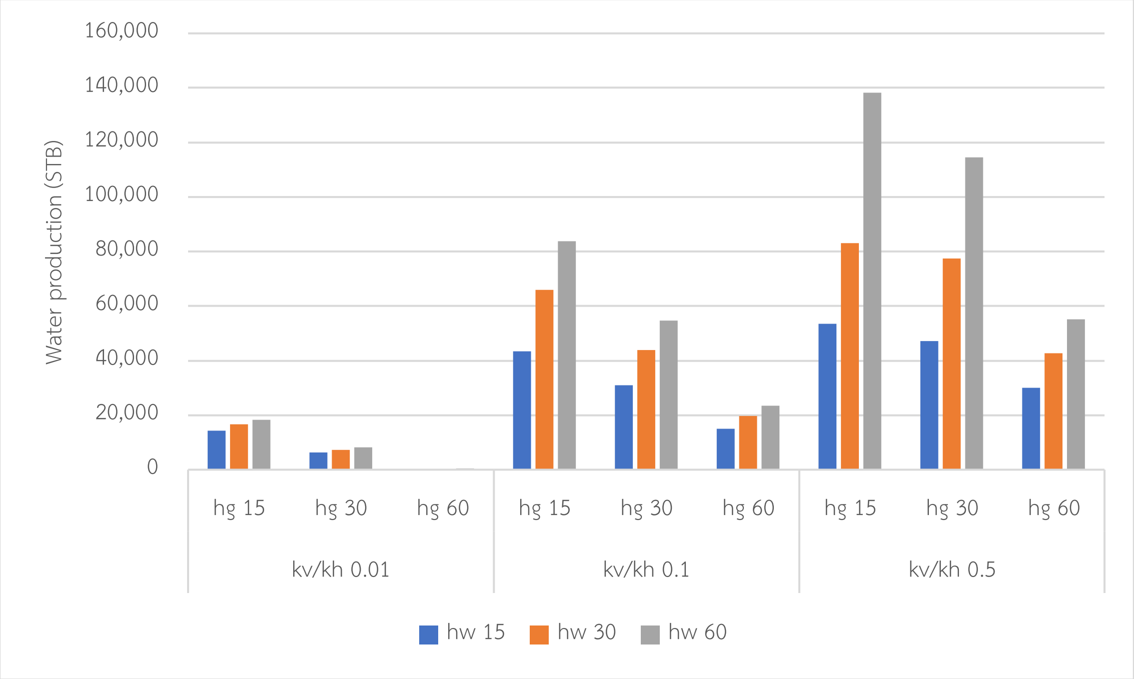


Figure 5.26 Water production at horizontal permeability of 100 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

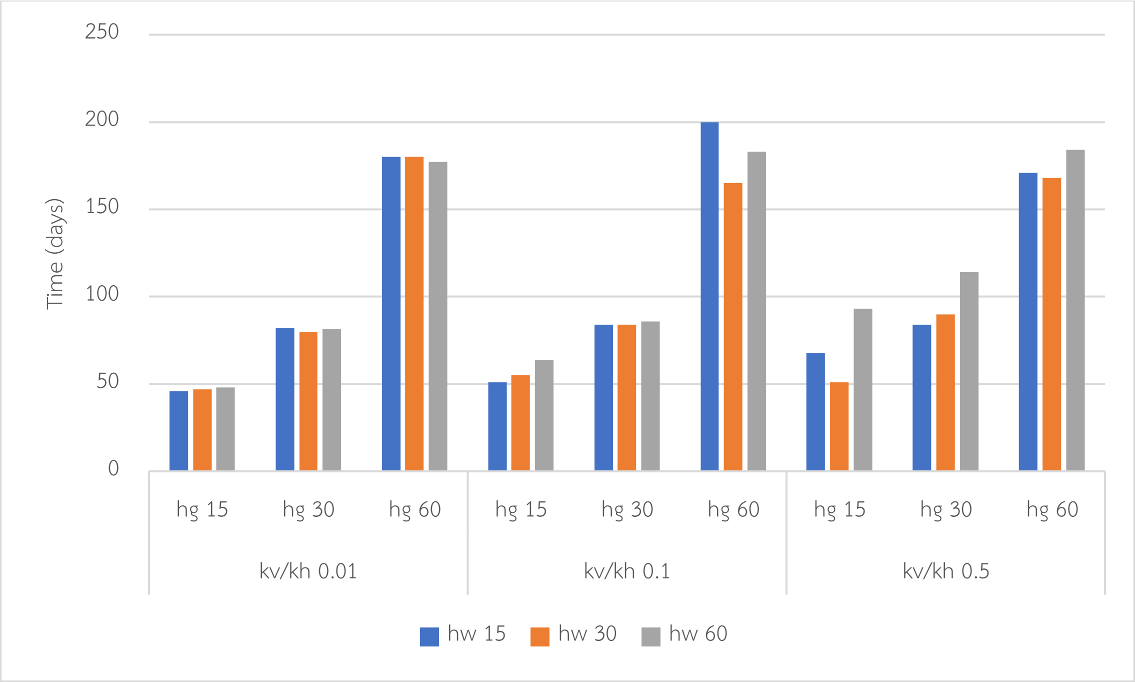


Figure 5.27 Total production period at horizontal permeability of 100 mD for various gas and water column as a function of various kv/kh ratios for bottom-up production scenario.

Table 5.11 Cumulative gas production, gas recovery, BOE, water production, production time and plateau production time for bottom-up production scenario at horizontal permeability of 100 mD, various kv/kh ratios, different columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Cumulative gas production	Gas recovery factor	Barrel of oil equivalent	Water production	Time	Plateau
	Gas	Water	(MMSCF)	(MMSCF)	(%)	(BOE)	(STB)	(days)	(days)
0.01	15	15	727	569	78.35	94,876	14,398	46	22
		30		571	78.53	95,095	16,727	47	22
		60		573	78.87	95,514	18,182	48	22
	30	15	1,453	1,203	82.80	200,547	6,403	82	52
		30		1,193	82.09	198,807	7,323	80	52
		60		1,198	82.45	199,679	8,219	81.4	52
	60	15	2,906	2,537	87.28	422,780	195	180	114
		30		2,537	87.28	422,786	311	180	114
		60		2,535	87.21	422,426	454	177	114
0.1	15	15	727	556	76.58	92,742	43,356	51	18
		30		543	74.71	90,467	66,048	55	16
		60		531	73.07	88,480	83,890	64	15
	30	15	1,453	1,155	79.51	192,568	30,916	84	48
		30		1,140	78.45	189,991	43,826	84	44
		60		1,137	78.23	189,477	54,584	86	44
	60	15	2,906	2,514	86.50	419,016	15,006	200	111
		30		2,436	83.82	406,018	19,625	165	108
		60		2,429	83.58	404,836	23,447	183	108
0.5	15	15	727	551	75.79	91,776	53,587	68	18
		30		501	69.00	83,551	83,131	51	14
		60		507	69.76	84,481	138,284	93	10
	30	15	1,453	1,144	78.74	190,701	47,079	84	44
		30		1,131	77.80	188,427	77,502	90	42
		60		1,133	77.94	188,770	114,481	114	38
	60	15	2,906	2,418	83.20	403,033	30,029	171	105
		30		2,398	82.50	399,631	42,757	168	102
		60		2,384	82.02	397,290	55,090	184	100

In order to investigate the applicability of DWDDF, i.e., suitable reservoir conditions for DWDDF, the performance of bottom-up scenario and DWDDF scheme at various reservoir conditions are comparatively studied. Therefore, gas recovery obtained from the bottom-up production scenario under different reservoir conditions is converted to BOE and combined with the highest BOE of 875,854 barrels obtained from the combination of total oil and dissolved gas production from the lower oil reservoir. Note that the best operating condition of the lower oil reservoir is 40% oil perforation, which yields BOE of 875,854 barrels and 1,719 STB of water, and its production time is 1188 days. The total BOE (oil and dissolved gas production from lower oil reservoir and gas production from the upper gas reservoir), total water production (connate water production from lower oil reservoir and water production from the upper gas reservoir), total production time (production time of lower reservoir and upper reservoir including 30 days of completion period), BOE in terms of recovery factor and contribution of the gas reservoir in the bottom-up scenario at different reservoir conditions are summarized in Tables 5.12 – 5.14.

For horizontal permeability of 15 mD, BOE recovery ranges from 18.64% to 23.7%. Its contribution to total BOE and total water production of the bottom-up scenario ranges from 7.15% to 31.87% and from 16.25% to 98.64%. For horizontal permeability of 50 mD, BOE recovery ranges from 18.85% to 23.89%. Its contribution to total BOE and total water production of the bottom-up scenario ranges from 8.16% to 32.41% and from 15.70% to 98.68%. For horizontal permeability of 100 mD, BOE recovery ranges from 18.96% to 23.94%. Its contribution to total BOE and total water production of the bottom-up scenario ranges from 8.71% to 32.56% and from 10.18% to 98.77%. Therefore, cases of horizontal permeability of 100 mD are higher BOE recovery than cases of horizontal permeability of 15 mD and 50 mD according to the ranges of BOE recovery (both lower bound and upper bound values). As a result, gas reservoir BOE contribution to the total BOE production range of horizontal permeability of 100 mD (both lower bound and upper bound values) is higher than horizontal permeability of 15 mD and 50 mD. As discussed above, fluid flow inside porous media is easier in the reservoir with higher horizontal permeability since there is less flow restriction compared to the reservoir with lower horizontal permeability. As a result, more gas recovery can be obtained from the reservoir with good horizontal permeability and longer plateau rate production periods of gas wells can also be achieved.

Among horizontal permeability of 100 mD, cases with kv/kh ratio of 0.01 show the range of BOE recovery from 19.18% to 23.94%. The range of the gas reservoir's total BOE and total water production contributions are 9.77% – 32.56% and 10.18% - 91.36%, respectively. For the cases with horizontal permeability of 100 mD and kv/kh ratio of 0.1, the BOE recovery ranges from 19.06% to 23.87%, the gas reservoir's total BOE contribution ranges from 9.18 % to 32.36%, and the gas reservoir total water production contribution is in the range of 89.72% - 97.99%. Regarding the cases with horizontal permeability of 100 mD and kv/kh ratio of 0.5, the range of BOE recovery is within 18.96% - 23.58% while total BOE contribution is within 8.71% - 31.51% and total water production contribution is within 94.59% - 98.77%. Hence, cases with kv/kh ratio of 0.01 show a higher gas recovery range, higher BOE contribution range to total BOE and lower range of contribution to total water production compared to the cases with kv/kh ratio of 0.1 and 0.5. As discussed in the above sections, higher kv/kh ratio induces higher vertical permeability, which is a favourable condition for water from GWC to flow up to the perforations. As a result, water conning becomes more intense, and recovery of the gas well becomes lower due to producing a significant amount of water. It is clear to see that the lower bound of gas reservoir total water production contribution range of kv/kh ratio of 0.01 is only 10.18% whereas it is 89.72% in kv/kh ratio of 0.1 and 94.59% in kv/kh ratio of 0.5. Thus, somewhat higher gas recovery can be obtained in lower kv/kh ratio cases for bottom water drive gas reservoirs because the water coning problem is less severe in lower vertical permeability reservoirs.

Among the cases with horizontal permeability of 100 mD and kv/kh ratio of 0.01, 15 ft gas reservoir cases show the BOE recovery range between 19.18% and 19.20% and its contribution to total BOE recovery and total water production ranges are 9.77% - 9.83% and 89.34% - 91.36%, respectively. In 30 ft gas reservoir, the range of BOE recovery is between 20.74% and 20.77% while the range of its BOE contribution and water production contribution are 18.5% - 18.63% and 78.84% - 82.71%, respectively. Despite the height of the water column varying from 15ft to 60ft, BOE recovery of 60 ft gas reservoir remains unchanged at 23.94% and its contribution to BOE recovery and total water production ranges from 32.54% to 32.56% and from 10.18% to 20.89%. It is found that extending gas column height moderately increases gas recovery and significantly increases its contribution to BOE. In fact, a thicker gas column contains higher GIIP, and it can generate more gas recovery as reservoir pressure declination of a thicker gas reservoir are slower than a thinner gas reservoir. Also, gas reservoir contribution to total BOE for the bottom-up scenario is considerably increased when the gas reservoir becomes thicker because a thicker gas reservoir can bring more cumulative gas production as it contains high GIIP. Regarding gas reservoir water production contribution to the bottom-up scenario, the contribution considerably decreases when the gas column height becomes longer because the impact on gas well water production becomes insignificant due to the greater impact of gas column height. Therefore, BOE recovery and BOE recovery contribution of 60 ft gas reservoir does not change in spite of varying water column height. At 15ft gas reservoir, it is strange to see that there is a negligible increment in BOE recovery when the water column height becomes longer. In fact, little gas recovery increment was obtained in 15 ft gas reservoir (horizontal permeability of 100 mD and kv/kh ratio of 0.01), due to some pressure support from the aquifer, however, this kind of behaviour can only be seen in kv/kh ratio of 0.01, where vertical permeability is poor.

To be concluded, the case yielding the highest BOE recovery of 23.94% (gas recovery of 87.28% and BOE of 422,786 barrels) is obtained from horizontal permeability of 100 mD, kv/kh ratio of 0.01, gas column height of 60 ft and water column height of 30 ft; total water production from this case is 2,030 STB (311 STB of water production from gas wells).

Table 5.12 Total BOE, total water production, total production time, BOE recovery factor, and contribution of gas reservoir for bottom-up scenario at horizontal permeability of 15 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		Total HIIP	Total production (Lower oil reservoir and upper gas reservoir)			BOE (Recovery factor)	Contribution from gas reservoir	
	Gas	Water	(BOE)	BOE	Water (STB)	Time (days)	(%)	BOE (%)	Water (%)
0.01	15	15	5,060,468	961,517	12,762	1,286	19.00	8.91	86.53
		30		961,641	14,448	1,288	19.00	8.92	88.10
		60		962,015	15,391	1,288	19.01	8.96	88.83
	30	15	5,181,565	1,067,583	7,677	1,335	20.60	17.96	77.61
		30		1,066,282	8,635	1,332	20.58	17.86	80.10
		60		1,066,494	9,292	1,332	20.58	17.88	81.51
	60	15	5,423,760	1,285,096	2,052	1,438	23.69	31.85	16.25
		30		1,285,144	2,202	1,438	23.69	31.85	21.97
		60		1,285,522	2,348	1,438	23.70	31.87	26.80
0.1	15	15	5,060,468	957,645	36,692	1,294	18.92	8.54	95.32
		30		952,991	52,135	1,296	18.83	8.09	96.70
		60		949,785	63,882	1,298	18.77	7.78	97.31
	30	15	5,181,565	1,057,448	32,877	1,335	20.41	17.17	94.77
		30		1,054,219	47,493	1,338	20.35	16.92	96.38
		60		1,052,257	59,316	1,341	20.31	16.76	97.10
	60	15	5,423,760	1,267,305	22,200	1,418	23.37	30.89	92.26
		30		1,260,337	30,524	1,414	23.24	30.51	94.37
		60		1,254,752	36,625	1,410	23.13	30.20	95.31
0.5	15	15	5,060,468	957,704	46,807	1,296	18.93	8.55	96.33
		30		951,893	76,571	1,304	18.81	7.99	97.76
		60		943,333	107,189	1,308	18.64	7.15	98.40
	30	15	5,181,565	1,056,449	49,531	1,338	20.39	17.09	96.53
		30		1,051,779	83,791	1,347	20.30	16.73	97.95
		60		1,045,038	126,432	1,356	20.17	16.19	98.64
	60	15	5,423,760	1,259,547	42,992	1,418	23.22	30.46	96.00
		30		1,251,326	68,564	1,418	23.07	30.01	97.49
		60		1,248,562	101,421	1,430	23.02	29.85	98.31

Table 5.13 Total BOE, total water production, total production time, BOE recovery factor, and contribution of gas reservoir for bottom-up scenario at horizontal permeability of 50 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		Total HIIP	Total production (Lower oil reservoir and upper gas reservoir)			BOE (Recovery factor)	Contribution from gas reservoir	
	Gas	Water	(BOE)	BOE	Water (STB)	Time (days)	(%)	BOE (%)	Water (%)
0.01	15	15	5,060,468	968,869	15,610	1,270	19.15	9.60	88.99
		30		968,595	17,647	1,270	19.14	9.57	90.26
		60		968,969	18,881	1,270	19.15	9.61	90.90
	30	15	5,181,565	1,074,912	8,411	1,311	20.74	18.52	79.57
		30		1,073,893	9,516	1,308	20.73	18.44	81.94
		60		1,073,950	10,227	1,308	20.73	18.45	83.20
	60	15	5,423,760	1,295,591	2,039	1,406	23.89	32.40	15.70
		30		1,295,576	2,186	1,406	23.89	32.40	21.38
		60		1,295,770	2,357	1,406	23.89	32.41	27.10
0.1	15	15	5,060,468	966,199	44,059	1,276	19.09	9.35	96.10
		30		963,230	66,038	1,280	19.03	9.07	97.40
		60		960,732	83,332	1,282	18.99	8.83	97.94
	30	15	5,181,565	1,063,881	33,590	1,304	20.53	17.67	94.88
		30		1,064,146	50,392	1,314	20.54	17.69	96.59
		60		1,063,039	62,719	1,317	20.52	17.61	97.26
	60	15	5,423,760	1,276,370	19,851	1,383	23.53	31.38	91.34
		30		1,272,136	26,981	1,395	23.45	31.15	93.63
		60		1,268,002	31,761	1,380	23.38	30.93	94.59
0.5	15	15	5,060,468	965,733	54,246	1,275	19.08	9.31	96.83
		30		960,672	90,031	1,298	18.98	8.83	98.09
		60		953,694	130,351	1,301	18.85	8.16	98.68
	30	15	5,181,565	1,064,700	51,485	1,311	20.55	17.74	96.66
		30		1,061,526	86,126	1,317	20.49	17.49	98.00
		60		1,058,340	129,750	1,329	20.43	17.24	98.68
	60	15	5,423,760	1,271,406	39,072	1,386	23.44	31.11	95.60
		30		1,263,283	57,904	1,386	23.29	30.67	97.03
		60		1,259,510	78,667	1,386	23.22	30.46	97.82

