EVALUATION OF INTELLIGENT DUAL-LATERAL WELL IN MULTI-LAYERED RESERVOIRS

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หลุมน้ำมันหลายแขนงได้ถูกนำมาใช้อย่างแพร่หลายในอุตสาหกรรมปิโตรเลียมในช่วงหลายศตวรรษที่ผ่านมา หลุมน้ำมันดังกล่าวไม่เพียงแต่จะช่วยลดค่าใช้จ่ายของหลุมผลิต แต่ยังสามารถที่จะช่วยผลิตน้ำมันได้น้ำมันมากเทียบเท่าหรืออาจจะมากกว่าการเจาะหลุมแนวตั้งหรือหลุมแนวนอนแบบพื้นฐานหลายๆหลุมเมื่อรวมวิธีการเจาะแบบนี้เข้ากับหนึ่งในเทคโนโลยีการผลิตที่ใหม่ที่สุดชนิดหนึ่งซึ่งก็คือหลุมน้ำมันอัจฉริยะเป็นที่คาดหวังว่าวิธีนี้จะสามารถช่วยแก้ปัญหาน้ำที่ถูกผลิตขึ้นมาโดยไม่ต้องการได้

จุดประสงค์การศึกษานี้คือเพื่อบ่งชี้การปรับแต่งคุณหลุมน้ำมันหลายแขนง อัจริยะซึ่งจะช่วยให้เกิดข้อดีในการเพิ่มผลผลิตน้ำมันและลดปริมาณน้ำที่เกิดจากการผลิตการศึกษานี้ยังได้ถูกต่อยอดไปถึงการศึกษาผลกระทบของตัวแปรต่างๆในแหล่งกักเก็บน้ำมันที่ถูกเลือกมาอีกด้วย

ผลการศึกษาแสดงให้เห็นว่าการปรับอัตราส่วนการไหลของน้ำในหลุมผลิต หรือการปรับเปลี่ยนความลึกของแขนงของหลุมแนวนอนไม่ได้ให้ผลดีกับการออกแบบหลุมอัจฉริยะแนวนอนหลายแขนงในทุกกรณีเกณฑ์หลักในการติดตั้งหลุมอัจฉริยะขึ้นอยู่การตั้งค่าอัตราส่วนการไหลของน้ำในหลุมก่อนผลิต และ ตำแหน่งของแขนงของหลุมที่ปรับเปลี่ยนความลึกได้ การศึกษานี้ยังได้พิสูจน์อีกว่าขนาดของชั้นน้ำใต้แหล่งกักเก็บน้ำมันยังเป็นอีกหนึ่งเกณฑ์การตัดสินว่าควรจะติดตั้งหลุมอัจฉริยะในกรณีศึกษาต่าง ๆ หรือไม่ ในการศึกษานี้การติดตั้งหลุมอัจฉริยะที่ตำแหน่งหลุมแนวนอนแขนงที่สองที่ความลึกแนวตั้งอันดับที่ 25 และ 15 แสดงให้เห็นถึงปริมาณการผลิตน้ำมันที่มากขึ้นเมื่อเทียบกับกรณีหลุมกรุ ในการศึกษาผลกระทบของตัวแปรพบว่า ขนาดของชั้นหินอุ้มน้ำขนาด 100 เท่าของความจุแหล่งกักเก็บได้ถูกพิสูจน์ว่าเป็นคุณสมบัติของแหล่งกักเก็บกับที่เหมาะแก่การติดตั้งหลุมอัจฉริยะ อัตราส่วนในแนวตั้งต่อแนวนอนของค่าความซึมผ่านที่มีค่ามากกว่า 0.1 ได้แสดงให้เห็นถึงความไม่มีประสิทธิภาพของการติดตั้งหลุมอัจฉริยะ

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Multilateral well has been widely introduced in petroleum industry in the past few decades. With its main benefit of cost saving yet able to let the production field obtaining reserve underneath as much as or even more than drilling multiple conventional vertical or horizontal wells. Integrating this drilling method with one of the newest completion technologies, intelligent completion, is expected to solve or improve water coning problem.

The objective of this study is to identify intelligent well configuration when combining with dual-opposed multilateral well that could yield benefit on improving oil recovery factor as well as reducing water production. Further study is also performed on sensitivity analysis of selected reservoir parameters.

Results show that not every each water cut ratio of production scenarios or at every depth of the dual-lateral well should be designed for intelligent completion. The intelligent completion equipping criteria depends mainly on preset water cut ratio as well as location of one varied branch of dual opposed well. In this study, intelligent completion equipped at varied lateral located at 25th and 15th vertical grid block show benefit of oil recovery compared to the openhole cases. In terms of sensitivity analysis, aquifer strength of 100PV is proven to be a good reservoir property for installing intelligent completion. Ratio of vertical to horizontal permeability more than 0.1 shows ineffectiveness of intelligent completion installation.

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List of Abbreviations

GOC	Gas Oil Contact
ICS	Intelligent Completion System
ICV	Inflow Control Valve
md	Millidarcy
MMSTB	Million stock-tank barrel
MMMSCF	Billion standard cubic feet
Mscf	Thousand standard cubic feet
OOIP	Original Oil In Place
WOC	Water Oil Contact
psi	Pounds per square inch
psia	Pounds per square inch absolute
PVT	Pressure-Volume-Temperature
SCAL	Special core analysis
STB	Stock-tank barrel
STB/D	Stock-tank barrel per day

Nomenclatures

$\Delta\rho$	Density difference
ρ_g	Gas density
ρ_o	Oil density
ρ_w	Water density
μ_o	Oil viscosity
μ_w	Water viscosity
B_w	Water formation volume factor at reference pressure
C_w	Water compressibility
h	Oil pay zone thickness
k_h	Horizontal permeability
k_{rg}	Relative permeability to gas
k_{ro}	Relative permeability to oil
k_{rw}	Relative permeability to water
k_v	Vertical permeability
P_{bub}	Bubble point pressure
R_s	Solution gas oil ratio
S_{wmin}	Minimum water saturation (or irreducible water saturation)
S_{wcr}	Critical water saturation
S_{wi}	Initial water saturation (or connate water)
S_{wmax}	Maximum water saturation (equal to 1.0)
S_{gmin}	Minimum gas saturation (or irreducible water saturation)
S_{gcr}	Critical gas saturation
S_{gi}	Initial gas saturation
S_{org}	Residual oil saturation measured by gas
S_{orw}	Residual oil saturation measured by water

CHAPTER I

INTRODUCTION

Multilateral horizontal wells have been appreciably introduced in the past few decades in order to increase exposure contact area to reservoir and hence, enhance oil and gas recovery. One of the most challenging constraints is how to select a compatible configuration, completion system and other related parameters to ensure the effectiveness of well geometry as well as anticipated operational cost savings. Due to its complexity, it takes good, well-planned and realistically economic evaluation to ensure that the planned scenarios will be appropriately adapted to the actual reservoir and also its environment.

Water encroachment or typically known as water cresting, is one of the major common production problems happening in the aquifer-based reservoir and this can either be the advantage or disadvantage to the reservoir at the same time. Good and well-planned management of bottom-water boundary condition can help support the hydrocarbon production as constant pressure drive or imitated water flooding. While the unintentional allowance of letting the water cone into the reservoir, naturally without any preventive action (e.g., shut in well), can lead to an unfavorable level of water invasion into the wellbore, resulting in an early intervention of water production.

With the assistance of new technology “Intelligent Completion System (ICS)”, this helps the well, especially the horizontal well with water encroachment engaged, to be more conveniently predictable. Because of its main advantage sending the real-time information from the wellbore to those operating remotely, intelligent completion provides the data transmission without well intervention and thus, leads to the preventive solutions for each production those may happen, in this case water cresting. The well-matched characteristics of the horizontal wells itself and the intelligent completion is expected to yield many advantages over the normal conventional type of wells. Albeit that one main thing to be discrete is to consider the cost of operating as it is highly cost and quite extravagant, especially at the initial stage. Its success will be depending on installing the system to the right type of reservoirs and also their forecasted characteristics.

Therefore, for one to suitably operate the intelligent completion for multilateral horizontal wells with water cresting production problem, there will be some interesting variables related. Expected parameters are well configuration as well as petrophysical properties.

1.1 Objectives

1. To evaluate the effects of vertical location of varied lateral well and preset water cut ratio on intelligent completion system equipped in dual-opposing multilateral wells in multi-layered reservoirs.
2. To study the sensitivity analysis of petrophysical properties which are aquifer strength and ratio of vertical permeability to horizontal permeability on intelligent completion system equipped in dual-opposing multilateral wells in multi-layered reservoirs.

1.2 Expected Usefulness

Ultimate result of optimal production scenarios, with the consideration of intelligent completion system varying of petrophysical characteristics and well configuration, should be able to provide the selection of significant reservoir parameters. Moreover, the findings will provide cautions prior to the multilateral well implementation including drilling preparation and other associated production planning schemes.

1.3 Outline of Methodology

1. Construct an initial heterogeneous reservoir, having fining upward sand model (sequenced from the lowest to highest values from top to bottom layers).

2. Run base cases of single horizontal well with primary gas cap and bottom-driven aquifer, by having one whole horizontal branch at various depths of 10th, 15th, 20th and 25th vertical grid block.
3. Study dual lateral well position by having one lateral fixed at 20th vertical grid block and another lateral varied at various depths of 10th, 15th, 20th and 25th vertical grid block.
4. Study the configuration effects on the ICV-installed cases at different value of water cut ratios from 0.7 to 0.9.
5. Simulate sensitivity analysis over selected ICV-installed in dual-lateral cases compared to dual-lateral well at same depth. During the sensitivity analysis, the study parameter is varied, whereas the parameters are kept constant at the middle value (bold).
   5.1 Aquifer strength representing by the number of times of pore volume (PV). Chosen PV values are **50**, 100, 200 and 300 PV**.**
   5.2 Reservoir anisotropy representing by the ratio of vertical permeability to horizontal permeability (k_v/k_h). Chosen ratios for this study are **0.1**, 0.2, 0.3 and 0.5.
6 Analyze the simulation result in terms of field oil recovery and field water production.
7 Conclude the findings from the simulation study**.**

1.4 Thesis Outline

Chapter II presents previous works/studies related to horizontal well, multilateral well, intelligent completion and integration of all of these studies.

Chapter III describes related theories of multilateral well, intelligent completion and water encroachment production problem.

Chapter IV explains the feature of reservoir simulation model in this study.

Chapter V discusses the results of reservoir simulation.

Chapter VI provides conclusions and recommendations for potential further study.

CHAPTER II

LITERATURE REVIEW

In this chapter, previous studies relating to the knowledge of multilateral wells, intelligent completion system and also the integration of these topics are discussed. Moreover, successful cases of the integration of these technologies are presented for references.

Retnanto et al. [1] shared their views on the importance of choosing the right reservoir and completion technologies candidates for ones to operate the multilateral wells. As known that the common advantages of drilling this type of well geometry are to yield more productivity index, to decrease water cresting phenomenon and to expose the well to more natural-fractured systems. There are, however, some drawbacks on this operation such as the sensitivity to poor vertical permeability (k_v), complication of drilling as well as higher initial cost compared to the conventional vertical well drilling. In this particular study, the reservoir characteristics which are well geometry and permeability anisotropy are examples of main reservoir parameters to be considered if any reservoir candidate should be selected or not. Moreover, on the completion perspective, the good planning of well completion type can optimize the length and numbers of wells to be drilled.

The complexity and importance of multilateral well design had also been highlighted by Crumpton et al. [2]. Well path and position parameterization is calculated by its depth, length and angle to be sensitized to. The simulation model used in this observation was the long horizontal and multilateral Maximum Reservoir Contact (MRC) wells. This model had also been prepared by having the geological uncertainty and the common production factors taken into account. Analysis of reservoir uncertainty, determination of the set of operational constraints and completion design were demonstrated to be the results those should be processed in one single application. It was performed in order to accelerate the screening process of multilateral wells drilling selection. The practicability of having the completion design simulated data to be applied in the real field was also pointed out in this study.

Horizontal and multilateral wells those have been producing for several years may have experienced some production problems such as water cresting. This typical problem leads to the increment of water cut and finally affects the production expectation. Careful design of the affordable tools, to distantly trigger the problem occurring in the wells to the person operating remotely, will be one of the proactive actions for the wells to be taken care of. Not only the remotely-operated personnel can decide on what further activities should be performed to the wells but this smart completion system has also been recognized in its ability to ultimately allocate the optimum production rate as well as to enhance more ultimate oil recovery.

Zarea and Zhu [3] implicated that intelligent completion is one of the most competent completion techniques for the optimization of well completion in combined multilateral reservoirs. ICV or Inflow Control Valve in this type of completion system can be examined as a surface chokes with minor modifications of downhole conditions. By knowing the pressure and flow distribution in any well system, the better flow conditions which equivalently implied to the better ultimate oil recovery can be obtained by operating the ICV. ICV can generally be classified in accordance to the type of the flow control they are able to provide as binary, multi-position or infinitely variable. This is working in parallel with the downhole monitoring gauges which record and transmit real-time pressure, temperature and other date to the surface. Operator will not only be able to strategically plan the production pattern without well intervention but also will thus be able to optimize production by maximizing recovery yet maintaining the operating costs. The study described the mandatory nature of the ICV to have the capability of bearing the maximum potential flow rate, which is generated from the equilibrium point of the intersection between Inflow Performance Relationship (IPR) and Tubing Performance Curve. The calculation of pressure drop across ICV was also thoroughly presented based on the number of lateral wells drilled, valve flow coefficient and other associated reservoir common parameters. Valid realization of the flow characteristics can help prevent the cross-flow problem which naturally always occurred in the commingled production. This can be one of the major possible failures of the total production system.

Tubel and Hopmann [4] defined in their research about the application of ICS in subsea multilateral wells. The integrated set of ICS downhole system is comprised of elements to measure tubing and annulus pressure, temperature, flow and valves capable of controlling the hydrocarbon flow from formation to the production tubing. Each flow zone in this study was effectively isolated for the conveniences and systematic arrangement of any necessary wells activities to be done, especially when being triggered of something which was not as planned. Each zone's flow variables can also be adjusted by delivering a command to the device underneath and actuate the downhole mechanism through the smart completion system. With the set conditions of the processor, the valve device can be commanded to open, close, change status or even execute any desired action within the operating range. It is also emphasized as the significant benefit on the ease of having no or less as possible well intervention. All of these can be done by utilizing the advantage of getting and managing the wells' information distantly.

The necessity of pre-screening procedure to have the reliable ICS operated was introduced by Brownlee et al. [5] by having Chevron, Det Norske Veritas (DNV) developed together the estimation of the financial impact related to the component failure of intelligent completion system. The methodology steps of the proactive prevention of smart completion system failure were pointed out as 1) Define the completion system's components 2) Determine the failure modes and consequences of failure for each system component 3) Verify reliability data for each system component 4) Obtain production profile for each well and the whole process facility capacity and finally 5) Simulate field lifetime operation to get the key system performance parameters including production losses due to component failures, repair cost due to well intervention and etc.

Cullick and Sukkestad [6] gathered industry's concerns of operating the ICS, majorly due to their worry of provable long-term oil recovery and returns, risk of valves' failure due to well integrity and performance, overoptimistic results which usually from simulation and the uncertainty of effective future operational practices. The research validated the genuine benefit of intelligent completion over these concerns raised and also over the traditional completion system. Their work was based on simulation-based analysis and reliable procedure. Final result was to optimize the eventual result which was oil production being maximized while the water production was viably better managed as well. Cases shown in this study were varied from the single long horizontal well with fixed operational control strategy (triggered water-cut threshold was fixed and valve would then be closed incrementally in response) compared to the multilateral wells with many branches and having the totally different control strategy, which was the flexible one. There had been a substantial oil recovery improvement, less water production in the cases comparison presented in this investigation.

CHAPTER III

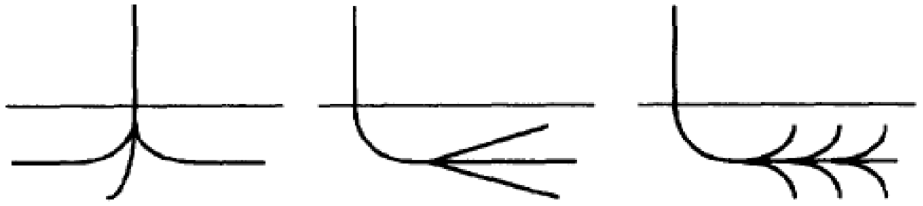
THEORY AND CONCEPT

This chapter explains key knowledge of multilateral wells, intelligent completion system and water encroachment, which all are considered to be significant parameters in the study.

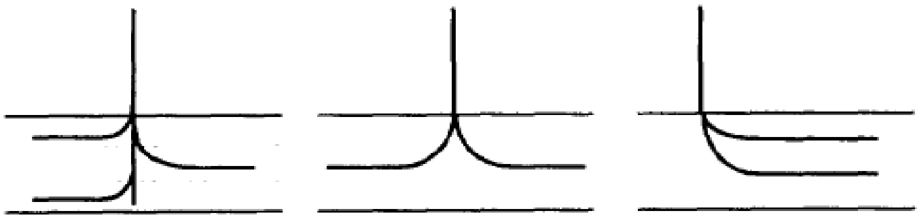
3.1 Multilateral wells

Many attempts had been duly recorded as part of multilateral horizontal well drilling since 1920s but the first significant one was the operation established in Austin Chalk formation of South Texas.

Basically, multilateral well or multiple lateral wells are wells with more than one lateral leg branching into the formation(s) and general definition gives rises to several configurations as listed in figure 1. By having the definition of the laterals as well bores drilled from the main well bore and meaning of branches as the well bores drilled from a horizontal lateral into the horizontal plane [7].



b. Multi-branched well a. Fork well c. Laterals into horizontal hole



d. Laterals into vertical e. Dual opposing f. Stacked laterals

Figure 3.1 Multilateral well geometry [8]

As selected well geometry in this study is the dual opposing one, further explanation should hereby be required for the clearer understanding. Instead of losing the ability to maintain directional control while the normal horizontal well's length is increased, dual-lateral well offers the solution of orienting the reservoir fluid to be more distributional and not consolidating only in the same side. Which after all, this suits the typical production drilling scenario. With the equipped additional configuration accessories those will be mentioned in the later section of ICS, this should together well suit to enhance more interesting production optimization result.

The main advantages of drilling horizontal and multilateral wells over the conventional vertical wells are such as [9]:

- Cost-saving by reducing the number of vertical wells and the cost of well construction/ completion i.e., in some of the environmentally or costly sensitive areas where surface facility installations maybe expensive. Multilateral wells can majorly help recover the reserves per area by having one mothered well without having to drill many vertical wells in order to get the same amount of reserves.
- Production improvement as the higher productivity indexes. This has been raised up due to the fact that the wells can be drilled in any direction on each of the branch plus with decreasing of water cresting especially in a thin reservoir.
- Adaptability in complex oil reservoir. Because each horizontal branch drains oil from each compartment as much as possible, this then is the important advantage.

However, in order to apply this horizontal drilling method, the initial drawbacks needed to be vigilant of are higher initial operating cost due to the complicated installation and management as well as the slower and less effective well clean-up.

Well completion technique in horizontal wells is also being considered as another perspective to be discretely chosen, for the goal of ultimately yielding the optimal production. They can generally be categorized as

1) Openhole completion: This technique is considered inexpensive but it is applicable for only several types of formations. Horizontal wells will also be difficult for any stimulation when using this completion.

2) Slotted liner completion: By installing the slotted liner for mainly guarding against the hole collapse, liner will also provide a convenient path for installation of other associated tools e.g., coiled tubing. In this completion system, the well stimulation is still considered a bit difficult as an annular space between the liner and the well do exist.

3) Liner with partial isolations: External casing packers or ECPS are installed in this system to separate the long horizontal wells into many sections. This will ultimately help in terms of well stimulation and production control.

4) Cemented and perforated liners: If one will apply this configuration into any horizontal wells, the main concern is to ensure that cement used should have significantly free water than the one used in vertical well cementing. As in typical horizontal wells, the poor cement job can occur when free water segregates near the well’s top portion. This normally happens due to the gravity and heavier cement will eventually fall down at the bottom.

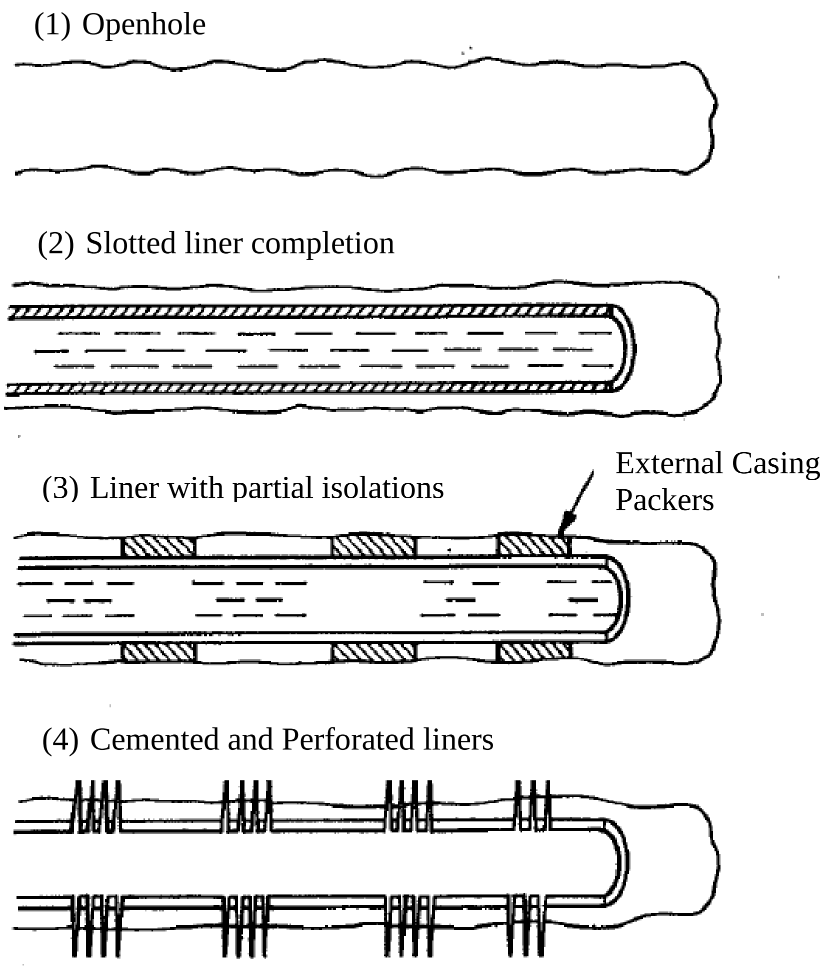


Figure 3.2 Typical completion configurations for horizontal wells [9]

3.2 Intelligent Completion System

The pursuit of remote downhole data acquisition without the well intervention has brought to the introduction of Intelligent Completion System or ICS in the past few decades. A so called smart or intelligent well is typically defined as the well, either single or multilateral, in which every lateral (in case multilateral) is controlled by ICV or Inflow Control Valves. This completion system can obtain the downhole pressure and temperature data in real time to identify problem in reservoir or wellbore. Ultimately this will optimize the production scenario without performing any costly well intervention. This ability will lead operator to minimize fluid loss, effectively manage the reservoir by maintaining well integrity and maximizing the production.

The component of intelligent completion can be categorized as [10]:

- Permanent monitoring systems: This part is contained of the advanced permanent downhole gauges and sensors those remotely transfer downhole data to the surface in real time. The samples of the instrument in this part are downhole permanent gauges, digital sensor array system, downhole network system and data acquisition and communication systems.
- Downhole inflow control valves: Basically known as ICV: It is primarily utilized in the commingled production system for controlling well flowing pattern so the production pattern can be monitored and taken actions as necessary (i.e., close the well when water production or water cut ratio intrudes the whole production unfavorably too much or keep producing when the production can still be maintained as expected).
- Zonal isolation packers: When efficiently separating well's zone, especially horizontal wells, packers will be used to prevent fluid loss in multi-zone wells so that wells can be managed individually in each of the zone.

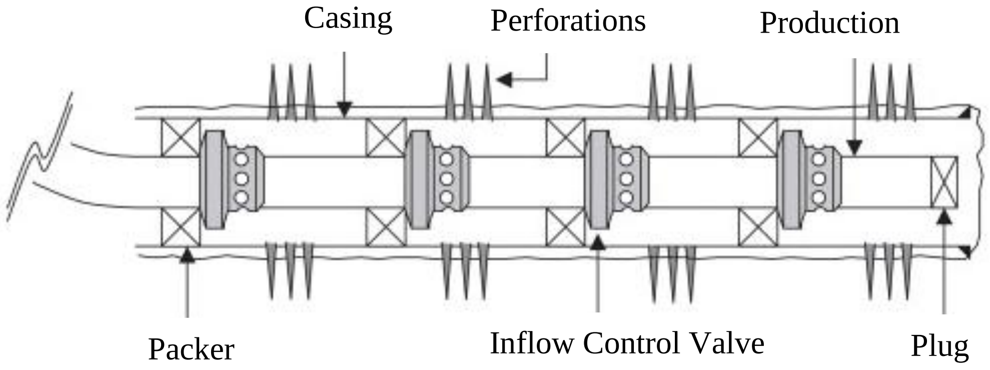


Figure 3.3 Illustration of intelligent completion composing ICV and zonal isolation packers [10]

It is expected that one effective intelligent well should be able to mitigate water production by allocating the optimum production rate or optimum production scenario and thus, increase the total production recovery. This all can be achieved by using its benefit of each downhole component. The component itself should be capable of adjusting fluid production from different production section and improving flow control. Major advantage is still distantly-acquired data of what happen underneath or in the well.

