CHAPTER 4
RESULTS AND DISCUSSION

The results of simulation study are presented and discussed in this chapter. The first part of the chapter is concerned with the efficiency of different well geometries applied in a fluvial reservoir model with variation in permeability, porosity, and saturation. Both openhole and intelligent completions are discussed. Consideration of production constraint (water cut) is included. The second part of the chapter discusses the effect of vertical permeability on oil and water productivity in multilateral wells.

Since the study is based on uncertainty of reservoir properties, a probabilistic function is then necessary in the analysis. To display results, probability curves were constructed by dividing results obtained from 150 synthetic reservoir models into 20 groups of histogram. The results are then reported in term of relative frequency. Simulation results that are analyzed in this study are oil production rate, water production rate, cumulative oil production (N_p), and cumulative water production (W_p).

The cumulative oil production (N_p) and cumulative water production (W_p) are presented in the same graph for each case in order to compare frequency and distribution of the results. After the curves are constructed, the most frequent range of data of each curve is picked as a representative value for that particular case. Other important values such as relative difference from a reference case, water fraction, and recovery factor are determined in order to verify the efficiency of each well geometry. Moreover, the preference of results is determined as the distance fraction, which shows the skewness of oil and water production curves.

In order to calculate the relative difference, the results from horizontal well geometry simulations were considered as references. To compare the results for different well completion systems, openhole case was set up as a reference case. Furthermore, oil and water production rates are plotted to show the effect of water cresting phenomenon for three well geometries.

The reliability of results for all three well geometries can be considered from probabilistic properties such as the mean (μ), standard deviation (σ), coefficient of variation (δ), and relative frequency of the most probable value.

4.1 Efficiency of Multilateral Wells

The average original oil in place can be obtained from the distribution curve as shown in Figure 4.1. The figure illustrates the possible range of results obtained from 150 cases of reservoir models.

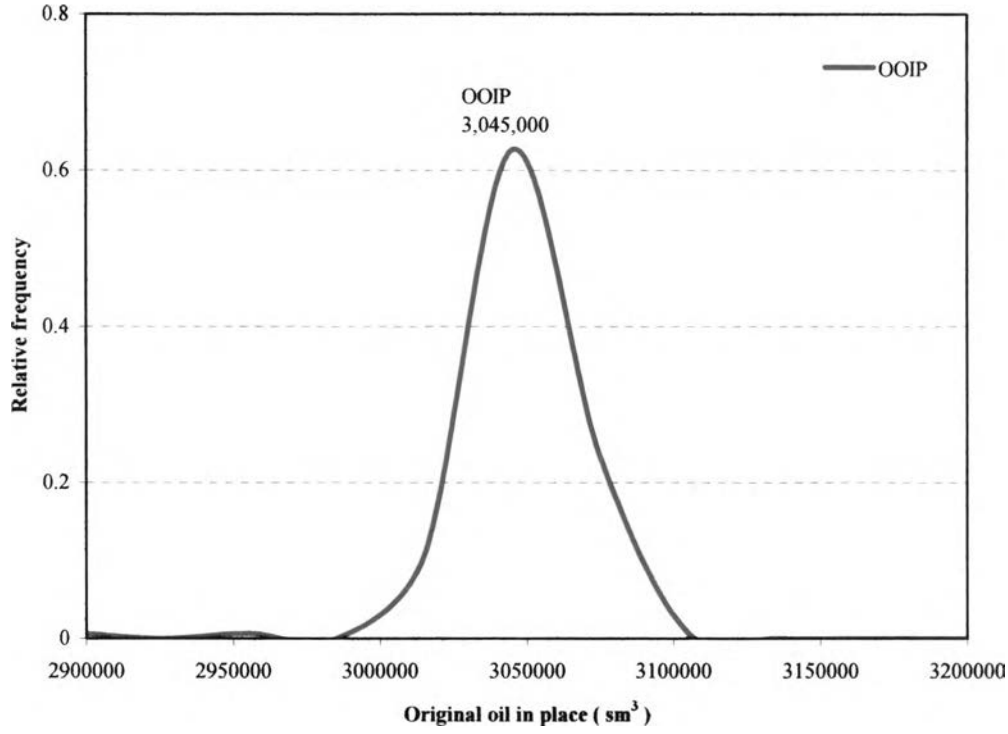

Figure 4.1: Original oil in place distribution curve.

From Figure 4.1, the OOIP of 3,045,000 sm^3 has the highest relative frequency; thus, it is picked as an average OOIP value. The recovery factor is obtained by the formula:

$$\text{Recovery factor } (RF) = \frac{\text{Cumulative oil production } (N_p)}{\text{Original oil in place } (OOIP)}$$

Water fraction which is another important parameter can be calculated from the formula:

$$\text{Water fraction} = \frac{\text{Total water production } (W_p)}{\text{Total liquid production } (N_p + W_p)}$$

The relative difference comparing with the reference case can be obtained by simple calculation:

$$\text{Relative difference} = \frac{\text{Interest value} - \text{Reference value}}{\text{Reference value}} \times 100$$