Table 5.14 Total BOE, total water production, total production time, BOE recovery factor, and contribution of gas reservoir for bottom-up scenario at horizontal permeability of 100 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		Total HIIP	Total production (Lower oil reservoir and upper gas reservoir)			BOE (Recovery factor)	Contribution from gas reservoir	
	Gas	Water	(BOE)	BOE	Water (STB)	Time (days)	(%)	BOE (%)	Water (%)
0.01	15	15	5,060,468	970,730	16,116	1,264	19.18	9.77	89.34
		30		970,949	18,445	1,265	19.19	9.79	90.68
		60		971,368	19,900	1,266	19.20	9.83	91.36
	30	15	5,181,565	1,076,401	8,122	1,300	20.77	18.63	78.84
		30		1,074,661	9,041	1,298	20.74	18.50	80.99
		60		1,075,533	9,938	1,299	20.76	18.57	82.71
	60	15	5,423,760	1,298,634	1,913	1,398	23.94	32.56	10.18
		30		1,298,640	2,030	1,398	23.94	32.56	15.33
		60		1,298,280	2,172	1,395	23.94	32.54	20.89
0.1	15	15	5,060,468	968,596	45,075	1,269	19.14	9.57	96.19
		30		966,322	67,767	1,273	19.10	9.36	97.46
		60		964,334	85,609	1,282	19.06	9.18	97.99
	30	15	5,181,565	1,068,422	32,635	1,302	20.62	18.02	94.73
		30		1,065,845	45,544	1,302	20.57	17.83	96.23
		60		1,065,331	56,302	1,304	20.56	17.79	96.95
	60	15	5,423,760	1,294,870	16,724	1,418	23.87	32.36	89.72
		30		1,281,872	21,344	1,383	23.63	31.67	91.95
		60		1,280,690	25,165	1,401	23.61	31.61	93.17
0.5	15	15	5,060,468	967,630	55,306	1,286	19.12	9.48	96.89
		30		959,405	84,850	1,269	18.96	8.71	97.97
		60		960,335	140,003	1,311	18.98	8.80	98.77
	30	15	5,181,565	1,066,555	48,797	1,302	20.58	17.88	96.48
		30		1,064,281	79,220	1,308	20.54	17.70	97.83
		60		1,064,624	116,200	1,332	20.55	17.73	98.52
	60	15	5,423,760	1,278,887	31,748	1,389	23.58	31.51	94.59
		30		1,275,485	44,476	1,386	23.52	31.33	96.14
		60		1,273,144	56,808	1,402	23.47	31.21	96.97

5.5 Effects from reservoir parameters for DWDDF

To perform the reservoir parametric study for the DWDDF scheme, the best operating condition of the DWDDF scheme selected from the investigation of the operating parameters (40% oil perforation, 80% gas perforation, 40% gas perforation, and starting dumpflood at the economic rate) was used for the simulation in this part. Although only the reservoir parameters of the upper gas reservoir were varied, there are impacts on both oil production from the lower oil reservoir and gas production from the upper gas reservoir for the DWDDF scheme. Because dumping well induces not only water crossflows but also gas crossflows from the upper reservoir to the lower reservoir, which contributes to improving oil production from the lower reservoir.

5.5.1 Investigation of effect of reservoir parameters under horizontal permeability of 15 mD

The simulation results of cases with 15mD horizontal permeability are illustrated in Figures 5.28 – 5.30 in terms of BOE recovery, total water production and total production time. BOE recovery for the cases with 15mD horizontal permeability ranges from 21.98% to 31.52%. As shown in Figure 5.28, varying the water column height from 15 ft to 30 ft has a small impact on BOE recovery while altering it to 60 ft has more impact on BOE recovery. Meanwhile, increasing gas column height can moderately increase BOE recovery at every condition of kv/kh ratio and water column height. For the kv/kh ratio, varying it from 0.01 to 0.5 has a little impact on BOE recovery. Increasing kv/kh ratio can slightly lower the BOE recovery in general.

In fact, a longer water column height allows more water to be dumped from the upper reservoir to the lower reservoir since it contains a higher amount of water initially in place. As a result, oil production is improved and BOE recovery increases because the lower reservoir is repressurized and more oil is displaced for production by dumping water. Also, the longer gas column induces a higher amount of gas crossflow from the upper gas reservoir to the lower oil reservoir, which also helps improve oil recovery. Regarding the BOE recovery for the cases with 15mD horizontal permeability, the higher BOE recovery was obtained from the cases with 60 ft column height of water and gas zones in general. There is very little impact on BOE recovery from the kv/kh ratio. In most cases, BOE recovery decreases with an increasing kv/kh ratio. BOE recovery ranges from 22.2% to 31.52% in kv/kh ratio of 0.01 cases, from 22.04% to 30.08% in kv/kh ratio of 0.1 cases and from 21.98% to 29.40% in kv/kh ratio of 0.5 cases. Generally, the upper reservoir with lower kv/kh ratio (poor vertical permeability) allows more water to be dumped. In fact, the upper reservoir pressure for the cases with lower kv/kh ratio declines a bit slower than in cases with higher kv/kh ratio. Thus, the possible reason for the case with lower kv/kh ratio is pressure sustaining of the upper reservoir.

For the reservoir with horizontal permeability of 15mD and vertical permeability of 0.15 (kv/kh ratio 0.01), varying water column height from 15 ft to 60 ft increases BOE recovery from 22.2% to 26.58% (4.39% increment) at 15 ft gas reservoir, 23.81% to 28.53% (4.73% increment) at 30 ft gas reservoir and 27.21% to 31.52% at 60 ft gas reservoir (4.31% increment), respectively. Hence, the DWDDF scheme can bring similar incremental BOE recovery (about 4%) by varying water column thickness from 15 ft to 60 ft at every gas reservoir thickness. It is clear that both thicker water and gas columns can increase BOE recovery. However, the amount of water and gas crossflows obtained from the 60 ft water and gas column case is not the highest one among the cases with kv/kh ratio of 0.01. In fact, BOE recovery increases because there is a good balance between water and gas crossflow volumes.

For the reservoir with horizontal permeability of 15mD and vertical permeability of 1.5 (kv/kh ratio 0.1), varying water column height from 15 ft to 60 ft increases BOE recovery from 22.04% to 25.78% (3.73% increment) at 15 ft gas reservoir, 23.71% to 27.79% (4.08% increment) at 30 ft gas reservoir and 27.4% to 30.08% at 60 ft gas reservoir (2.68% increment), respectively. Similar to the kv/kh ratio of 0.01, thicker water and gas columns can increase BOE recovery.

Comparing kv/kh ratios of 0.01 and 0.1, BOE recovery becomes lower when the kv/kh ratio becomes higher in general. It is found that more water has been dumped into the lower reservoir when the kv/kh ratio is at a lower value. Thus, a higher amount of water being dumped helps improve oil production by reservoir re-pressurization and displacing oil by dumpflooding. In general, the volume of gas crossflow becomes higher when the kv/kh ratio increases. However, there are some cases, especially in a shorter gas column such as 15ft, in which the amount of gas crossflow decreases with increasing kv/kh ratio. When vertical permeability is good and the gas column is long, more gas is drawn to gas water contact (GWC), resulting in higher gas cross flow to the lower reservoir. As described above, the amount of water dump is lower when vertical permeability is good (higher kv/kh). Since gas mobility is better than liquid, more gas may be more likely to flow toward the water zone (gas coning) when vertical permeability is good and cause a lot of gas cross flow into the lower reservoir. As the water mobility is not better than gas and the lower reservoir pressure become increases due to higher gas crossflow, the amount of water being dumped into the lower reservoir becomes lower in higher kv/kh ratio cases. When the kv/kh ratio is low, the amount of water being dumped is higher because gas is less likely to cone toward the water zone when vertical permeability is poor, resulting lower amount of gas crossflow.

In some cases, with the shorter gas column, despite having good vertical permeability, gas crossflow volume is not increasing with the kv/kh ratio. Therefore, there are mixed impacts between the kv/kh ratio and gas column height regarding the amount of gas crossflow in this condition.

For the reservoir with horizontal permeability of 15mD and vertical permeability of 7.5mD (kv/kh ratio 0.5), varying water column height from 15 ft to 60 ft increases BOE recovery from 21.98% to 25.37% (3.39% increment) at 15 ft gas reservoir, 23.62% to 27.82% (4.2% increment) at 30 ft gas reservoir and 27.43% to 29.4% at 60 ft gas reservoir (1.98% increment), respectively. Similar to cases with kv/kh ratios of 0.01 and 0.1, thicker water and gas columns can increase BOE recovery. Furthermore, BOE recovery increases with decreasing kv/kh ratio in general. As described above, the higher kv/kh ratio induces less water to be dumped, resulting in lower BOE recovery compared to the cases with lower kv/kh ratio. However, the amount of gas crossflow is higher especially in the thicker gas column when the kv/kh ratio is increased. Regarding BOE recovery improvement, it is always higher when there are lengthier gas and water columns and lower kv/kh ratio, due to the contribution of both water and gas crossflows. The highest BOE recovery for the cases with 15mD horizontal permeability obtain neither from the highest amount of water dump nor the largest volume of gas crossflow.

Among horizontal permeability of 15mD cases, the highest BOE recovery of 31.52% obtains from the cases with kv/kh ratio of 0.01, gas reservoir thickness of 60 ft and water column height of 60 ft. Its total amount of water and gas crossflows are 461,103 STB and 396 MMSCF, which are not the highest amount of water and gas crossflows among the cases with horizontal permeability of 15mD. Therefore, the highest BOE recovery obtains due to a good balance between the amount of water and gas crossflows.

For water production, cases with horizontal permeability of 15mD and vertical permeability of 0.15 (kv/kh ratio 0.01) range from 2,216 to 5,555 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,216 to 5,501 STB at 15 ft gas reservoir, from 2,265 to 5,555 STB at 30 ft gas reservoir and from 2,404 to 3,244 STB at 60 ft gas reservoir, respectively. Higher water production mostly comes from higher water dump volume, i.e., longer water column. However, it also depends on the amount of gas crossflow. When the gas zone has a higher thickness, more gas crossflow is founded. Higher water production for cases with horizontal permeability of 15mD is obtained when the water column height is 60 ft in thickness and the gas column is 15 ft and 30 ft in thickness. In fact, there is more amount of water to be dumped and less amount of gas crossflow when the water column is long, and the gas column is short. Therefore, a thicker water column contributes to increasing water production. At 60 ft water column height, a gas column height of 60ft induces higher gas crossflow volume and the amount of water being dumped becomes slightly lower compared to cases with 15 ft and 30 ft gas column heights. Since there are mixed impacts between the gas column height and water column height, the higher water production swings between the volume of gas and water cross flowing into the lower reservoir.

For water production, cases with horizontal permeability of 15mD and vertical permeability of 1.5 (kv/kh ratio 0.1) range from 2,188 to 2,906 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,188 to 2,906 STB at 15 ft gas reservoir, from 2,241 to 2,824 STB at 30 ft gas reservoir and from 2,430 to 2,770 STB at 60 ft gas reservoir, respectively. The longer the water column height, the greater water production is. Generally, increasing the kv/kh ratio from 0.01 to 0.1 decreases total water production since less amount of water is being dumped for the cases with kv/kh ratio of 0.1. As the kv/kh ratio becomes higher the vertical connectivity becomes better and it can lower the impact on the amount of water being dumped. As mentioned above, since gas can mobile better than liquid, gas is most likely to cone toward the water zone when vertical permeability becomes higher. Then, a substantial amount of gas crossflows into the lower reservoir as a result the lower reservoir pressure become increases and the amount of water being dumped becomes lower. Thus, the amount of water production for the cases with kv/kh ratio of 0.1 is lower than the cases with kv/kh ratio of 0.01.

Regarding water production, cases with horizontal permeability of 15mD and vertical permeability of 7.5 (kv/kh ratio 0.5) range from 2,176 to 2,853 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,176 to 2,652 STB at 15 ft gas reservoir, from 2,222 to 2,853 STB at 30 ft gas reservoir and from 2,426 to 2,674 STB at 60 ft gas reservoir, respectively. Comparing kv/kh ratios of 0.1 and 0.5, the amount of water production for the cases with kv/kh ratio of 0.5 is lower than the cases with kv/kh ratio of 0.1 in general. Generally, total water production becomes higher when the kv/kh ratio becomes lower since a higher amount of water is being dumped into the lower reservoir.

In this study, the amount of water production for the case yielding the highest BOE recovery in horizontal permeability of 15mD pair is 3,244 STB.

Regarding the production period for the cases with horizontal permeability of 15mD, it ranges from 1,854 to 3,171 days. At the kv/kh ratio of 0.01, varying water column from 15 ft to 60 ft increases total production time from 2,154 to 3,030 days at 15 ft gas reservoir, from 2,082 to 3,058 days at 30 ft gas reservoir, and from 1,909 to 2,645 days at 60 ft gas reservoir, respectively. At the kv/kh ratio of 0.1, varying water column from 15 ft to 60 ft increases total production time from 2,082 to 2,988 days at 15 ft gas reservoir, from 1,975 to 3,044 days at 30 ft gas reservoir, and from 1,865 to 2,250 days at 60 ft gas reservoir, respectively. At the kv/kh ratio of 0.5, varying water column from 15 ft to 60 ft increases total production time from 2,058 to 2,904 days at 15 ft gas reservoir, from 1,931 to 3,171 days at 30 ft gas reservoir, and from 1,854 to 2,118 days at 60 ft gas reservoir, respectively. Therefore, a longer water column extends the production period because it can dump more water into the lower oil reservoir, as a result, BOE recovery is improved. In general, the total production period of lower kv/kh ratio is longer than the higher kv/kh ratio because more water can be dumped in lower kv/kh ratio, which improves oil production with a longer production time. Generally speaking, the total production period is mainly impacted by water column thickness, however, it has some impacts from the kv/kh ratio and gas column thickness. For the case yielding the highest BOE recovery in horizontal permeability of 15mD pair, the total production time is 2,645 days, which is among the shorter production period cases.

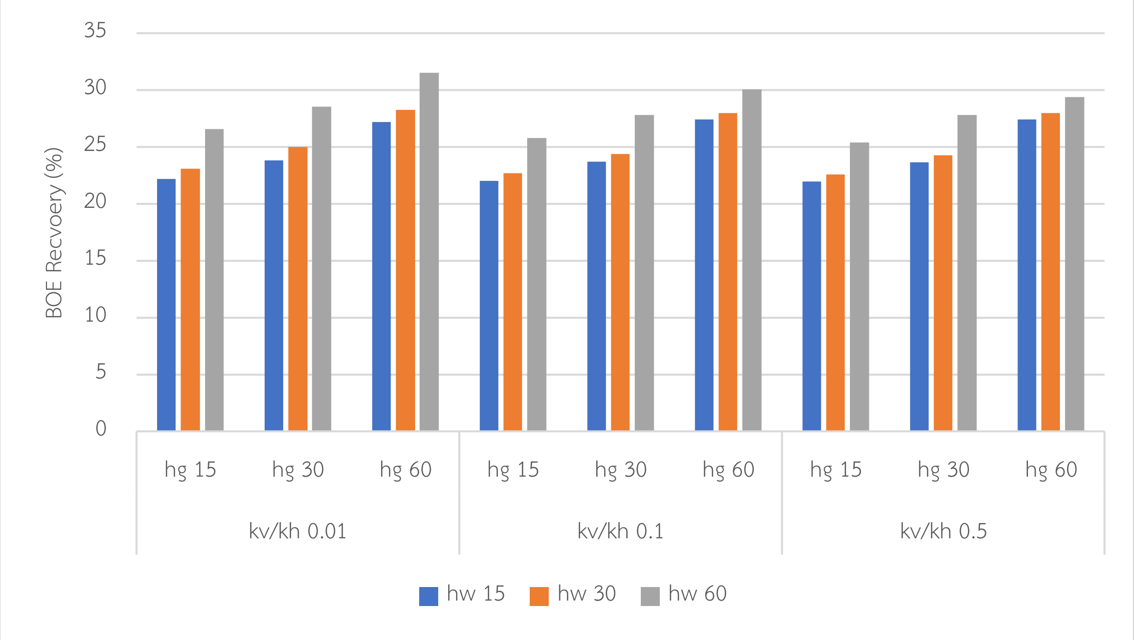


Figure 5.28 BOE recovery at horizontal permeability of 15mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