By having the benefits of ICS installing in any multilateral wells, it can majorly help trigger one of the main production problems which is water cresting, generally comes from the bottom water aquifer in case of water drive mechanism. As if one of the laterals experiences the water coning due to fracture existence, the whole production system is predicted to be suffering from this phenomena as well. Therefore, it is important to find the optimum ICV configuration and forecasted well operating scenario which will not lead to the problem or at least, lengthen the desired production scenario.

ICV chosen to be used in this study is simplified to be a water-triggering type that is able to detect water cut ratio as preset. Simplification approach in this study is to set one ICV in one lateral of the well. Details will be shown in reservoir model section in the next chapter.

3.3 Water Encroachment

Naturally-drive water influx has been described as the incursion of water into oil or gas bearing formations. This is one of the mechanisms of oil production in which the water displaces and moves the reservoir fluids towards the well borehole. Anyhow, similar to other natural phenomena that if the water influx affects too much, this can ultimately lead to the overwhelmed invasion of water in the targeted oil production or as known as water coning. This seems to be highly recognized as one of the main petroleum production problems that have been happening so far.

In case the aquifer is large enough to provide the constant-pressure drive aquifer, this will similarly be beneficial to the reservoir as the water flooding. On the contrary, if the mentioned unfavorable scenario of water invasion into the hydrocarbon production happens, the appropriate action such as temporarily shut the well in, will need to be performed.

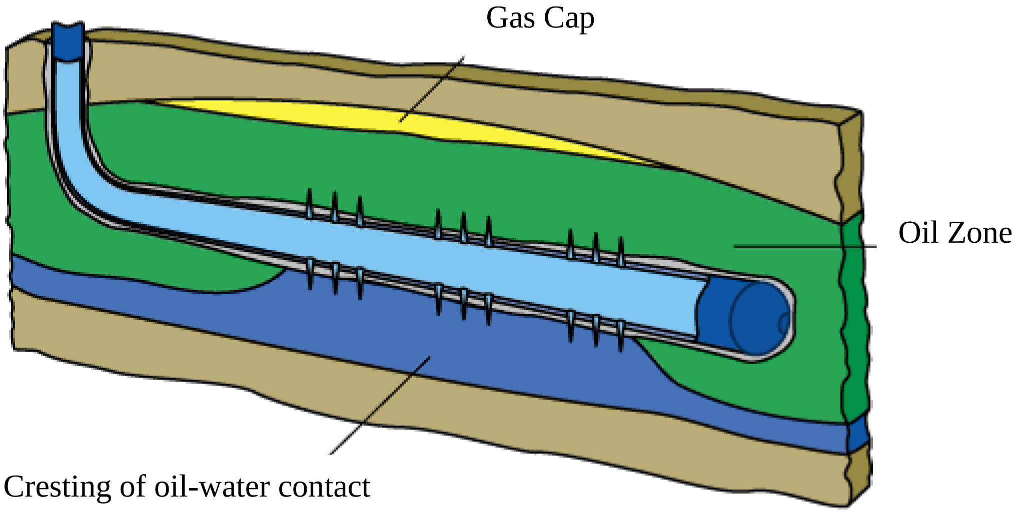


Figure 3.4 Water encroachment phenomena or water cresting [11]

CHAPTER IV

RESERVOIR SIMULATION AND METHODOLOGY

In this chapter, the reservoir model as well as its components for reservoir simulation will be discussed. A well-known reservoir simulator called ECLIPSE®100, commercialized by GeoQuest Schlumberger, is used for creating the black oil simulation. Simulations are conducted primarily on simple horizontal wells, followed by the dual-lateral wells and then the selected dual-opposed cases which have the intelligent completion equipped with. Details of methodology are described after simulation model. The comparison of results for each case and also discussion will be shown in the next chapter with all of the input simulation details being provided in the appendix.

4.1 Grid details

The reservoir size is set to be 2500 × 2500 × 300 feet with the total grid blocks of 50 × 50 × 50 feet in X, Y and Z direction, respectively. The facie of reservoir is fining upward sequence one with a variation of permeability as the lowest permeability at top layer to the highest permeability at the bottom of the reservoir. This depositional structure is caused by changes of sedimentary energy due to earth's dynamic. Initially, the reservoir simulation cases are set to have the ratio of vertical permeability to horizontal permeability (k_v/ k_h) to be 0.1. This value remains constant in other cases as well unless specified as others (will be further varied and discussed in the sensitivity analysis section). Table 4.1 summarizes the horizontal and vertical permeability of each layer and consecutively the three-dimensioned reservoir model illustrating permeability value in X direction (horizontal permeability) in each layer is shown in Figure 4.1.

Table 4.1 Horizontal and vertical permeability of each layer in reservoir model

Layer	Grid block	Horizontal permeability (md)	Vertical permeability (md)
1	1-6	50	5
2	7-12	75	7.5
3	13-18	100	10
4	19-25	125	12.5
5	26-30	150	15

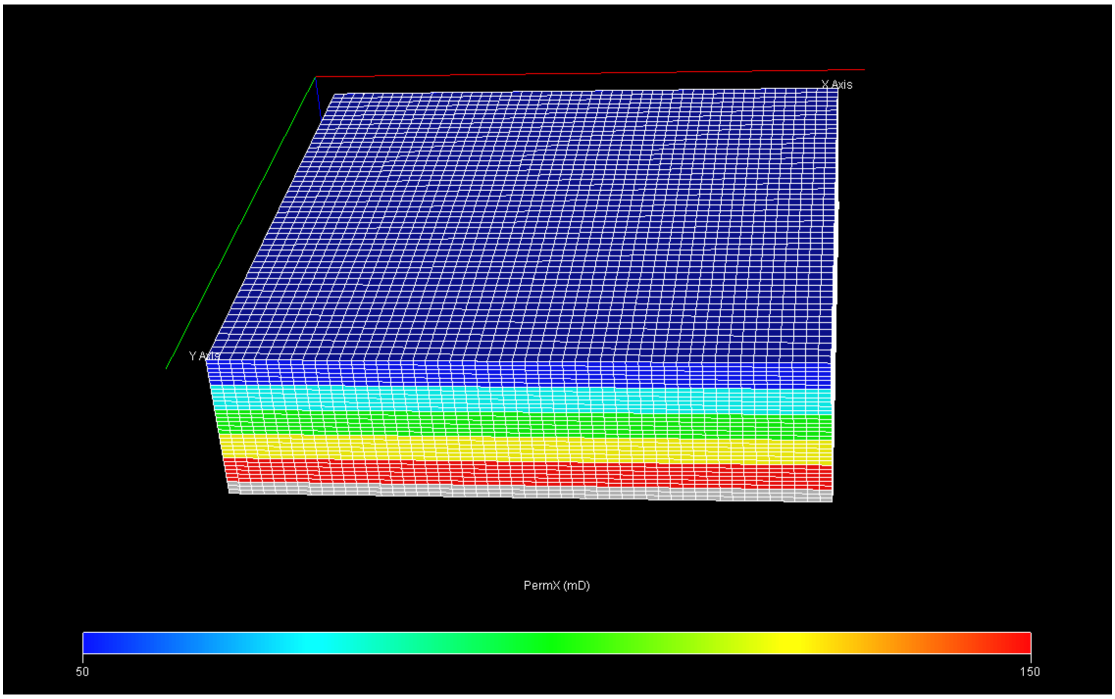


Figure 4.1 Horizontal permeability varied by reservoir layers

In this grid section, depth of the top reservoir layer is indicated at 5,000 feet. Reservoir thickness is represented by 30 Z-direction grid blocks (vertical direction) from no. 1 to 30 and all is actively created, whereas grid blocks no. 31 to 33 are indicated to be inactive grid blocks for aquifer repository purpose.

Bottom aquifer with the size of 50 reservoir Pore Volumes (PV) is chosen for the bottom-drive natural aquifer at the coordination (1,1,33). Total aquifer area is 6,250,000 square feet and has thickness of 15,000 feet along with the porosity of 0.2.

Command is used to connect the mentioned aquifer with the reservoir in K+ direction or in the upward flowing direction to the reservoir coordination of (50, 50, 30).

4.2 Pressure-Volume-Temperature (PVT) properties

Pressure-Volume-Temperature properties of the reservoir fluid are specified in this section. Table 4.2 shows PVT properties of formation water, while Table 4.3 indicates fluid densities at surface condition. Also, Figure 4.2 represents PVT properties of live oil used in this simulation study as functions of bubble point pressure (p_{bub}), including solution gas oil ratio (R_s), viscosity (μ_o), and Formation Volume Factor (FVF).

Table 4.2 PVT properties of formation water

Property	**Value**	**Unit**
Water FVF at P_{ref} (B_w)	1.021734	rb/ STB
Water compressibility (C_w)	3.09988×10^{-6}	psi^{-1}
Water viscosity at P_{ref} (μ_w)	0.3013289	cP
Water viscosibility	3.360806×10^{-6}	psi^{-1}

Table 4.3 Fluid densities at surface condition

Property	**Value (lb/ft^3)**
Oil density (ρ_o)	49.99914
Water density (ρ_w)	62.42797
Gas density(ρ_g)	0.04369958

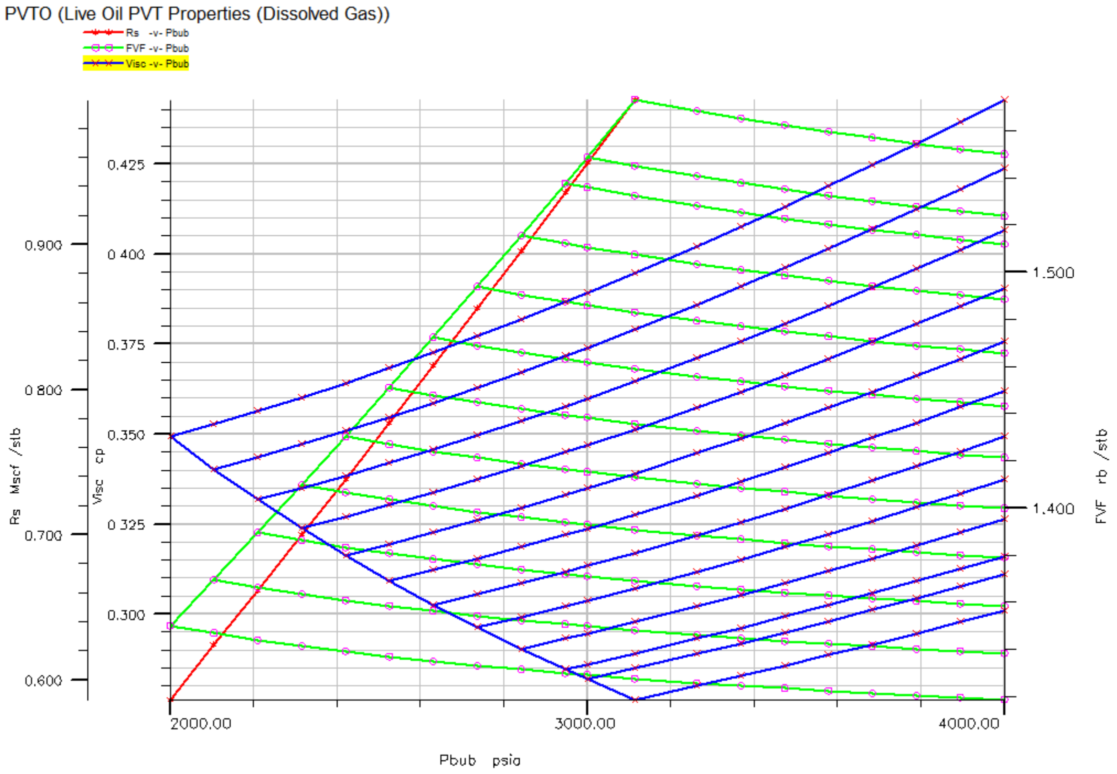


Figure 4.2 PVT properties of live oil

4.3 Petrophysical properties

Rock and fluid property plays a major role in flow property in porous medium. Wettability and relative permeability are defined in this section. The lithology of rock is this study is sedimentary sandstone with a fining upward facies. In general, sandstone is normally found water-wet and in several rare cases, its wettability could be altered maximally to mildly oil-wet. In this study, moderately water-wet is assumed and hence, relative permeability curves for both oil and water can be generated by the rule of thumb [12] together with Corey’s correlation. Relative permeability to gas is also generated by the use of Corey’s correlation. Table 4.4 summarizes required data to generate relative permeability curves.

In this study, the capillary pressure of rock is neglected. It is assumed that the rock surface does not have strong interaction with present fluids or could infer that the pore size of the rock is coarse enough to do not create the capillary pressure.

Table 4.4: Summary of required data to generate relative permeability by Corey's correlation

Water		**Gas**		**Oil**	
Property	**Value**	**Property**	**Value**	**Property**	**Value**
Corey Water	2	Corey Gas	2	Corey Oil/ Water	2
S_{wmin}	0.3	S_{gmin}	0	Corey Oil/ Gas	2
S_{wcr}	0.3	S_{gcr}	0.05	S_{org}	0.15
S_{wi}	0.3	S_{gi}	0	S_{orw}	0.3
S_{wmax}	1	k_{rg} at S_{org}	0.45	k_{ro} at S_{wmin}	1
k_{rw} at S_{orw}	0.32	k_{rg} at S_{gmax}	1	k_{ro} at S_{gmin}	1
k_{rw} at S_{wmax}	1				

The input data for Corey's correlation is then generated to be SWOF (water/oil saturation functions) and SGOF (gas/oil Saturation Functions) in the simulator as shown in Table 4.5 and Table 4.6, respectively. Relative permeability curves to oil and water are plotted as per shown in Figure 4.3 and relative permeability curves to oil and gas are shown in Figure 4.4.

Table 4.5 Relative permeability to water and oil as a function of water saturation

S_w	k_{rw}	k_{ro}
0.3	0	1
0.34444444	0.0039506173	0.79012346
0.38888889	0.015802469	0.60493827
0.43333333	0.035555556	0.4444444
0.47777778	0.063209877	0.30864198
0.52222222	0.098765432	0.19753086
0.56666667	0.14222222	0.11111111
0.61111111	0.19358025	0.049382716
0.65555556	0.25283951	0.012345679
0.7	0.32	0
1	1	0

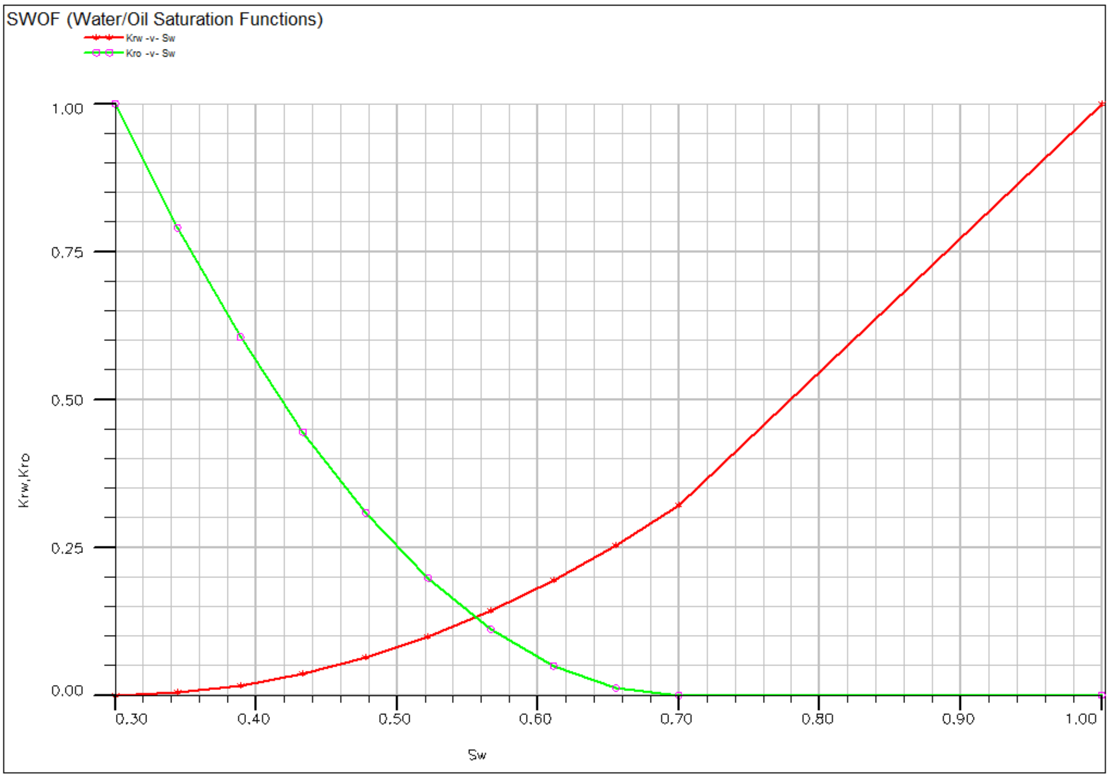


Figure 4.3 Water/oil saturation functions representing relative permeability to water and oil

Table 4.6 Relative permeability to gas and oil as a function of gas saturation

S_g	k_{rg}	k_{ro}
0	0	1
0.05	0	0.82644628
0.1125	0.00703125	0.63274793
0.175	0.028125	0.46487603
0.2375	0.06328125	0.32283058
0.3	0.1125	0.20661157
0.3625	0.17587125	0.11621901
0.425	0.253125	0.051652893
0.4875	0.34453125	0.012913223
0.55	0.45	0
0.7	1	0

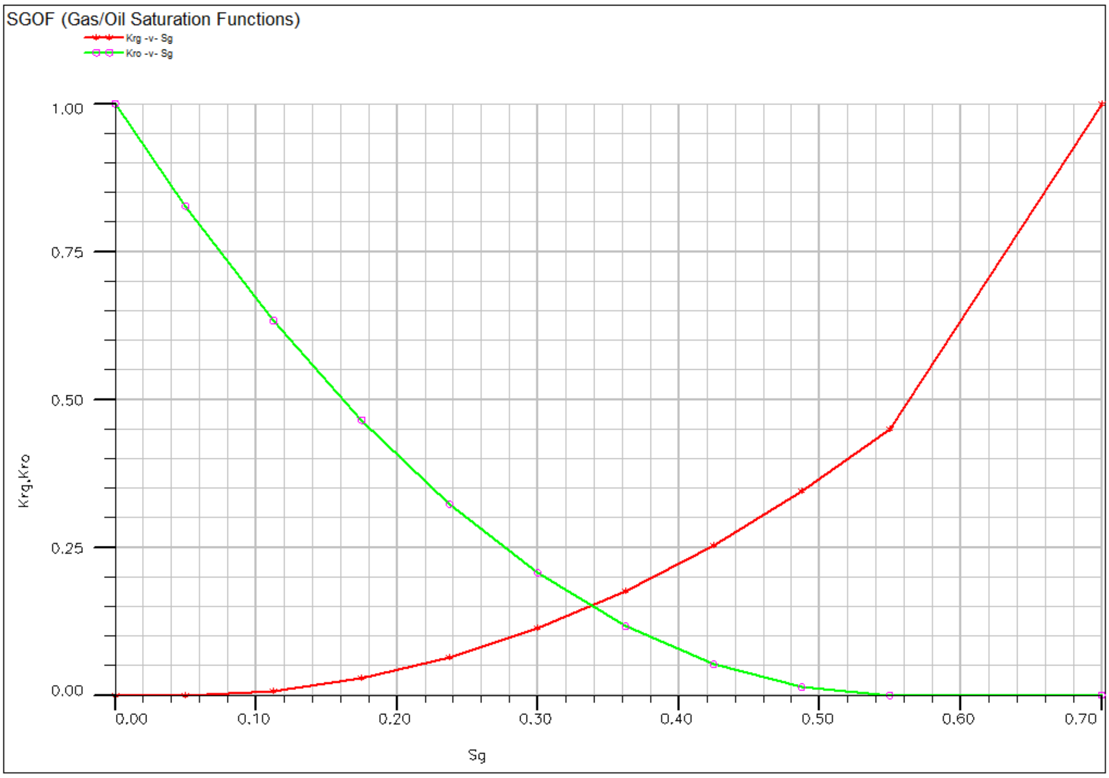


Figure 4.4 Gas/oil saturation functions representing relative permeability to gas and oil

4.4 Fluid contacts

In this section of the simulation model, Equilibration Data Specification is input as shown in Table 4.7. From the table the reservoir is set to have primary gas cap deposited with the thickness of 60 ft or equivalent to six grid blocks, which is first five layers having five different permeability values. The location of Gas Oil Contact (GOC) is shown in three-dimension model illustrated in Figure 4.5.

Table 4.7 Fluid contacts data

Data	**Value**	**Unit**
Datum depth	5,060	ft
Pressure at datum depth	2,242	psia
WOC depth	5300	ft
GOC depth	5,060	ft

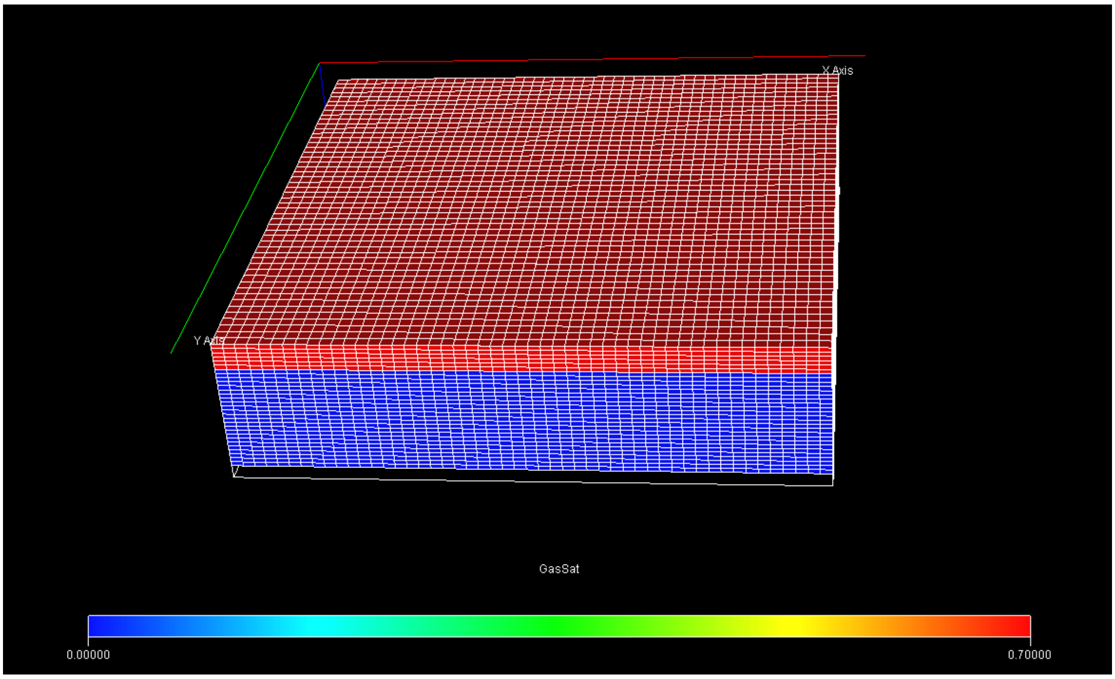


Figure 4.5 Primary gas cap fully filled the top of permeable zone (top face to sixth grid block)

4.5 Well geometry and completion

All wells in this study are fixed to have diameter of 0.358 feet with the assumption of no presence of skin nearby. Explanation of this section is detailed in the pattern of simple horizontal, dual-lateral and dual-lateral equipped with ICV well.

4.5.1 Horizontal well

Well specification data is input to have the wellhead location in terms of I and J axis at the coordinate of 25 and 10, accordingly. The effective length of the horizontal section is 1,000 feet or equivalent to 20 grid blocks. Horizontal well path is oriented by having the heel of the well at J location of 10th grid block. The effective drilling radius of 300 feet or six grid blocks [9] is also taken into account and is behaving as dummy drilling path (drilled as part of horizontal well but with no perforation).Toe of the well then ends at the 35th grid block in J direction. Table 4.8 to Table 4.12 show the details of main commands used in this section, which are WELSPECS to identify wellhead location, COMPDAT as a command for perforation (OPEN to perforate while SHUT to indicated otherwise, WCONPROD to set the production rate and WECON to fix the minimum condition for producing.