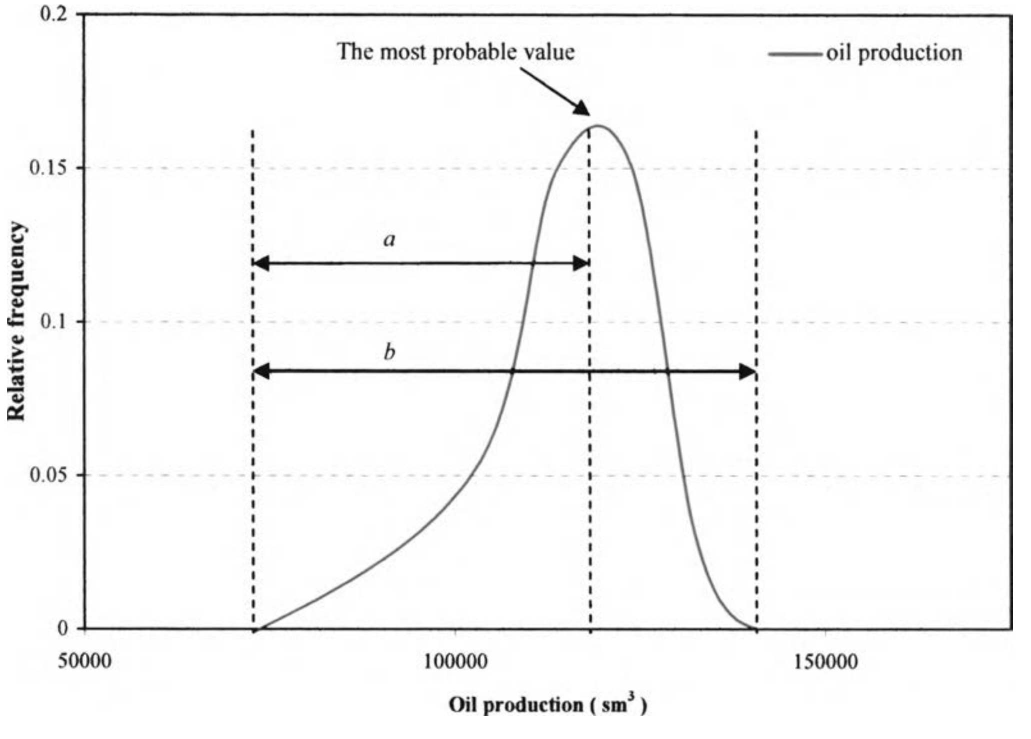

Figure 4.2: Statistical analysis for oil production distribution curve.

In order to compare results from different cases, a distance fraction is defined. As seen in Figure 4.2, *a* is the difference between the most probable value (mode) and the minimum value while *b* represents the difference between the maximum and the minimum value. Consequently, the ratio *a/b* represents the distance fraction of the mode. The distance fraction is used to determine the skewness of curves. For oil production, the favorable result is the right-skewed curve (the most probable value appears on the right side) which signifies good possibility of obtaining high oil production. On the other hand, water production which should be as little as possible can be analyzed in the opposite manner. The optimal result can be obtained when the distance fraction is small (left – skewed curve). Figure 4.3 illustrates the meaning of this parameter.

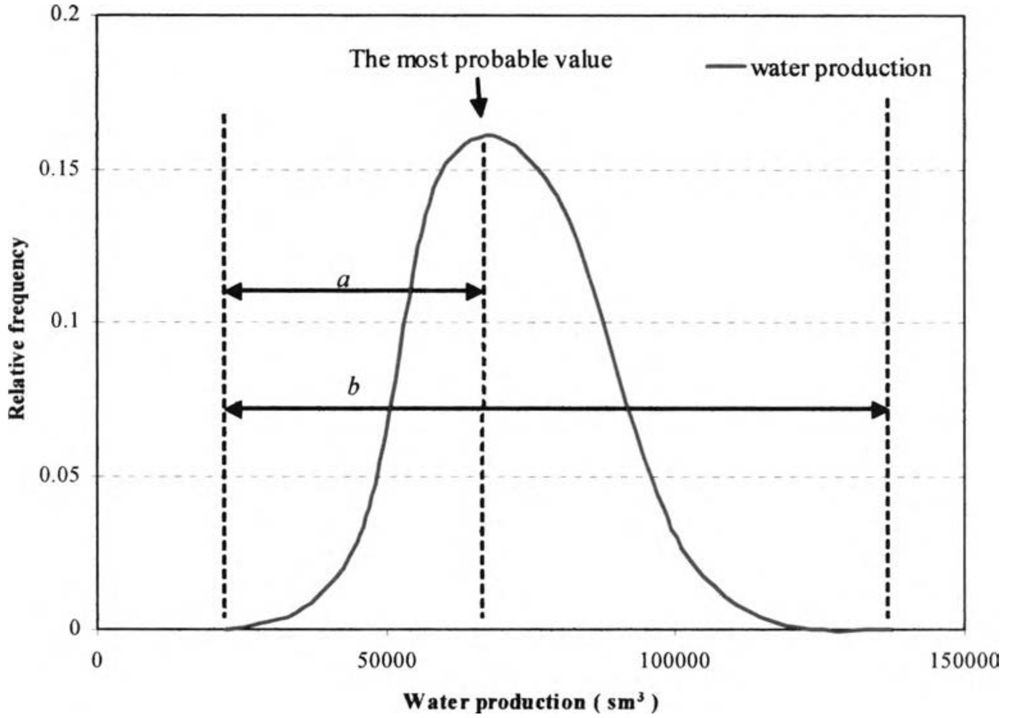

Figure 4.3: Statistical analysis for water production distribution curve.

The significance of statistical values can be analyzed in term of standard deviation which explains the distribution and dispersion of simulation results, shape of the distribution curve, and the position of the most probable value. In order to compare the curves, the coefficient of variation is computed by the formula:

$$\text{Coefficient of variation } (\delta) = \frac{\text{Standard deviation } (\sigma)}{\text{Average value}}$$

4.1.1 Openhole Completion without Water Cut Constraint

In this case, all the wells are completed as openhole (level 1 in TAML classification). The well production period was set up for three years which is adequate to study the advantages obtained by intelligent completion (Marescalco, 2003). Probabilistic distribution curves of total oil and water production were constructed for simulation results of three well geometries: traditional horizontal, bilateral, and fishbone (demonstrated as the capital letters H, B, and F, respectively). Figure 4.4 shows graphical results of the three well geometries.