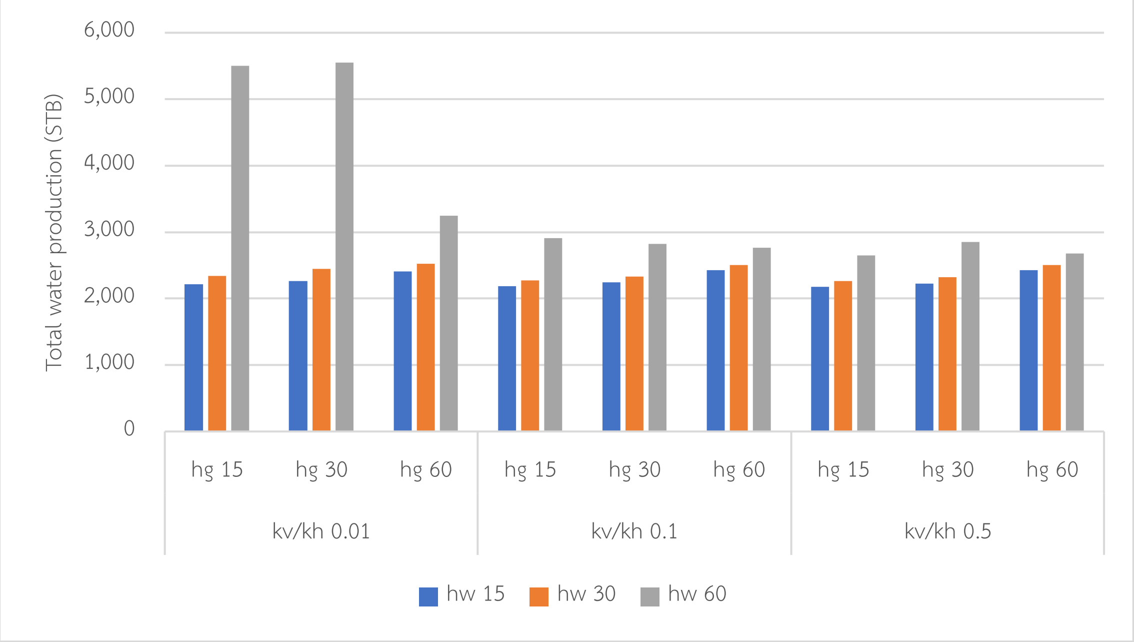


Figure 5.29 Total water production at horizontal permeability of 15mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

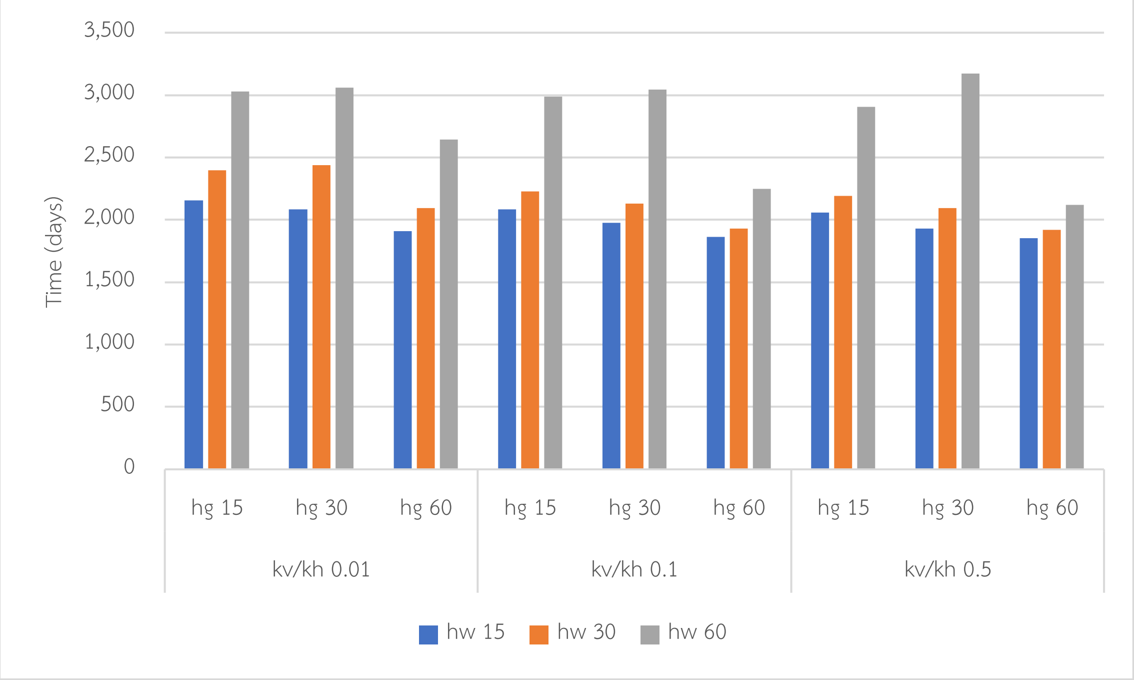


Figure 5.30 Total production time at horizontal permeability of 15mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

Table 5.15 Cumulative gas production, gas recovery, BOE, water production, production time and plateau production time for DWDDF scheme at horizontal permeability of 15 mD, various kv/kh ratios, different columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Cumulative gas production	Gas recovery factor	Barrel of oil equivalent	Water production	Time	Plateau
	Gas	Water	(MMSCF)	(MMSCF)	(%)	(BOE)	(STB)	(days)	(days)
0.01	15	15	727	419	57.65	69,811	6	236	2
		30		418	57.50	69,627	6	236	3
		60		406	55.81	67,583	107	226	2
	30	15	1,453	924	63.55	153,918	14	406	39
		30		917	63.12	152,873	14	396	48
		60		935	64.35	155,846	14	406	48
	60	15	2,906	1,926	66.25	320,907	33	687	156
		30		1,925	66.22	320,781	33	687	147
		60		1,974	67.93	329,035	34	698	156
0.1	15	15	727	426	58.69	71,066	6	236	3
		30		413	56.89	68,897	6	226	4
		60		400	55.05	66,661	207	216	4
	30	15	1,453	922	63.47	153,732	15	396	48
		30		902	62.07	150,322	14	386	48
		60		905	62.24	150,750	14	386	48
	60	15	2,906	1,870	64.32	311,576	32	665	147
		30		1,835	63.12	305,769	32	654	147
		60		1,864	64.12	310,592	32	643	147
0.5	15	15	727	431	59.26	71,768	5	236	3
		30		416	57.19	69,255	5	226	5
		60		407	55.97	67,774	6	216	6
	30	15	1,453	932	64.13	155,324	14	396	48
		30		903	62.15	150,519	14	376	48
		60		897	61.75	149,545	14	376	48
	60	15	2,906	1,864	64.14	310,683	31	654	152
		30		1,816	62.49	302,677	30	632	147
		60		1,819	62.59	303,191	30	621	147

5.5.2 Investigation of effect of reservoir parameters under horizontal permeability of 50 mD

Results from reservoir simulation run for cases with horizontal permeability of 50mD are illustrated in Figures 5.31 – 5.33 in terms of BOE recovery, total water production and total production time. BOE recovery for the cases with horizontal permeability of 50mD ranges from 21.5% to 32.26%. Similar to 15mD horizontal permeability cases, varying the water column height from 15 ft to 30 ft has a small impact on BOE recovery while altering it to 60 ft has more impact on BOE recovery. Generally, increasing gas column height can moderately increase BOE recovery at every condition of water column height. For kv/kh ratio, varying it from 0.01 to 0.5 has a very small impact on BOE recovery. Increasing kv/kh ratio can slightly lower the BOE recovery in general. Comparing horizontal permeability of 15mD and 50mD cases, 50mD cases are always slightly higher BOE recovery than 15mD cases at a gas zone thickness of 60 ft. But for the gas thickness of 15 ft and 30 ft, higher BOE recovery swings between the cases with horizontal permeability of 15mD and 50mD due to the mixed impacts getting from kv/kh ratio and water zone thickness. Thus, increasing horizontal permeability from 15mD to 50mD can slightly improve BOE recovery only at thicker gas reservoirs such as 60ft.

According to simulation results, not all cases with 50mD horizontal permeability induce higher water production compared to cases with 15mD horizontal permeability. There is no strong relationship between horizontal permeability and total water production. A higher amount of water production swings between horizontal permeability of 15mD and 50mD since other reservoir parameters highly influence it. Generally speaking, this swinging result comes from the amount of water crossflow. Theoretically, higher horizontal permeability induces water to flow easier into water perforation. However, since there are some influences from three other reservoir parameters, not every case with higher horizontal permeability could not yield a larger dumping water volume. In fact, most cases with horizontal permeability of 50mD induce some interesting phenomenon, in which the amount of water being dumped on the last day of production is lower than the amount of water being dumped at some points within the production period, i.e., there is some water crossflowed back to the upper reservoir from the lower reservoir. Basically, when the DWDDF scheme is initiated, upper reservoir pressure declined rapidly since gas production and dumpflooding start simultaneously. Consequently, the lower reservoir is repressurized to some point depending on the amount of water and gas crossflows. Although lower reservoir pressure declines again due to oil production, the pressure difference between the lower and upper reservoir becomes higher at some points, resulting in some reverse water crossflow from the lower reservoir to the upper reservoir. Then, the upper reservoir regains some pressure and allows water to cross flows into the lower reservoir again. This phenomenon occurs throughout the production period because the lower and upper reservoirs try to maintain equilibrium conditions. Note that this phenomenon can happen even though upper reservoir pressure is always lower than lower reservoir pressure, it is basically related to extent of the pressure gap between upper and lower reservoirs. Despite the upper reservoir pressure being lower, the gravity effect allows water to cross flow from the upper to the lower reservoir. However, gravity overriding works only until some limit of pressure difference. Once lower reservoir pressure passes that limit, the gravity effect is overridden by greater lower reservoir pressure and reverse crossflow occurs. This condition is found in most cases with horizontal permeability of 50mD, but not in cases with horizontal permeability of 15mD. However, the amount of this reverse water crossflow is not very high.

Regarding the BOE recovery for the cases with 50mD horizontal permeability, the higher BOE recovery was obtained from the cases with 60 ft water and gas columns. Like 15mD horizontal permeability cases, there is very little impact on BOE recovery from kv/kh ratio for the cases with 50mD horizontal permeability. Mostly, higher kv/kh ratio induces lower BOE recovery. BOE recovery ranges from 21.71% to 32.26% in kv/kh ratio of 0.01 cases, from 21.5% to 30.78% in kv/kh ratio of 0.1 cases and from 21.55% to 30.24% in kv/kh ratio of 0.5 cases. Generally, most cases with lower kv/kh ratio show a higher amount of water being dumped compared to cases with higher kv/kh ratio.

For the reservoir with horizontal permeability of 50mD and vertical permeability of 0.5 (kv/kh ratio 0.01), varying water column height from 15 ft to 60 ft increases BOE recovery from 21.71% to 27.28% (5.57% increment) at 15 ft gas reservoir, 24.20% to 27.17% (2.97% increment) at 30 ft gas reservoir and 28.57% to 32.26% at 60 ft gas reservoir (3.69% increment), respectively. Thus, both longer water and gas columns can increase BOE recovery. Similar to 15mD horizontal permeability cases, the amount of water and gas crossflow obtained from the 60 ft water and gas column case of the 50mD horizontal permeability pair is not the highest one among the cases with kv/kh ratio of 0.01. Therefore, BOE recovery increases when there is a good balance between water and gas crossflow volumes.

For the reservoir with horizontal permeability of 50mD and vertical permeability of 5 (kv/kh ratio 0.1), varying water column height from 15 ft to 60 ft increases BOE recovery from 21.5% to 27.04% (5.55% increment) at 15 ft gas reservoir, 23.93% to 27.54% (3.61% increment) at 30 ft gas reservoir and 28.64% to 30.78% at 60 ft gas reservoir (2.14% increment), respectively. Similar to kv/kh ratio of 0.01, thicker water and gas columns can increase BOE recovery. Generally speaking, BOE recoveries obtained from the cases with kv/kh ratio of 0.1 are lower than cases with kv/kh ratio of 0.01 since most lower kv/kh ratio cases can dump more amount of water compared to higher kv/kh ratio.

Comparing kv/kh ratios of 0.01 and 0.1 for the cases with horizontal permeability of 50mD, it is clear to notice that BOE recovery becomes lower when kv/kh ratio becomes higher. Lower kv/kh ratio induces slower pressure decline and higher water dump volume, resulting in slightly higher BOE recovery in general as more oil is displaced by dumpflooding.

In most cases, especially longer gas column cases, the volume of gas crossflow becomes higher when kv/kh ratio increases. Higher vertical permeability and thicker gas column induce gas coning toward GWC, resulting in higher gas cross flow to the lower reservoir. However, some cases with thinner gas columns show the volume of gas crossflow becomes lower although kv/kh ratio increase. In these cases, some impacts from other reservoir parameters may become dominant and the impact from kv/kh ratio becomes smaller. Then, gas crossflow volume becomes not increase with kv/kh ratio due to mixed impacts between kv/kh ratio and gas column height.

For the reservoir with horizontal permeability of 50mD and vertical permeability of 25mD (kv/kh ratio 0.5), varying water column height from 15 ft to 60 ft increases BOE recovery from 21.55% to 26.94% (5.39% increment) at 15 ft gas reservoir, 23.97% to 25.62% (1.65% increment) at 30 ft gas reservoir and 28.65% to 30.24% at 60 ft gas reservoir (1.59% increment), respectively. Similar to cases with kv/kh ratio of 0.01 and 0.1, thicker water columns can increase BOE recovery. Furthermore, BOE recovery increases with decreasing kv/kh ratio. Regarding BOE recovery improvement, it becomes higher when there are thicker water and gas columns and lower kv/kh ratio, due to the mixed impacts of water and gas crossflows. Similar to the highest BOE recovery case in horizontal permeability of

15mD pair, the highest BOE recovery obtained in horizontal permeability of 50mD pair is due to a good balance between the amount of water and gas crossflows, not from the amount of highest gas and water crossflow cases.

All in all, BOE recovery of cases with horizontal permeability of 50mD is higher than BOE recovery of cases with horizontal permeability of 15mD when gas reservoir thickness is 60 ft. At 30 ft and 15 ft gas column heights, the higher BOE swings between the horizontal permeability of 50mD and 15mD due to the mixed impacts from other reservoir parameters such as kv/kh ratio and column height of water zone. Among horizontal permeability of 50mD cases, the highest BOE recovery of 32.26% obtains from the cases with an kv/kh ratio of 0.01, gas reservoir thickness of 60 ft and water column height of 60 ft. Its total amount of water and gas crossflows are 469,738 STB and 459 MMSCF, which are not the highest amount of water and gas crossflows. Therefore, the highest BOE recovery obtains due to a good balance between the amount of water and gas crossflows. Furthermore, the highest BOE recovery obtain from horizontal permeability of 50mD is higher than the highest BOE recovery obtain from horizontal permeability of 15mD, the increment is 0.74%. The amount of water being dumped, and gas crossflows obtain from horizontal permeability of 50mD are higher than the ones obtained from horizontal permeability of 15mD. In addition, the highest BOE recovery of 32.26% is the case that shows another trend of plateau rate (1000 STB/day) production for a day during the DWDDF production scheme.

For water production, cases with horizontal permeability of 50mD and vertical permeability of 0.5 (kv/kh ratio 0.01) range from 2,115 to 8,602 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,115 to 8,602 STB at 15 ft gas reservoir, from 2,280 to 2,564 STB at 30 ft gas reservoir and from 2,517 to 2,985 STB at 60 ft gas reservoir, respectively. Higher water production mostly comes from the long column of the water zone. Considerably higher water production case obtains from the case with a water column height of 60 ft and gas column height of 15 ft. The amount of gas crossflow has some impacts on water production. When the gas zone is thicker, more gas crossflow is founded, as a consequence, the amount of water production can be affected indirectly. Similar to 15mD horizontal permeability cases, there is more amount of water being dumped and less amount of gas crossflow when the water column is long, and the gas column is relatively short. In general, a thicker water column contributes to increasing water production.

For water production, cases with horizontal permeability of 50mD and vertical permeability of 5 (kv/kh ratio 0.1) range from 2,082 to 4,047 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,082 to 4,047 STB at 15 ft gas reservoir, from 2,471 to 2,688 STB at 30 ft gas reservoir and from 2,540 to 2,829 STB at 60 ft gas reservoir, respectively. Generally, the longer the water column height, the greater water production is. Mostly, increasing kv/kh ratio from 0.01 to 0.1 decreases total water production since less amount of water is being dumped for the cases with kv/kh ratio of 0.1. Thus, the amount of water production for the cases with kv/kh ratio of 0.1 is lower than the cases with kv/kh ratio of 0.01 in general.

Regarding water production, cases with horizontal permeability of 50mD and vertical permeability of 25mD (kv/kh ratio 0.5) range from 2,087 to 3,308 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,087 to 3,308 STB at 15 ft gas reservoir and from 2,535 to 2,754 STB at 60 ft gas reservoir, respectively. Also, varying water column height from 30 ft to 60 ft at the 30 ft gas reservoir increases water production from 2,275 to 2,420 STB. However, there is an unusual case in the 30 ft gas reservoir in which water production of 15 ft water column height (2,800 STB) is higher than 60 ft water column height. The 15 ft water column case induces higher water production compared to the 60 ft water column because of gas well water production. The water production from the gas well at 15 ft water thickness is 549 STB higher than 60 ft water thickness. In DWDDF, there are a lot of mixed impacts getting from each reservoir parameter. Typically, there is less mixed impact only at thicker the gas column like 60 ft. Comparing kv/kh ratios of 0.1 and 0.5, the higher water production swings between kv/kh ratios of 0.5 and 0.1 due to mixed impacts from other reservoir parameters.