Table 4.8 Well specification [WELSPECS] – for horizontal well

Well name	H1
I location	25
J location	10
Preferred phase	OIL
Inflow equation	STD
Automatic shut-in instruction	SHUT
Cross flow	YES
Density calculation	SEG

Table 4.9 Well connection data (for dummy drilling path) [COMPDAT] – for horizontal well

Well name	H1
I location	25
J location	10 to 15
K upper	at Z axis location of the horizontal well’s depth
K lower	at Z axis location of the horizontal well’s depth
Open/shut flag	SHUT
Wellbore ID	0.358 ft
Direction	Y

Table 4.10 Well connection data [COMPDAT] – for horizontal well

Well name	H1
I location	25
J location	16 to 35
K upper	at Z axis location of the horizontal well's depth
K lower	at Z axis location of the horizontal well's depth
Open/shut flag	OPEN
Wellbore ID	0.358 ft
Direction	Y

Table 4.11 Production Well Control [WCONPROD]

Well name	H1
Open/shut flag	OPEN
Control	LRAT
Liquid rate	3,000 STB/D
BHP target	200 psia

Table 4.12 Production Well Economics Limit [WECON]

Well name	H1
Minimum oil rate	100 STB/D
Workover procedure	WELL
End run	NO
Quantity for economic limit	RATE
Secondary workover procedure	NONE

4.5.2 Dual-lateral well

Main commands are mimicked from the commands in the previous section of horizontal well to be used in this well's geometry. However, additional important commands to section the well to be left and right lateral are implemented, which are Segmented Well Definition or WELSEGS and Segmented Well Completions or COMPSEGS. The effective drilling radius of six blocks in the single horizontal well scenario is also split to be three blocks for each side while L1 and L2 are newly defined for right lateral and left lateral, respectively.

Table 4.13 Well specification [WELSPECS] – for dual-lateral well

Well name	H1
I location	25
J location	25
Preferred phase	OIL
Inflow equation	STD
Automatic shut-in instruction	SHUT
Cross flow	YES
Density calculation	SEG

Table 4.14 Segmented Well Definition [WELSEGS] – for dual-lateral well, general information

Well name	H1
Depth to top seg node	5000
Length & Depth	INC
Pressure Drop	HFA
Flow Model	HO

Table 4.15 Segmented Well Definition [WELSEGS] – for dual-lateral well, segment information

First Segment	**Last Segment**	**Branch**	**Outlet Segment**	**Length (ft)**	**Depth (ft)**	**Diameter (ft)**	**Roughness (ft)**
2	30	1	1	10	10	0.358	0.001
31	43	2	L1’s depth	50	0	0.358	0.001
44	56	3	20	50	0	0.358	0.001

Table 4.16 Well connection data (for dummy drilling path) [COMPDAT] – for dual-lateral well

Well name	H1
I location	25
J location	22 to 25 (Left lateral) & 25 to 28 (Right lateral)
K upper	at Z axis location of each lateral
K lower	at Z axis location of each lateral
Open/shut flag	SHUT
Wellbore ID	0.358 ft
Direction	Y

Table 4.17 Well connection data [COMPDAT] – for dual-lateral well

Well name	H1
I location	25
J location	12 to 21 (Left lateral) 29 to 38 (Right lateral)
K upper	at Z axis location of each lateral
K lower	at Z axis location of each lateral
Open/shut flag	OPEN
Wellbore ID	0.358 ft
Direction	Y

Table 4.18 Segmented Well Completions [COMPSEG] – for dual-lateral well

I	**J**	**K**	**Branch**	**Direction**
25	25	2 to 30	1	K
25	25 to 38	L1's depth	2	J
25	12 to 25	20	3	J

4.5.3 Dual-lateral well equipped with ICV

Commands used in the dual-lateral well equipped with ICV are all the same as in the simple dual-lateral well part but add up three other commands which are Lump Well Connections (COMPLUMP) to lump the well in each lateral to clearly segregated as completion number 1 or 2, Production Well Connection Economic Limits (CECON) to set the maximum water cut and Testing Instructions (WTEST) to let the system test the well under the fixed testing interval after the ICV is triggered to operate.

Table 4.19 Lump Well Connections [COMPLUMP] – for dual-lateral well with ICV equipped

Well	H1
I Location	25
J Location	12 to 25 and 25-38
K Upper	@ Depth of L1/ L2
K Lower	@ Depth of L1/ L2
Completion No.	(1 and 2 for right and left lateral)

Table 4.20 Production Well Connection Economic Limits [CECON] – for dual-lateral well with ICV equipped

Well name	H1
Maximum Water Cut	@ each case's water cut ratio
Workover Procedure when Limit Violated	CON

Table 4.21 Testing Instructions [WTEST] – for dual-lateral well with ICV equipped

Well name	H1
Testing Interval	1 day
Closure Reason	C

Simulation time step has been set as one day in the first month of the simulation to make the simulation be precise and ready for any effect. This then is changed to be on a monthly basis from 2nd month to the end of the simulation. Once being triggered to perform its function, ICV performs the shut in of the well when observing that water cut is higher than the maximum water cut set in CECON. The well is tested again at the beginning of the next timestep and let the well be reopened if water cut is lower than the set water cut or operating vice versa if water cut if still higher than fixed value.

4.6 Thesis methodology

This subsection describes 2 main parts of simulation performed in this research which are part of well configuration and effect of intelligent completion as well as sensitivity analysis on selected cases of intelligent completion equipped in dual-lateral wells.

4.6.1 Well configuration and effect of intelligent completion

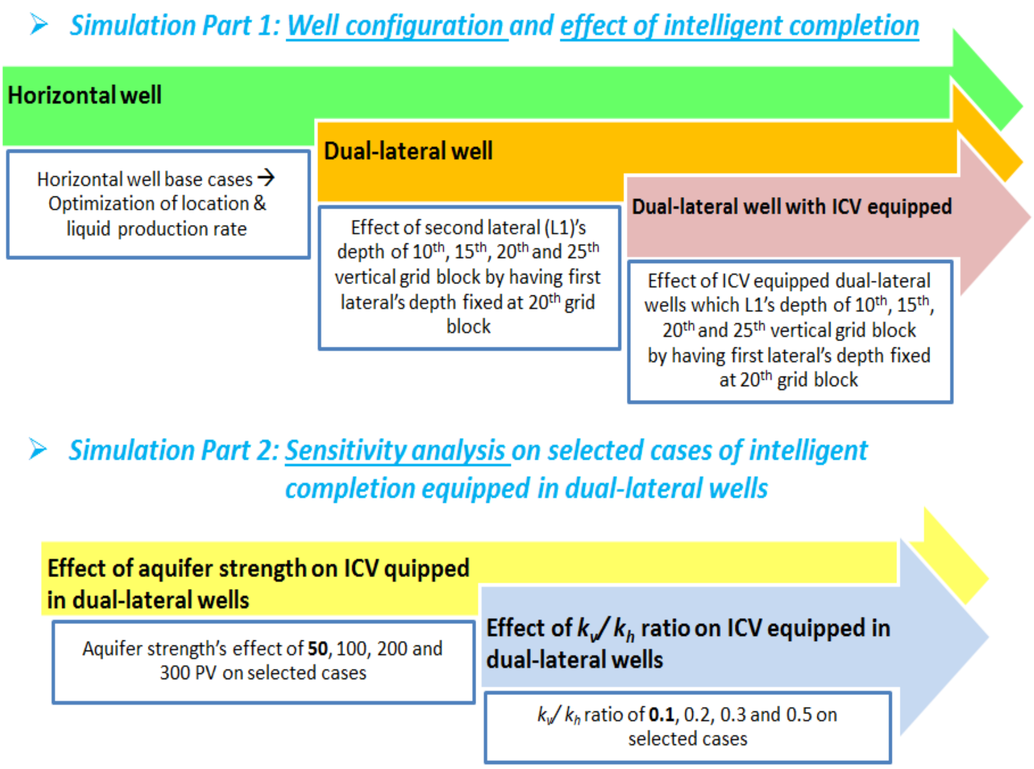
1. Construct an initial heterogeneous reservoir as fining upward sand model. Permeability of grid blocks of the reservoir is varied from the lowest to highest values from top to bottom layers. Ratio of vertical permeability and horizontal permeability (k_v/k_h) is constantly kept at 0.1 which is typical value in sandstone stone lithology.
2. Run base cases of single horizontal well with primary gas cap thickness of 60 ft and bottom-driven aquifer of 50PV, by having one whole horizontal branch at various depths of 10th, 15th, 20th and 25th vertical grid block to observe main differences of result obtained from each case. Production rate of 3,000 STB/D is initially chosen as production rate used in horizontal well. This rate is, however, compared to other rates of 4,000 and 5,000 STB/ D to ensure in perspective of optimization of production liquid rate.
3. Study dual lateral well position and its effect, by having left lateral (L2) fixed at 20th vertical grid block and right lateral (L1) varied at various depths of 10th, 15th, 20th and 25th vertical grid block.
4. Study configuration effects on the ICV-installed cases at different value of water cut ratios from 0.7 to 0.9, water cut ratio of each cases by trial and error of selecting specific water cut ratio within the range of 0.7 to 0.9 and indicate one which allows well to shut it or to operate effectively for each depth of the varied lateral.

4.6.2 Sensitivity analysis on selected cases of intelligent completion equipped in dual-lateral wells

1. Perform sensitivity analysis over selected ICV-installed in dual-lateral cases compared to dual-lateral well at same depth. During sensitivity analysis, the study parameters are varied from ones in initial simulations.
    - 1.1 Aquifer strength representing by aquifer size (number of times of pore volume, PV). Chosen PV values are 100, 200 and 300 PV**.**
    - 1.2 Reservoir anisotropy representing by the ratio of vertical permeability to horizontal permeability (k_v/k_h). Chosen values for this study are 0.2, 0.3 and 0.5.

    Specific water cut ratio is used for each selected case based on the depth of varied L1 lateral. This water cut ratio is varied up and down by one second-digit decimal (i.e., picked initial water cut ratio in one depth which ICV can work effectively is 0.91, this then varied down and up to 0.90 and 0.92) and finally pair each water cut ratio up with the chosen value of the sensitivity analysis in terms of aquifer strength as well as ratio of k_v/k_h). For example, water cut ratio of 0.9, 0.91 and 0.92 is used to be simulated with the aquifer strength of 100PV then 200PV and 300PV one case at a time. Once finish this set, k_v/k_h then is used later.

3. Analyze simulation result in terms of oil recovery factor and cumulative water production and summarize findings from study.



➢ *Simulation Part 1: Well configuration and effect of intelligent completion*

Horizontal well

Horizontal well base cases → Optimization of location & liquid production rate

Dual-lateral well

Effect of second lateral (L1)'s depth of 10th, 15th, 20th and 25th vertical grid block by having first lateral's depth fixed at 20th grid block

Dual-lateral well with ICV equipped

Effect of ICV equipped dual-lateral wells which L1's depth of 10th, 15th, 20th and 25th vertical grid block by having first lateral's depth fixed at 20th grid block

➢ *Simulation Part 2: Sensitivity analysis on selected cases of intelligent completion equipped in dual-lateral wells*

Effect of aquifer strength on ICV quipped in dual-lateral wells

Aquifer strength's effect of **50**, 100, 200 and 300 PV on selected cases

Effect of k_v/k_h ratio on ICV equipped in dual-lateral wells

k_v/k_h ratio of **0.1**, 0.2, 0.3 and 0.5 on selected cases

Figure 4.6 Summary of simulation planning and steps in the study

CHAPTER V

RESULTS AND DISCUSSION

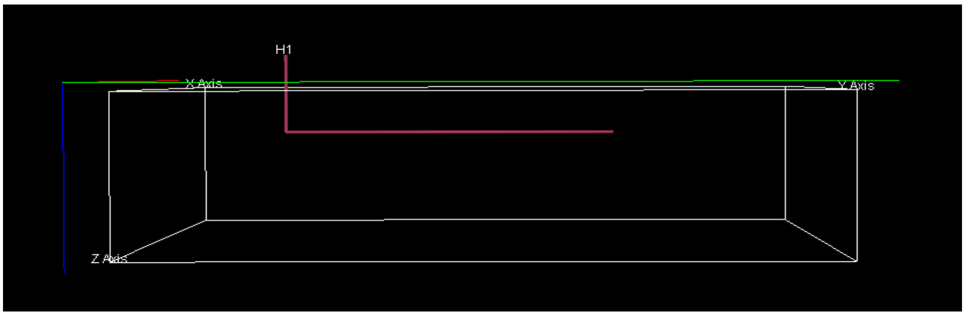
This chapter discusses results obtained from the reservoir simulations from previous section. Initially, the discussion is conducted over horizontal well base cases, followed by the dual-lateral wells at different depths and finally the simulation results of the dual-lateral wells equipped with ICV at different water cut ratios are described. All reservoir simulations are performed based on 30-years of production time as an assumption of concession period for this project. Liquid production rate is varied within the range of 3,000-5,000 STB/D at first then the optimize rate is chosen to represent the production rate for the rest of the simulation cases under other constraints.

5.1 Horizontal well base cases

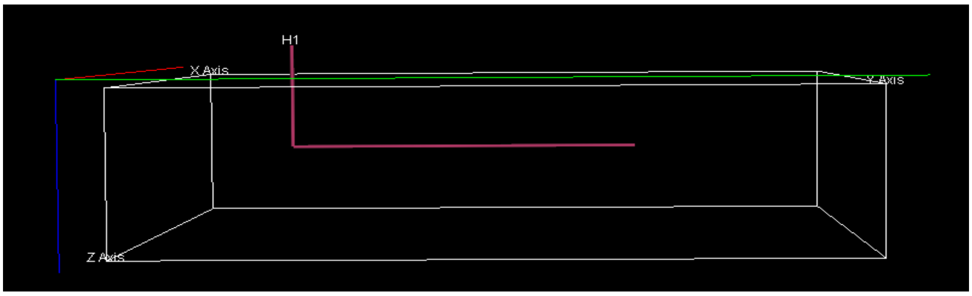
5.1.1 Optimization of horizontal well location

Since there are 30 active blocks in the vertical direction, single-layered horizontal wells are set to be varied from the depth of 10th, 15th, 20th and 25th grid block, accordingly. Figures 5.1 a) to d) illustrate simple horizontal wells located at different depth in the reservoir model.

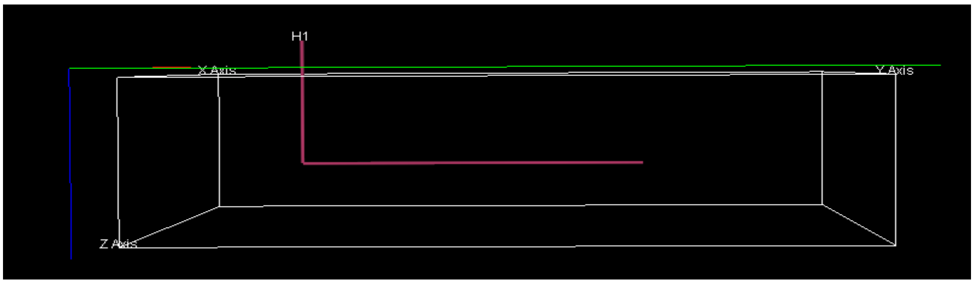
Since reservoir model is constructed as multi-layers with fining upward sequence, the bottommost layer which is in contact with aquifer possesses the highest permeability value of 150 md. This results in high water cresting rate due to high vertical permeability. Therefore, the lateral of horizontal well should be located as far as possible from this mentioned layer. But as reservoir fluid could as well yield solution gas after the well is produced (due to reservoir pressure below bubble point), locating lateral well on top layers also causes well to face gas coning phenomena. Hence, optimization of horizontal well location has to be performed.



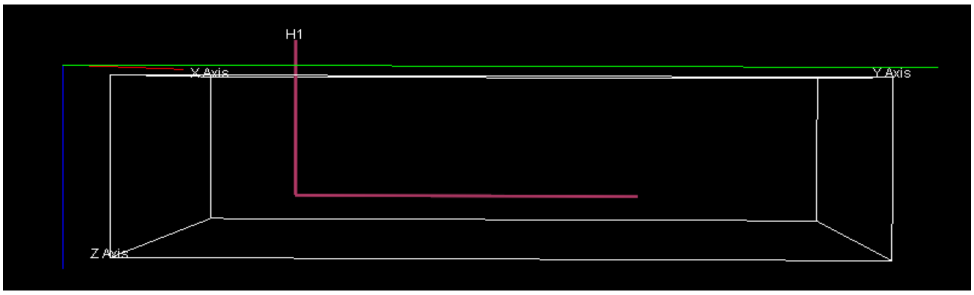
a) Horizontal well at 10th vertical grid block



b) Horizontal well at 15th vertical grid block



c) Horizontal well at 20th vertical grid block



d) Horizontal well at 25th vertical grid block

Figure 5.1 Horizontal wells at different depths of vertical grid block

Simulations are performed on horizontal well located at each depth to observe outcome at liquid production rate of 3,000 STB/D. The summary of results obtained from each simulation with different location of horizontal well are shown in Table 5.1 and Figure 5.2., in terms of oil recovery factor, cumulative oil production and cumulative gas production. These simulation outcomes are main criteria to be considered and discussed for each case of the simulation.

Table 5.1 Oil recovery factors, cumulative oil production and cumulative gas production obtained from horizontal well located at different depths

Location of horizontal well	**Oil recovery factor (fraction)**	**Cumulative oil production (MM STB)**	**Cumulative gas production (MMMSCF)**
10th grid block (5,100 feet)	0.433	11.551	19.537
15th grid block (5,150 feet)	0.489	13.054	15.984
20th grid block (5,200 feet)	0.535	14.274	10.985
25th grid block (5,250 feet)	0.454	12.102	6.969

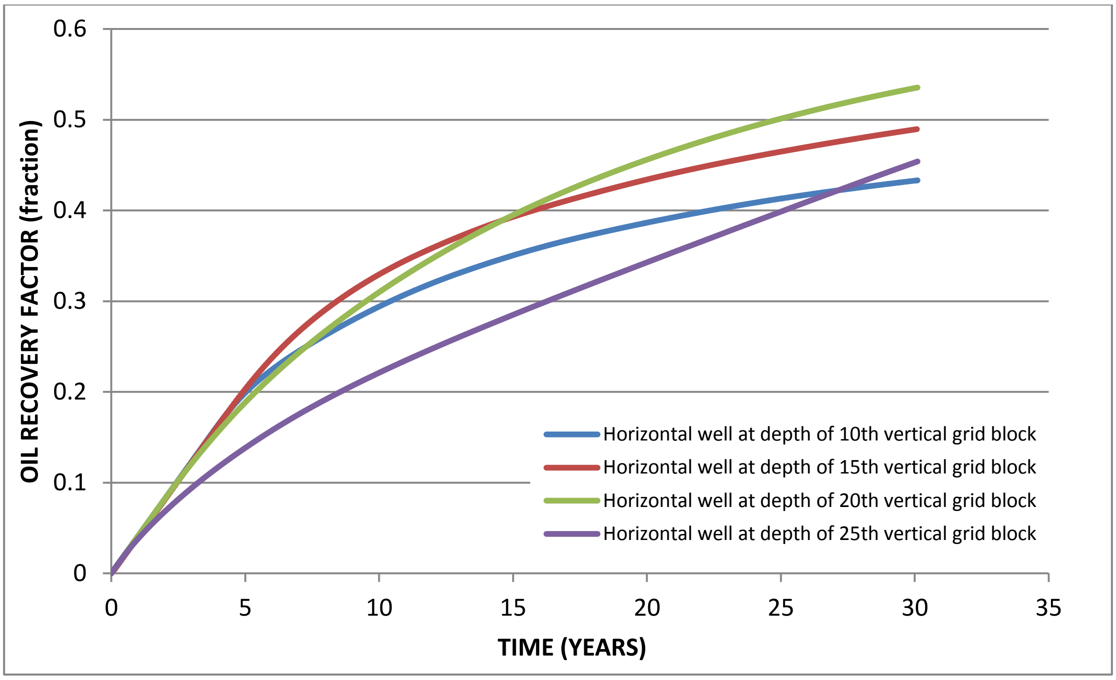


Figure 5.2 Comparison of oil recovery factors of horizontal wells located at various depths

It can be clearly seen from Figure 5.2 that locating depth of horizontal section which yields the best value of oil recovery factor is at the depth of 20th vertical grid block, followed by depth of 15th, 25th and 10th grid block, respectively. First, considering the horizontal well located at the 10th grid block which is the shallowest location, it can be seen that horizontal well at this location does not contribute the best oil recovery factor due to gas production. This location is the nearest to primary gas cap on the top of reservoir and hence, oil production rate is partly reduced by the gas inflow and water creasing from higher rate of encroachment. When reservoir pressure is reduced below bubble point pressure, solution gas is liberated from oil phase. The accumulation of gas saturation is raised around wellbore due to residual gas saturation. Together with gas coning effect, the lateral is completely affected from gas flow which results in forced movement of water crest to maintain liquid rate at 3,000 STB/D.

Similarly, horizontal well at the depth of 25th grid block is also affected by the bottom-drive aquifer so that oil cannot be effectively produced at maximum rate. The effects of competitive flow of gas coning and water cresting phenomena are illustrated in Figure 5.3 and 5.4.

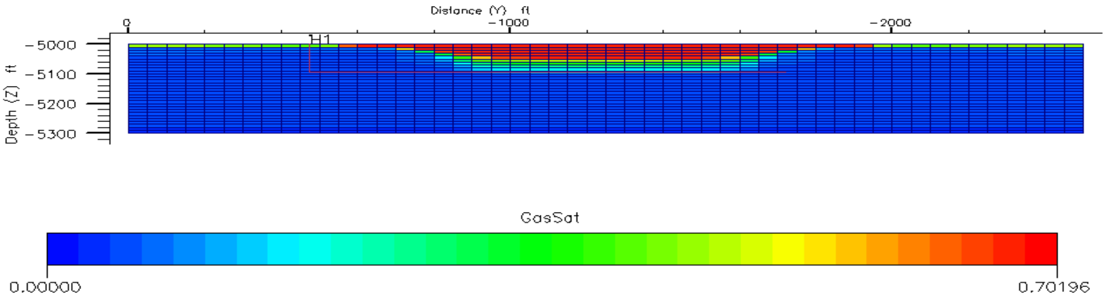


Figure 5.3 Gas coning effect in horizontal well at the depth of 10th grid block

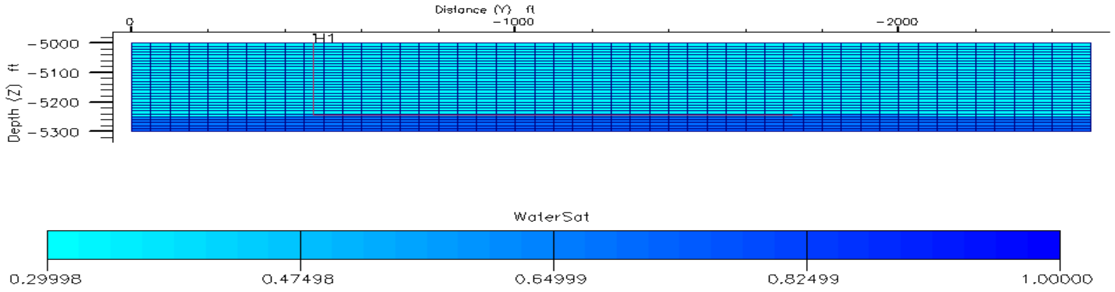
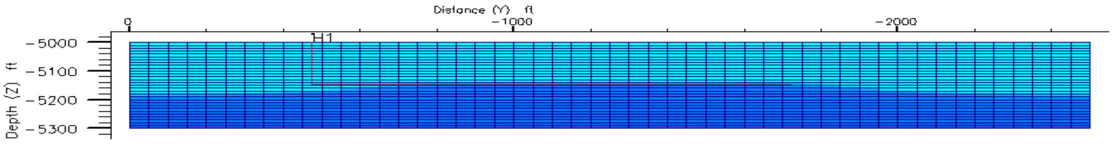
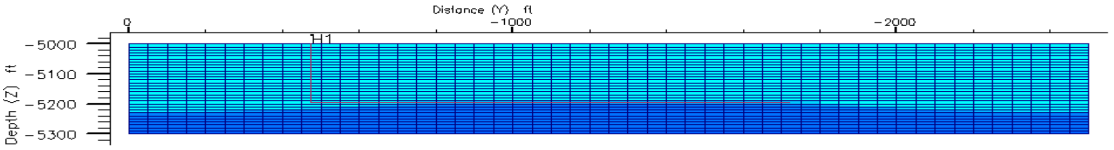


Figure 5.4 Water cresting effect in horizontal well at the depth of 25th grid block

Oil recovery factor obtained from horizontal well located at 15th grid block depth yields better result than two previously mentioned cases but yet yields less oil recovery factor compared to the horizontal well at the depth of 20th grid block. At location of 20th grid block, this depth is sufficiently apart from primary gas cap and bottom aquifer for oil to be produced effectively. Figure 5.5 compares water saturation profile at the same production period (around year 10th of production) between horizontal wells located at 15th and 20th vertical grid blocks.



a) water cresting effect at depth of 15th grid block



b) water cresting effect at depth of 20th grid block

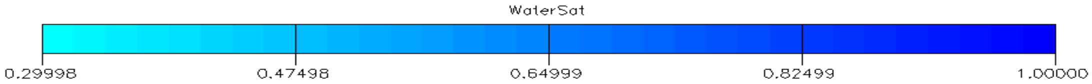


Figure 5.5 Comparison of water cresting effect between horizontal well at the depth of 15th and 20th grid block

5.1.2 Optimization of liquid production rate

Liquid production rate of 3,000 STB/D is initially selected to confirm that horizontal well at the depth of 20th grid block should be yielding maximum oil production compared to other depths. Though this chosen rate is typical value for horizontal well production, optimization of liquid production rate is performed to ensure that selected rate is proper one for the whole study. When oil is being more produced, more amount of water could be produced in the same time especially for reservoir that is supported by strong water aquifer. Generally, high water production is an unfavorable condition due to water disposal problem that could leads to high cost of water treatment. Table 5.2 shows comparison of oil recovery factor and cumulative water production obtained from different liquid production rates.