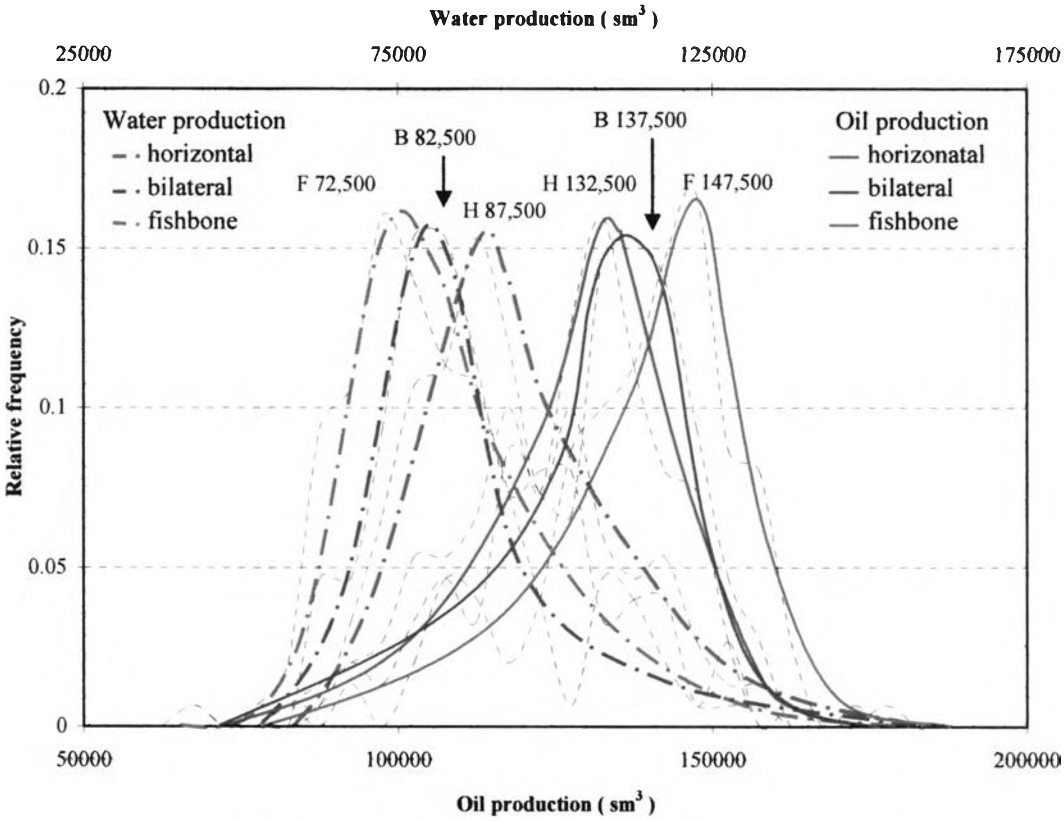

Figure 4.4: N_p and W_p distribution curves of openhole wells.

The solid lines shown in Figure 4.4 (and in subsequent figures) are fitted to the middle value of each histogram linked together as by dash lines. As depicted in Figure 4.4, oil production curves from all well geometries skew to the right side while all water production curves skew to the left. The values of oil and water production with the highest frequency as well as relative differences of oil and water production are tabulated in Table 4.1. Also shown in the table are water fraction and recovery factor.

Table 4.1: Simulation results of openhole completion.

Well geometry	N_p (sm^3)	ΔN_p	W_p (sm^3)	ΔW_p	Water fraction	Recovery Factor
Horizontal well	132,500	-	87,500	-	0.398	0.044
Bilateral well	137,500	3.8 %	82,500	-5.7 %	0.375	0.045
Fishbone well	147,500	11.3 %	72,500	-17.1 %	0.330	0.048

Considering oil and water production, the fishbone well geometry is the most suited for openhole completion. Comparing with traditional horizontal well, the fishbone well increases the oil production by 11.3 % and decreases the water production by 17.1 % while the bilateral well can increase the oil production by 3.8 % and decrease the water production by 5.7 %. Considering well dimension, the fishbone well has the longest total productive length (540 m). Therefore, fluid velocity around the wellbore is smaller than that of the horizontal case (300 m), resulting in the retardation of water cresting phenomena. Moreover, in some cases the branches of bilateral and fishbone wells can totally or partially intercept oil channel stripes which helps increase oil production.

In this openhole case, total liquid production for the 3-year period is constant at 220,000 sm^3 since total liquid production rate is kept constant at 200 sm^3/day. Water fraction from the three well geometries appears to be around 0.3 – 0.4. The lowest value is in the case of fishbone well geometry since it has the smallest water production.

The recovery factor obtained from the fishbone well geometry is the highest in comparison with others because it has the longest total well length and lowest fluid velocity. The recovery factor which is a function of oil production indicates the same improvement as seen in oil production. Since the simulations were run at the a short period of time, the values of recovery factor in these cases are still small.

The preferences for results obtained from each well geometry with openhole completion are illustrated in Table 4.2. As described before, the distance fraction demonstrates the relative location of the most probable values respect to the highest and the lowest values obtained from 150 simulation cases. As seen in the table, the distance fraction of oil production obtained by three well geometries clearly shows an increasing trend when more lateral branches are added. On the other hand, the distance fraction of water production obtained from the three well geometries shows a decreasing trend when there are more of lateral branches. The results indicate that fishbone well provides the most favorable value for both oil and water production compared with other well geometries.

Table 4.2: Distance fraction of oil and water production of openhole wells.

Well geometry	Distance fraction of oil production	Distance fraction of water production
Horizontal well	0.536	0.464
Bilateral well	0.584	0.416
Fishbone well	0.697	0.303

Oil and water rate from one of the 150 models (the case giving the mode value) for each well geometry is shown in Figure 4.5 in order to describe the effect of well geometry on water cresting phenomenon appearing around the laterals. As shown in Figure 4.5, oil production increases in the first period due to horizontal flow of oil from oil zones (oil outside oil channel stripes). After a few days, oil production rate sharply decreases as a result of water cresting arriving from the water aquifer via high permeability channel stripes. On the other hand, an increasing trend in water production after the initial period can be seen in all well geometries. The fishbone well geometry can sustain the plateau production period, longer than traditional horizontal and bilateral geometries. Nevertheless, all well geometries give almost the same oil production rate around 110–115 sm^3/ day in the final period of production.

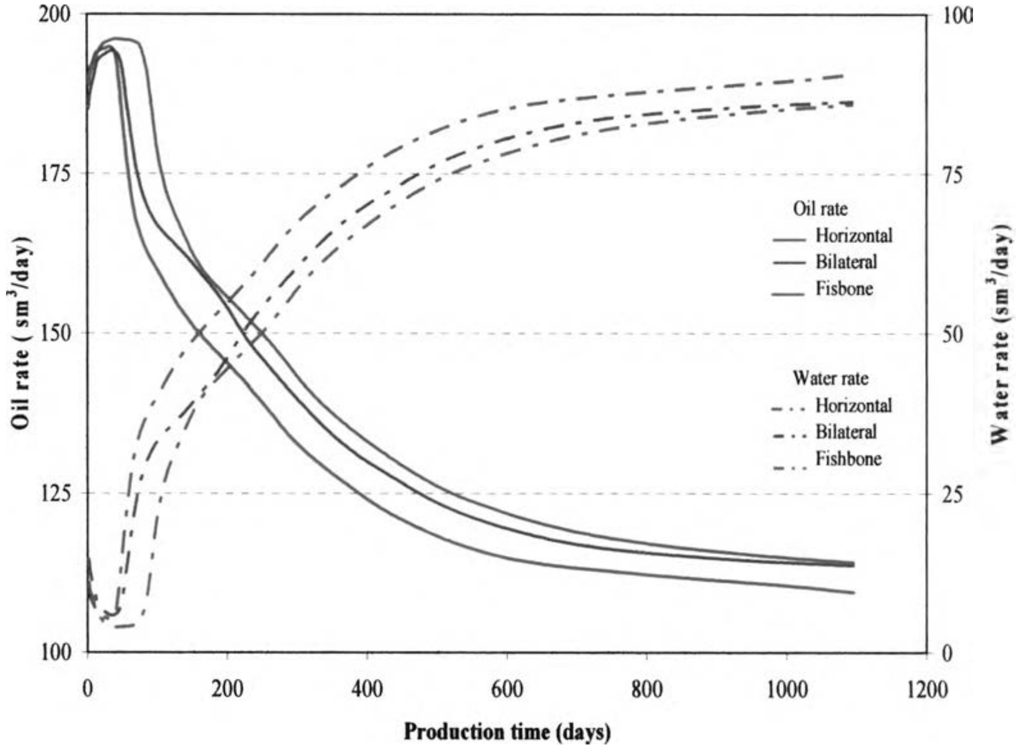

Figure 4.5: Oil and water rate of openhole completion wells.