The amount of water production for the case yielding the highest BOE recovery in horizontal permeability of 50mD pair is 2,985 STB, which is among lower water production cases. Furthermore, it is lower than water production of the highest BOE recovery case from horizontal permeability of 15mD pair.

Regarding the production period for the cases with horizontal permeability of 50mD, it ranges from 1,689 to 3,501 days. At kv/kh ratio of 0.01, varying water column from 15 ft to 60 ft increases total production time from 1,810 to 3,030 days at 15 ft gas reservoir, from 1,854 to 2,082 days at 30 ft gas reservoir, and from 1,744 to 2,142 days at 60 ft gas reservoir, respectively. At kv/kh ratio of 0.1, varying water column from 15 ft to 60 ft increases total production time from 1,744 to 3,396 days at 15 ft gas reservoir, from 1,689 to 2,476 days at 30 ft gas reservoir, and from 1,744 to 1,924 days at 60 ft gas reservoir, respectively. At kv/kh ratio of 0.5, varying water column from 15 ft to 60 ft increases total production time from 1,755 to 3,501 days at 15 ft gas reservoir, from 1,689 to 1,942 days at 30 ft gas reservoir, and from 1,733 to 1,848 days at 60 ft gas reservoir, respectively. Therefore, a longer water column extends the production period because it can dump more water into the lower oil reservoir, as a result, BOE recovery is improved. However, the lengthier total production period swings between higher and lower kv/kh ratios due to mixed impact from the water and gas column thicknesses. For the case yielding the highest BOE recovery in horizontal permeability of 50mD pair, the total production time is 2,142 days, which is among the shorter production period cases. Also, it is shorter than the total production period of the highest BOE recovery case from the horizontal permeability of 15mD pair.

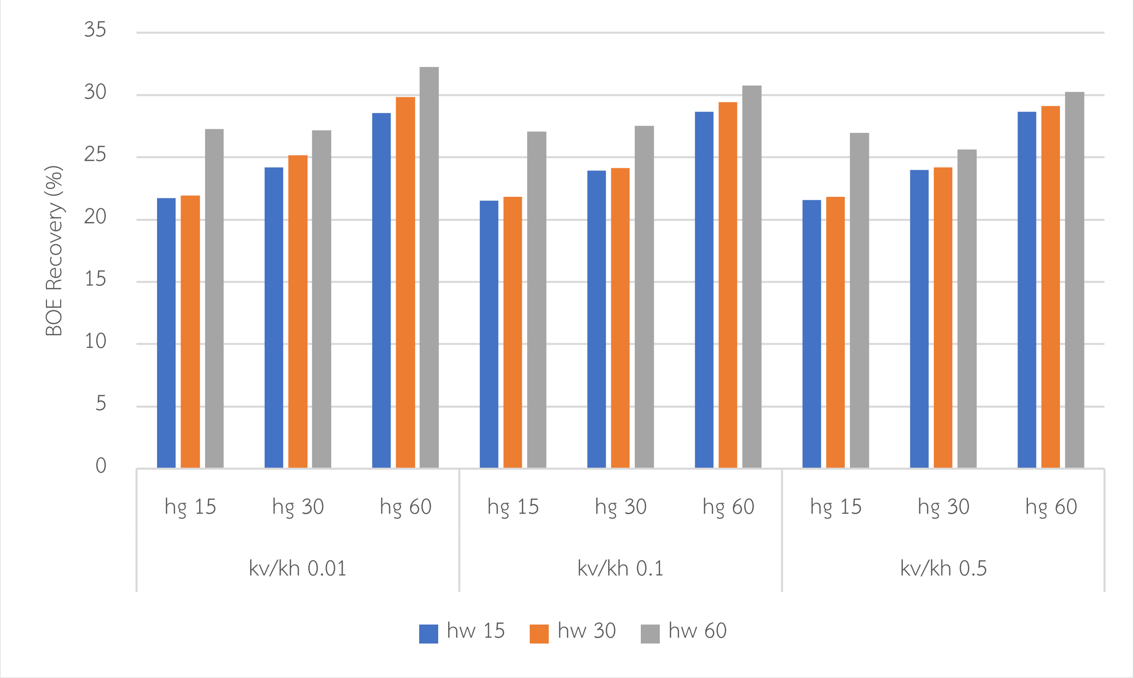


Figure 5.31 BOE recovery at horizontal permeability of 50 mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

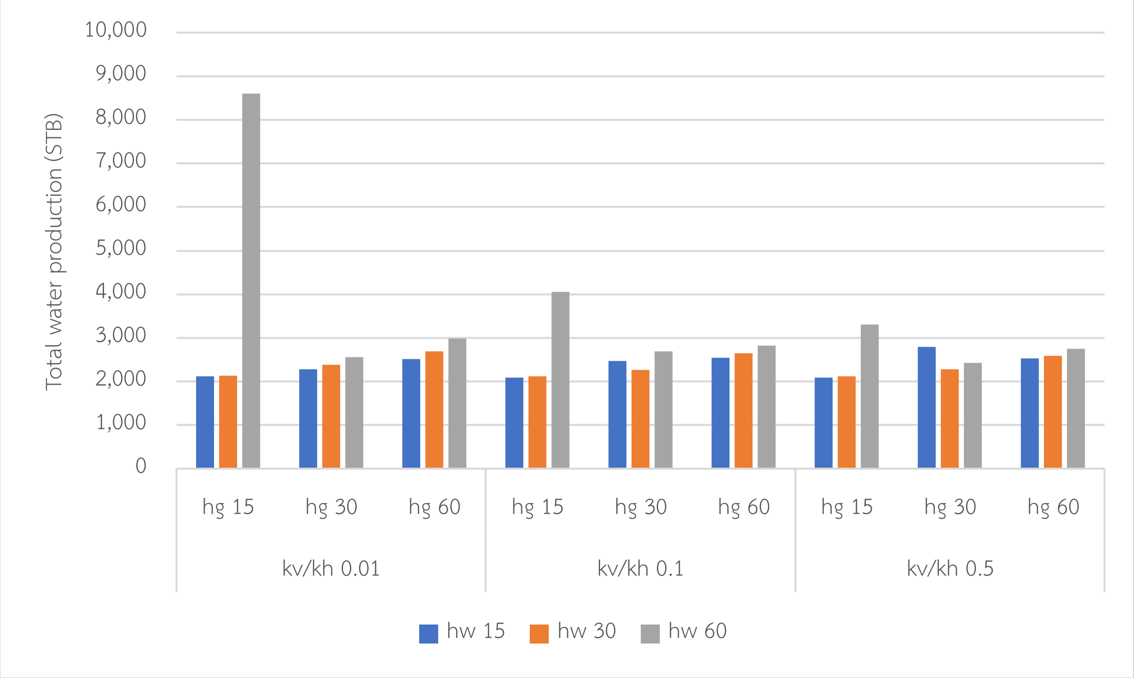


Figure 5.32 Total water production at horizontal permeability of 50 mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

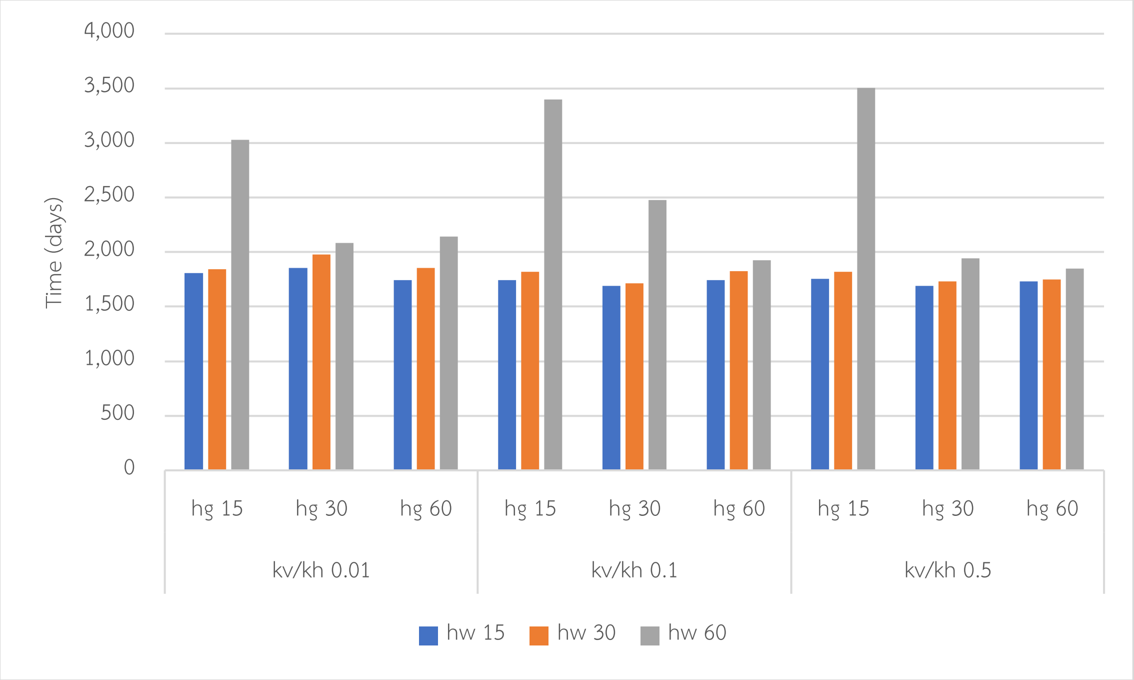


Figure 5.33 Total production time at horizontal permeability of 50 mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

Table 5.16 Cumulative gas production, gas recovery, BOE, water production, production time and plateau production time for DWDDF scheme at horizontal permeability of 50 mD, various kv/kh ratios, different columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Cumulative gas production	Gas recovery factor	Barrel of oil equivalent	Water production	Time	Plateau
	Gas	Water	(MMSCF)	(MMSCF)	(%)	(BOE)	(STB)	(days)	(days)
0.01	15	15	727	456	62.76	75,995	8	186	30
		30		458	63.07	76,382	8	176	30
		60		477	65.58	79,414	183	186	33
	30	15	1,453	914	62.91	152,368	18	306	75
		30		941	64.78	156,893	18	316	84
		60		991	68.19	165,148	19	326	89
	60	15	2,906	1,862	64.06	310,292	38	544	186
		30		1,920	66.04	319,906	38	533	206
		60		2,008	69.07	334,584	39	544	216
0.1	15	15	727	450	61.92	74,987	8	176	30
		30		445	61.20	74,115	8	166	30
		60		457	62.95	76,232	57	166	35
	30	15	1,453	869	59.81	144,856	238	276	77
		30		878	60.39	146,262	16	276	80
		60		923	63.50	153,787	17	286	84
	60	15	2,906	1,755	60.38	292,451	34	489	186
		30		1,794	61.73	299,013	34	489	191
		60		1,879	64.65	313,143	35	500	206
0.5	15	15	727	449	61.76	74,792	6	176	30
		30		443	60.97	73,830	6	166	30
		60		455	62.67	75,891	7	166	35
	30	15	1,453	865	59.53	144,187	563	276	80
		30		865	59.53	144,171	13	266	79
		60		898	61.77	149,615	14	276	84
	60	15	2,906	1,724	59.32	287,364	27	462	182
		30		1,736	59.73	289,313	27	467	186
		60		1,809	62.24	301,475	28	478	201

5.5.3 Investigation of effect of reservoir parameters under horizontal permeability of 100 mD

Results from reservoir simulation run for cases with 100mD horizontal permeability are illustrated in Figures 5.34 – 5.36 in terms of BOE recovery, total water production and total production time. BOE recovery for the cases with horizontal permeability of 100mD ranges from 21.69% to 32.88%. In general, varying the water column height from 15 ft to 30 ft has a small impact on BOE recovery while altering it to 60 ft has more impact on BOE recovery. Mostly, increasing gas column height somewhat increases BOE recovery at every condition of water column height.

For kv/kh ratio, varying it from 0.01 to 0.5 has a small impact on BOE recovery and increasing kv/kh ratio can slightly lower the BOE recovery in general. Comparing horizontal permeability of 100mD and 50mD cases, all cases of 100mD are always slightly higher BOE recovery than 50mD cases at the gas zone thickness of 60 ft. Only a few cases with the gas zone thickness of 15 ft and 30 ft in horizontal permeability of 100mD pair show a very small decrease in BOE recovery compared to horizontal permeability of 50 mD, due to the mixed impacts getting from kv/kh ratio and water zone thickness.

When cases with horizontal permeability of 100mD are compared to cases with horizontal permeability of 15mD, all cases of 100mD are also always slightly higher BOE recovery than 15mD cases at a gas zone thickness of 60 ft. Only a few cases with the gas thickness of 15 ft and 30 ft in horizontal permeability of 100mD pair show a slight decrease in BOE recovery compared to horizontal permeability of 15mD, due to the mixed impacts getting from kv/kh ratio and water zone thickness.

Thus, increasing horizontal permeability from 15mD to 50mD can slightly improve BOE recovery only at thicker gas reservoirs such as 60ft. At thinner gas reservoirs, the impact on BOE recovery due to horizontal permeability can be either negative or positive depending on the mixed impacts getting from other reservoir parameters.

According to simulation results, not all cases with 100mD horizontal permeability induce higher water production compared to cases with horizontal permeability of 15mD and 50mD. To make simple analysis, increasing horizontal permeability increases water production only at a 60 ft gas reservoir. At other thinner gas reservoirs, there is no strong relationship between horizontal permeability and total water production. Higher amount of water production swings between three different horizontal permeability values due to the mixed impacts getting from other reservoir parameters.

Similar to cases with horizontal permeability of 50mD, reverse crossflow is found in most cases with horizontal permeability of 100mD. Therefore, reverse crossflow can happen when the horizontal permeability is good because it is not founded only in the cases with horizontal permeability of 15mD.

Regarding the BOE recovery for the cases with 100mD horizontal permeability, the higher BOE recovery was obtained from the cases with 60 ft water and gas columns. Like 15mD and 50mD horizontal permeability cases, there is little impact on BOE recovery from kv/kh ratio for the cases with 100mD horizontal permeability. Mostly, higher kv/kh ratio induces lower BOE recovery. BOE recovery ranges from 21.69% to 32.88% in kv/kh ratio of 0.01 cases, from 22.17% to 31.79% in kv/kh ratio of 0.1 cases and from 21.6% to 30.67% in kv/kh ratio of 0.5 cases.

For the reservoir with horizontal permeability of 100mD and vertical permeability of 1mD (kv/kh ratio 0.01), varying water column height from 15 ft to 60 ft increases BOE recovery from 21.69% to 27.47% (5.78%

increment) at 15 ft gas reservoir, 23.62% to 27.85% (4.23% increment) at 30 ft gas reservoir and 29.11% to 32.88% at 60 ft gas reservoir (3.77% increment), respectively. Thus, both longer water and gas columns can increase BOE recovery. Similar to cases with horizontal permeability of 15mD and 50mD, the amount of water and gas crossflow obtained from the case with water and gas column height of 60 ft is not the highest one among the cases with kv/kh ratio of 0.01 for the cases 100mD horizontal permeability. Therefore, BOE recovery increases when there is a good balance between water and gas crossflow volumes.

For the reservoir with horizontal permeability of 100mD and vertical permeability of 10mD (kv/kh ratio 0.1), varying water column height from 15 ft to 60 ft increases BOE recovery from 22.17% to 27.54% (5.37% increment) at 15 ft gas reservoir, 24.31% to 29.26% (4.95% increment) at 30 ft gas reservoir and 29.05% to 31.79% at 60 ft gas reservoir (2.73% increment), respectively. Like kv/kh ratio of 0.01, thicker water and gas columns can increase BOE recovery. BOE recoveries obtained from the cases with kv/kh ratio of 0.1 are lower than cases with kv/kh ratio of 0.01 only at a 60 ft gas reservoir. At 15 ft and 30 ft gas reservoirs, the higher BOE swing between kv/kh ratio of 0.01 and 0.1 due to the mixed impacts from water zone thickness. Cases with longer gas column cases show a higher amount of gas crossflow when kv/kh ratio increases. Higher vertical permeability and thicker gas column induce gas coning toward GWC and the higher amount of gas to intrude into the water zone, resulting in higher gas cross flow to the lower reservoir.

For the reservoir with horizontal permeability of 100mD and vertical permeability of 50mD (kv/kh ratio 0.5), varying water column height from 15 ft to 60 ft increases BOE recovery from 21.6% to 27.22% (5.63% increment) at 15 ft gas reservoir, 24.04% to 25.73% (1.7% increment) at 30 ft gas reservoir and 28.98% to 30.67% at 60 ft gas reservoir (1.7% increment), respectively. Similar to cases with kv/kh ratios of 0.01 and 0.1, thicker water and gas columns can increase BOE recovery. Furthermore, BOE recovery increases with decreasing kv/kh ratio in general. Regarding BOE recovery improvement, it is always higher when there are thicker gas and water columns and lower kv/kh ratio, due to the mixed impacts of water and gas crossflows.

Similar to the highest BOE recovery case in horizontal permeability of 15mD and 50mD pairs, the highest BOE recovery obtained in horizontal permeability of 100mD pair is due to a good balance between the amount of water and gas crossflows, not because of the highest amount of gas and water crossflow cases.

All in all, BOE recovery of cases with horizontal permeability of 100mD is higher than cases with horizontal permeability of 15mD and 50mD when gas reservoir thickness is 60 ft. At 30 ft and 15 ft gas column heights, the higher BOE swings between the three different horizontal permeability values due to the mixed impacts from other reservoir parameters such as kv/kh ratio and column height of water zone.