Table 5.2 Oil recovery factors and cumulative water production obtained from horizontal well at different liquid production rates

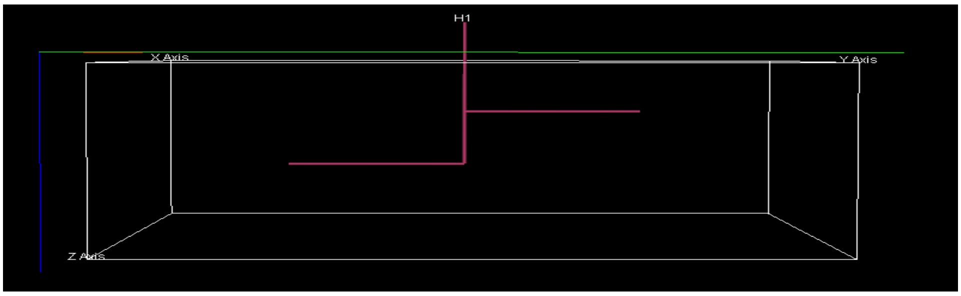
Liquid production rate (STB/ D)	**Oil recovery factor (fraction)**	**Cumulative oil production (MM STB)**
3,000	0.535	18.689
4,000	0.550	29.285
5,000	0.554	40.161

From Table 5.2, it is obvious that though rates of 4,000 and 5,000 STB/D yield slightly higher value of oil recovery factor than that of 3,000 STB/D oil production rate. However, cumulative water production obtained from these cases is significantly higher than keeping liquid production rate at 3,000 STB/D (56.7% and 114.9% for production rate of 4,000 and 5,000, respectively). Thus, 3,000 STB/D is remained as an optimum liquid production rate for other following cases.

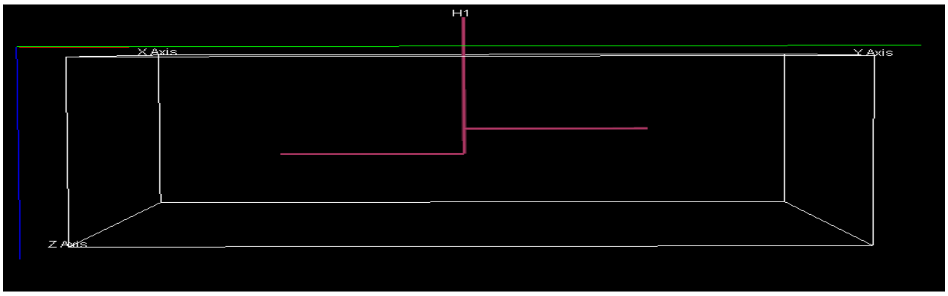
5.2 Dual-Lateral well cases

5.2.1 Effect of depth of second varied lateral

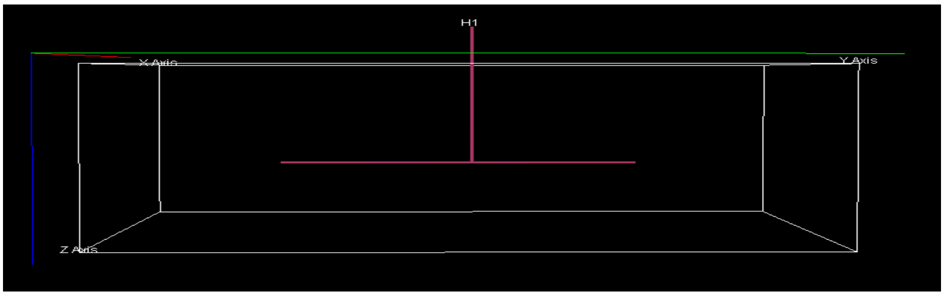
Dual-lateral wells simulated in this study is designed to have one lateral fixed at the vertical location of 20th grid block (left lateral = L2), which is part of the best horizontal well case, and another lateral (right lateral = L1) varied at the depth of 10th, 15th, 20th and 25th vertical grid block respectively. Figures 5.6 a) to d) illustrate these four cases representing dual-lateral well with second laterals located at different vertical grid block.



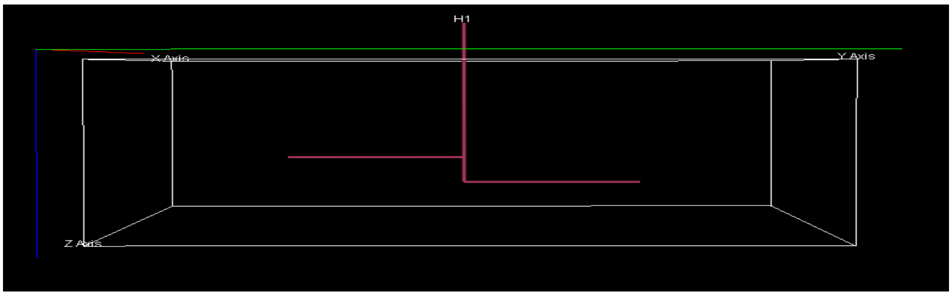
a) L1 at 10th vertical grid block



b) L1 at 15th vertical grid block



c) L1 at 20th vertical grid block



d) L1 at 25th vertical grid block

Figure 5.6 Dual-lateral wells with L2 fixed at 20th vertical grid block and different depth varied on L1

Simulations are conducted at each dual-lateral case with liquid production rate of 3,000 STB/D, by having primary gas cap located between 5,000 – 5,060 ft and also 50 PV of bottom-drive aquifer as same as in horizontal base case. Results are presented in Table 5.3 in terms of oil recovery factor and water cut at the end of production.

Table 5.3 Oil recovery factors and water cut obtained from dual lateral wells with second laterals located at different vertical grid blocks

Dual-lateral well with varied depth on L1	**Oil recovery factor (fraction)**	**Water cut (fraction)**
10th grid block	0.418	0.908
15th grid block	0.515	0.882
20th grid block	0.555	0.856
25th grid block	0.504	0.828

The result from this section will be related to the next part of study on how to improve oil recovery by controlling water cut using the intelligent completion. From Table 5.3 the highest oil recovery factor is obtained when second lateral is located at 20th vertical grid. Reason can similarly be explained as same as previous section that effective depth for varying L1 of dual lateral should be located at which oil production can be maximally prolonged without disturbance from gas cone and water crest. In this case the best vertical location is 20th grid block. Water cuts obtained from all cases are relatively high but they do not show significant difference.

However, it is important to compare oil recovery factor of horizontal well to that of dual-lateral well at the same depth (layer of horizontal well and varied L1) to observe advantage of dual-lateral well over single horizontal well. Comparison of oil recovery factor obtained from dual-lateral well and horizontal well is shown in Table 5.4.

Table 5.4 Comparison of oil recovery factors between single horizontal well and dual-lateral well

Depth of horizontal well	Oil recovery factor (fraction)	Dual-lateral well with varied depth on L1 at	Oil recovery factor (fraction)
10th grid block	0.433	10th grid block	0.418
15th grid block	0.489	15th grid block	0.515
20th grid block	0.535	20th grid block	0.555
25th grid block	0.454	25th grid block	0.504

In most cases except the case where second lateral is located at the 10th vertical grid block where lateral branch is majorly affected from gas coning, results from Table 5.4 show that dual-lateral well is more effective than single horizontal well. This is because of the fact that branches in dual-lateral well drain fluid more distributional, not emphasizing only just on one side as in the case of single-layered horizontal well. One of horizontal well cases that significantly improved after being drilled as dual-lateral is the horizontal well depth at 25th grid block. As when having half of the well or so called left lateral stepped up to be at 20th grid block, this yields around 11% increase of oil recovery factor, compared to that obtained from single horizontal well having one whole branch at the depth of 25th grid block. Though results are already shown in Table 5.4, they are clearly compared again in the Figure 5.7.

Also in terms of cumulative gas production, Table 5.5 represents comparison of gas production between case of horizontal well and dual-lateral. It can be understood that in most of the cases, drilling well dual-laterally offers lower gas production compared to drilling simple horizontal well.

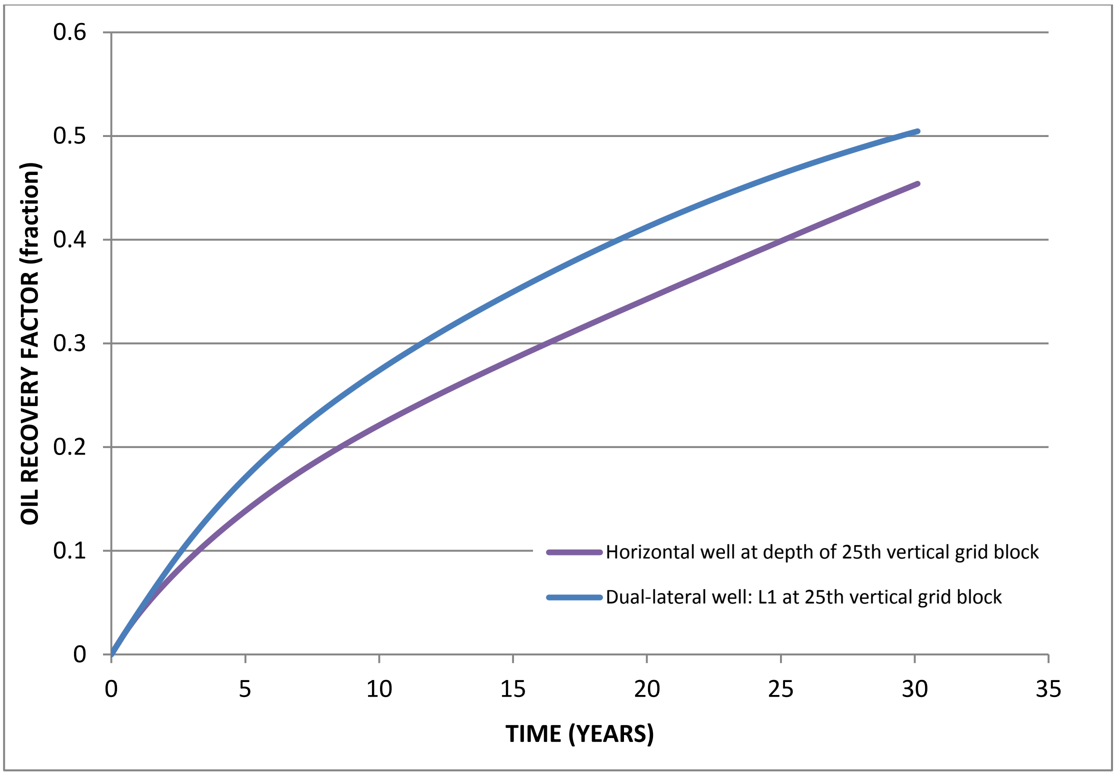


Figure 5.7 Comparison of oil recovery factor between horizontal well at depth of 25th grid block and dual-lateral well when L1 is at 25th grid block

Table 5.5 Comparison of cumulative gas production between single horizontal well and dual-lateral well

Depth of horizontal well	**Cumulative gas production (MMMSCF)**	**Dual-lateral well with varied depth on L1 at**	**Cumulative gas production (MMMSCF)**
10th grid block	19.537	10th grid block	17.367
15th grid block	15.984	15th grid block	14.064
20th grid block	10.985	20th grid block	10.613
25th grid block	6.989	25th grid block	9.242

5.3 Dual-Lateral well equipped with intelligent completion cases

Simulations conducted in this section are additionally performed on previous section to evaluate effectiveness of intelligent completion when combined with dual-lateral wells. Simulation is accomplished by lumping well connections by the use of COMPLUMP command in Eclipse®100. The mentioned command is specifically used for separating L1 and L2 laterals from each other. Reason of performing intelligent completion in dual-lateral well simulations is to allow each segment to operate independently by setting water production constraint for each lateral. Inflow control valve used in this research is set to be the selective water-triggering one which performs when water production in each lateral reaches ratio of preset water cut. Water-triggering mechanism of valves results in automatically shut in of particular lateral, whereas another lateral remains produced. This shut in of one lateral remains until potential water production is decreased below preset water cut and hence this lateral is re-opened again. The command used orders the well to be operating under condition that either one or two laterals still open but whole system is no longer operating if both laterals are shut in due to high water production above specific preset water cut. Important part is to relate each of the laterals defined in COMPLUMP section to be operating in accordance to water cut ratio set in Production Well Connection Economic Limits or CECON. Discussions will be made over the various depths of L1 at 10th, 15th, 20th and 25th vertical grid block with ICV equipped at different preset water cut accordingly. Water cut used in this simulation is varied from 0.7 to 0.9 to identify any particular preset water cut that would result in the highest efficiency of oil production and water production limitation by intelligent completion.

5.3.1 Result of intelligent completion equipped in dual-lateral well, with L1 at the depth of 10th grid block

Simulations conducted over the cases of dual lateral at L1 fixed at 10th grid block show that intelligent completion should not be invested under this type of well geometry. No matter how preset water cut ratios are varied, well is shut in before production period of 30 years. This is affected from gas coning at the top of reservoir which does not only reduces oil production but somehow also impacts continuous water cresting and eventually leaves the well closed as water cresting fully appears over both laterals. When gas starts to cone into the upper lateral, both oil and water have less area to flow due to occupied space of gas phase. Since liquid rate is fixed at 3,000 STB/D, oil and water moves into lateral faster than the case with no gas presence. This leads to rapid movement of water cresting from bottom aquifer and eventually results in early production termination of both laterals regardless of any preset water cut. Both Figures 5.8 and 5.11 show that even the preset water cut ratios is raised up to 0.8 and 0.95, these values are still not able to prevent the well from being closed eventually.

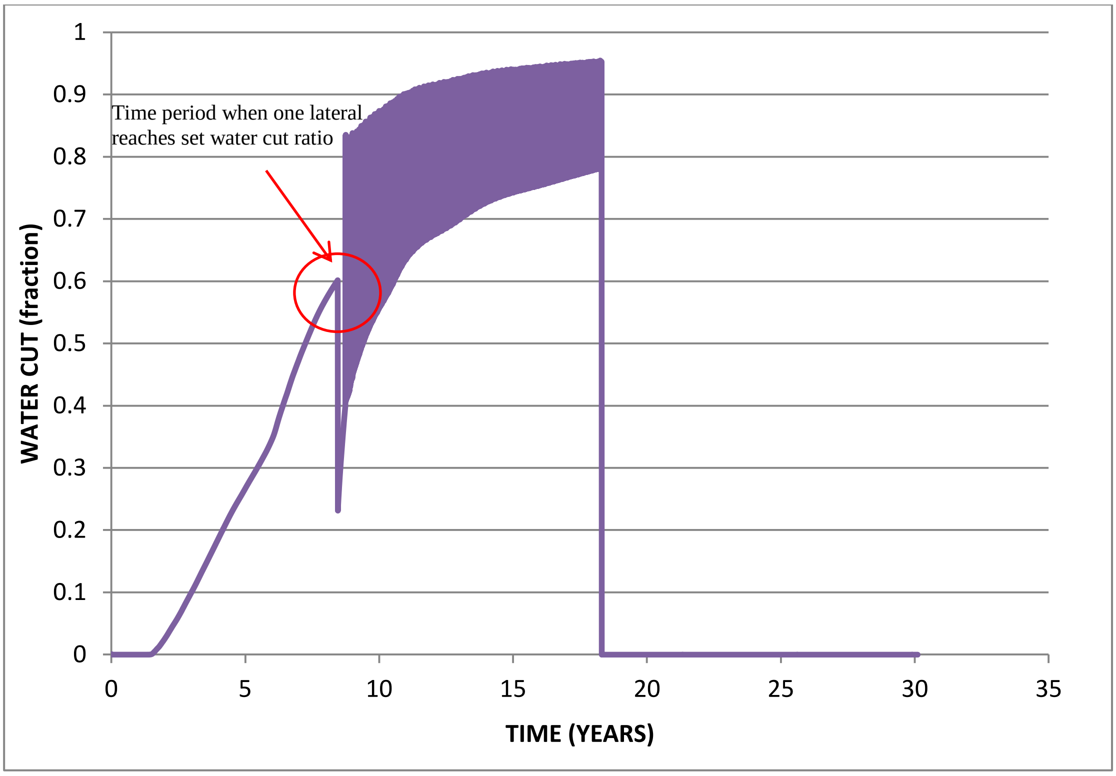


Figure 5.8 Water cut when preset water cut ratio is set at 0.8, of dual-lateral case where L1 is fixed at 10th grid block with ICV installed

In the case of preset water cut ratio of 0.80, it can be seen from Figure 5.8 that at around half pass 8th year, water cut ratio of the whole system is reduced from 0.6 to be 0.23. This is because one lateral, L2 which is located at lower depth, is closed due to water cresting phenomenon by bottom aquifer. Inflow control valve in this lateral functions to let well shut in and re-open again when water cut ratio is less than 0.8, while lateral L1 at upper location remains operated normally as it is not affected by water cresting yet. This shut in and re-opening sequence repetitively occurs until both laterals are fully surrounded by water that yield water cut higher than value of 0.8 in both laterals. At around 18th year, well is shut in permanently, while water from bottom aquifer keeps coning.

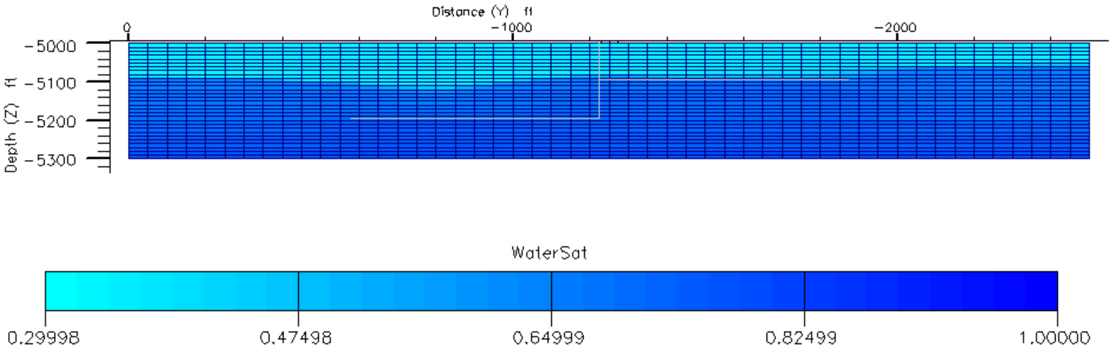


Figure 5.9 Two-dimensioned view of water saturation at the termination of well, of dual-lateral where L1 is fixed at 10th grid block with ICV installed

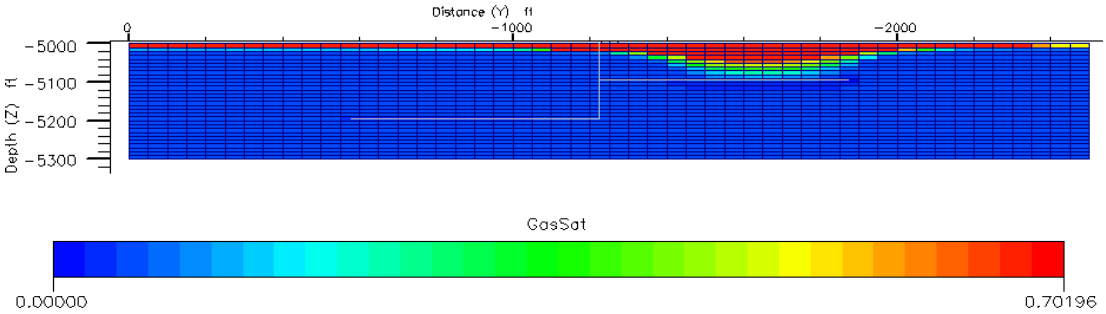


Figure 5.10 Two-dimensioned view of gas saturation at the termination of well, of dual-lateral where L1 is fixed at 10th grid block with ICV installed

To ensure that understanding of intelligent completion equipped in this well geometry is correct, water cut ratio is increased up to 0.9. However, simulation result still shows that well is shut in quite early and thus confirms that inflow control valve cannot be effectively functioned over time as the whole system is disturbed by both water cresting and gas coning phenomena. This is illustrated in Figure 5.11that the inflow control valve started working at around 18th year and well shut in permanently when passing half of 22nd year.

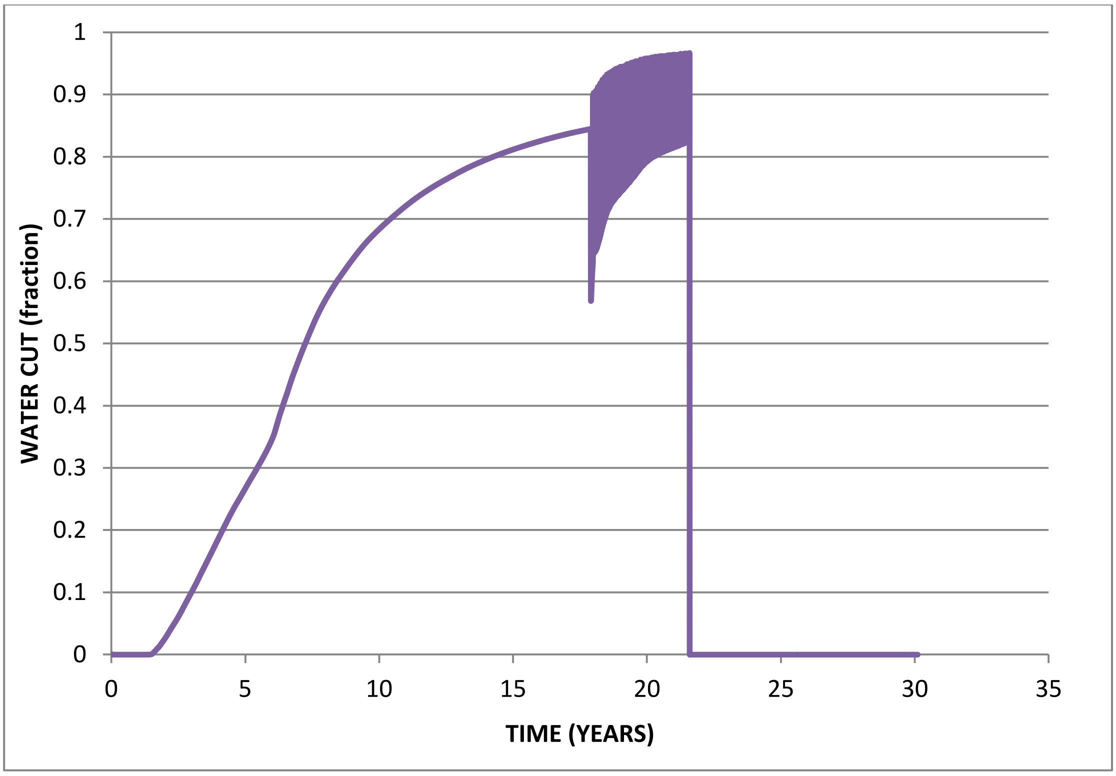


Figure 5.11 Water cut when preset water cut ratio is set at 0.95, of dual-lateral case where L1 is fixed at 10th grid block with ICV installed

5.3.2 Result of intelligent completion equipped in dual-lateral well, with L1 at the depth of 15th grid block

Simulation results shows that the well can maintain producing without lateral close when water cut ratio is more than or equal to 0.91. For any water cut ratio, for example, that is less than 0.91 like 0.90 the well is shut down before the simulation ends. Illustration for the early ending case is clearly shown as Figure 5.12.