The reliability of the results obtained for the three well geometries is determined from the coefficient of variation for both oil and water production as shown in Table 4.3. As seen in Table 4.3, the standard deviations for both oil and water production are exactly the same for all well geometries since the total liquid production is controlled to be 220,000 sm^3 for all 150 cases. However, the coefficients of variable for the three well geometries have small difference. The fishbone well has the least value of 0.117 for coefficient of variation of oil production. This means that fishbone well provides the best result in term of reliability of oil production compared with other well geometries. For water production, an increasing trend of coefficient of variation indicates that the fishbone well geometry provides the worst reliability of water production. In any case, the coefficients of variation of oil and water production for all well geometries are considered to be similar.

Table 4.3: Statistical values of oil and water production of openhole wells.

Well geometry	Oil production			Water production		
	μ	σ	δ	μ	σ	δ
Horizontal well	126,047	15,963	0.127	92,953	15,963	0.172
Bilateral well	130,893	16,322	0.125	88,107	16,322	0.185
Fishbone well	137,240	16,053	0.117	81,760	16,053	0.196

Table 4.4: Relative frequency of oil and water production of openhole wells.

Well geometry	Relative frequency of oil production	Relative frequency of water production
Horizontal well	0.160	0.153
Bilateral well	0.153	0.153
Fishbone well	0.167	0.160

The relative frequencies of oil and water production are illustrated in Table 4.4. As seen in Table 4.4, the relative frequencies of the most probable values represented by the heights of the distribution curves appear to be around 0.15 – 0.16 for oil and water production and for all well geometries. From these values, it is difficult to determine the best result in terms of reliability of the results.

In conclusion, the fishbone openhole well provides higher oil production and small water production comparing with other well geometries. However, the reliability of the results from three wells is almost similar and it is difficult to indicate the best well geometry based on reliability of the results.

4.1.2 Application of Intelligent Completion

Since a well with intelligent completion can automatically control water production, the well in this study is equipped with intelligent components as described in Chapter 3. This phase of study emphasizes on the advantages and disadvantages obtained from intelligent completion. Moreover, the comparison between well geometries is discussed. Example of results obtained from the well with inflow control valves is show in Figure 4.6 in terms of oil rate. The mechanism of valve consists of two patterns: opening and shutting. In the first period, all valves are opened, resulting in the oil rate decline as seen in phase 1 in the figure. After the water production reaches a preset limit of 0.2 in some branches, some valves are shut as can be seen in the rising period of the oil rate (phase 2). However, only some valves operate in this phase as seen from lower oil production compared with the first phase. The valve is reopened and shut alternately depends on the water cut value as seen in the phases 3 and 4.

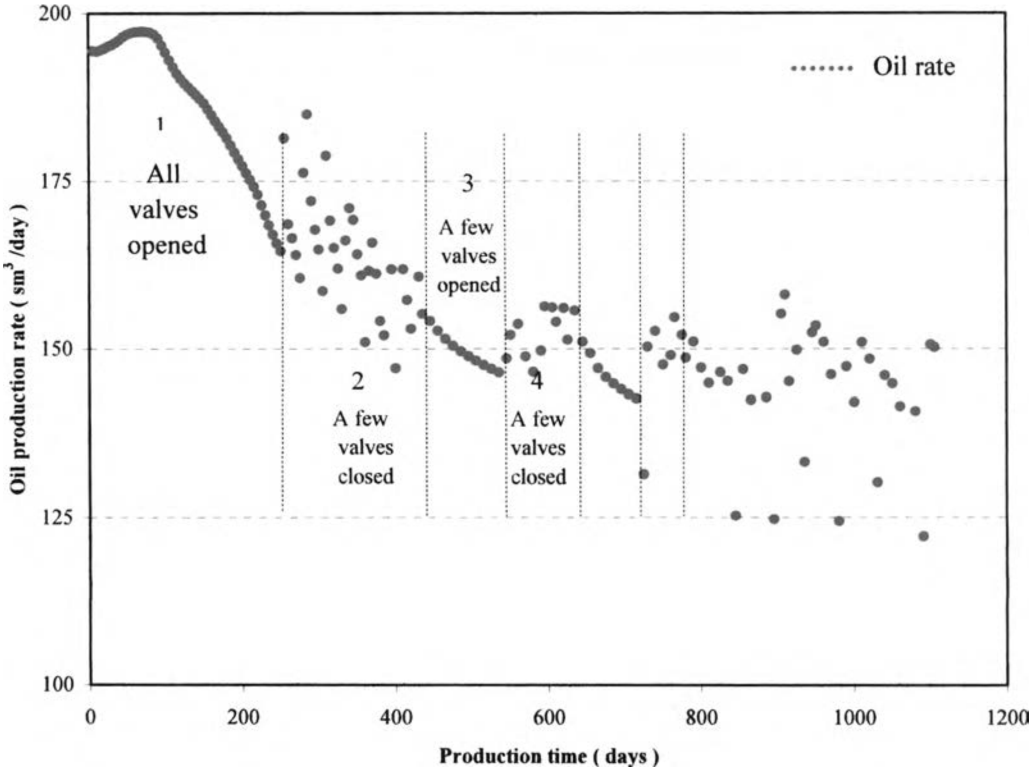

Figure 4.6: The effect from inflow control valve on oil rate taken from fishbone well.

Figure 4.7 illustrates the oil and water production obtained from horizontal and multilateral wells equipped with intelligent completion. As seen in Figure 4.7, the skewness of each curve is quite different. The horizontal configuration has the left-skewed curves for both oil and water production. The bilateral configuration provides right-skewed and left-skewed for oil and water production, respectively. And, the fishbone well has right-skewed curves for both oil and water production. In terms of oil production, the fishbone well geometry provides the best most preferential result.