According to the results, BOE recovery of 32.88% obtains from the cases with horizontal permeability of 100mD, kv/kh ratio of 0.01, gas reservoir thickness of 60 ft and water column height of 60 ft, which is the highest BOE recovery case among 81 cases of reservoir parametric study. Its total amount of water and gas crossflows are 535,168 STB and 488 MMSCF, which are not the highest amount of water and gas crossflows. Again, the highest BOE recovery obtains due to a good balance between the amount of water and gas crossflows. Furthermore, the highest BOE recovery obtains from horizontal permeability of 100mD is 0.62% higher than the highest BOE recovery obtain from horizontal permeability of 50mD and 1.35% higher than the highest BOE recovery obtain from horizontal permeability of 15mD. The amount of water being dumped and gas crossflows obtain from horizontal permeability of 100mD are also higher than the ones obtain from horizontal permeability of 50mD and 15mD. In addition, the highest BOE recovery of 32.88% is the case that shows another trend of plateau rate (1000 STB/day) production for 49.5 days during the DWDDF production scheme.

For water production, cases with horizontal permeability of 100mD and vertical permeability of 1 (kv/kh ratio 0.01) range from 2,116 to 8,954 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,116 to 8,954 STB at 15 ft gas reservoir, from 2,309 to 2,648 STB at 30 ft gas reservoir and from 2,542 to 3,364 STB at 60 ft gas reservoir, respectively. Higher water production mostly comes from thicker water zone. The amount of gas crossflow rate has some impacts on water production. When the gas zone is thicker, more gas crossflow is founded. Considerably higher water production case obtains from the case with a water column height of 60 ft and gas column height of 15 ft. Similar to cases with horizontal permeability of 15mD and 50mD, there is more amount of water being dumped and less amount of gas crossflow when the water column is long, and the gas column is short. In general, a thicker water column contributes to increasing water production.

For water production, cases with horizontal permeability of 100mD and vertical permeability of 10 (kv/kh ratio 0.1) range from 2,173 to 6,680 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,173 to 6,680 STB at 15 ft gas reservoir and from 2,571 to 2,959 STB at 60 ft gas reservoir, respectively. The longer the water column height, the greater water production is. Varying the water column height from 30 ft to 60 ft at a 30 ft gas reservoir also increases water production from 2,378 to 3,372 STB. Nevertheless, there is an unusual case in a 30 ft gas reservoir in which water production of 15 ft water column height (4,422 STB) is higher than 60 ft water column height. The 15 ft water column case induces higher water production compared to the 60 ft water column because of gas well water production. The water production from the gas well at 15 ft water thickness is 2,132 STB higher than 60 ft water thickness. In DWDDF, there are a lot of mixed impacts getting from each reservoir parameter. Typically, there is less mixed impact only at the thicker gas column like 60 ft. Higher total water production swings between kv/kh ratios of 0.01 and 0.1 due to the mixed impacts from water and gas column thicknesses.

Regarding water production, cases with horizontal permeability of 100mD and vertical permeability of 50mD (kv/kh ratio 0.5) range from 2,090 to 4,565 STB. Varying water column height from 15 ft to 60 ft increases water production from 2,090 to 4,564 STB at 15 ft gas reservoir, from 2,321 to 2,411 STB at 30 ft gas reservoir and from 2,553 to 2,795 STB at 60 ft gas reservoir, respectively. Comparing kv/kh ratios of 0.1 and 0.5, water production for cases kv/kh ratio of 0.5 is lower than kv/kh ratio of 0.1

The amount of water production for the case yielding the highest BOE recovery in horizontal permeability of 100mD pair is 3,365 STB, which is among lower water production cases. However, it is higher than water production of the highest BOE recovery cases from the horizontal permeability of 15mD and 50mD.

Regarding the production period for the cases with horizontal permeability of 100mD, it ranges from 1,546 to 3,246 days. At kv/kh ratio of 0.01, varying water column from 15 ft to 60 ft increases total production time from

1,711 to 3,246 days at 15 ft gas reservoir, from 1,546 to 2,094 days at 30 ft gas reservoir, and from 1,777 to 2,178 days at 60 ft gas reservoir, respectively. At kv/kh ratio of 0.1, varying water column from 15 ft to 60 ft increases total production time from 1,876 to 3,186 days at 15 ft gas reservoir, from 1,700 to 2,876 days at 30 ft gas reservoir, and from 1,700 to 2,130 days at 60 ft gas reservoir, respectively. At kv/kh ratio of 0.5, varying water column from 15 ft to 60 ft increases total production time from 1,689 to 3,186 days at 15 ft gas reservoir, from 1,616 to 1,843 days at 30 ft gas reservoir, and from 1,684 to 1,849 days at 60 ft gas reservoir, respectively. Therefore, the longer water column extends the production period because it can dump more water into the lower oil reservoir, as a result, BOE recovery is improved. However, the lengthier total production period swings between higher and lower kv/kh ratios due to mixed impact from the water and gas column thicknesses.

For the case yielding the highest BOE recovery in horizontal permeability of 100mD pair, the total production time is 2,178 days, which is among the shorter production period cases. It is shorter than the total production period of the highest BOE recovery case from horizontal permeability of 15mD pair while longer than the ones from horizontal permeability of 50mD pair.

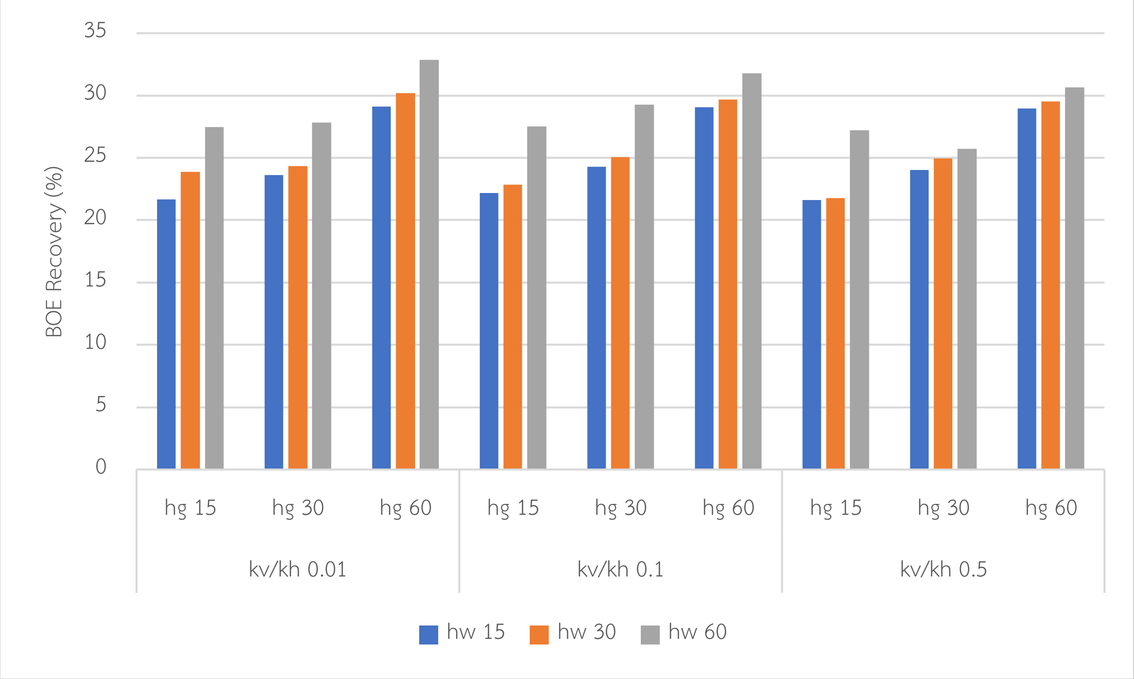


Figure 5.34 BOE recovery at horizontal permeability of 100 mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

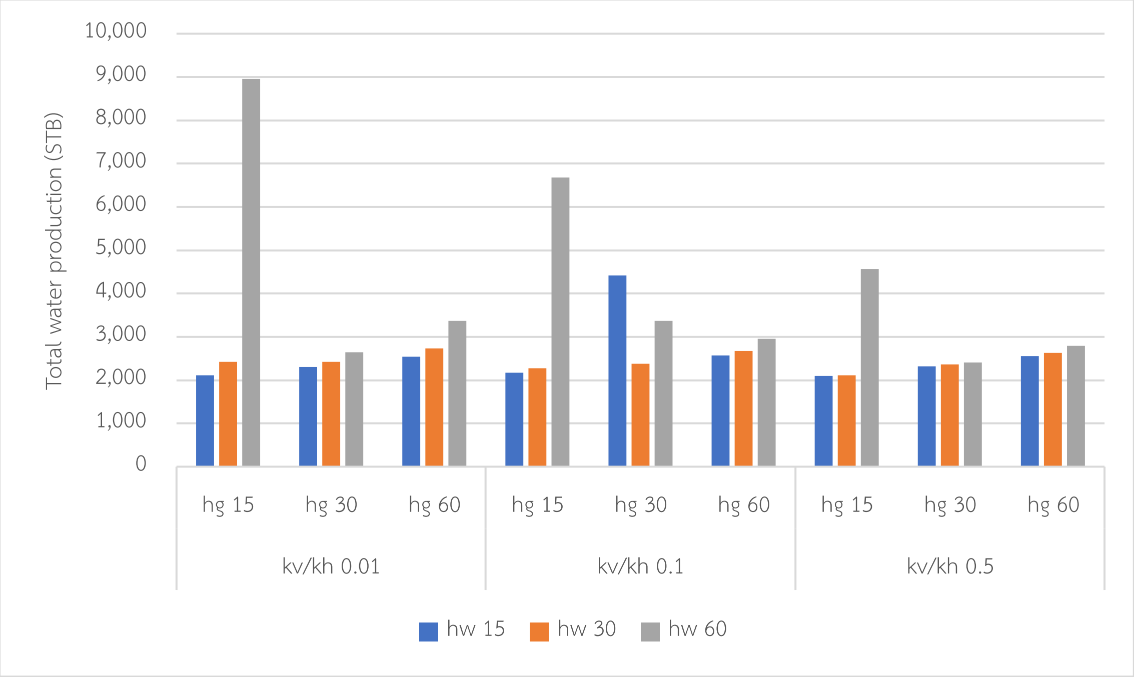


Figure 5.35 Total water production at horizontal permeability of 100 mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

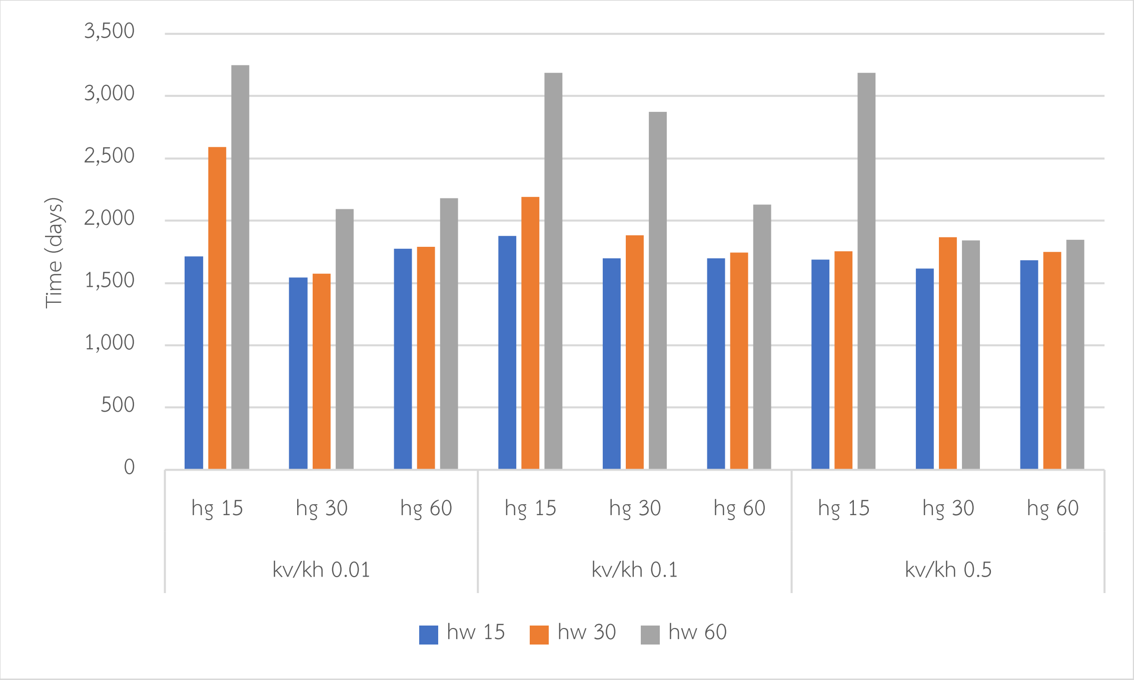


Figure 5.36 Total production time at horizontal permeability of 100 mD for various gas and water column as a function of various kv/kh ratios for the DWDDF scheme.

Table 5.17 Cumulative gas production, gas recovery, BOE, water production, production time and plateau production time for DWDDF scheme at horizontal permeability of 100 mD, various kv/kh ratios, different columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Cumulative gas production	Gas recovery factor	Barrel of oil equivalent	Water production	Time	Plateau
	Gas	Water	(MMSCF)	(MMSCF)	(%)	(BOE)	(STB)	(days)	(days)
0.01	15	15	727	436	60.01	72,668	21	138	35
		30		461	63.48	76,871	9	156	39
		60		487	67.01	81,150	71	156	45
	30	15	1,453	968	66.64	161,392	170	346	89
		30		1,014	69.75	168,924	234	376	93
		60		1,001	68.87	166,790	20	286	102
	60	15	2,906	1,947	67.00	324,557	45	577	206
		30		1,922	66.12	320,257	40	489	216
		60		2,020	69.50	336,641	41	500	236
0.1	15	15	727	430	59.14	71,620	8	147	37
		30		441	60.68	73,477	8	147	39
		60		466	64.15	77,687	17	147	44
	30	15	1,453	836	57.55	139,372	2,149	251	86
		30		862	59.33	143,704	16	236	91
		60		926	63.72	154,333	17	256	100
	60	15	2,906	1,726	59.39	287,660	33	436	198
		30		1,779	61.22	296,550	33	431	206
		60		1,885	64.85	314,110	34	456	226
0.5	15	15	727	423	58.22	70,501	5	138	37
		30		435	59.88	72,517	5	138	39
		60		460	63.31	76,671	6	147	44
	30	15	1,453	826	56.85	137,697	84	226	85
		30		848	58.34	141,298	11	236	90
		60		897	61.75	149,560	11	246	98
	60	15	2,906	1,685	57.98	280,831	21	411	191
		30		1,731	59.54	288,415	22	429	203
		60		1,819	62.58	303,152	22	436	216

By comparing all 81 cases, it is found that the highest BOE of 32.88% obtains from the cases with horizontal permeability of 100mD, kv/kh ratio of 0.01, gas reservoir thickness of 60 ft and water column height of 60 ft. The 100mD horizontal permeability allows more water and gas to crossflow, and both improve oil production.

The kv/kh ratio of 0.01 induces less gas to cone toward the water zone, as a result, more water can crossflow which displaces more oil for production. The 60 ft gas reservoir thickness allows more gas to crossflow and facilitates oil flow inside the reservoir. The 60 ft water zone thickness allows more water to dump, which helps to increase oil production. All these four parameters perform better in their way to improve BOE recovery. Nevertheless, the effect of a combination of these four parameters on BOE recovery can result in both negative and positive impacts due to mixed impacts between each other. Therefore, the perfect combination should be investigated for the DWDDF scheme using reservoir simulation. In this study, it is found that the DWDDF scheme can perform better when the water column and gas reservoir are having a greater thickness. It is also found that the importance of horizontal permeability and kv/kh ratio is less compared to water and gas column thickness. Both horizontal permeability and kv/kh ratio induce negative or positive impact on BOE recovery at shorter gas columns due to mixed impacts. However, it is found that horizontal permeability and kv/kh ratio slightly increase BOE recovery when the gas reservoir is greater in thickness (60 ft). Therefore, the contribution from horizontal permeability and kv/kh ratio is more pronounced in the thicker gas reservoir.

5.6 Comparative study of bottom-up and DWDDF for different reservoir parameters

As described in the previous sections, the highest BOE recovery obtained from the bottom-up production scenario is 23.94% whereas the DWDDF scheme is 32.88%. For the case yielding the highest BOE recovery from the DWDDF scheme (horizontal permeability of 100mD, kv/kh ratio of 0.01, gas column height of 60 ft and water column height of 60 ft), the water production is 3,365 STB and the total production time is 2,178 days. Comparing bottom-up and DWDDF under the same reservoir condition of horizontal permeability of 100mD, kv/kh ratio of 0.01, gas column height of 60 ft and water column height of 60 ft, it is found that DWDDF can produce more BOE recovery (incremental BOE recovery of 8.94%) than bottom-up. Thus, DWDDF can produce more BOE than the bottom-up scenario since both water and gas from the upper reservoir cross flow into the lower oil reservoir in DWDDF. As illustrated in Figure 5.37, oil production in DWDDF is increased by extending the oil production period longer than the ones in the bottom-up scenario. Since there are three gas wells in the bottom-up scenario whereas one gas well in DWDDF, the bottom-up scenario can produce more gas at the surface. DWDDF produce less gas at the surface, however, some of the gas also cross flow into lower oil reservoir which helps improve oil production. Under the same reservoir condition of horizontal permeability of 100mD, kv/kh ratio of 0.01, gas column height of 60 ft and water column height of 60 ft, water production of DWDDF is 1,192 STB higher than the bottom-up scenario. Comparing water production from gas wells at bottom-up and DWDDF, DWDDF (41 STB) is lower than bottom-up (454 STB). Therefore, higher water production obtained in DWDDF mainly comes from oil wells. Oil is displaced by the significant amount of water being dumped and some of those water is produced along with oil production. The field water production rate of bottom-up and DWDDF are compared in Figure 5.38.