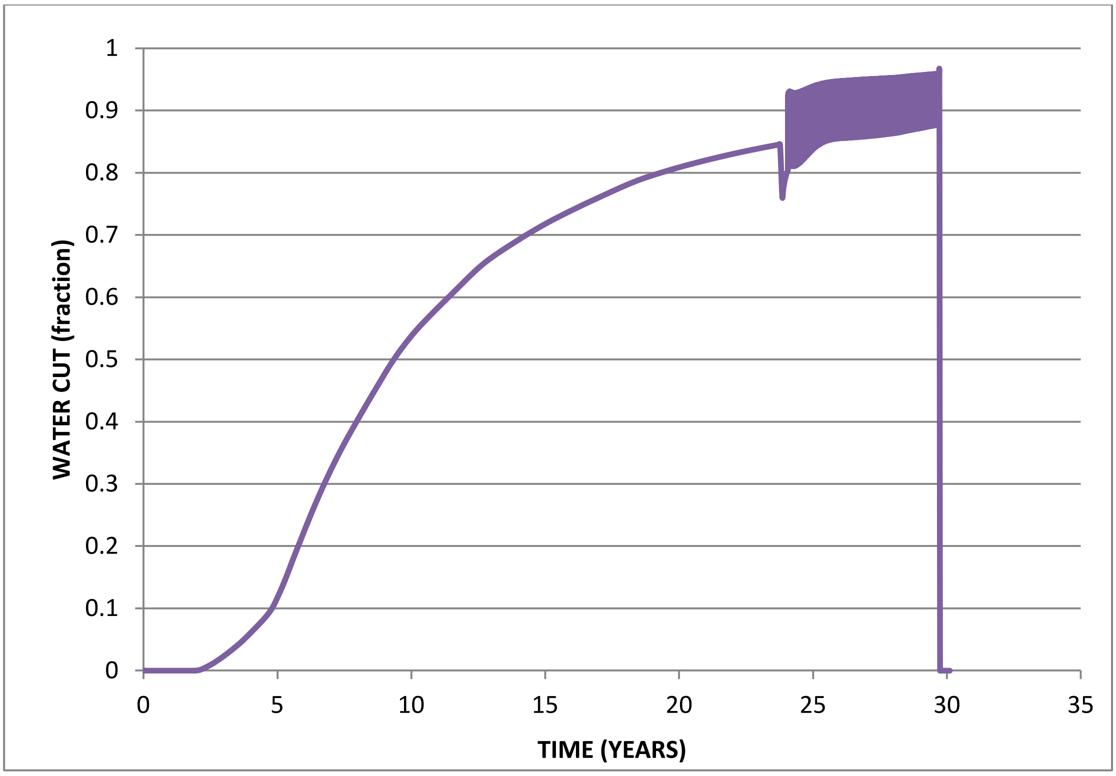


Figure 5.12 Water cut when preset water cut ratio is set at 0.9, of dual-lateral case where L1 is fixed at 15th grid block with ICV installed

It can be observed from the figure that well is shut in at around 29th year. Though period is almost close to the end of simulation time purpose of simulation is primarily to find water cut ratio that allows well to last it production time until the end of 30th year, which is still be the case that water cut ratio is more than or equal to 0.91. This is understandable that at the depth of one lateral fixed at 15th grid block, water cresting still majorly impact well drilled in geometry. Preset water cut ratio of 0.91 is seemingly quite high but is still acceptable as typical water cut ratio to be used in industry and however, this case is a good candidate for installing intelligent completion if water production can be better managed.

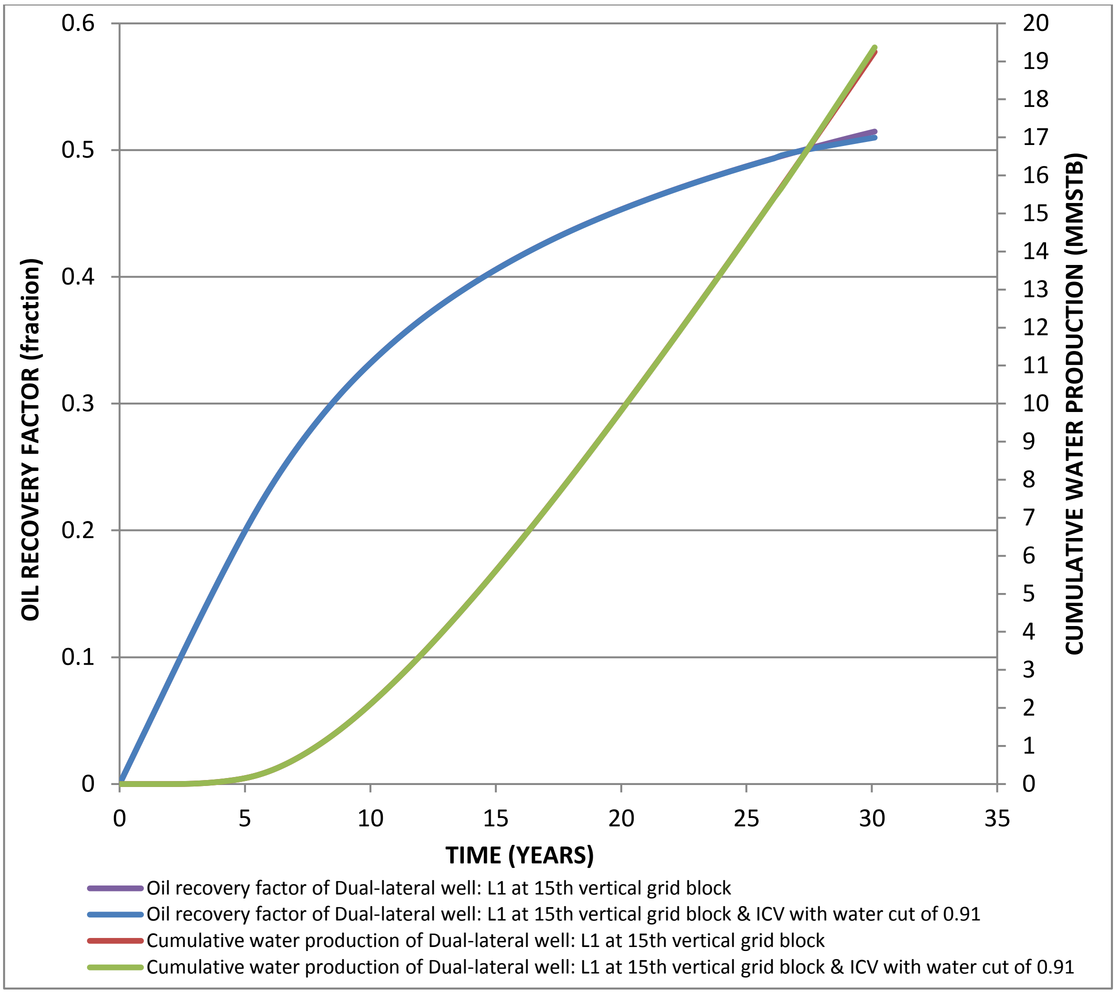


Figure 5.13 Comparison of oil recovery factors and cumulative water production between cases of having no ICV installed and ICV installed at water cut ratio of 0.91, of dual-lateral well where L1 is fixed at 15th grid block

It can be seen from Figure 5.13 that both cases of having no ICV and ICV equipped yield quite similar results. Therefore, sensitivity analysis in terms of aquifer strength and ratio of vertical over horizontal permeability are performed and will be discussed in the later section.

5.3.3 Result of intelligent completion equipped in dual-lateral well, with L1 at the depth of 20th grid block

Having intelligent completion equipped at this depth displays that intelligent completion would not be able to perform its function effectively (shut in and re-open well). As both laterals are at the same depth therefore while water keeps encroaching from bottom-drive aquifer, both are majorly affected from this phenomenon at the same time. This ultimately leaves well no chance to have just even one lateral opened and leads to scenario where the whole system cannot be further produced. Simulations are performed at various values of preset water cut ratio. Results are illustrated in Figure 5.14.

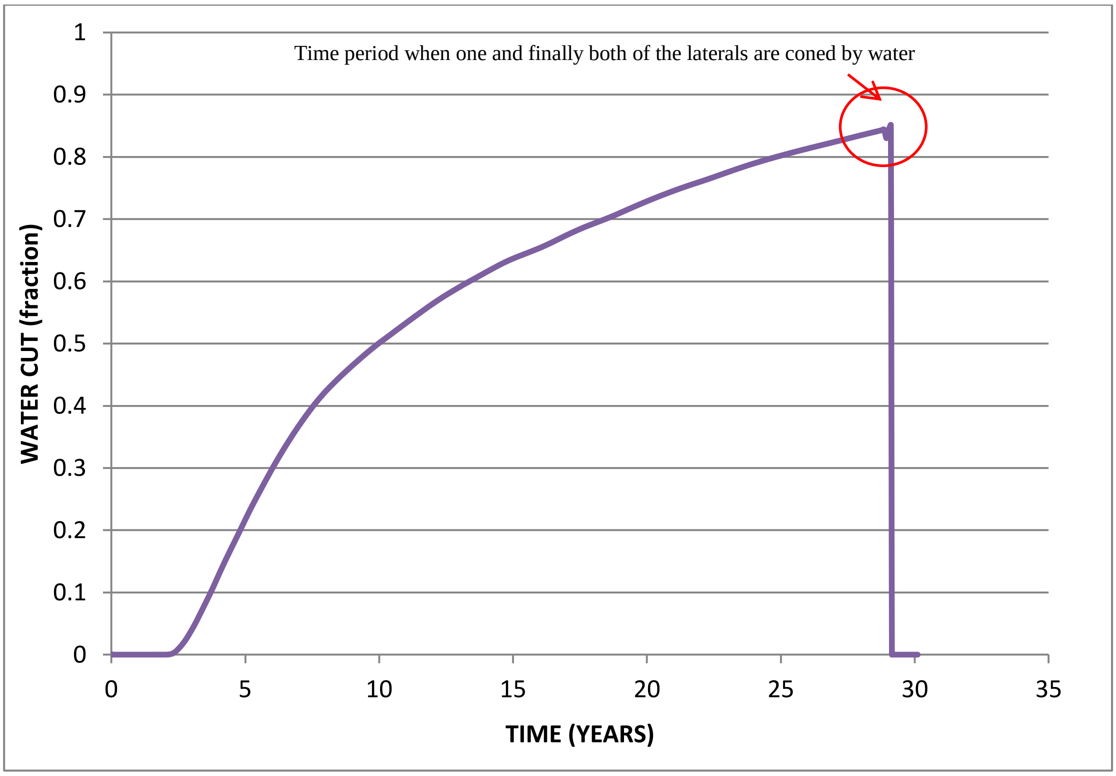


Figure 5.14 Water cut when preset water cut ratio is set at 0.85, of dual-lateral case where L1 is fixed at 20th grid block with ICV installed

Figure 5.14 shows that at around 29th year, well is closed and cannot be further produced. From the figure, it can be seen that period before water cut ratio starts to decrease and increase again is very short. That is period when one of laterals has a water cut ratio reaches preset ratio of 0.85. At this time, whole system is still able to produce by one lateral which is not impacted from water cresting yet. Very soon after that, since both laterals are located at the same depth, remaining lateral is also affected by water cresting and finally the whole well is shut in.

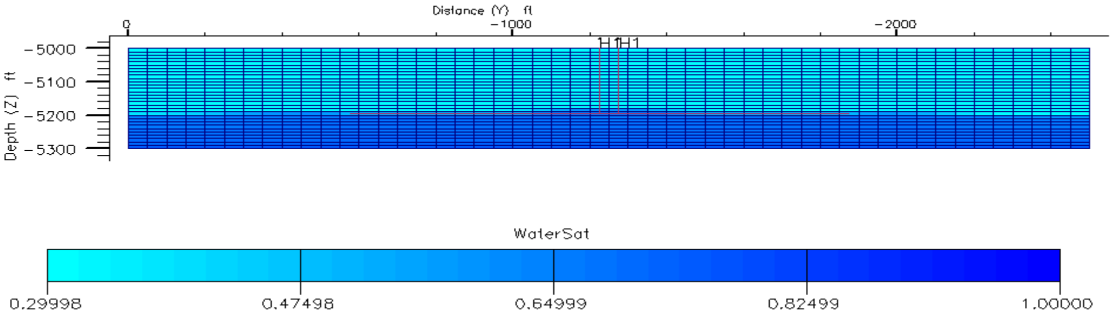


Figure 5.15 Two-dimensioned view of water saturation at 10th year of the simulation, of dual-lateral where L1 is fixed at 20th grid block with ICV installed

Figure 5.15 clearly illustrates that both laterals are affected from the water cresting at the same time as they are located at the same depth. This confirms the fact that intelligent completion barely performs its function in this case as the geometry of the well lefts no room for the inflow control valve to re-open.

5.3.4 Result of intelligent completion equipped in dual-lateral well, with L1 at the depth of 25th grid block

As known that single horizontal well at the depth of 25th vertical grid block is majorly impacted from water cresting from bottom aquifer and can be significantly improved by dual-lateral well where L1 and L2 is located at the 20th and 25th grid block depth. Simulation results of those wells having the ICV equipped show that ICV can be effectively operated once water cut ratio is more than or equal to 0.85.

Comparison is made, similar to the case of having L1 at 15th vertical grid block which is the case where intelligent completion is proved to be worth of trial installation, between system without and with the ICV equipped. Figure 5.16 displays that results of two cases are quite similar by having a case of no presence of ICV even a bit better. By understanding that ICV should be able to manage water production under appropriate aquifer strength and also other related factors, this will be carried over and further investigated in sensitivity analysis part as same as the case of L1 at 15th grid block.

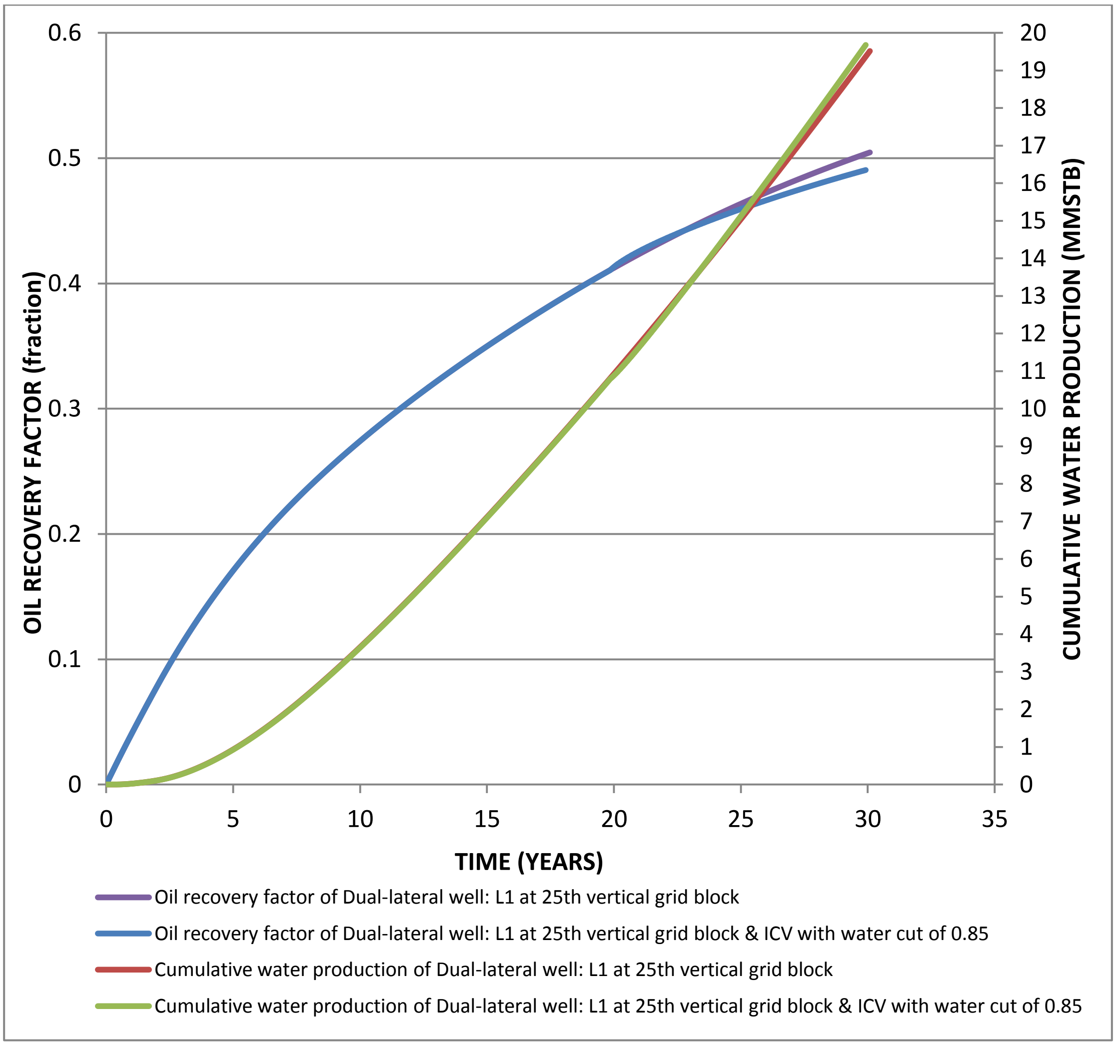


Figure 5.16 Comparison of oil recovery factors and cumulative water production between cases of having no ICV installed and ICV installed at water cut ratio of 0.85, of dual-lateral well where L1 is fixed at 25th grid block

As water cut ratio, which allows intelligent completion to be effectively implemented is different in each case, is varied by depth L1 depth. Table 5.6 summarizes results of cases discussed earlier.

Table 5.6 Summary of effective preset water cut ratio for intelligent completion implementation

Dual-lateral well with varied depth on L1 at	**Effective water cut ratio**
10th grid block	Nil
15th grid block	More or equal than 0.91
20th grid block	Nil
25th grid block	More or equal than 0.85

In summary, interesting cases in this section are chosen for sensitivity analysis in the next section to study effectiveness of intelligent completion when reservoir properties are altered from those in base case model.

5.4 Sensitivity analysis on selected cases of intelligent completion equipped in dual-lateral wells

Selected cases from previous section containing doubtful over effectiveness of ICV installation are carried over in this section under basic understanding that intelligent completion should still generally yield less cumulative water production, and thus more oil recovery factor. Sensitivity analysis is performed in this section as former simulation results however indicated no significant difference on value of oil recovery factor or cumulative water production obtained from cases having ICV equipped in dual-lateral wells with location of L1 at depth of 15th and 25th grid block and similar dual-lateral well cases but without intelligent completion equipped. This section will be covering study of effect of aquifer strength as well as ratio of vertical to horizontal permeability to intelligent completion equipped in dual-lateral wells.

5.4.1 Effect of aquifer strength on intelligent completion equipped in dual-lateral wells

It is shown in previous section that all of simulation cases performed over aquifer strength of 50PV does not provide substantial benefits of installing intelligent completion in dual-lateral wells. In this section, aquifer strength is then varied from 50PV to 100PV, 200PV and 300PV in order to investigate possible benefit of intelligent completion.

5.4.1.1 Impact of aquifer strength on dual-lateral wells with intelligent completion, with L1 at the depth of 15th grid block

It is observed in previous simulation results that well is not early shut in by this well geometry when preset water cut ratio is more than or equal to 0.91. Sensitivity analysis conducted in this section does not only vary aquifer strength but also preset water cut ratio to be one decimal up and down which are at water cut ratio of 0.90 and 0.92. This is to observe if aquifer strength does any impact on minimum preset water cut ratio to be changed or not.

In the case of aquifer strength of 100 PV, Figure 5.17 presents simulation results of dual-lateral well when L1 is at the depth of 15th grid block with no intelligent completion compared to ones with ICV equipped at water cut ratio of 0.90, 0.91 and 0.92. Cases of no intelligent completion and ones with water cut ratio set at 0.91 and 0.92 show almost the same result of oil recovery factor as well as cumulative water production (curves overlay each other). While the case of preset water cut ratio of 0.9 still has the same behavior as discussed in previous section, which is an early shut in before 30 years of simulation period (finished early around 4 months), it is also able to significantly improve oil recovery factor from 0.493 to 0.504 and better manage to get less water production from 19.819 to 19.075 MMSTB. This expresses that at least, it is not always necessary for well to last until the end of production life time. But rather that better case can be yielded even when well is shut in at the last year of production but still able to perform quite effectively as a whole picture.

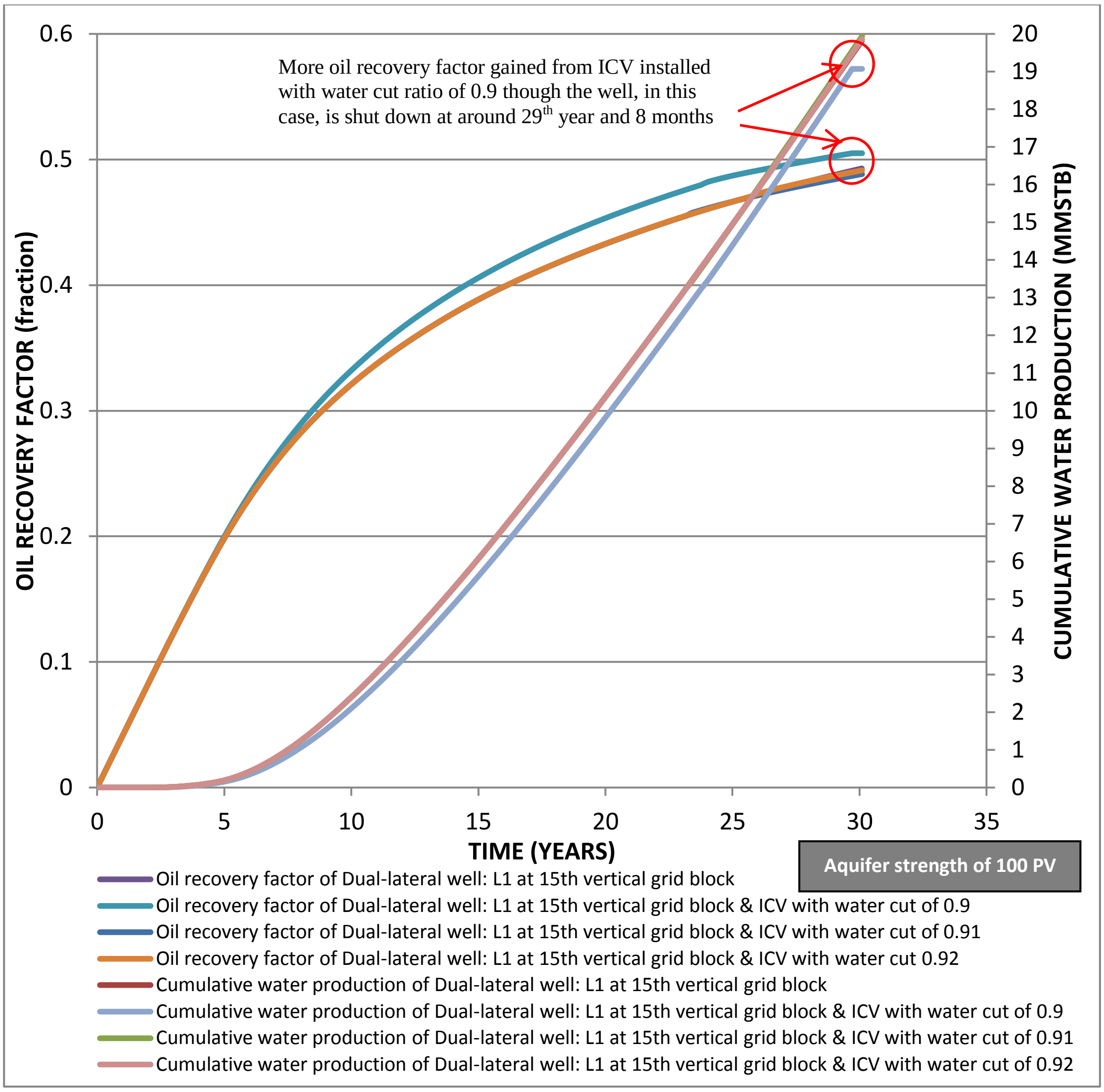


Figure 5.17 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.90, 0.91 and 0.92, of dual-lateral well where L1 is fixed at 15th grid block and bottom aquifer strength is 100PV

On the contrary, results are not in the same trend for different values of aquifer strengths varied of this study which are 200PV and 300PV. Figure 5.18 and Figure 5.19 show that there are no perceptible differences in all cases of without and with intelligent completion equipped at various water cut ratios; this is when aquifer strength is increased to 200PV or even 300PV. This can be simply observed as all lines overlay on each other. So in these cases, it can be indicated that there is no requirement to install ICV because it would not make any difference.