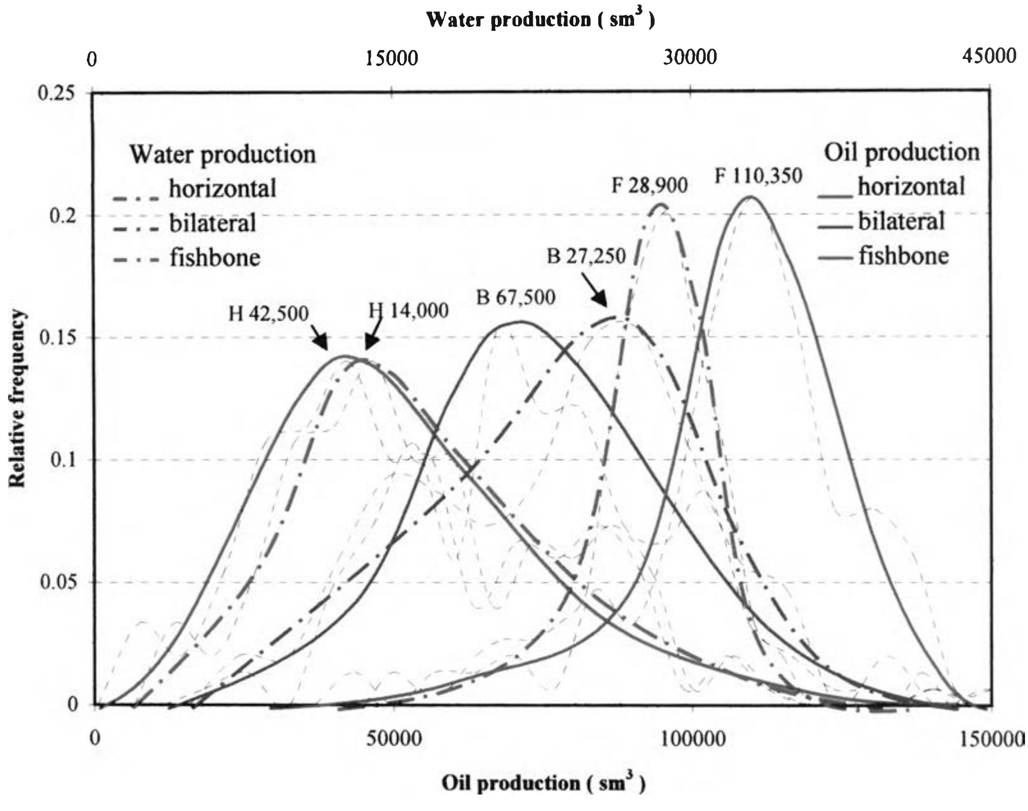

Figure 4.7: N_p and W_p distribution curves of intelligent wells.

From the representative values shown in Figure 4.7, Table 4.5 is then constructed. As depicted in the table, the fishbone well geometry has the highest oil production. A remarkable value of 159.7 % of oil production increment obtained in the case of fishbone well geometry indicates that the combination between fishbone geometry and intelligent completion technology becomes the best nominee comparing with other two well geometries combining with the same technology.

Table 4.5: Simulation results of intelligent wells.

Well geometry	N_p (sm^3)	ΔN_p	W_p (sm^3)	ΔW_p	Total production (sm^3)	Water Fraction	Recovery Factor
Horizontal well	42,500	-	14,000	-	56,500	0.248	0.014
Bilateral well	67,500	58.8 %	27,250	94.6 %	94,750	0.286	0.022
Fishbone well	110,350	159.7 %	28,900	106.4 %	139,250	0.208	0.036

The water production of fishbone well geometry is more than horizontal well by 106.4 %. The reason for high water production in this case is the automatic opening and shutting mechanism of inflow control valves. In the traditional horizontal well, the valve is often shut due to a high pressure drawdown, resulting in a decrease in total liquid production. On the other hand, the fishbone is shut less frequently resulting in higher liquid production (both oil and water production). Nevertheless, water production is proportional to total liquid production, giving a ratio around 0.2-0.3 (due to limiting water cut value).

The recovery factor obtained by the combination of each well geometry and intelligent completion shows a clear incremental trend as a higher number of lateral branches is used. Based on the recovery factor, the fishbone well geometry combined with intelligent completion is the best candidate since its recovery factor is around three times higher than that of horizontal well and 1.5 times higher than that of bilateral well.

The distance fractions of intelligent wells are illustrated in Table 4.6. As seen in the table, fishbone well geometry shows the most favorable result comparing with traditional horizontal and bilateral geometries. This can be observed from the distance fraction which is 0.282, 0.363, and 0.511 for horizontal, bilateral, and fishbone well geometries, respectively. This indicates that the most probable value tends to appear closer to the highest value when more lateral branches are applied. The same trend can be obtained in the distance fraction of water production meaning that there is a high possibility to have high water production in the fishbone case.

The results indicate that intelligent well provides more favorable results in term of oil production when more branches are added to the horizontal mainbore. However, in water production tends to increase as more branches are applied.

Table 4.6: Distance fraction of oil and water production of intelligent wells.

Well geometry	Distance fraction of oil production	Distance fraction of water production
Horizontal well	0.282	0.251
Bilateral well	0.363	0.434
Fishbone well	0.511	0.522

In order to study the effect of water cresting phenomena, oil and water production rates from all well geometries are plotted in Figures 4.8 and 4.9, respectively. In this case, graphical results are presented as dots instead of continuous line in order to represent non-continuous well production due to automatic opening and shutting of inflow control valves. As shown in Figure 4.8, the fishbone well geometry combined with intelligent completion has an ability to retard water cresting phenomena. The oil rate from the fishbone well (green dot) remains more or less constant around 195 sm^3/day until the day 100^{th}. The gradual decline in oil rate is due to water crest retardation ability. Non-continuous and sharply decreasing rates shown in red color obtained from traditional horizontal well indicates that intelligent completion starts its function in a few days of production due to a rapid decline in production rate. In the final production period, the production rate from horizontal well scatters meaning that the lateral is sometimes opened (high oil production rate). On the other hand, the lateral of bilateral and fishbone wells are opened more often, thus yielding higher oil flow rates. Figure 4.9 illustrates water production rate of intelligent wells. From the figure, the inverse trends of those shown in figure 4.8 are illustrated. This confirms that water cresting phenomenon arrives first in the horizontal well and last in the fishbone well. In summary, high oil production and water cresting phenomenon retardation obtained from the fishbone well geometry equipped with intelligent completion verify that the fishbone is the best choice.