Figures 5.39 and 5.40 show the rate of water being dumped from the gas reservoir into the underlying oil reservoir and the rate of gas cross flow into the oil reservoir from the gas reservoir, respectively. The initial water dumping rate is about 12000 STB/D, however, it dramatically declines afterwards as the pressure of the underlying oil reservoir becomes higher. Meanwhile, the gas crossflow rate is around 5,130 MSCF in the early times and it rapidly fell as the lower oil reservoir is re-pressurized by both crossflows simultaneously. When the gas well dies due to reaching its abandonment rate of 500 MSCF/D, the gas crossflow rate becomes slightly rising again. As the gas production is immediately stopped due to reaching the economic rate of the well, some amounts of gas are redirected to other ends of the well for dumping into the oil reservoir. However, this occurrence takes for short periods, and the gas crossflow rate becomes steadily declines as the lower oil reservoir pressure becomes higher and the upper reservoir pressure becomes lower.

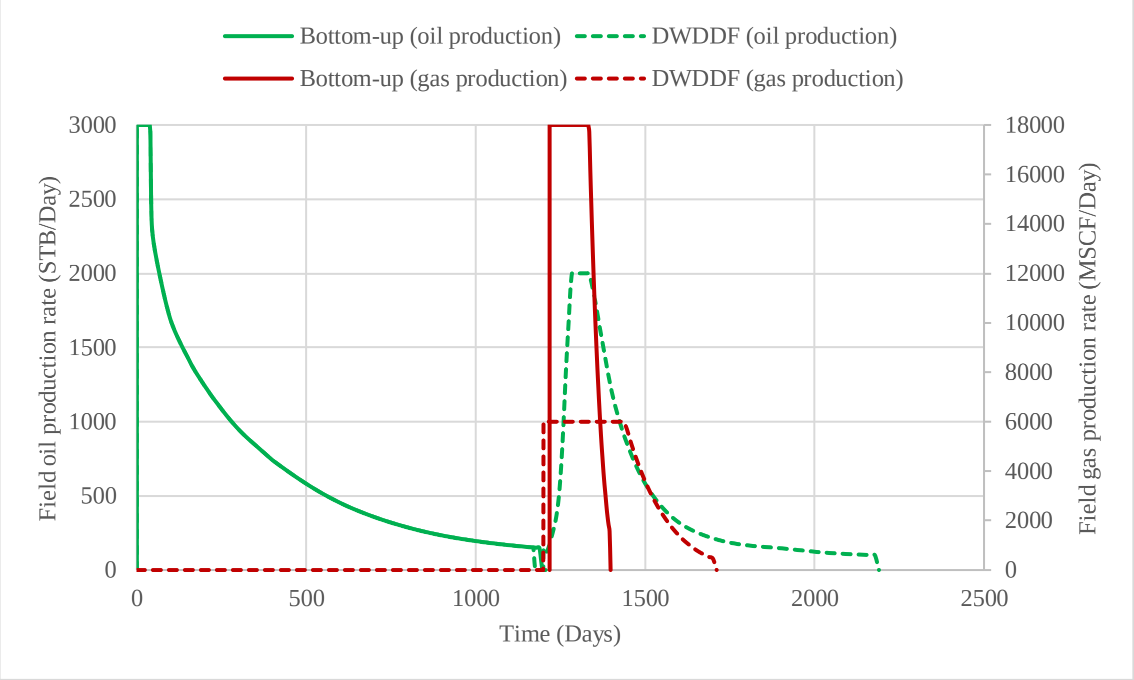


Figure 5.37 Oil and gas production rates for bottom-up and DWDDF scenarios at horizontal permeability of 100mD, kv/kh ratio of 0.01, gas column height of 60 ft and water column height of 60 ft.

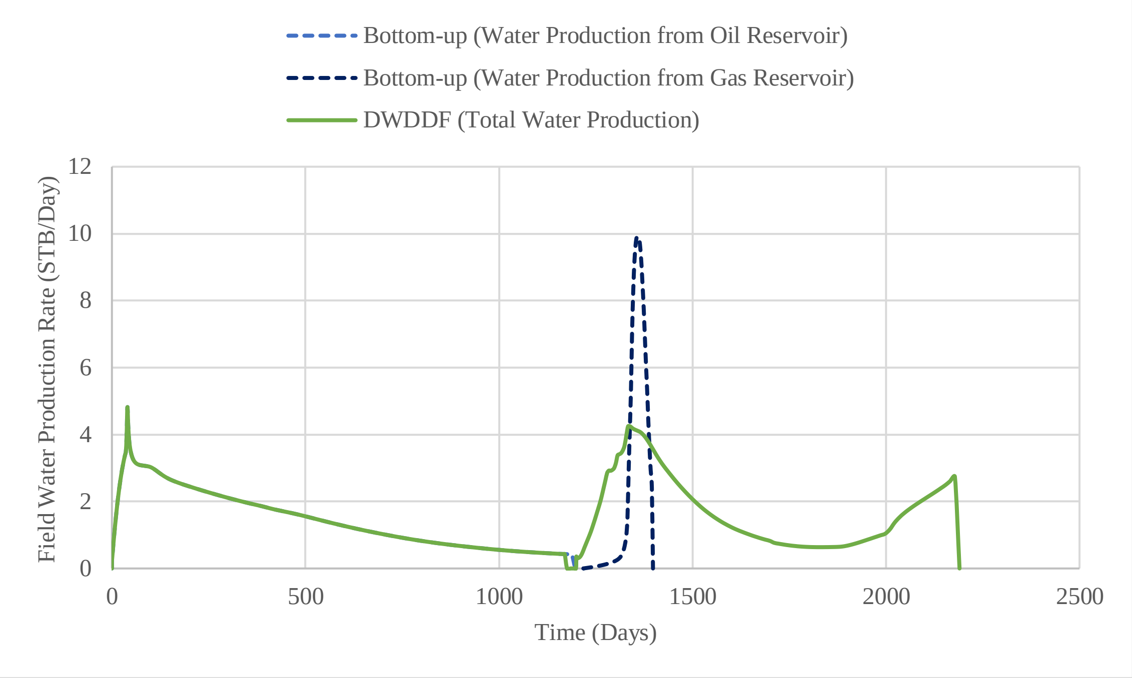


Figure 5.38 Water production rate for bottom-up scenario and DWDDF scenario at horizontal permeability of 100mD, kv/kh ratio of 0.01, gas column height of 60 ft and water column height of 60 ft.

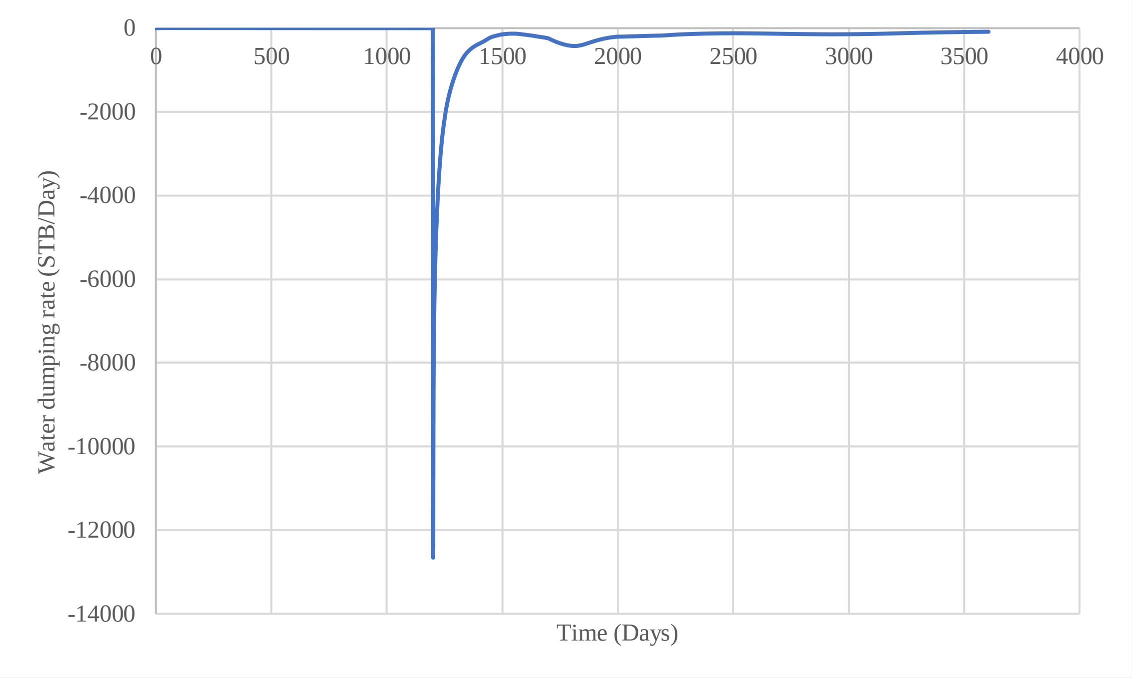


Figure 5.39 Water dumping rate from bottom-water drive gas reservoir to underlying oil reservoir in best reservoir condition of DWDDF scenario.

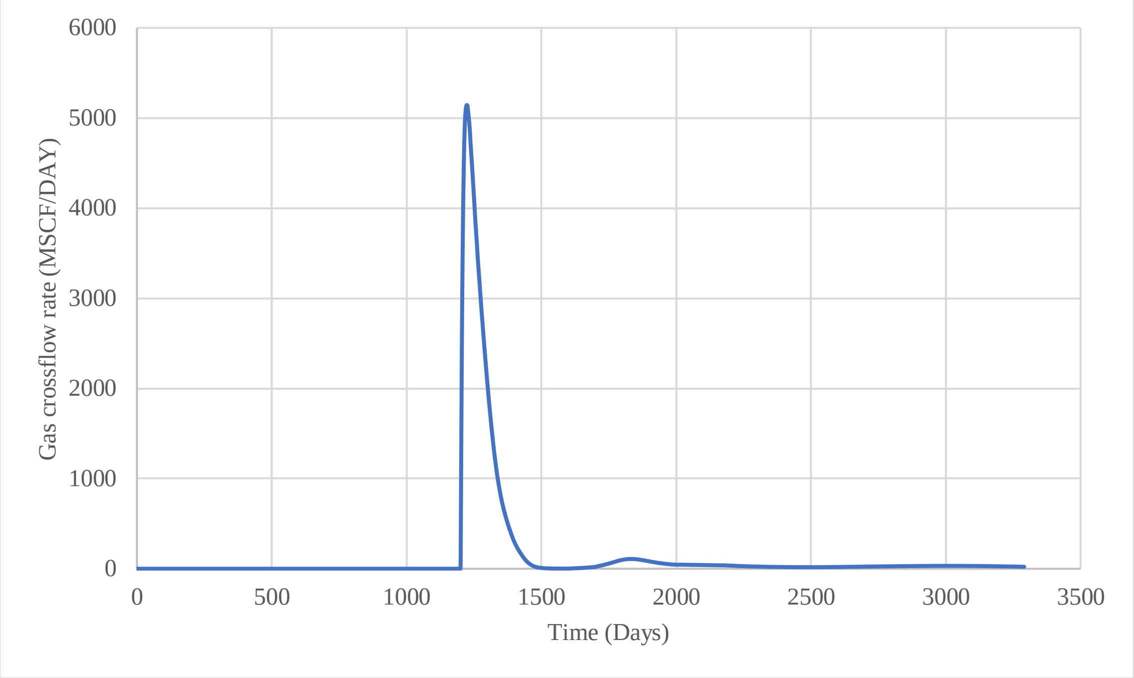


Figure 5.40 Gas crossflow rate from bottom-water drive gas reservoir to underlying oil reservoir in best reservoir condition of DWDDF scenario.

As illustrated in Figure 5.41, every DWDDF case can perform better than bottom-up when they have the same horizontal permeability, kv/kh ratio, and gas and water column heights. Not only total BOE is increased but also unwanted water production is reduced when the DWDDF technique is applied in most cases except for some cases with kv/kh ratio of 0.01 and gas column height of 60 ft (See. Figure 5.42). In fact, hydrocarbon production is improved by extending the total production period in the DWDDF scenario, which implies that production time is extended by re-pressurizing the lower oil reservoir with the aid of both water and gas crossflows. This can be clearly seen in Figure 5.43. According to Figure 5.44, it is obvious to see that the total production time of all DWDDF scenarios is longer than bottom-up.

To compare the applicability of DWDDF and conventional bottom-up production techniques effectively, the total BOE is used as a key criterion in this section. Comparing bottom-up and DWDDF at horizontal permeability of 100mD, kv/kh ratio of 0.01, gas column height of 60 ft and water column height of 60 ft, DWDDF can perform better in terms of improving total BOE by 37.35% (percent increase) from 1,298,280 to 1,783,251 barrels. However, water production of DWDDF is higher than bottom-up comparing at this reservoir condition, in which DWDDF increases water production by 54.93% (percent increase) from 2,172 to 3,365 STB. The production time of DWDDF is 783 days longer than bottom-up production scenario. Hence, economic analysis needs to be considered for decision-making regarding this project. Since this study is focused only on a technical point of view, an economic analysis of the project is ignored.

To see things more clearly, BOE recovery of DWDDF and Bottom-up production scenarios at different reservoir conditions are compared in Figure 5.45. As described above, DWDDF can improve hydrocarbon recovery at every reservoir condition. Comparing DWDDF and bottom-up scenarios at different reservoir conditions, incremental BOE recovery ranges from 8.94% to 2.4% by applying DWDDF. Therefore, investigating reservoir parameter that is suitable for DWDDF is very important. Performing DWDDF at suitable reservoir conditions can generate better outcomes. Since there are several mixed impacts due to different reservoir parameter values studied in this work, it is difficult to draw a specific conclusion. In general, DWDDF is suitable to apply for the reservoir with a thicker water column, which can increase BOE recovery by dumping more water. A thicker gas reservoir is important because not only it can increase gas recovery from the upper reservoir but also it can increase the amount of gas crossflow that facilitates oil flow inside the lower reservoir. The contribution of kv/kh ratio relies on gas and water zone thickness, which can generate a positive or negative impact on BOE recovery by increasing or decreasing it depending on mixed impacts coming from other reservoir parameters. Basically, the contribution of horizontal permeability also relies on gas and water zone thickness. At shorter gas zone thickness, the higher BOE recovery swings between higher and lower horizontal permeability due to the mixed impacts from the other three reservoir parameters. At 60 ft gas zone thickness, BOE recovery is always higher at higher horizontal permeability.