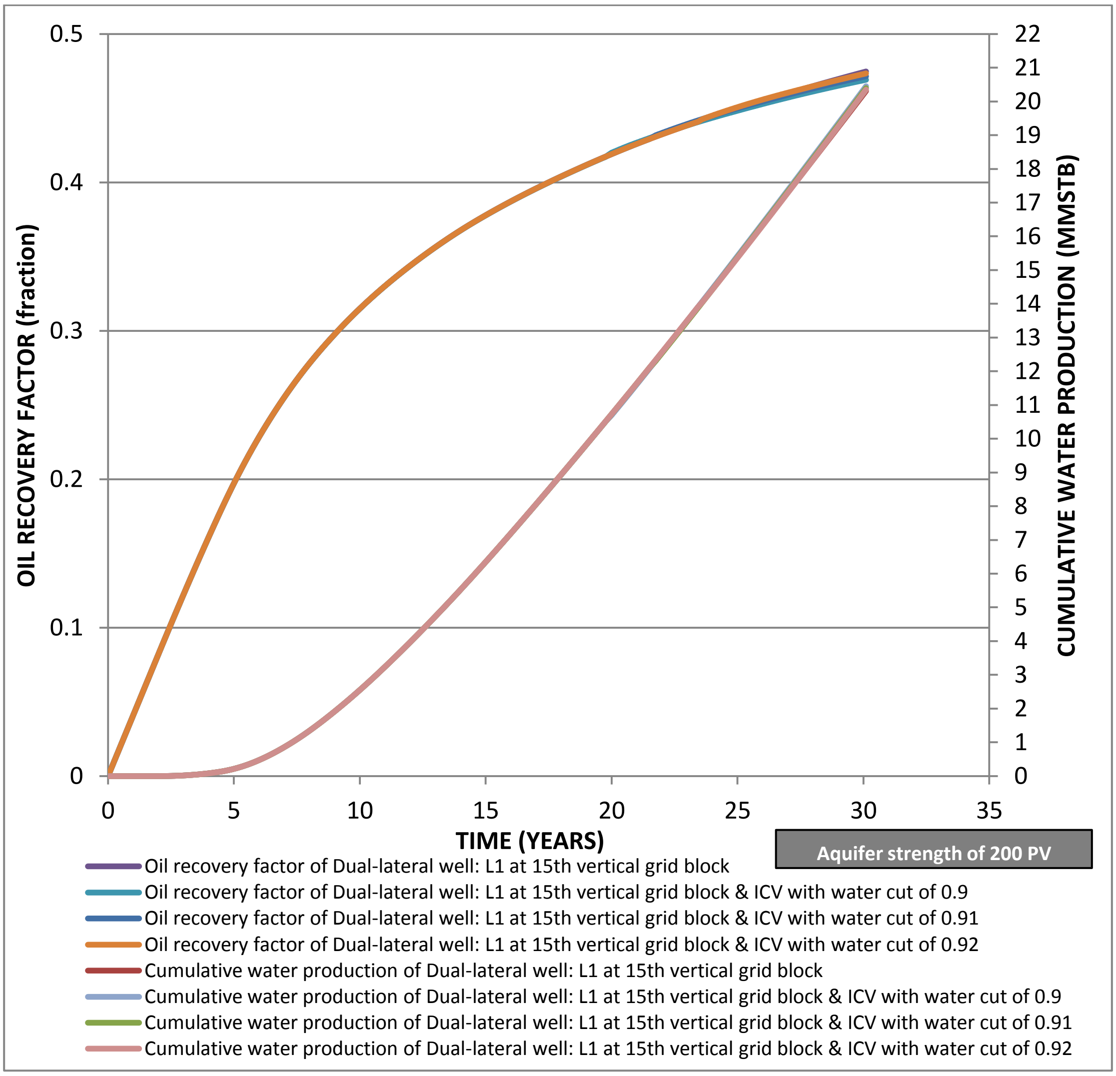


Figure 5.18 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.90, 0.91 and 0.92, of dual-lateral well where L1 is fixed at 15th grid block and bottom aquifer strength is 200PV

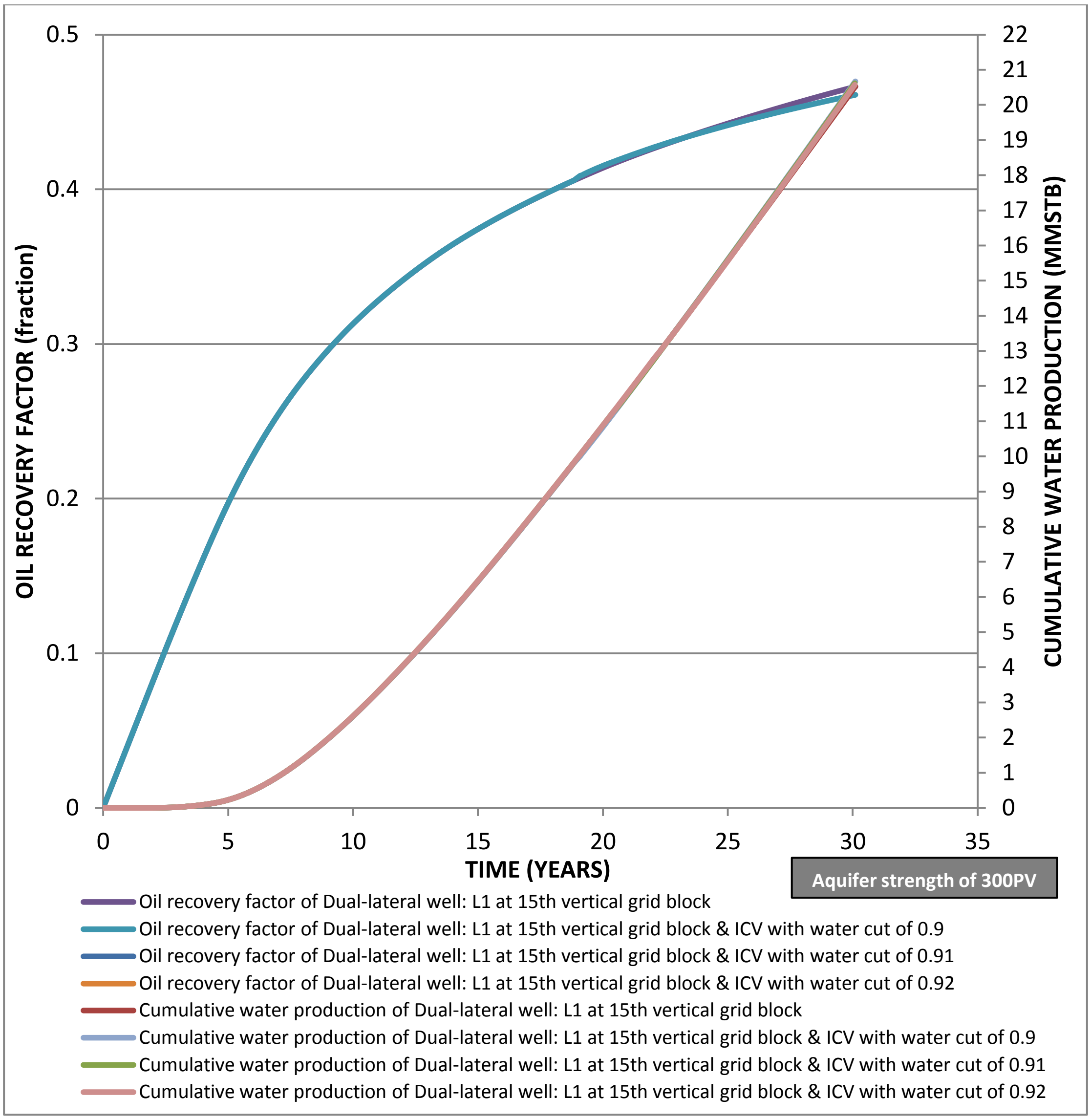


Figure 5.19 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.90, 0.91 and 0.92, of dual-lateral well where L1 is fixed at 15th grid block and bottom aquifer strength is 300PV

Summarily, it is clearly seen that there are some improvements of oil recovery factor as well as cumulative water production based on the changes of effect of aquifer strength in 3 sizes of 100, 200 and 300 PV. Value of oil recovery factor and cumulative water production factor are displayed in below Table 5.7 for references.

Table 5.7 Summary of oil recovery factors and cumulative water production obtained from various sizes of aquifer strength in dual-lateral well having L1 at 15th grid block

Aquifer strength	**Dual-lateral well where L1 is fixed at 15th grid block**	**Oil recovery factor (fraction)**	**Cumulative water production (MMSTB)**
100PV	No ICV	0.493	19.819
	ICV with water cut of 0.9	0.488	19.94
	ICV with water cut of 0.91	0.504	19.075
	ICV with water cut of 0.92	0.491	19.862
200 PV	No ICV	0.474	20.31
	ICV with water cut of 0.9	0.469	20.455
	ICV with water cut of 0.91	0.471	20.395
	ICV with water cut of 0.92	0.473	20.343
300 PV	No ICV	0.466	20.531
	ICV with water cut of 0.9	0.461	20.672
	ICV with water cut of 0.91	0.463	20.616
	ICV with water cut of 0.92	0.465	20.529

5.4.1.2 Impact of aquifer strength in dual-lateral wells with intelligent completion, with L1 at the depth of 25th grid block

The simulation results of this well geometry are similar to previous subsection of L1 at the depth of 15thvertical grid block. However, it is identified from previous simulation result that the effective water cut ratio at this depth is around 0.85. Instead of vary one decimal up and down as in case of L1 at the depth of 15th grid block, water cut ratio is varied to be 0.825, 0.85 and 0.875 instead as these are much more realistic values being used in industry.

According to result obtained from reservoir supported by aquifer strength of 50PV in base case where well is shut in at water cut ratio of 0.825 as shown in Figure 5.20, it displays that well does not produce beyond the year of 28th year as water cresting occurs in both laterals. Comparing this to the simulation results when performing at aquifer strength of 100 PV as shown in Figure 5.21, every ICV-equipped case with any ratio of water cut still work and yield better oil recovery factor as well as less cumulative water production compared to one without intelligent completion. Oil recovery factor is improved from 0.435 to 0.453, while cumulative water production is reduced from 21.363 to 20.877 MMSTB. However, it is observed that value of preset water cut ratio of ICV does not affect simulation as all values yield similar result, which is better than the case without intelligent completion.

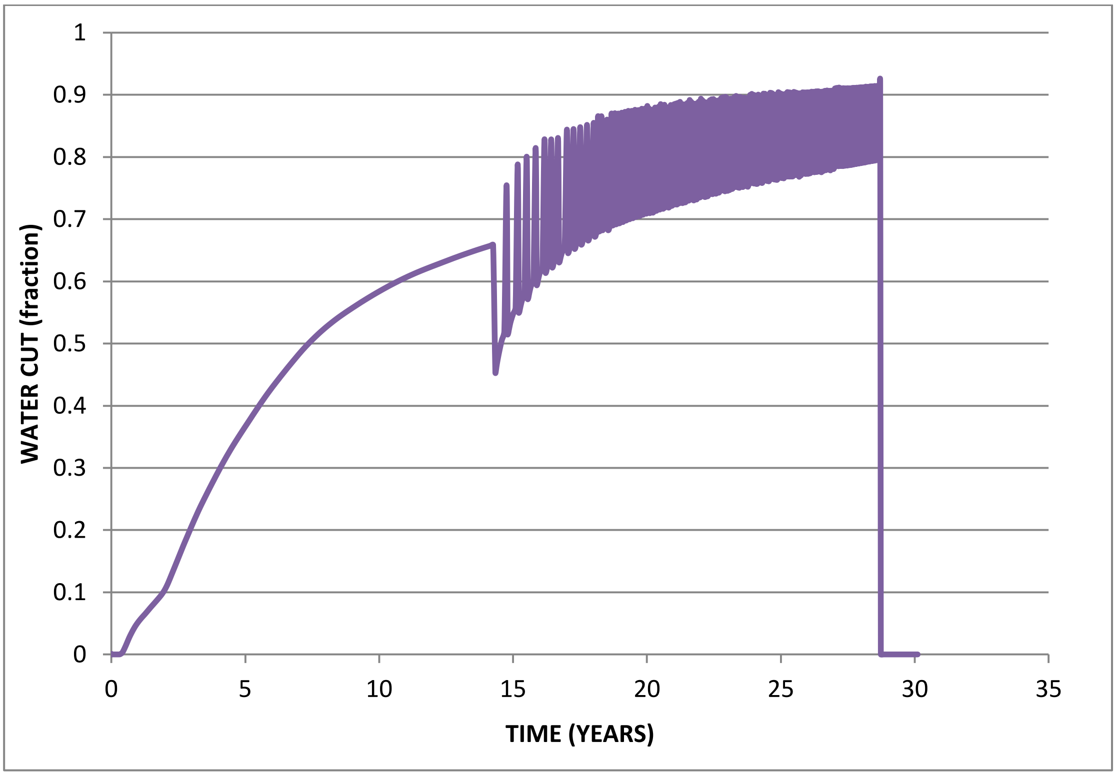


Figure 5.20 Water cut when preset water cut ratio is set at 0.825, of dual-lateral case where L1 is fixed at 25th grid block with ICV installed, aquifer strength of 50PV

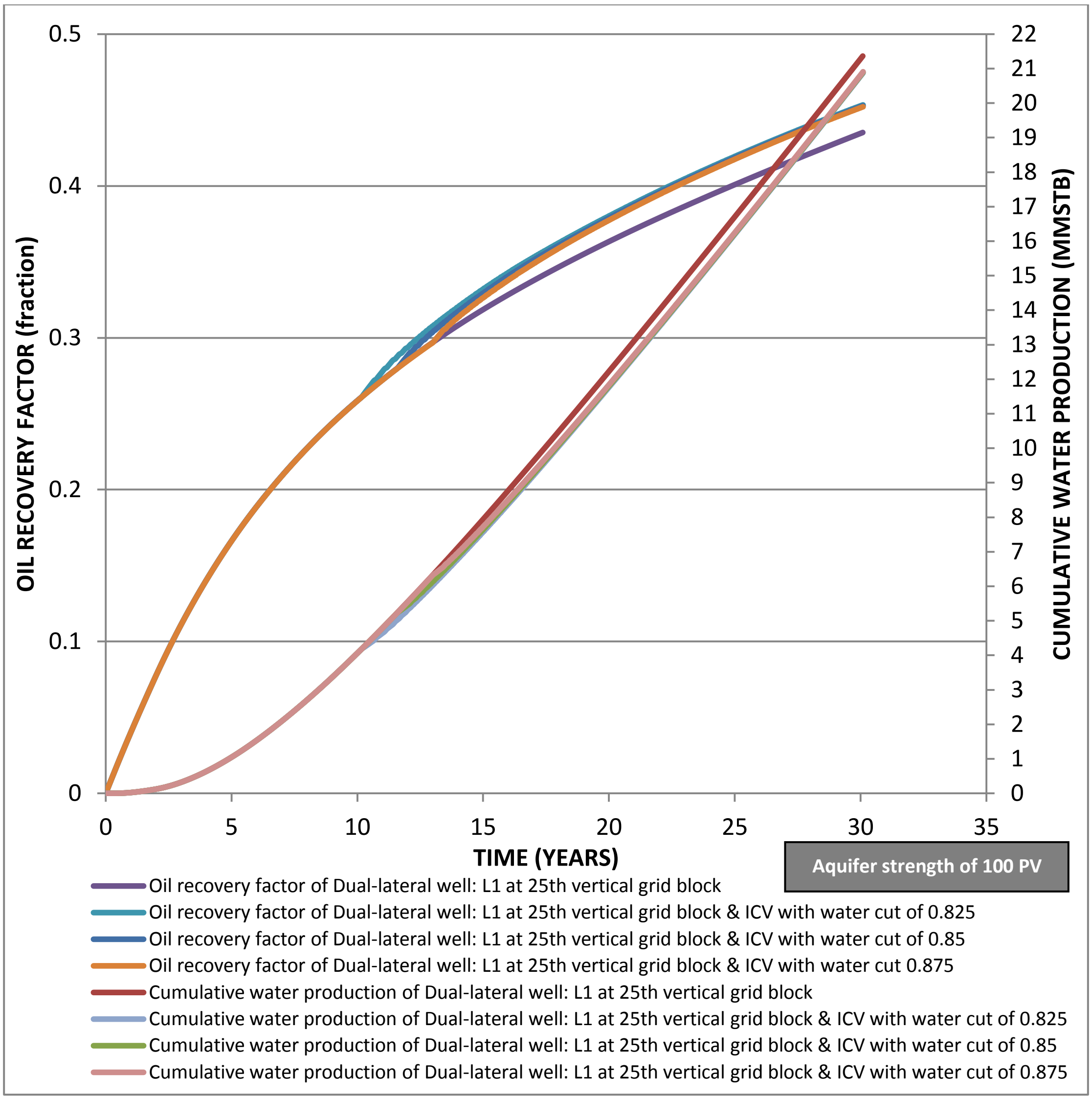


Figure 5.21 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.825, 0.85 and 0.875, of dual-lateral case where L1 is fixed at 25th grid block and bottom aquifer strength is 100PV

Reservoir simulations are further conducted on reservoir models having stronger aquifer strength of 200PV and 300 PV. Reservoir simulation results obtained from these reservoirs with aquifer size of 200 and 300 PV are shown in Figure 5.22 and Figure 5.23 respectively. From both figures, similar trends as described in previous section are observed. Intelligent completion installation results in an improving of oil recovery factor as well as reducing cumulative water production. It is clearly shown in both figures that preset water cut ratio of 0.825 cannot maintain well from water encroachment as well is shut in at around 27th and 25th year for the cases of aquifer size 200PV and 300 PV, respectively. The result is somehow understandable as this preset water cut ratio is one would not originally be selected as candidate for intelligent completion since it allows well to shut in when aquifer strength is only 50PV. Nevertheless, this value though turns out to be good one in only the case of 100PV aquifer strength. It can be inferred from the case of aquifer strength of 200PV that oil recovery factor is improved from 0.391 to be 0.417 and cumutive water production is reduced from 22.534 to 21.838 MMSTB when well is equipped with ICV at etiher water cut ratio of 0.85 or 0.875. While in the case of aquifer strength is raised to 300PV, oil recovery factor is also improved from 0.378 to 0.405 and water production is reduced from 22.872 to around 22.145 MMSTB for either water cut ratios of 0.85 or 0.875.

Likewise, this sensitivity analysis part of various sizes of aquifer strength in dual-lateral well of L1 at the depth of 25th vertical grid block also show a clear difference, in some cases, between having no ICV equipped and ICV installed at some water cut ratios. The summary is captured and shown in Table 5.8.

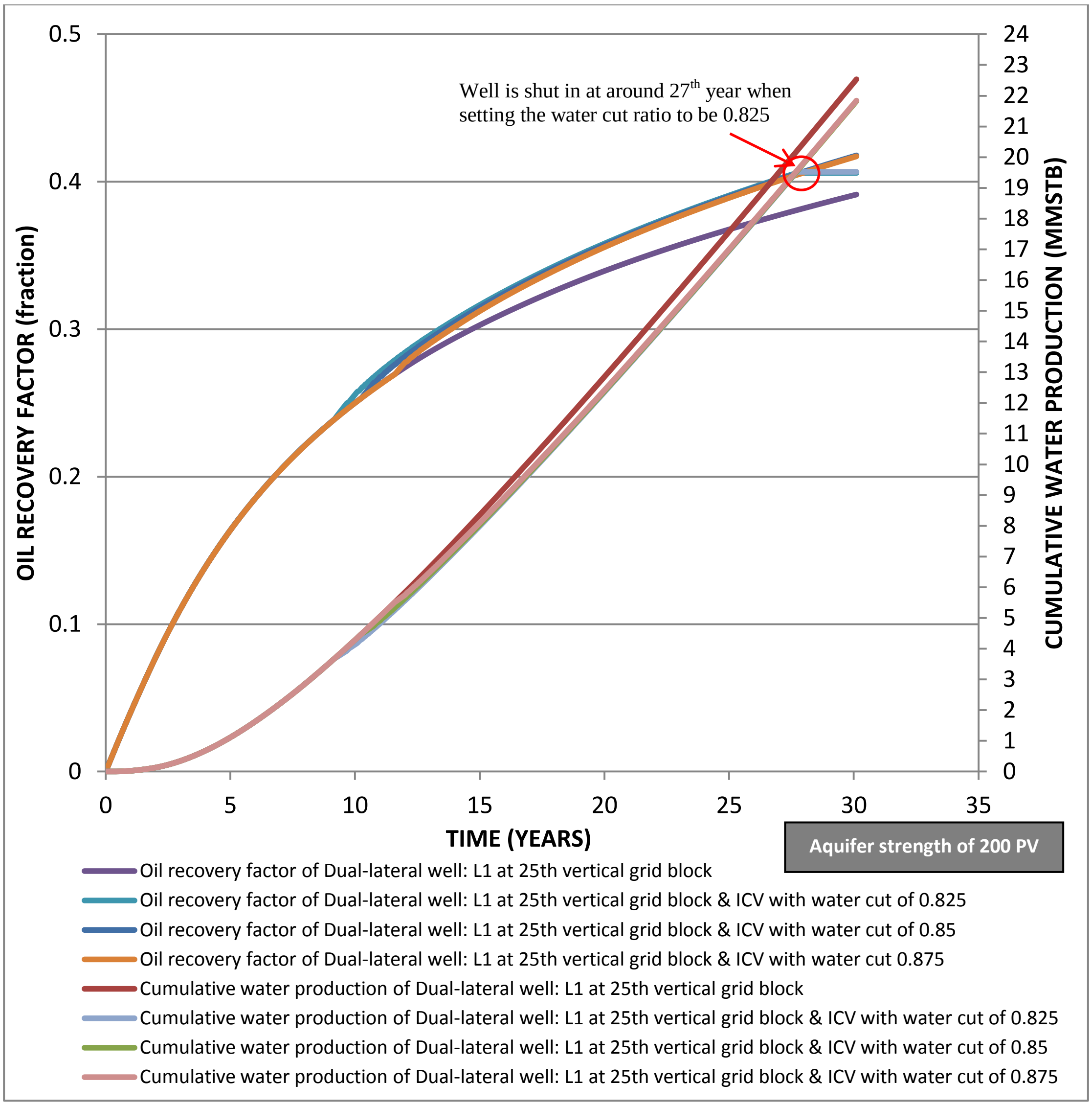


Figure 5.22 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.825, 0.85 and 0.875, of dual-lateral case where L1 is fixed at 25th grid block and bottom aquifer strength is 200PV

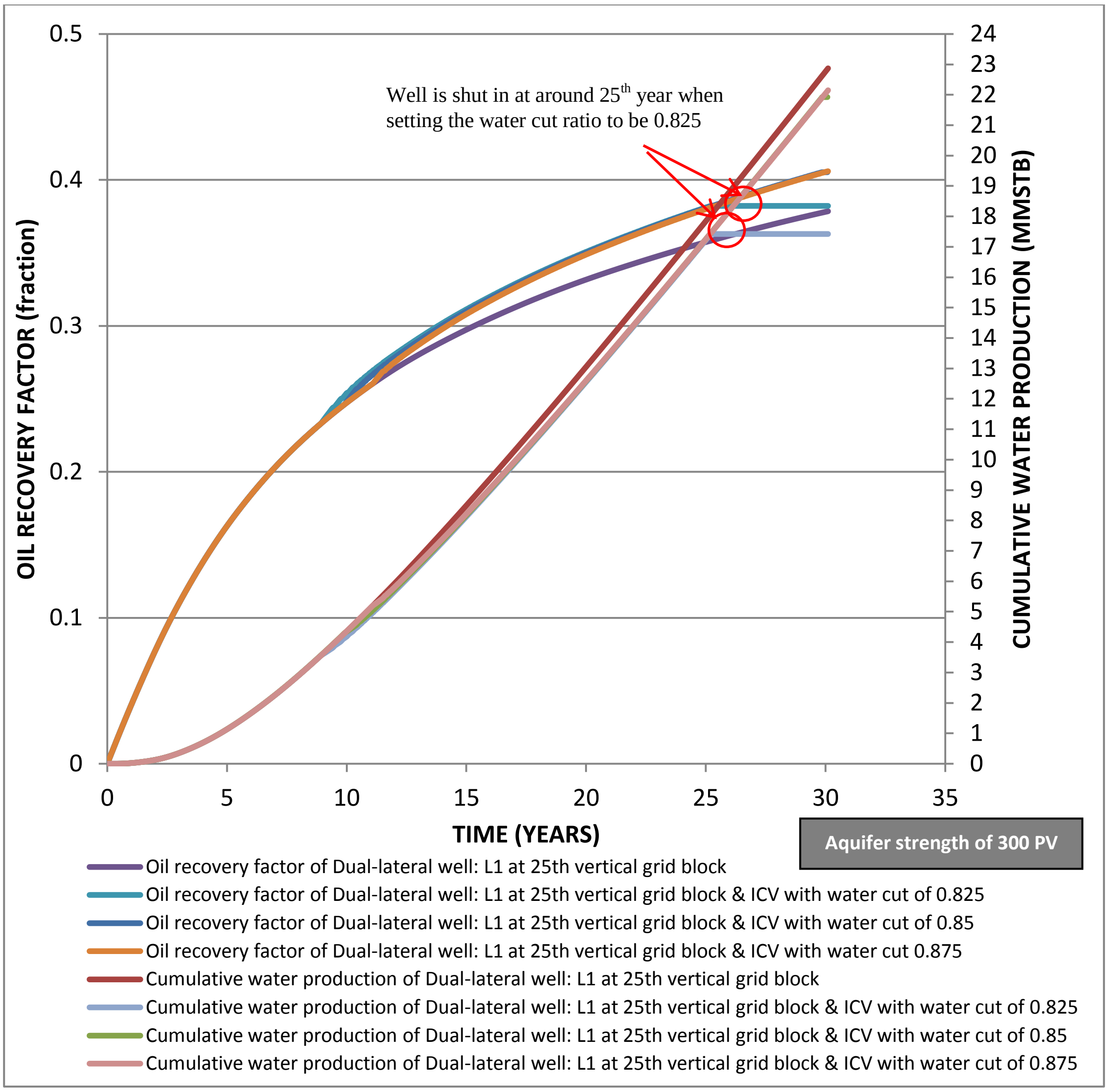


Figure 5.23 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.825, 0.85 and 0.875, of dual-lateral case where L1 is fixed at 25th grid block and bottom aquifer strength is 300PV

Table 5.8 Summary of oil recovery factors and cumulative water production obtained from various sizes of aquifer strength in dual-lateral well having L1 at 25th grid block

Aquifer strength	**Dual-lateral well where L1 is fixed at 25th grid block**	**Oil recovery factor (fraction)**	**Cumulative water production (MMSTB)**
100PV	No ICV	0.435	21.363
	ICV with water cut of 0.825	0.453	20.877
	ICV with water cut of 0.85	0.452	20.892
	ICV with water cut of 0.875	0.452	20.907
200 PV	No ICV	0.391	22.534
	ICV with water cut of 0.825	0.405	19.527
	ICV with water cut of 0.85	0.417	21.838
	ICV with water cut of 0.875	0.417	21.838
300 PV	No ICV	0.378	22.872
	ICV with water cut of 0.825	0.382	17.417
	ICV with water cut of 0.85	0.405	21.919
	ICV with water cut of 0.875	0.405	22.145

5.4.2 Effect of ratio of vertical to horizontal permeability on intelligent completion equipped in dual-lateral wells

Ratio of vertical to horizontal permeability or k_v/k_h is one of the most important reservoir properties and is expected to majorly impact well with intelligent completion. As noticed in base case that ratio is initially kept at 0.1, sensitivity analysis in this section is attempted to evaluate effect of higher value of this parameter which are 0.2, 0.3 and 0.5. Reservoir simulation of selected potential cases of dual-lateral wells combined with intelligent completion at the depth of 15th and 25th grid block is performed in order to observe how interest parameter impacts on oil recovery factor and cumulative water production. Generally, vertical permeability is impacted from overburden pressure in vertical direction during sedimentation and lithification of sand grains. Hence, sand grain orientation favors flow in horizontal well and this results in ratio of vertical permeability to horizontal permeability less than unity. It is suspicious that when higher value of k_v/ k_h ratio is applied, better flow of fluid in vertical direction in reservoir should be observed. This suspicious phenomenon is clarified and further investigated in the following section of simulation result.