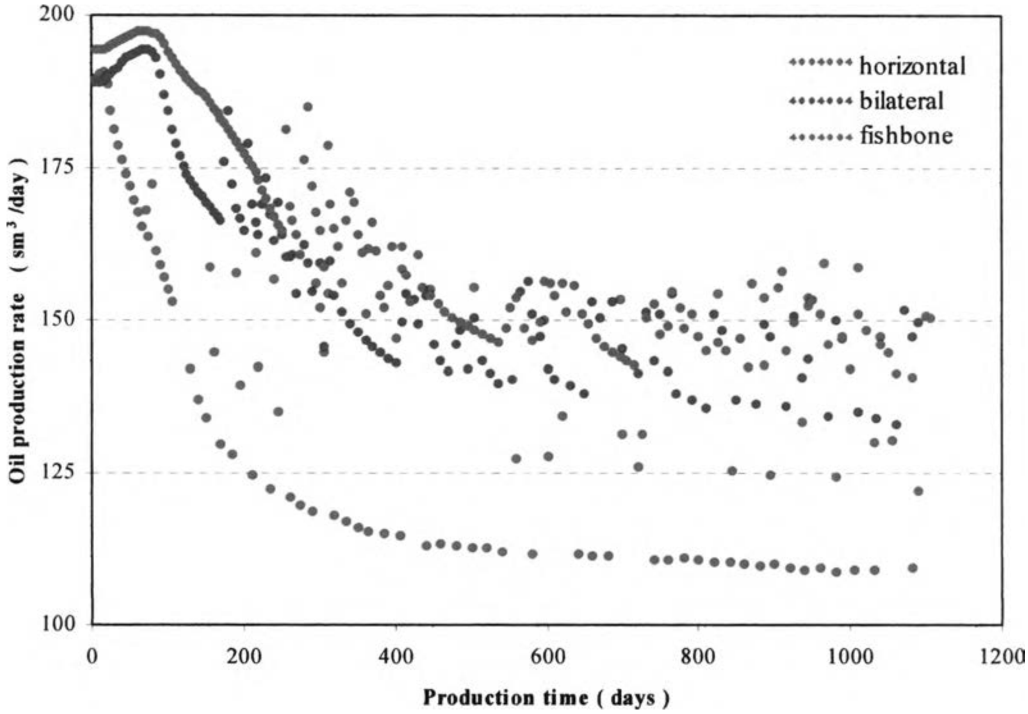

Figure 4.8: Oil rate of intelligent wells.

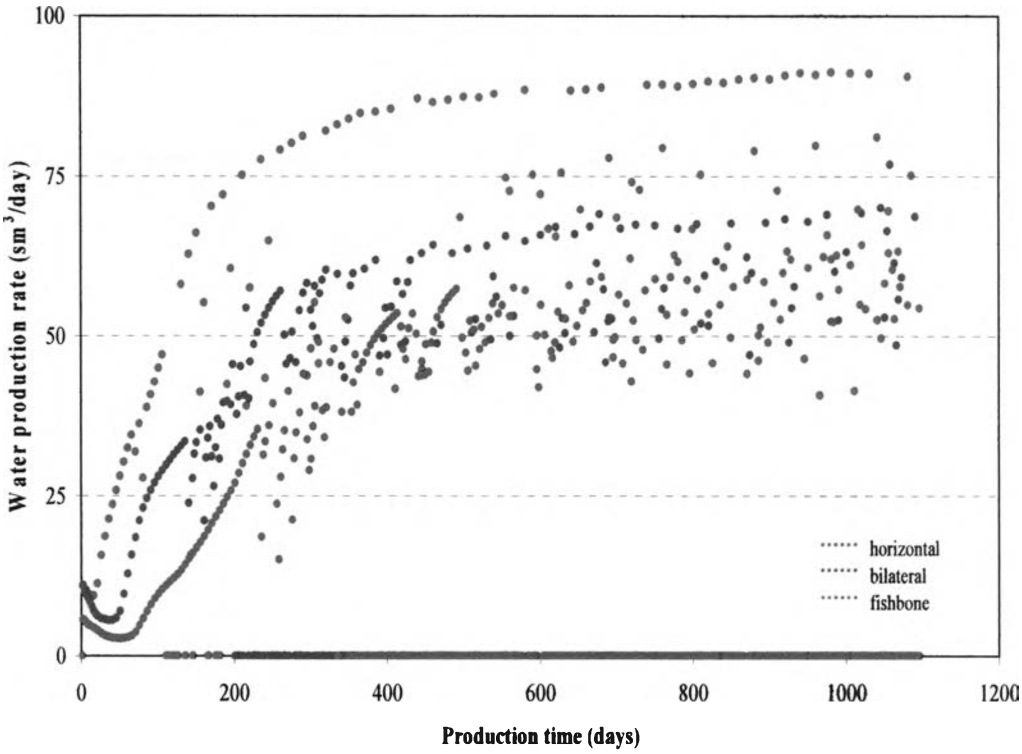

Figure 4.9: Water rate of intelligent wells.

In order to confirm the reliability of the results, statistical values of oil and water production were calculated. Table 4.7 and 4.8 show these values calculated for the case of completion. As seen in Table 4.7, the coefficient of variation of oil and water production obtained from the intelligent fishbone well are the smallest when compared with the values for other well geometries. This means that the result of the fishbone well with intelligent completion is less disperse than results of other. For this reason, the values of oil and water production in the case of fishbone well are more certain. Above all, the reason that the fishbone well geometry has better reliability than other well geometries is that the lateral branches are appropriately placed to intersect as much as possible the channel stripes (this is also seen in the bilateral well geometry).

Table 4.7: Statistical values of oil and water production of intelligent wells.

Well geometry	Oil production			Water production		
	μ	σ	δ	μ	σ	δ
Horizontal well	52,349	25,157	0.481	20,960	10,262	0.490
Bilateral well	74,745	22,472	0.301	23,838	8,168	0.343
Fishbone well	110,009	19,678	0.179	27,842	4,001	0.144

Table 4.8: Relative frequency of oil and water production of intelligent wells.