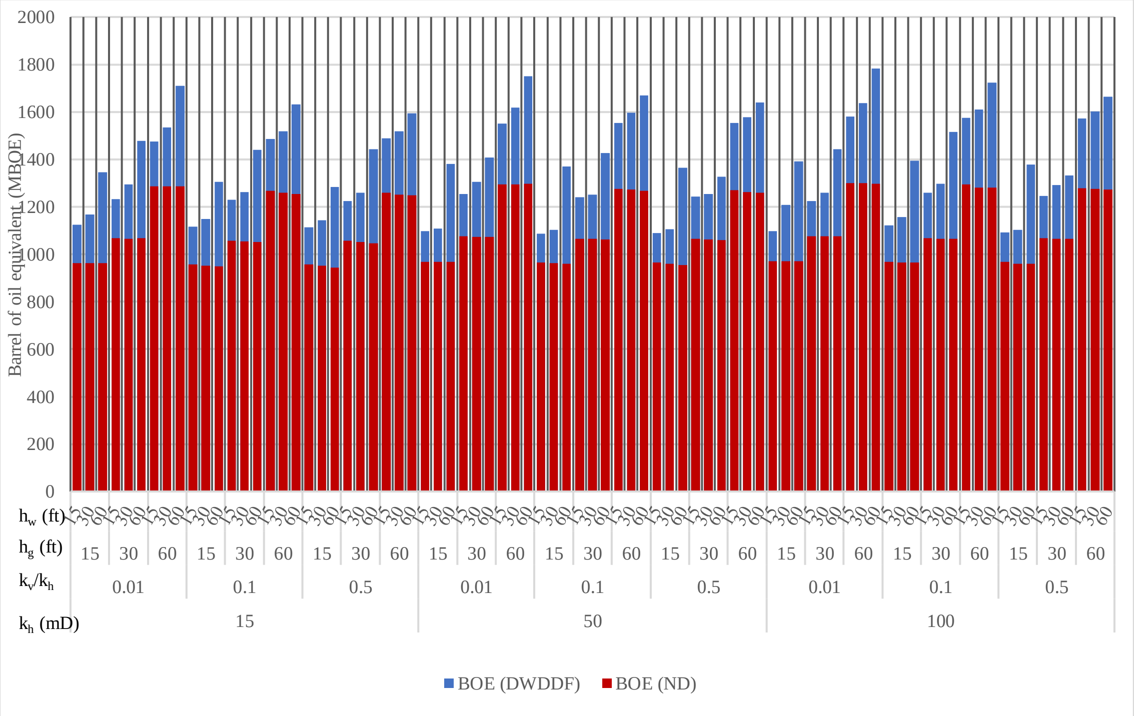


Figure 5.41 Total BOE for Bottom-up production and DWDDF at various horizontal permeabilities, kv/kh ratios, and gas column height as a function of different water column height *(Note that hw, hg and kh represent water column height, gas column height and horizontal permeability, respectively).*

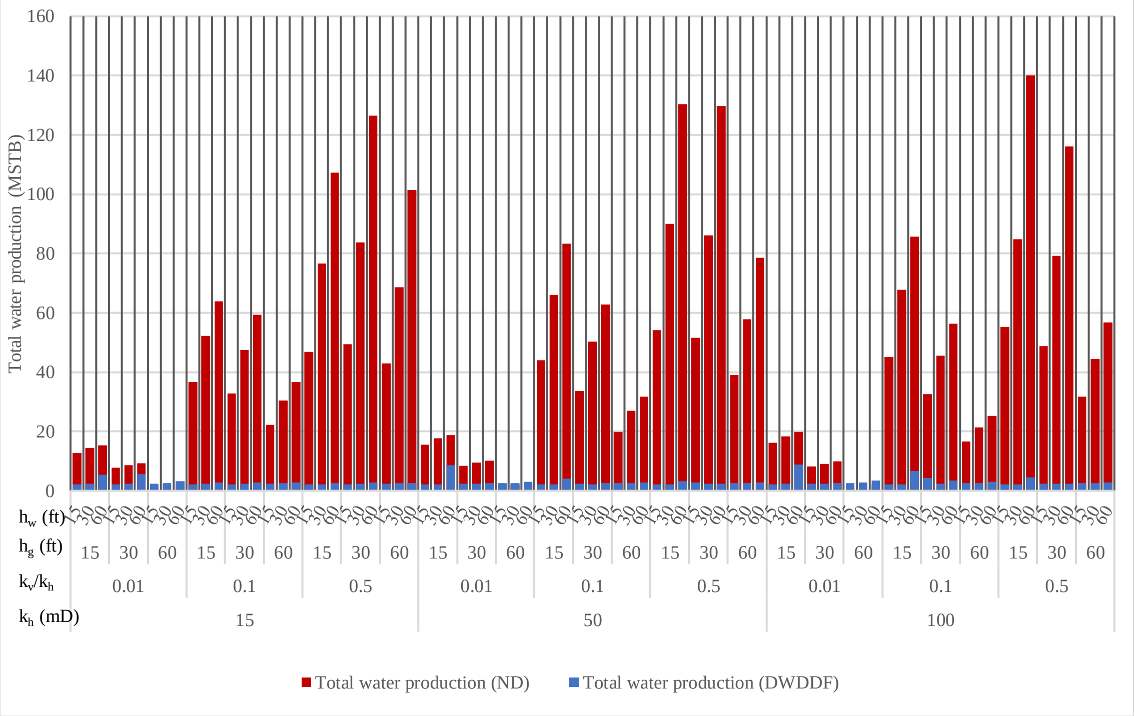


Figure 5.42 Total water production for Bottom-up production and DWDDF at various horizontal permeabilities, kv/kh, and gas column height as a function of different water column height *(Note that hw, hg and kh represent water column height, gas column height and horizontal permeability, respectively).*

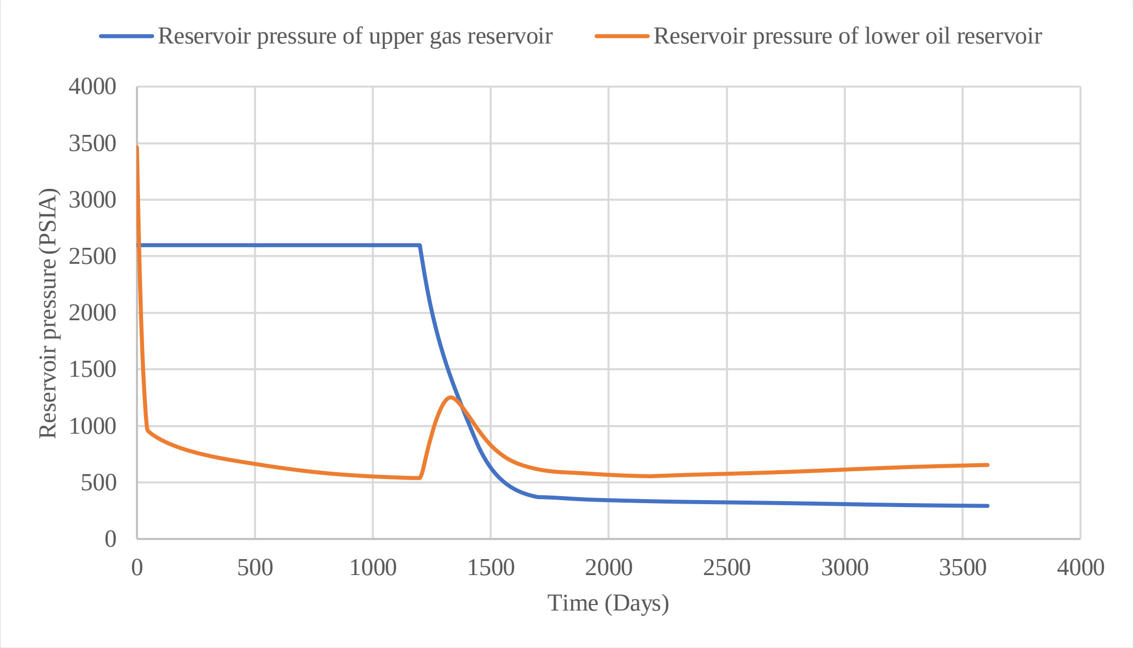


Figure 5.43 Reservoir pressures of bottom-water drive gas reservoir and underlying oil reservoir in DWDDF scenario at its best reservoir condition.

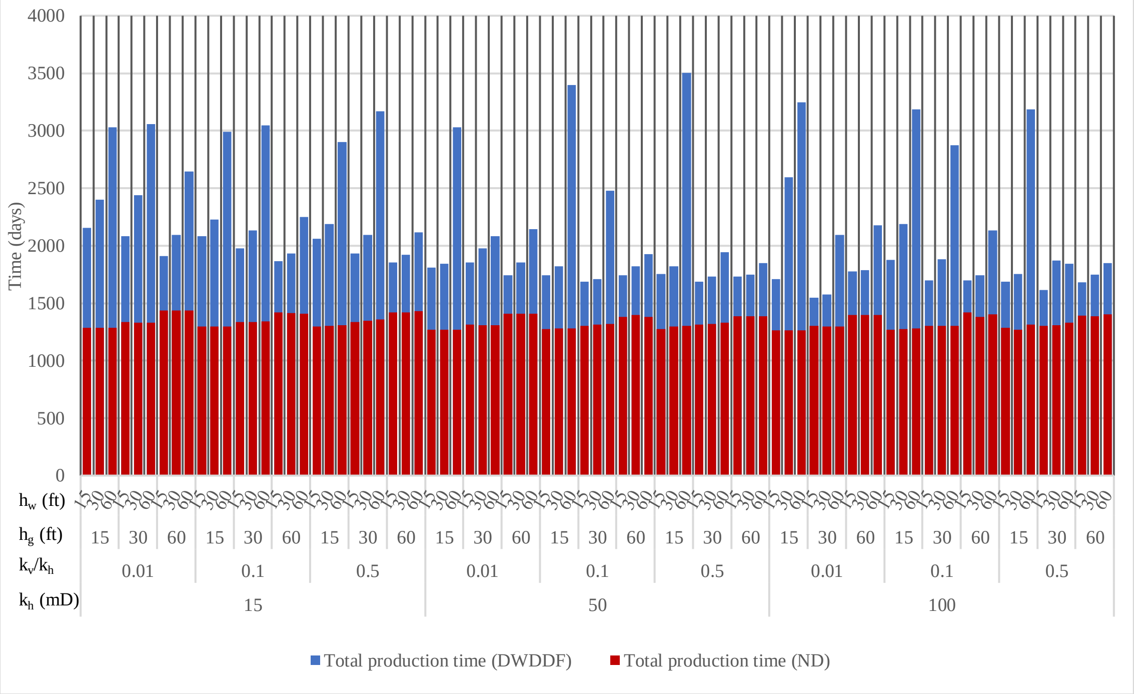


Figure 5.44 Total production period for Bottom-up production and DWDDF at various horizontal permeabilities, kv/kh, and gas column height as a function of different water column height (Note that hw, hg and kh represent water column height, gas column height and horizontal permeability, respectively).

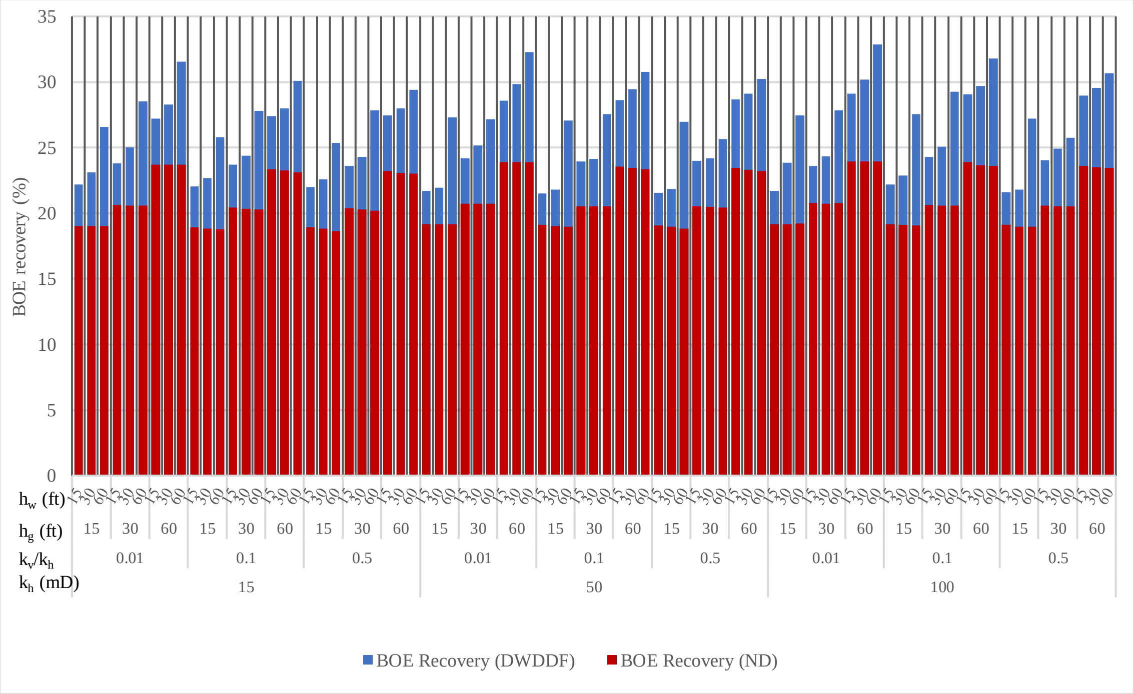


Figure 5.45 BOE recovery for Bottom-up production and DWDDF at various horizontal permeabilities, kv/kh and gas column height as a function of different water column height (Note that hw, hg and kh represent water column height, gas column height and horizontal permeability, respectively).

Table 5.18 Total BOE, total water production, total production time, BOE recovery factor, and contribution of gas reservoir for DWDDF scheme at horizontal permeability of 15 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		Total HIIP	Total production (Lower oil reservoir and upper gas reservoir)			BOE (Recovery factor)
	Gas	Water	(BOE)	BOE	Water (STB)	Time (days)	(%)
0.01	15	15	5,060,468	1,123,300	2,216	2,154	22.20
		30		1,168,664	2,341	2,398	23.09
		60		1,345,268	5,501	3,030	26.58
	30	15	5,181,565	1,233,670	2,265	2,082	23.81
		30		1,295,392	2,443	2,437	25.00
		60		1,478,528	5,555	3,058	28.53
	60	15	5,423,760	1,475,818	2,404	1,909	27.21
		30		1,533,774	2,527	2,094	28.28
		60		1,709,793	3,244	2,645	31.52
0.1	15	15	5,060,468	1,115,416	2,188	2,082	22.04
		30		1,147,811	2,278	2,226	22.68
		60		1,304,394	2,906	2,988	25.78
	30	15	5,181,565	1,228,458	2,241	1,975	23.71
		30		1,262,205	2,336	2,130	24.36
		60		1,439,778	2,824	3,044	27.79
	60	15	5,423,760	1,486,124	2,430	1,865	27.40
		30		1,517,833	2,507	1,931	27.98
		60		1,631,704	2,770	2,250	30.08
0.5	15	15	5,060,468	1,112,297	2,176	2,058	21.98
		30		1,142,732	2,261	2,190	22.58
		60		1,284,029	2,652	2,904	25.37
	30	15	5,181,565	1,223,872	2,222	1,931	23.62
		30		1,258,082	2,322	2,094	24.28
		60		1,441,757	2,853	3,171	27.82
	60	15	5,423,760	1,487,597	2,426	1,854	27.43
		30		1,518,232	2,509	1,920	27.99
		60		1,594,774	2,674	2,118	29.40

Table 5.19 Total BOE, total water production, total production time, BOE recovery factor, and contribution of gas reservoir for DWDDF scheme at horizontal permeability of 50 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		Total HIIP	Total production (Lower oil reservoir and upper gas reservoir)			BOE (Recovery factor)
	Gas	Water	(BOE)	BOE	Water (STB)	Time (days)	(%)
0.01	15	15	5,060,468	1,098,661	2,115	1,810	21.71
		30		1,109,343	2,136	1,843	21.92
		60		1,380,562	8,602	3,030	27.28
	30	15	5,181,565	1,253,821	2,280	1,854	24.20
		30		1,303,870	2,382	1,975	25.16
		60		1,407,643	2,564	2,082	27.17
	60	15	5,423,760	1,549,693	2,517	1,744	28.57
		30		1,618,079	2,697	1,854	29.83
		60		1,749,873	2,985	2,142	32.26
0.1	15	15	5,060,468	1,087,846	2,082	1,744	21.50
		30		1,103,809	2,124	1,821	21.81
		60		1,368,574	4,047	3,396	27.04
	30	15	5,181,565	1,239,946	2,471	1,689	23.93
		30		1,251,360	2,269	1,711	24.15
		60		1,427,096	2,688	2,476	27.54
	60	15	5,423,760	1,553,484	2,540	1,744	28.64
		30		1,596,669	2,648	1,823	29.44
		60		1,669,301	2,829	1,925	30.78
0.5	15	15	5,060,468	1,090,571	2,087	1,755	21.55
		30		1,104,352	2,124	1,821	21.82
		60		1,363,503	3,308	3,501	26.94
	30	15	5,181,565	1,242,176	2,800	1,689	23.97
		30		1,252,815	2,275	1,733	24.18
		60		1,327,702	2,420	1,942	25.62
	60	15	5,423,760	1,553,716	2,535	1,733	28.65
		30		1,577,803	2,589	1,750	29.09
		60		1,639,899	2,754	1,849	30.24

Table 5.20 Total BOE, total water production, total production time, BOE recovery factor, and contribution of gas reservoir for DWDDF scheme at horizontal permeability of 100 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		Total HIIP	Total production (Lower oil reservoir and upper gas reservoir)			BOE (Recovery factor)
	Gas	Water	(BOE)	BOE	Water (STB)	Time (days)	(%)
0.01	15	15	5,060,468	1,097,680	2,116	1,711	21.69
		30		1,207,224	2,420	2,593	23.86
		60		1,390,330	8,954	3,246	27.47
	30	15	5,181,565	1,224,077	2,310	1,546	23.62
		30		1,260,368	2,429	1,576	24.32
		60		1,443,263	2,648	2,094	27.85
	60	15	5,423,760	1,579,028	2,542	1,777	29.11
		30		1,637,049	2,728	1,788	30.18
		60		1,783,251	3,365	2,178	32.88
0.1	15	15	5,060,468	1,121,777	2,173	1,876	22.17
		30		1,156,101	2,268	2,190	22.85
		60		1,393,637	6,680	3,186	27.54
	30	15	5,181,565	1,259,385	4,422	1,700	24.31
		30		1,298,397	2,378	1,882	25.06
		60		1,515,996	3,372	2,876	29.26
	60	15	5,423,760	1,575,709	2,571	1,700	29.05
		30		1,610,524	2,673	1,744	29.69
		60		1,724,028	2,959	2,130	31.79
0.5	15	15	5,060,468	1,092,870	2,090	1,689	21.60
		30		1,102,566	2,110	1,755	21.79
		60		1,377,541	4,565	3,186	27.22
	30	15	5,181,565	1,245,537	2,321	1,616	24.04
		30		1,291,703	2,362	1,869	24.93
		60		1,333,377	2,411	1,843	25.73
	60	15	5,423,760	1,571,639	2,554	1,684	28.98
		30		1,602,544	2,635	1,749	29.55
		60		1,663,684	2,795	1,849	30.67

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the key finding obtained from the simulation study of the bottom-up scenario and Downhole Water Drain for Water Dumpflood (DWDDF) scheme. This conclusion could be used as a guideline for selecting suitable reservoir conditions for the proposed technique of the DWDDF scheme.