5.4.2.1 Impact of k_v/ k_h ratio on dual-lateral wells with intelligent completion, with L1 at the depth of 15th grid block

Scope of simulation is described in similar pattern as the study of effect from aquifer strength over dual-lateral wells at the same scenario. Water cut ratio of ICV is varied from 0.91 up and down of one decimal to 0.90 and 0.92, respectively. It can be explained from Figure 5.24 that in the case of k_v/ k_h is 0.2, there is no difference between wells without and with ICV equipped. Although water cut ratio is not taken into consideration as intelligent completion does not matter in the figure but it can be seen that that dual-lateral well at this geometry and configuration (with water cut ratio set at 0.9) still behave in the similar pattern as previous cases. Same mentioned behavior is about early well shut in at almost the end of 30-years production lifetime, like in other cases performed over intelligent dual-lateral well case as well as the study of effect of aquifer strength at 100PV. It can be then concluded for this case that when k_v/ k_h ratio is 0.2, intelligent completion would not be required as it does not yield any difference or improvement of oil recovery factor and reduction of water production compared to the cases where ICV is not installed.

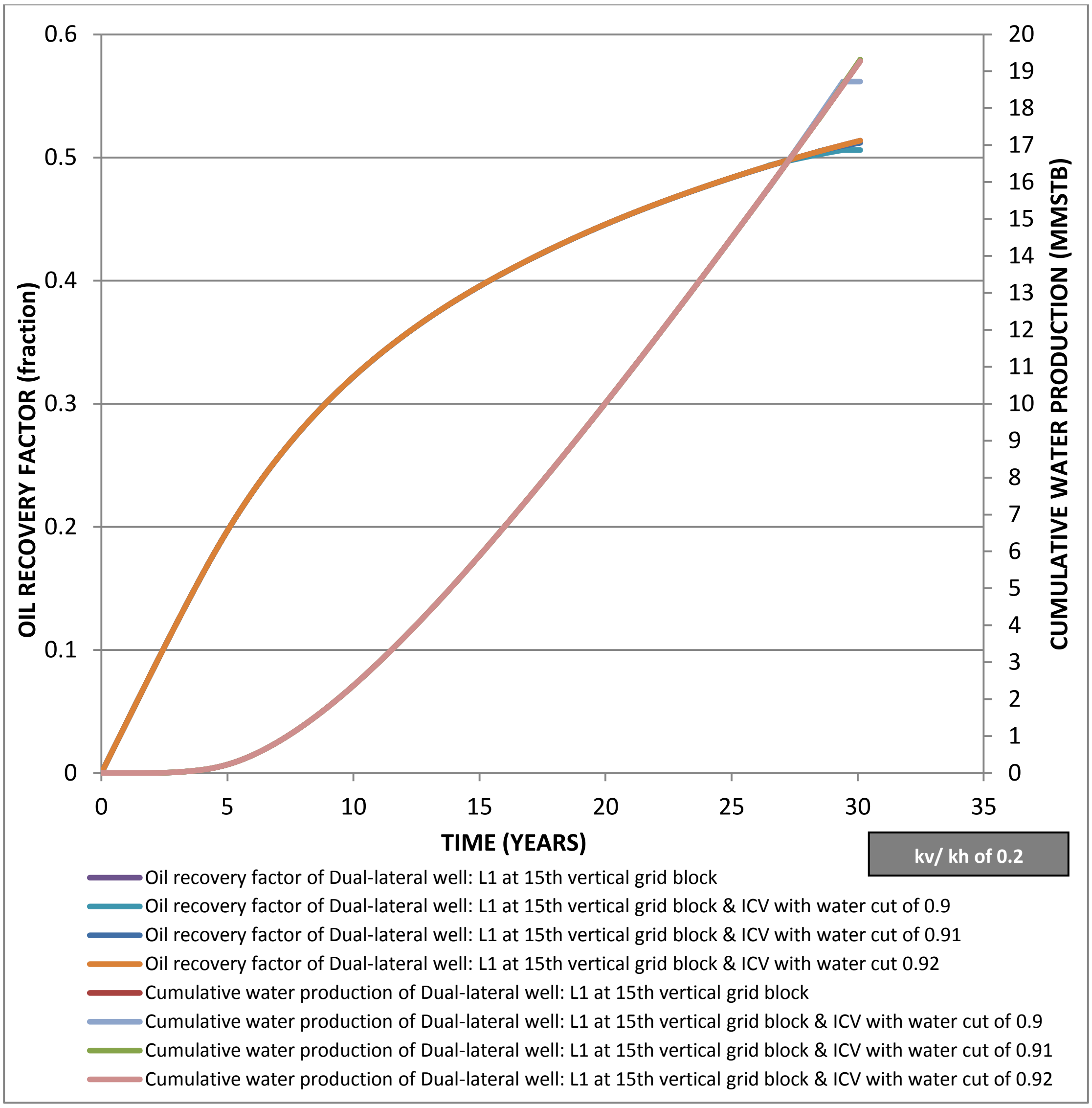


Figure 5.24 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.90, 0.91 and 0.92, of dual-lateral case where L1 is fixed at 15th grid block and k_v/ k_h is 0.2

Correspondingly, simulations are performed over k_v/ k_h ratio of 0.3 and 0.5 to observe effectiveness of intelligent completion combined in multilateral wells when vertical flow properties are higher. Results are shown in Figure 5.25 and Figure 5.26 respectively.

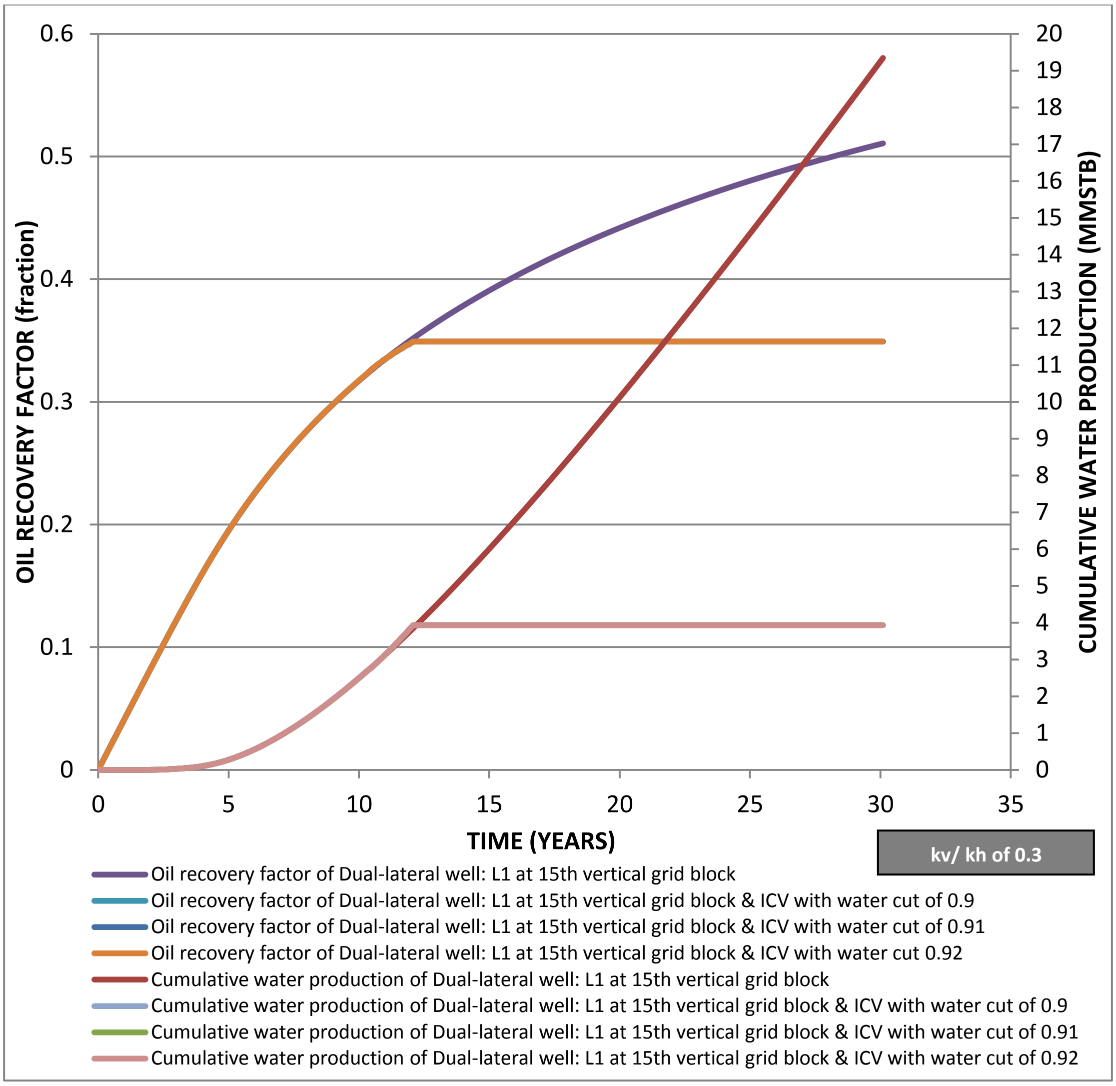


Figure 5.25 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.90, 0.91 and 0.92, of dual-lateral case where L1 is fixed at 15th grid block and k_v / k_h is 0.3

From Figure 5.25 where ratio of vertical to horizontal permeability is 0.3, it is observed that cases without ICV installed yields similar result as ones having ICV equipped at water cut ratio of 0.90 and 0.91. It turns out to be preset water cut ratio set at 0.92 that causes well to shut in around 12th year or less than half way of simulation or production life time.

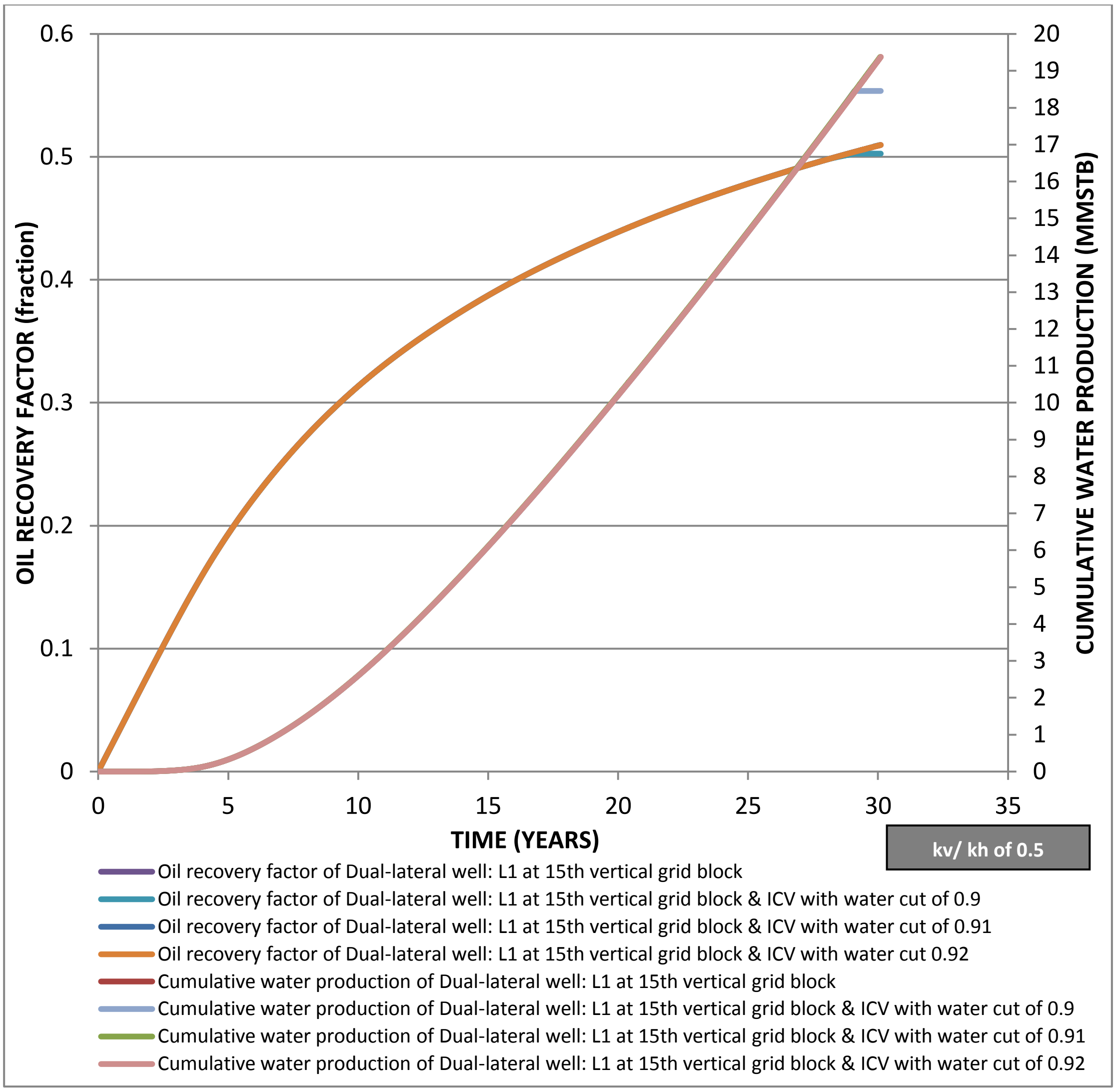


Figure 5.26 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.90, 0.91 and 0.92, of dual-lateral case where L1 is fixed at 15th grid block and k_v/ k_h is 0.5

From Figure 5.26 where k_v/ k_h ratio is increased to 0.5, pattern of result is as similar as obtained from k_v/ k_h ratio is 0.1 where there is no difference between case with no intelligent completion equipped and with intelligent completion equipped at any preset water cut ratio. At preset water cut ratio of 0.90, well is shut in before the end of 30th year production.

5.4.2.2 Impact of k_v/ k_h on dual-lateral wells with intelligent completion, with L1 at the depth of 25th grid block

Simulation study in this section is performed in similar way as in previous section where k_v/k_h is varied up to 0.2, 0.3 and 0.5 on chosen cases of intelligent completion in dual-lateral with L1 at depth of 25th grid block combined with preset water cut ratio of 0.825, 0.85 and 0.875, simplified as in the study of aquifer strength over reservoir with the same environment. Figure 5.27 illustrates the effect of k_v/ k_h ratio of 0.2.

It can be concluded from results at this value of ratio, all cases having intelligent completion equipped allow all of the wells to shut in before the end of simulation and hence, yield very low oil recovery factor, starting from the case with ICV equipped and preset water cut ratio of 0.85 & 0.875 and 0.825 which let well to shut in at 16th and 25th year respectively.

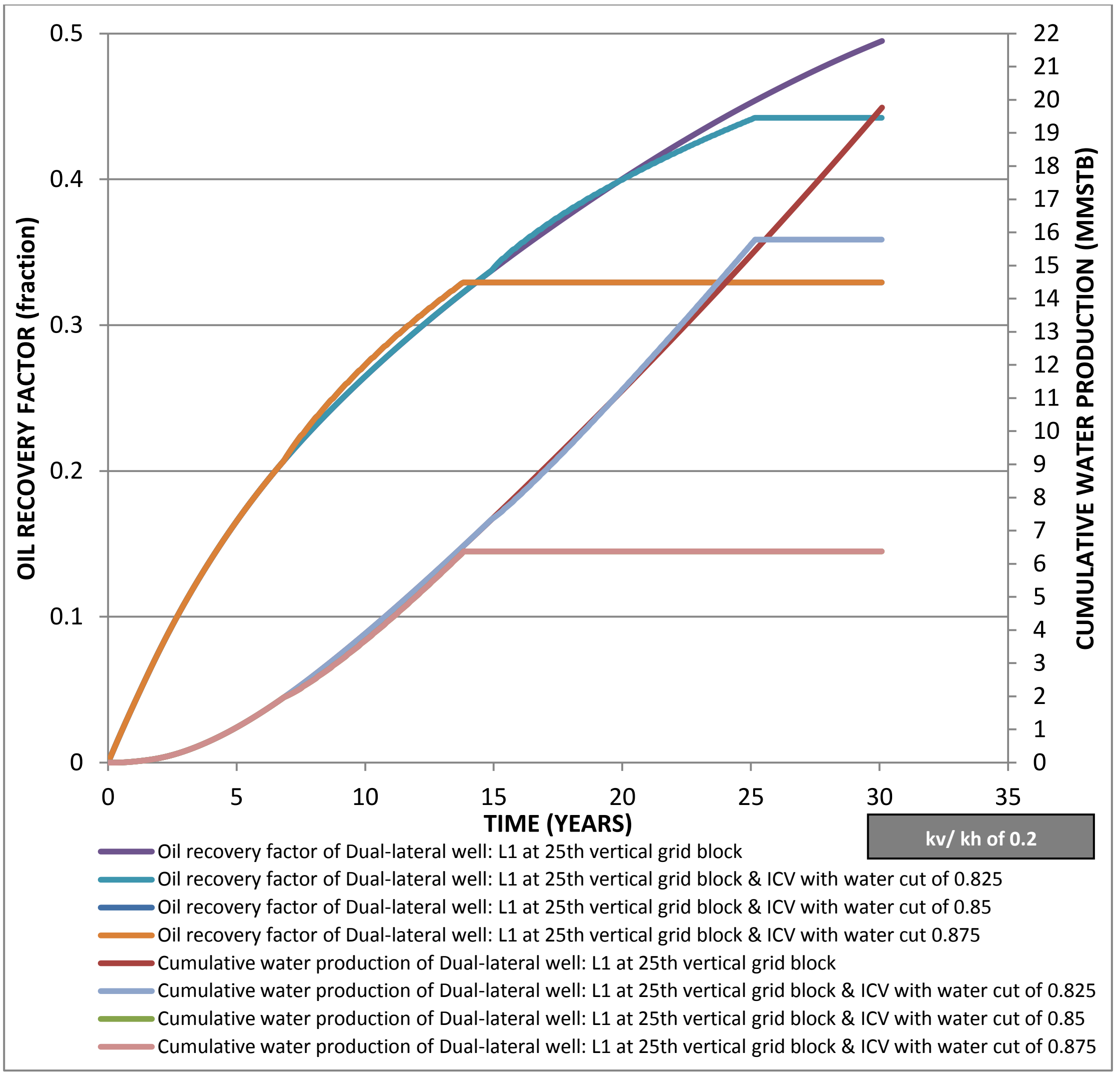


Figure 5.27 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.825, 0.85 and 0.875, of dual-lateral case where L1 is fixed at 25th grid block and $k_v/\ k_h$ is 0.2

Result of simulation conducted over $k_v/\ k_h$ of 0.3 is displayed in Figure 5.28. The trend of simulation result can be explained likewise to simulation performed before at ratio of $k_v/\ k_h$ equals to 0.2.

It is obvious that all ICV- equipped cases yields worse result compared to the case without intelligent completion installed. The preset water cut ratio of 0.825 and 0.85 causes well to shut in at around 26th and 28th year accordingly, while preset water cut ratio of 0.875 yields similar result as the case without ICV equipped.

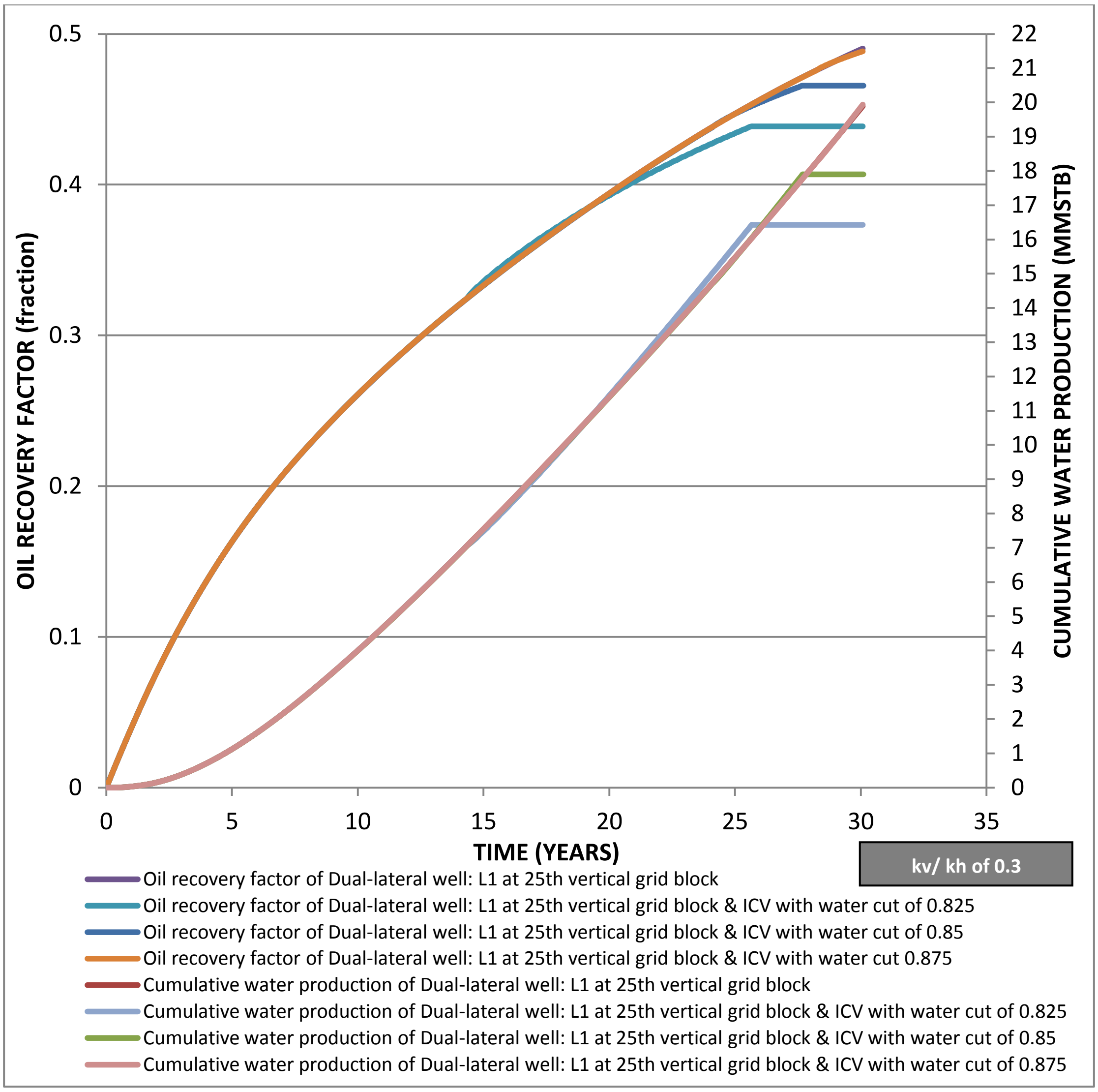


Figure 5.28 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.825, 0.85 and 0.875, of dual-lateral case where L1 is fixed at 25th grid block k_v/ k_h is 0.3

Results obtained from the last study are shown in Figure 5.29 and it also provides the same pattern as found in previous case where k_v/ k_h is 0.3. Preset water cut ratios of 0.825 and 0.85 cause well to shut in at around 27th and 28th year, whereas preset water cut ratio of 0.875 yields the same result as the case without an installation of intelligent completion.