Well geometry	Relative frequency of oil production	Relative frequency of water production
Horizontal well	0.140	0.100
Bilateral well	0.154	0.153
Fishbone well	0.207	0.200

As seen in Table 4.8, the higher relative frequency of oil production of the fishbone well (0.207) comparing with those of the other two geometries (0.140 and 0.153) indicates that the most probable value of oil production has a higher chance of occurring. Since the most probable oil production of the fishbone geometry is the highest, it means that the fishbone well geometry is the best choice for intelligent completion. For water production, the relative frequency value obtained from the fishbone well geometry is substantially higher than the values obtained from horizontal and bilateral geometries (0.200 comparing with 0.100 and 0.153). This means that it is more likely that the fishbone well produces water at the most probable value which is quite high. Therefore, we are likely to have a large amount of water production.

It can be concluded that intelligent completion is remarkably suited with the fishbone well geometry. The combination yields the highest oil production among the cases considered.

4.1.3 Comparison between Openhole and Intelligent Completion

In the comparison between openhole and intelligent completion, the total liquid production is substantially decreased since the wells are applied with intelligent elements. Intelligent wells are often interrupted by the automatic opening and shutting mechanism of inflow control valves to limit water production not to exceed a pre-specified value.

In intelligent completion, lateral branch and horizontal mainbore are considered as independent segments. Each segment is equipped with inflow control valve in order to limit water production at a maximum water cut. In our study, we used 0.2 as the maximum water cut. Therefore, it is possible that all the segments are shut if the water cut in horizontal mainbore which is the only one for fluid to transfer to the surface is greater than 0.2 even the rest of the branches have water cuts lower than 0.2.

Although the junction between lateral branches and the horizontal mainbore of intelligent well are plugged using plugging materials in order to avoid water cresting, the production is mainly influenced by the mechanism of intelligent elements.

The comparisons between openhole and intelligent completion are divided into two aspects; quantity and reliability. For quantity aspect, six values are used in order to compare:

- Total oil production
- Total water production
- Water fraction
- Total liquid production
- Distance fraction of oil production
- Distance fraction of water production

In the reliability aspect, the investigated values are:

- Coefficient of variation of oil production
- Coefficient of variation of water production
- Relative frequency of oil production
- Relative frequency of water production

These values are used to evaluate the reliability of results obtained from simulation cases.

4.1.3.1 Traditional Horizontal Well Geometry

In order to compare the effectiveness between openhole and intelligent completion, two sets of simulation results were plotted as shown in Figure 4.10. In the figure, it demonstrates oil and water production obtained from openhole and intelligent completion for horizontal well. Using the openhole completion as a reference case, Tables 4.9 and 4.10 were created to compare results from the two cases in terms of relative differences.

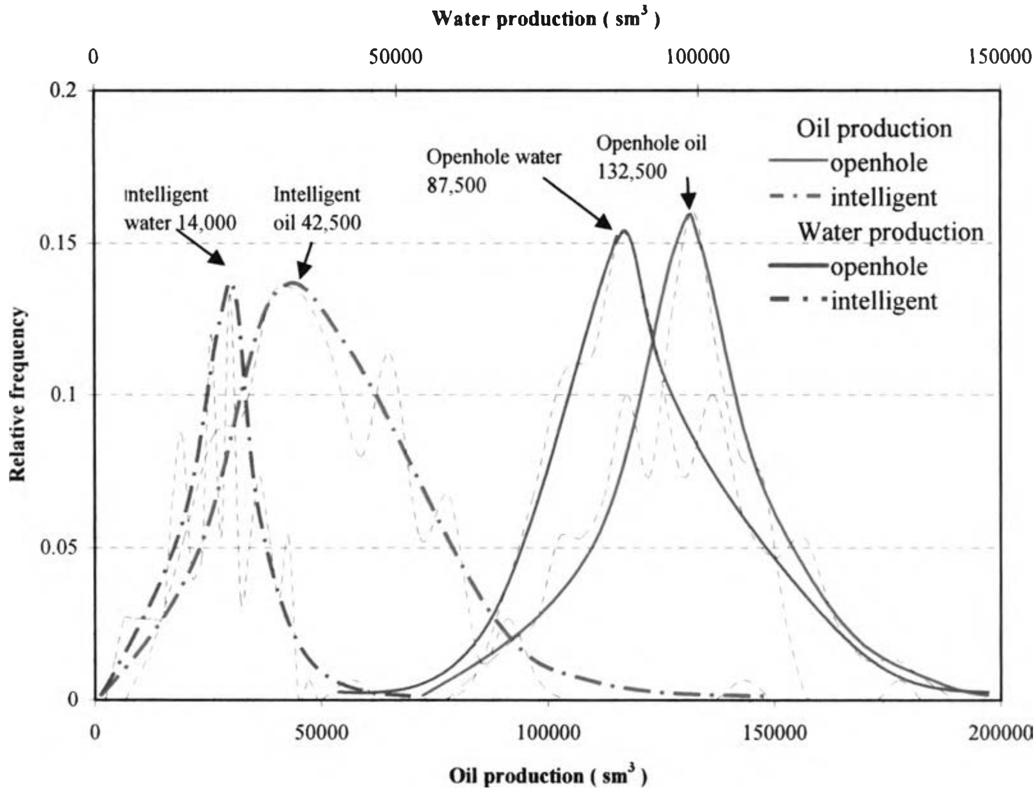

Figure 4.10: N_p and W_p distribution curves of traditional horizontal well geometry.

As seen in Figure 4.10, better results are obviously obtained from openhole completion. In intelligent completion, oil production skews to the left which is considered as a bad result. However, interpretation of the results can be done using parameters shown in Tables 4.9 and 4.10.

Table 4.9: Relative differences between horizontal openhole and intelligent wells.

Δ N_p	Δ W_p	Δ Water fraction	Δ Total production	Distance fraction of oil	Distance fraction of water
-211.8 %	-525.0 %	-60.5 %	-289.4 %	-47.4 %	-45.9 %

As shown in Table 4.9, significant disadvantages are obtained when the intelligent elements are installed. First, total liquid production is remarkably decreased by 289.4 % by automatic shutting and opening of inflow control valve function. This results in a great reduction of oil production by 211.8 % which is a major disadvantage.

A decrease of 47.4 % in the value of distance fraction for oil production means that the most probable value in intelligent completion favors to appear close to the maximum value less than that in the openhole case. For water production, a reduction of 45.9 % shows a great advantage. This signifies that the most probable value could appear closer to the minimum value.

Table 4.10: Relative differences of statistics between horizontal openhole and intelligent wells.

$\Delta\ \delta$ N_p	$\Delta\ \delta$ W_p	Δ Relative frequency N_p	Δ Relative frequency W_p
278.7 %	184.9 %	-12.5 %	-34.6 %

The consideration in reliability aspect is shown in Table 4.8. The coefficients of variation of oil and water production is considered as disadvantages of intelligent completion due to high variation of oil and water production.