6.1 Conclusions

1) For oil production in the bottom-up scenario, oil recovery almost does not vary with well location whereas it slightly increases when the perforation interval of oil column becomes shorter. As the oil reservoir has moderate permeability, the impact on well location is minimal effect on oil recovery. For the perforation interval of oil column, the longer interval has a negative impact on oil recovery since it increases the chance of liberated gas to flow into oil perforations, impeding oil flow and reducing the secondary gas cap drive energy. Water production from oil reservoir is due to connate water expansion and water cut is very small. A shorter perforation interval of the oil column induces longer production time compared to longer ones since shorter oil perforations harness secondary gas cap drive by not producing liberated gas, as a result, oil recovery is increased by extending longer production time.

2) For gas production in the bottom-up scenario, the longer perforation interval of gas column moderately increases gas recovery but considerably increases water production. As the longer perforation interval of gas column reduces the pressure loss around the well, it allows more gas to flow into the well which increases gas recovery. At the same time, it increases higher water production since the longer gas interval is near the GWC. The longer perforation interval of gas column induces longer plateau production compared to shorter ones. As a consequence, longer ones can increase the gas recovery by extending longer plateau period.

3) For the operating parameter study in the bottom-up scenario, the highest total BOE of 957,645 barrels (18.92% of BOE recovery) is obtained with total water production of 36,692 STB and total production time of 1,294 days from 40% oil perforation and 80% gas perforation.

4) For the DWDDF scheme, altering well location has a minimal impact on BOE recovery whereas both the perforation interval of oil, gas, and water and starting time for dumpflood have a moderate impact on BOE recovery and a significant impact on water production and total production time. Overall, the shorter perforation interval of oil column impedes free gas from flowing into the well, the longer perforation interval of water column allows both more water and gas to be dumped into the lower reservoir, the shorter perforation interval of gas column help reduce water production at the surface and starting dumpflood at the economic rate induces more water and gas crossflows to the lower reservoir

as there is the large pressure difference between the upper and lower reservoir at the economic rate condition compared to other two starting time for dumpflood.

5) For the operating parameter study in the DWDDF scheme, the highest total BOE of 1,115,416 barrels (22.04% of BOE recovery) is obtained with total water production of 2,188 STB and total production time of 2,082 days from 40% oil perforation, 80% water perforation, 40% gas perforation, and starting dumpflood at the economic rate.

6) Comparing both production scenarios at their best-operating conditions, performing DWDDF instead of bottom-up production can improve BOE recovery by 3.12% which is equivalent to a percent increase of 16.47%. Also, unwanted water production can also be reduced by 94.04% from 36,692 to 2,188 STB in this comparative investigation. Furthermore, comparing bottom-up and DWDDF under the same operating conditions, every DWDDF case can perform better than bottom-up in terms of both improving BOE recovery and reducing water production. The total production time of DWDDF is always longer than bottom-up since both water and gas from the upper reservoir cross flow into the lower oil reservoir which improves oil production.

7) Only the reservoir parameter of the upper reservoir was varied to conduct the reservoir parametric study in the bottom-up scenario. Thus, gas recovery obtained in this part is converted to BOE and combined with hydrocarbon production from the lower oil reservoir. Overall, increasing horizontal permeability has a slight positive impact on gas recovery. The impact on recovery increment is more significant when horizontal permeability is varying from 15mD to 50mD, and it becomes less when horizontal permeability is increasing beyond 50mD. The higher kv/kh ratio has a moderate negative impact on gas recovery in general. The column height of the gas zone has a significant impact on gas recovery, lengthier gas column induces higher gas recovery. The impact on gas recovery due to the column height of the water zone is also subject to both kv/kh ratio and gas zone thickness. The column height of the water zone has a very small impact on gas recovery at lower kv/kh ratio, but it becomes significant when kv/kh ratio becomes higher. The column height of the water zone shows more impact at thinner gas reservoirs compared to the thicker gas reservoir in this simulation study.

8) For gas production in the bottom-up scenario of reservoir parametric study, two cases are yielding the highest gas recovery of 87.28%, both cases possess the same horizontal permeability of 100mD, kv/kh ratio of 0.01, gas zone column height of 60 ft, but different water zone column height of 15 ft and 30 ft. Different column height of the water zone results in different amount of water production from gas wells: 195 STB from 15 ft and 311 STB from 30 ft. Besides, both cases possess the same total gas production period of 180 days. Higher horizontal permeability can increase gas recovery as fluids can flow inside the reservoir with fewer restrictions. The lower kv/kh ratio allows less water to be produced since water coning is less intense in the reservoir with lower vertical permeability. The thicker gas reservoir induces higher gas recovery as it possesses higher GIIP, and its reservoir pressure declines slower than thinner ones. In addition, thicker gas reservoirs come up with lower water production compared to thinner ones

since the aquifer strength is less strong in the thicker gas reservoir. Longer water column height brings higher water production as the aquifer strength is stronger in the longer water column.

9) Although two cases yield the highest gas recovery of 87.28% in the reservoir parameter study for the bottom-up scenario, the case with a 30 ft water column height is 0.001% higher in terms of gas recovery is selected to compare with the DWDDF scheme. This selected case yields the highest total BOE of 422,786 barrels (23.944% of BOE recovery) obtained with total water production of 2,030 STB and a total production time of 1,398 days.

10) For reservoir parameter study in the DWDDF scheme, increasing horizontal permeability has a slight positive impact on BOE recovery only at a gas column thickness of 60 ft. At thinner gas column thicknesses of 15 ft and 30 ft, both increasing or decreasing horizontal permeability have a slight impact on BOE recovery, which can be either positive or negative increment due to mixed impacts getting from other reservoir parameters. Generally, kv/kh ratio has a small impact on BOE recovery and increasing it can slight lower the BOE recovery. The column height of the gas zone has a moderate impact on BOE recovery, lengthier gas column induces higher BOE recovery in general. Commonly, varying the water column height from 15 ft to 30 ft has a small impact on BOE recovery while altering it to 60 ft has more impact on BOE recovery.

11) Among the cases within the reservoir parametric study of the DWDDF scheme, the highest BOE recovery of 32.88% obtains from the case with horizontal permeability of 100mD, kv/kh ratio of 0.01, gas reservoir thickness of 60 ft and water column height of 60 ft, which total water production is 3,365 STB and the total production time is 2,178 days. Higher horizontal permeability allows more water and gas crossflows, therefore, oil production from the lower reservoir is improved. The lower kv/kh ratio induces less gas to cone toward the water zone, thus, more water can crossflow since gas and water have different mobility. As a result, dumping more water can displace more oil for production. The thicker gas column allows more gas to crossflow and that facilitates oil flow inside the reservoir. The thicker water column allows more water to dump, which also helps to improve oil production. In this investigation, DWDDF can perform better when both water and gas columns are having a greater thickness. However, the highest BOE recovery obtains due to a good balance between the amount of water and gas crossflows, not the highest amount of water and gas crossflows. The impacts from horizontal permeability and kv/kh ratio are trivial compared to water and gas column thickness. The contribution from both parameters is more pronounced in the thicker gas column compared to thinner ones.

12) Comparing both production scenarios under the same reservoir condition of horizontal permeability of 100mD, kv/kh ratio of 0.01, gas reservoir thickness of 60 ft and water column height of 60 ft, performing DWDDF instead of bottom-up production can improve BOE recovery by 8.94% which is equivalent to a percent increase of 37.35%. Total water production of DWDDF is higher than bottom-up by 54.93% from 2,172 to 3,365 STB. However, only a few cases that yield total water production of DWDDF are beyond bottom-up. Furthermore, comparing bottom-up and DWDDF under the same reservoir conditions, not

only BOE recovery is increased but also water production is reduced when the DWDDF technique is applied in most cases except for some cases with kv/kh ratio of 0.01 and gas column height of 60 ft. Besides, the total production time of DWDDF is always longer than bottom-up since both water and gas from the upper reservoir cross flow into the lower oil reservoir which improves oil production.

6.2 Recommendations

1) Since reservoir heterogeneity is not considered in this work, the degree of heterogeneity should be investigated for further study, which would result in different conclusions.

2) The dip angle of the reservoir should also be investigated as the displacement mechanism against gravity segregation of oil, water and gas would result in different hydrocarbon recovery.

3) Since the production time of the DWDDF scheme in this study is longer than the bottom-up production scenario, it is better to perform an economic analysis in order to find out the profitability of the DWDDF technique compared to conventional production techniques.

4) In this work, the upper reservoir is the bottom water-drive gas reservoir, thus, it is good to make a new study for the DWDDF scheme in case of edge water-drive gas reservoir condition.

APPENDIX

Table A.1 Volume of water, gas, and oil crossflows for DWDDF at 80% oil perforation interval for various gas and water perforation intervals, and different starting times for water dumpflood.

Perforation interval (%)		Starting time	Water dump volume	Gas crossflow volume	Oil crossflow volume
Gas column	Water column	(days)	(STB)	(MMSCF)	(STB)
80	80	First day	62,083	24	747
80	60	First day	72,157	38	0
80	40	First day	64,268	41	0
80	80	End of plateau	57,961	16	665
80	60	End of plateau	71,001	29	0
80	40	End of plateau	64,803	13	0
80	80	Economic oil rate	43,430	11	534
80	60	Economic oil rate	70,321	19	0
80	40	Economic oil rate	56,135	0	0
60	80	First day	63,239	34	675
60	60	First day	72,594	52	0
60	40	First day	63,006	62	0
60	80	End of plateau	58,039	21	586
60	60	End of plateau	72,462	38	0
60	40	End of plateau	62,312	26	0
60	80	Economic oil rate	43,489	11	482
60	60	Economic oil rate	71,913	26	0
60	40	Economic oil rate	58,908	1	0
40	80	First day	62,004	43	568
40	60	First day	71,348	87	0
40	40	First day	67,561	127	0
40	80	End of plateau	58,634	25	486
40	60	End of plateau	71,376	63	0
40	40	End of plateau	57,633	51	0
40	80	Economic oil rate	49,084	13	382
40	60	Economic oil rate	70,838	43	0
40	40	Economic oil rate	57,862	52	0

Table A.2 Volume of water, gas, and oil crossflows for DWDDF at 60% oil perforation interval for various gas and water perforation intervals, and different starting times for water dumpflood.

Perforation interval (%)		Starting time	Water dump volume	Gas crossflow volume	Oil crossflow volume
Gas column	Water column	(days)	(STB)	(MMSCF)	(STB)
80	80	First day	64,555	30	747
80	60	First day	73,522	40	24
80	40	First day	74,467	69	0
80	80	End of plateau	60,299	19	666
80	60	End of plateau	72,483	31	3
80	40	End of plateau	73,999	39	0
80	80	Economic oil rate	46,125	16	534
80	60	Economic oil rate	71,609	22	0
80	40	Economic oil rate	60,262	1	0
60	80	First day	66,346	42	675
60	60	First day	74,986	53	0
60	40	First day	73,567	94	0
60	80	End of plateau	60,843	27	586
60	60	End of plateau	75,112	42	0
60	40	End of plateau	73,310	61	0
60	80	Economic oil rate	46,017	16	481
60	60	Economic oil rate	74,490	32	0
60	40	Economic oil rate	60,608	2	0
40	80	First day	65,569	53	568
40	60	First day	74,591	88	0
40	40	First day	72,647	91	0
40	80	End of plateau	61,874	32	486
40	60	End of plateau	74,827	67	0
40	40	End of plateau	72,250	103	0
40	80	Economic oil rate	51,904	19	382
40	60	Economic oil rate	74,211	51	0
40	40	Economic oil rate	70,935	54	0

Table A.3 Volume of water, gas, and oil crossflows for DWDDF at 40% oil perforation interval for various gas and water perforation intervals, and different starting times for water dumpflood.

Perforation interval (%)		Starting time	Water dump volume	Gas crossflow volume	Oil crossflow volume
Gas column	Water column	(days)	(STB)	(MMSCF)	(STB)
80	80	First day	68,835	40	747
80	60	First day	77,005	41	197
80	40	First day	76,080	69	0
80	80	End of plateau	64,755	29	666
80	60	End of plateau	77,137	37	67
80	40	End of plateau	76,349	42	0
80	80	Economic oil rate	51,573	27	533
80	60	Economic oil rate	75,809	30	2
80	40	Economic oil rate	71,100	29	0
60	80	First day	71,835	55	676
60	60	First day	80,081	62	49
60	40	First day	75,493	98	0
60	80	End of plateau	66,112	39	586
60	60	End of plateau	80,484	54	12
60	40	End of plateau	76,023	64	0
60	80	Economic oil rate	51,505	26	480
60	60	Economic oil rate	79,712	41	0
60	40	Economic oil rate	74,627	36	0
40	80	First day	71,028	64	569
40	60	First day	80,382	97	0
40	40	First day	74,702	150	0
40	80	End of plateau	67,777	45	487
40	60	End of plateau	81,239	79	0
40	40	End of plateau	74,963	106	0
40	80	Economic oil rate	57,489	31	380
40	60	Economic oil rate	80,759	63	0
40	40	Economic oil rate	74,680	62	0

Table A.4 Volume of water, gas, and oil crossflows for DWDDF at horizontal permeability of 15 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Water dump volume	Gas crossflow volume	Oil crossflow volume
	Gas	Water	(MMSCF)	(STB)	(MMSCF)	(STB)
0.01	15	15	727	87,847	155	0
		30		201,468	158	0
		60		471,358	162	0
	30	15	1,453	81,660	230	0
		30		205,704	249	0
		60		491,200	234	0
	60	15	2,906	74,015	441	0
		30		180,922	436	0
		60		461,103	396	0
0.1	15	15	727	74,702	150	0
		30		159,895	165	0
		60		379,543	187	0
	30	15	1,453	72,814	238	0
		30		160,053	260	0
		60		401,902	285	0
	60	15	2,906	60,752	517	0
		30		143,703	546	0
		60		350,394	514	0
0.5	15	15	727	72,013	147	0
		30		150,140	163	0
		60		347,294	185	0
	30	15	1,453	72,287	231	0
		30		152,705	260	0
		60		380,679	306	0
	60	15	2,906	66,963	532	0
		30		147,475	574	0
		60		320,581	559	0

Table A.5 Volume of water, gas, and oil crossflows for DWDDF at horizontal permeability of 50 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Water dump volume	Gas crossflow volume	Oil crossflow volume
	Gas	Water	(MMSCF)	(STB)	(MMSCF)	(STB)
0.01	15	15	727	87,720	142	1.75
		30		182,724	116	0.31
		60		551,687	127	0
	30	15	1,453	76,419	313	1.8
		30		193,961	279	0.1
		60		418,159	189	0
	60	15	2,906	70,514	622	0
		30		172,572	554	0
		60		469,738	459	0
0.1	15	15	727	75,139	137	1.81
		30		152,856	129	0.5
		60		493,647	150	0.5
	30	15	1,453	71,932	336	7.1
		30		154,222	314	0
		60		410,292	282	0
	60	15	2,906	59,186	738	0
		30		159,022	695	0
		60		371,570	586	0
0.5	15	15	727	74,307	142	1.06
		30		145,657	133	0.25
		60		468,392	161	0.1
	30	15	1,453	74,914	345	5.9
		30		152,977	329	0
		60		304,116	263	0
	60	15	2,906	72,122	765	0.5
		30		152,677	741	0
		60		342,398	652	0

Table A.6 Volume of water, gas, and oil crossflows for DWDDF at horizontal permeability of 100 mD, various kv/kh ratios and columns height of gas and water zones.

kv/kh	Column height (ft)		GIIP	Water dump volume	Gas crossflow volume	Oil crossflow volume
	Gas	Water	(MMSCF)	(STB)	(MMSCF)	(STB)
0.01	15	15	727	78,867	165	32.87
		30		262,434	167	0
		60		586,295	92	0
	30	15	1,453	47,871	269	5.81
		30		109,967	212	0.5
		60		451,017	214	0
	60	15	2,906	66,441	566	0
		30		151,563	585	0
		60		535,168	488	0
0.1	15	15	727	87,941	193	12.5
		30		193,840	167	0.2
		60		570,794	156	0
	30	15	1,453	58,976	395	53.5
		30		172,418	372	4.7
		60		545,105	327	0
	60	15	2,906	44,563	794	2.4
		30		155,481	724	0.2
		60		475,472	627	0
0.5	15	15	727	73,632	167	2.81
		30		148,546	142	0.06
		60		538,671	164	0
	30	15	1,453	69,559	383	2.6
		30		168,352	390	3
		60		303,160	265	0
	60	15	2,906	66,991	823	0.3
		30		160,997	782	0
		60		375,536	667	0

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VITA

NAME	Htet Myet Zin Naing
DATE OF BIRTH	17 June 1997
PLACE OF BIRTH	Yangon, Myanmar
INSTITUTIONS ATTENDED	- Master's Degree: Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University - Bachelor's Degree: Department of Petroleum Engineering, Technological University (Thanlyin) - High School: BEHS (6) Botahtaung (St.Paul)
HOME ADDRESS	1010, Mya Khwar Nyo Condo, Ayerwun Main Road, Thaketa, Yangon, Myanmar
PUBLICATION	"Downhole Water Drain from Gas Reservoir for Water Dumpflood in Oil Reservoir to Increase Hydrocarbon Production" published in 25th PARIS International Conference on "Advances in Science, Engineering & Waste Management" (PASEW-22), April 2022.
AWARD RECEIVED	- Year 2020: Graduate Scholarship Program for ASEAN or Non-ASEAN Countries, Chulalongkorn University - Year 2019: One Semester Scholarship Program for ASEAN or Non-ASEAN Countries, Chulalongkorn University