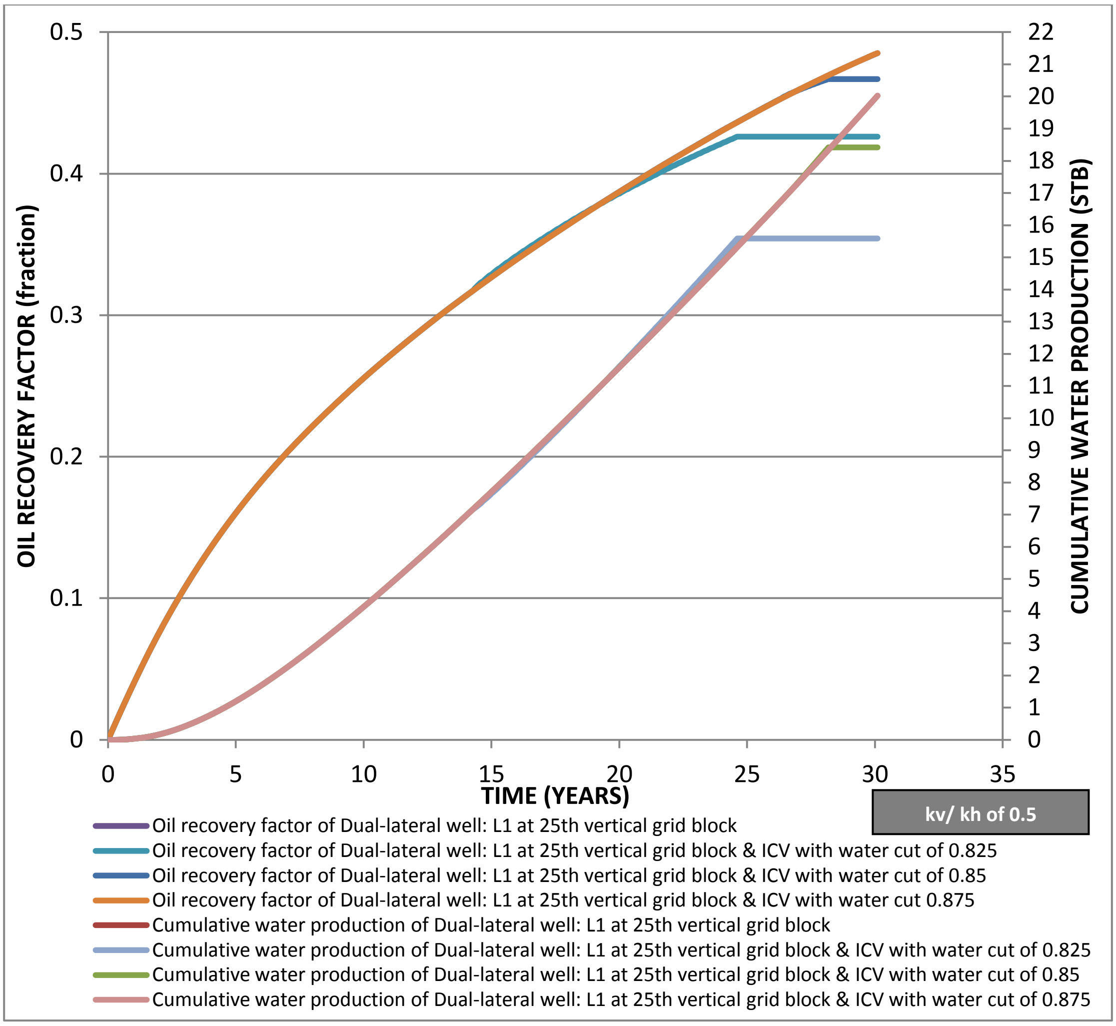


Figure 5.29 Comparison of oil recovery factors and cumulative water production of cases which have no ICV installed and ICV installed at water cut ratio of 0.825, 0.85 and 0.875, of dual-lateral case where L1 is fixed at 25th grid block and k_v/ k_h is 0.5

It is clearly understood from all cases performed over two different depths of L1, under sensitivity of varying k_v/ k_h ratios of 0.2, 0.3 and 0.5, that intelligent completion would not be totally recommended. This is because any preset water cut ratio applying to multilateral wells does not give any difference or even worse result than ones without intelligent completion equipped. This could be possible that at variation of k_v/ k_h ratios, aquifer strength is set at 50 PV. At this value, effect of water encroachment does not make any benefit on installation of ICV and hence, strength of water aquifer is dominant criteria for operation lifetime of well.

CHAPTER VI

CONCLUSION AND RECOMMENDATION

In this section, conclusions of various conducted cases from reservoir simulation are summarized. Also, further recommendations for future study related to this topic are reviewed.

6.1 Conclusion

Conclusions are divided in two main sections: effects of physical aspects multilateral well and sensitivity analysis of chosen petrophysical properties.

6.1.1 Effect of physical aspects of multi-lateral well

1. Dual-lateral well shows advantage over single horizontal well by improving oil production approximately 2% when both have equal effective length. Location depth of second lateral is important design parameter. Upper location could result in gas coning effect which consecutively causes early breakthrough of water cresting from bottom aquifer. On the contrary, lower location close to water-oil contact yields high water cut from high vertical permeability of bottom layer in fining upward sequence. Hence, location of varied lateral should be at the depth where gas coning and water cresting effects are minimal. From this study, the 20th vertical grid block is the best depth for second varied lateral.

2. Improvement of dual-lateral well over horizontal well can be accomplished by installation of intelligent completion to the right location of dual-lateral well as well as presetting appropriate water cut ratio. Wells with two laterals at the same depth are not recommended for intelligent completion to be equipped because wells are quickly shut in when both

branches suffer from water cresting at the same time. Thus, there is no possible space for intelligent completion to work effectively.

3. Preset water cut ratio has to be carefully chosen for each specific depth of branch of dual-lateral well. Inappropriate water cut ratio has to be avoided. Too less water cut ratio affects the ineffectiveness of intelligent completion as well is shut in too quickly before production lifetime terminates. On the contrary, too high water cut ratio leads to the unworthiness of installing intelligent completion.

6.1.2 Sensitivity analysis of petrophysical properties

1. Aquifer strength represented by aquifer size, bigger than 50PV is recommended for installation of intelligent completion. However, when aquifer size exceeds certain value, well can be shut in too early than expected production life time for some values of water cut ratio. In this study, aquifer size of 100PV is best suited for having intelligent completion installed and all chosen preset water cut ratio yields benefit over the same well geometry without intelligent well installed. Aquifer size of 200PV and 300PV are more sensitive to preset water cut ratio because this could lead to early shut in of well. Benefit of intelligent well is more evident when one lateral branch is located close to water aquifer. In this study, when one lateral is located at the 25th vertical grid block, benefit of intelligent completion is higher than when it is located at the 15th.

2. Ratio of vertical permeability to horizontal permeability also plays a major role in effectiveness of intelligent completion installed in dual-lateral well. When this ratio is higher than most common value of 0.1, water cresting phenomena can early reach lateral wells especially if they are located close to bottom aquifer. This condition leads to shutting in of both laterals and consecutively yielding low oil recovery.

6.2 Recommendations

Recommendations are provided for further studies as following:

1. More precise ICV locations in each lateral can be studied. As in more realistic working environment, ICVs are installed in various sections in each branch of horizontal or multilateral wells. Each of the laterals with more sub-segments can be simulated to see effects of ICV installed location. In this study, simplification is performed to adopt one lateral as one segment and have just one ICV installed. As dual-lateral well geometry, by having one depth varied in this study, is complicated enough to see combined effect of intelligent completion equipped in. This recommendation is then suggested to be studied in less complicated well geometry.

2. ICV for gas triggering can be installed for further study. More accurate result of ultimate best possible oil recovery is expected to be yielded if gas coning effect can be observed as much as water in this study.

3. Preset water cut ratio is slightly varied in this study. A more practical study should be performed with broader range.

4. More petrophysical properties can be explored in similar study to see if there is any significance emphasizing on importance of having intelligent completion installed such as aquifer strength of 100PV in this study.

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APPENDIX

APPENDIX

ECLIPSE 100 INPUT DATA FOR RESERVOIR MODELS

Reservoir simulation model is constructed by inputting the required data in Eclipse office simulator as below details

1. Case Definition:

Simulator: Black Oil
Model dimensions
Number of grid in x direction: 50
Number of grid in y direction: 50
Number of grid in z direction: 33
Simulation start date: 1 Jan 2013
Grid type: Cartesian
Geometry type: Corner Point
Oil-gas-water properties: Water, oil, gas and dissolved gas

2. Grid:

Active Grid Block X(1-50) = 1
Y(1-50) = 1
Z (1-30) = 1
Z (31-33) = 0
X Permeability : 50 to 150 md
Y Permeability : 50 to 150 md
Z Permeability : varied by k_v/ k_h ratio
Porosity : 0.2
Grid block sizes : 50 ft for x and y direction & 10 ft for z direction

3. PVT:

PVT properties of formation water

Property	**Value**	**Unit**
Reference pressure (P_{ref})	3,000	psia
Water FVF at P_{ref}	1.021734	rb/ STB
Water compressibility	3.09988E-6	/psi
Water viscosity at P_{ref}	0.3013289	cp
Water viscosibility	3.360806E-6	/psi

Fluid densities at surface condition

Property	**Value (lb/cuft)**
Oil density (ρ_o)	49.99914
Water density (ρ_w)	62.42797
Gas density(ρ_g)	0.04369958

Dry gas PVT properties (No vapourised oil)

Press (psia)	FVF (rb /Mscf)	Visc (cp)
2000	1.4437047	0.016912872
2105.2632	1.3683059	0.017228364
2210.5263	1.300988	0.01755283
2315.7895	1.2406475	0.017885469
2421.0526	1.1863675	0.018225438
2526.3158	1.1373781	0.018571874
2631.5789	1.0930286	0.018923901
2736.8421	1.0527639	0.019280653
2842.1053	1.0161084	0.019641285
2947.3684	0.98265147	0.020004984
3000	0.96700949	0.020187742
3114.1615	0.93533418	0.020585696
3263.1579	0.89814008	0.021107059
3368.4211	0.87434928	0.021475872
3473.6842	0.85237681	0.021844459
3578.9474	0.83203943	0.022212333
3684.2105	0.81317542	0.022579068
3789.4737	0.79564176	0.022944292
3894.7368	0.77931169	0.023307682
4000	0.7640727	0.023668963

Live Oil PVT properties (Dissolved gas)

Rs (Mscf /STB)	Pbub (psia)	FVF (rb /STB)	Visc (cp)
0.58647981	2000	1.3500325	0.34930646
	2105.2632	1.3468712	0.35272421
	2210.5263	1.3440224	0.35633618
	2315.7895	1.3414379	0.36014046
	2421.0526	1.3390824	0.36413023
	2526.3158	1.3369268	0.36829928
	2631.5789	1.3349468	0.37264189
	2736.8421	1.3331217	0.37715282
	2842.1053	1.331434	0.3818272
	2947.3684	1.3298687	0.3866605
	3000	1.3291279	0.3891354
	3114.1615	1.3276085	0.39463413
	3263.1579	1.3257876	0.40207266
	3368.4211	1.3245996	0.4075015
	3473.6842	1.3234846	0.4130702
	3578.9474	1.322436	0.41877547
	3684.2105	1.3214481	0.4246141
	3789.4737	1.3205158	0.43058301
	3894.7368	1.3196345	0.43667918
	4000	1.3188001	0.44289967
0.6238665	2105.2632	1.3695574	0.3402327
	2210.5263	1.3663807	0.34355677
	2315.7895	1.3635047	0.34705876
	2421.0526	1.360884	0.35073777
	2526.3158	1.3584862	0.35458765
	2631.5789	1.3562839	0.35860282
	2736.8421	1.3542542	0.36277808
	2842.1053	1.3523775	0.36710865
	2947.3684	1.3506373	0.37159007
	3000	1.3498137	0.37388604
	3114.1615	1.3481246	0.37898981
	3263.1579	1.3461007	0.38589895
	3368.4211	1.3447803	0.3909444
	3473.6842	1.3435412	0.39612201
	3578.9474	1.3423761	0.40142857
	3684.2105	1.3412784	0.40686097
	3789.4737	1.3402425	0.41241619
	3894.7368	1.3392634	0.41809133
	4000	1.3383365	0.42388352
0.66163814	2210.5263	1.3894295	0.33174693
	2315.7895	1.3862335	0.33498233
	2421.0526	1.3833276	0.33838113
	2526.3158	1.3806693	0.34194328
	2631.5789	1.3782281	0.34566326

	2736.8421	1.3759786	0.34953599
	2842.1053	1.373899	0.35355673
	2947.3684	1.3719707	0.35772112
	3000	1.3710582	0.35985589
	3114.1615	1.369187	0.36460392
	3263.1579	1.366945	0.37103633
	3368.4211	1.3654827	0.37573659
	3473.6842	1.3641104	0.38056217
	3578.9474	1.3628201	0.38550991
	3684.2105	1.3616046	0.39057679
	3789.4737	1.3604577	0.39575987
	3894.7368	1.3593736	0.40105631
	4000	1.3583475	0.40646336
0.69978007	2315.7895	1.4096404	0.32379042
	2421.0526	1.4064215	0.3269417
	2526.3158	1.4034836	0.33024337
	2631.5789	1.4007861	0.33369616
	2736.8421	1.3983007	0.33729507
	2842.1053	1.3960033	0.34103544
	2947.3684	1.3938734	0.34491298
	3000	1.3928657	0.34690191
	3114.1615	1.3907991	0.35132813
	3263.1579	1.3883236	0.3573294
	3368.4211	1.386709	0.36171756
	3473.6842	1.3851941	0.36622488
	3578.9474	1.3837697	0.3708483
	3684.2105	1.3824281	0.37558485
	3789.4737	1.3811622	0.38043168
	3894.7368	1.3799658	0.38538603
	4000	1.3788333	0.3904452
0.73827884	2421.0526	1.4301824	0.31631216
	2526.3158	1.4269375	0.31938348
	2631.5789	1.4239653	0.32259349
	2736.8421	1.4212273	0.32594362
	2842.1053	1.4186967	0.3294293
	2947.3684	1.416351	0.33304628
	3000	1.4152412	0.33490276
	3114.1615	1.4129656	0.33903675
	3263.1579	1.41024	0.34464657
	3368.4211	1.4084626	0.34875141
	3473.6842	1.406795	0.35296988
	3578.9474	1.4052273	0.35729898
	3684.2105	1.4037507	0.36173583
	3789.4737	1.4023577	0.36627762
	3894.7368	1.4010411	0.37092168
	4000	1.3997951	0.3756654

0.77712205	2526.3158	1.4510481	0.30926766
	2631.5789	1.4477743	0.31226282
	2736.8421	1.444766	0.31538613
	2842.1053	1.4419861	0.31863961
	2947.3684	1.4394095	0.32201908
	3000	1.4381906	0.32375483
	3114.1615	1.4356916	0.3276225
	3263.1579	1.4326988	0.33287562
	3368.4211	1.4307475	0.33672233
	3473.6842	1.4289168	0.34067769
	3578.9474	1.4271959	0.34473874
	3684.2105	1.4255753	0.34890265
	3789.4737	1.4240464	0.35316671
	3894.7368	1.4226017	0.35752829
	4000	1.4212343	0.36198486
0.81629822	2631.5789	1.4722307	0.30261788
	2736.8421	1.4689255	0.3055404
	2842.1053	1.4658792	0.3085815
	2947.3684	1.4630561	0.31174376
	3000	1.4617208	0.31336911
	3114.1615	1.4589833	0.31699324
	3263.1579	1.4557053	0.32192026
	3368.4211	1.4535683	0.32553102
	3473.6842	1.4515637	0.32924589
	3578.9474	1.4496795	0.33306196
	3684.2105	1.4479052	0.33697649
	3789.4737	1.4462315	0.34098681
	3894.7368	1.44465	0.34509035
	4000	1.4431534	0.34928465
0.85579672	2736.8421	1.4937237	0.29632847
	2842.1053	1.4903847	0.29918158
	2947.3684	1.4872987	0.30214458
	3000	1.4858392	0.30366866
	3114.1615	1.4828474	0.30706943
	3263.1579	1.4792655	0.31169737
	3368.4211	1.4769307	0.31509178
	3473.6842	1.4747407	0.31858616
	3578.9474	1.4726825	0.32217767
	3684.2105	1.4707446	0.3258636
	3789.4737	1.4689166	0.32964137
	3894.7368	1.4671896	0.33350845
	4000	1.4655553	0.33746245
0.89560764	2842.1053	1.515521	0.29036904
	2947.3684	1.512146	0.29315572
	3000	1.5105542	0.29458666
	3114.1615	1.5072915	0.29778197

	3263.1579	1.5033861	0.30213486
	3368.4211	1.5008407	0.30533031
	3473.6842	1.4984535	0.30862195
	3578.9474	1.4962101	0.31200699
	3684.2105	1.4940981	0.31548279
	3789.4737	1.4921061	0.31904679
	3894.7368	1.4902243	0.32269656
	4000	1.4884436	0.32642972
0.93572175	2947.3684	1.5376168	0.28471261
	3000	1.5358748	0.28606475
	3114.1615	1.5323241	0.28907058
	3263.1579	1.5280744	0.29316982
	3368.4211	1.5253052	0.29618182
	3473.6842	1.5227083	0.29928654
	3578.9474	1.5202682	0.30248125
	3684.2105	1.5179711	0.30576335
	3789.4737	1.5158049	0.30913033
	3894.7368	1.5137585	0.31257982
	4000	1.5118225	0.31610949
0.95588977	3000	1.5487749	0.2819904
	3114.1615	1.5450637	0.28491413
	3263.1579	1.5406341	0.28889388
	3368.4211	1.5377476	0.29181945
	3473.6842	1.5350411	0.29483611
	3578.9474	1.5324981	0.29794116
	3684.2105	1.5301043	0.30113201
	3789.4737	1.5278469	0.30440621
	3894.7368	1.5257146	0.30776137
	4000	1.5236973	0.31119521
0.99988378	3114.1615	1.5732262	0.27631232
	3263.1579	1.5683767	0.28005545
	3368.4211	1.5652239	0.28280461
	3473.6842	1.562268	0.28564154
	3578.9474	1.5594911	0.2885636
	3684.2105	1.5568773	0.29156826
	3789.4737	1.5544128	0.29465309
	3894.7368	1.5520851	0.29781578
	4000	1.5498832	0.3010541

4. SCAL:

Water/ Oil Saturation Functions

Sw	Krw	Kro	Pc (psia)
0.3	0	1	0
0.34444444	0.003950617	0.79012346	0
0.38888889	0.015802469	0.60493827	0
0.43333333	0.035555556	0.44444444	0
0.47777778	0.063209877	0.30864198	0
0.52222222	0.098765432	0.19753086	0
0.56666667	0.14222222	0.11111111	0
0.61111111	0.19358025	0.049382716	0
0.65555556	0.25283951	0.012345679	0
0.7	0.32	0	0
1	1	0	0

Gas/ Oil Saturation Functions

Sg	Krg	Kro	Pc (psia)
0	0	1	0
0.05	0	0.82644628	0
0.1125	0.00703125	0.63274793	0
0.175	0.028125	0.46487603	0
0.2375	0.06328125	0.32283058	0
0.3	0.1125	0.20661157	0
0.3625	0.17578125	0.11621901	0
0.425	0.253125	0.051652893	0
0.4875	0.34453125	0.012913223	0
0.55	0.45	0	0
0.7	1	0	0

5. Initialization:

Equilibration data specification

Datum depth : 5,060 ft

Pressure at datum depth : 2,242 psia

WOC depth : 12000 ft

GOC depth : 5060 ft

6. Regions: N/A

7. Schedule:

- Horizontal well's schedule

Well specification [WELSPECS]

Well name	H1
I location	25
J location	10
Preferred phase	OIL
Inflow equation	STD
Automatic shut-in instruction	SHUT
Cross flow	YES
Density calculation	SEG

Well connection data (for dummy drilling path) [COMPDAT]

Well name	H1
I location	25
J location	10 to 15
K upper	at Z axis location of the horizontal well's depth
K lower	at Z axis location of the horizontal well's depth
Open/shut flag	SHUT
Wellbore ID	0.358 ft
Direction	Y

Well connection data [COMPDAT]

Well name	H1
I location	25
J location	16 to 35
K upper	at Z axis location of the horizontal well's depth
K lower	at Z axis location of the horizontal well's depth
Open/shut flag	OPEN
Wellbore ID	0.358 ft
Direction	Y

Production Well Control [WCONPROD]

Well name	H1
Open/shut flag	OPEN
Control	LRAT
Liquid rate	3000 STB/D
BHP target	200 psia

Production Well Economics Limit [WECON]

Well name	H1
Minimum oil rate	100 STB/D
Workover procedure	WELL
End run	NO
Quantity for economic limit	RATE
Secondary workover procedure	NONE

- Dual-lateral well's schedule

Well specification [WELSPECS]

Well name	H1
I location	25
J location	25
Preferred phase	OIL
Inflow equation	STD
Automatic shut-in instruction	SHUT
Cross flow	YES
Density calculation	SEG

Segmented Well Definition [WELSEGS]

Well name	H1
Depth to top seg node	5000
Length & Depth	INC
Pressure Drop	HFA
Flow Model	HO

Segmented Well Definition [WELSEGS] – for segment information

First Seg	Last Seg	Branch	Outlet Seg	Length (ft)	Depth (ft)	Diameter (ft)	Roughness (ft)
2	30	1	1	10	10	0.358	0.001
31	43	2	L1's depth	50	0	0.358	0.001
44	56	3	20	50	0	0.358	0.001

Well connection data (for dummy drilling path) [COMPDAT]

Well name	H1
I location	25
J location	22 to 25 (Left lateral) & 25 to 28 (Right lateral)
K upper	at Z axis location of each lateral
K lower	at Z axis location of each lateral
Open/shut flag	SHUT
Wellbore ID	0.358 ft
Direction	Y

Well connection data [COMPDAT]

Well name	H1
I location	25
J location	12 to 21 (Left lateral) 29 to 38 (Right lateral)
K upper	at Z axis location of each lateral
K lower	at Z axis location of each lateral
Open/shut flag	OPEN
Wellbore ID	0.358 ft
Direction	Y

Segmented Well Completions [COMPSEG]

I	J	K	Branch	Direction
25	25	2 to 30	1	K
25	25 to 38	L1's depth	2	J
25	12 to 25	20	3	J

- Dual-lateral well equipped with ICV's schedule

Lump Well Connections [COMPLUMP]

Well	H1
I Location	25
J Location	12 to 25 and 25-38
K Upper	@ Depth of L1/ L2
K Lower	@ Depth of L1/ L2
Completion No.	(1 and 2 for right and left lateral)

Production Well Connection Economic Limits [CECON]

Well name	H1
Maximum Water Cut	@ each case's water cut ratio
Workover Procedure when Limit Violated	CON

Testing Instructions [WTEST] – for dual-lateral well with ICV equipped

Well name	H1
Testing Interval	1 day
Closure Reason	C

VITAE

Rinyapat Charoengosan was born on August 11st, 1984 in Bangkok, Thailand. She obtained her bachelor degree in Industrial Engineering from Faculty of Engineering, Chulalongkorn University in 2007. She started her study in Master degree of Petroleum Engineering, Faculty of Engineering, Chulalongkorn University since academic year of 2011.