The relative frequencies for oil and water production in intelligent completion case decrease relatively by 12.5 % and 34.6 %, respectively when compared with openhole completion. A big reduction in the relative frequency of water production incurs less reliability in the result and difficulty to predict the water production amount.

In summary, the application of intelligent completion combined with traditional horizontal well geometry results in many disadvantages espectially a big reduction of oil production. Moreover, decrease in reliability is also considered as a disadvantage.

4.1.3.2 Bilateral Well Geometry

In order to determine an appropriate completion strategy for bilateral well geometry, two sets of simulation runs using openhole and intelligent completion were carried out. The bilateral well has the effective length of 480 m. In intelligent completion, the well is divided into three parts: horizontal mainbore and two lateral branches. An inflow control valve is installed at the junction of each segment. The length of bilateral intelligent well is extended in order for the well to have the same effective length with the openhole case since there is plugging at the junction in order to avoid water cresting phenomenon.

Nevertheless, the junction plug protects the well from water crest only the first period of production since the well is located in a strong water drive area. After the water crest arrives at each segment, the intelligent system automatically operates by shutting a high water cut branch while increases production rate in other segments which have water cut less than the limiting rate. The closed segment is reopened again when the water cut ratio decreases below the preset allowance.

Figure 4.11 compares oil and water productions from openhole and intelligent completion. As seen in Figure 4.11, the shapes of openhole curves are right-skewed for oil production and left-skewed for water production. On the other hand, results obtained in intelligent completion case behave just the opposite. Although bilateral well combined with intelligent completion has two lateral branches appropriately located in oil channel stripes, the inflc w control valves still often operate by water cut constraint. This results in a reduction of total liquid production by 76.8 % and a decrease of 103.7 % in oil production comparing with the value in the openhole case.. The water production and water fraction substantially decrease by 202.8 % and 31.1 %, respectively. These advantages partially compensated the disadvantage in reduction of oil production.

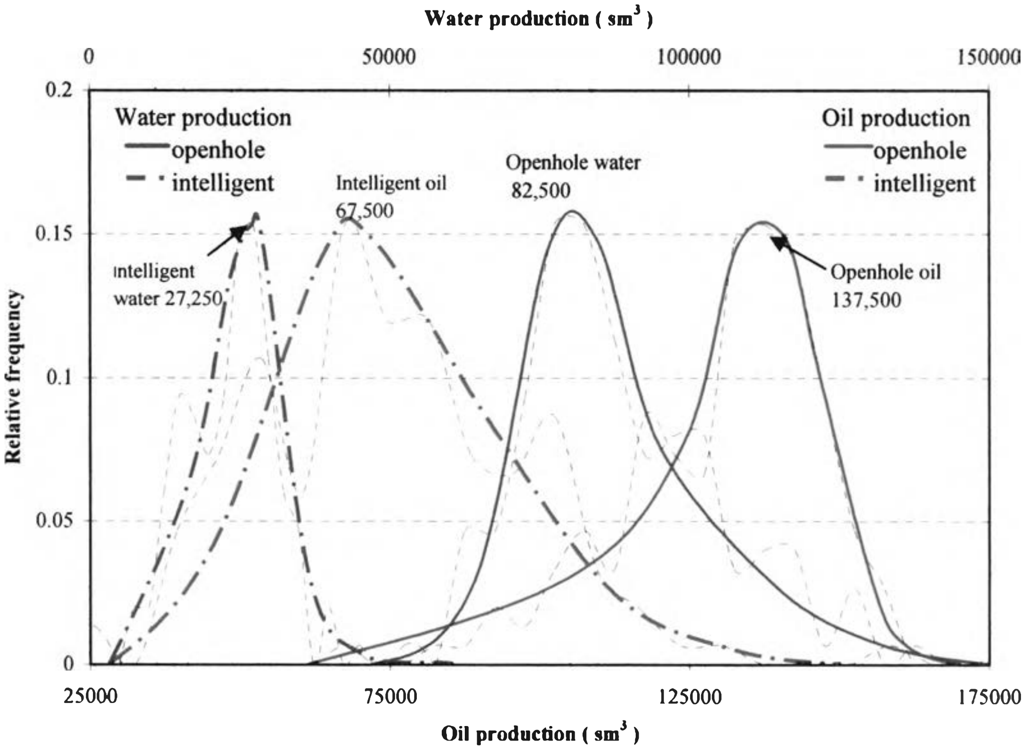

Figure 4.11: N_p and W_p distribution curves of bilateral well geometry.

Table 4.11: Relative differences between bilateral openhole and intelligent wells.

ΔN_p	ΔW_p	Δ Water fraction	Δ Total production	Distance fraction of oil	Distance fraction of water
-103.7 %	-202.8 %	-31.1 %	-76.8 %	-37.8 %	5.0 %

Moreover, Table 4.11 illustrates the distance fractions of oil and water productions of bilateral well combined with openhole and intelligent completions. The distance fraction of oil production decreases by -37.8 %, indicating that the application of intelligent completion yields less value of the most probable oil production while that of water production increases by 5.0 % which is considered to be small and does not give much significance.

Table 4.12: Relative differences of statistics between bilateral openhole and intelligent wells.

$\Delta\,\delta$ N_p	$\Delta\,\delta$ W_p	Δ Relative frequency N_p	Δ Relative frequency W_p
140.8 %	85.4 %	0.7 %	0 %

Table 4.12 shows the statistical values obtained from bilateral well. The coefficient of variation of oil and water production changes by 140.8 % and 85.4 %, respectively. This indicates worse result in terms of data distribution due to variation of oil and water production incurred from automatic mechanism of inflow control valves. Regarding relative frequencies for both oil and water production, it is obvious that the application of intelligent completion does not change these values since the relative differences are around zero.

In summary, the application of intelligent completion with bilateral well geometry gives disadvantage in terms of less oil and worse reliability for oil and water production.

4.1.3.3 Fishbone Well Geometry

In order to investigate the effect of completion type on the fishbone geometry, two sets of simulation cases were performed: one for openhole completion and the other for intelligent completion. The fishbone well has the longest effective length which is 540 m.

Figure 4.12 illustrates the probability curves of oil and water productions for both completion systems. As seen in Figure 4.12, the openhole well provides right-skewed curve for oil production and left-skewed curve for water production. However, the distribution curves for oil and water production from intelligent completion are more or less symmetrical (there is only a slight skewness for oil production).

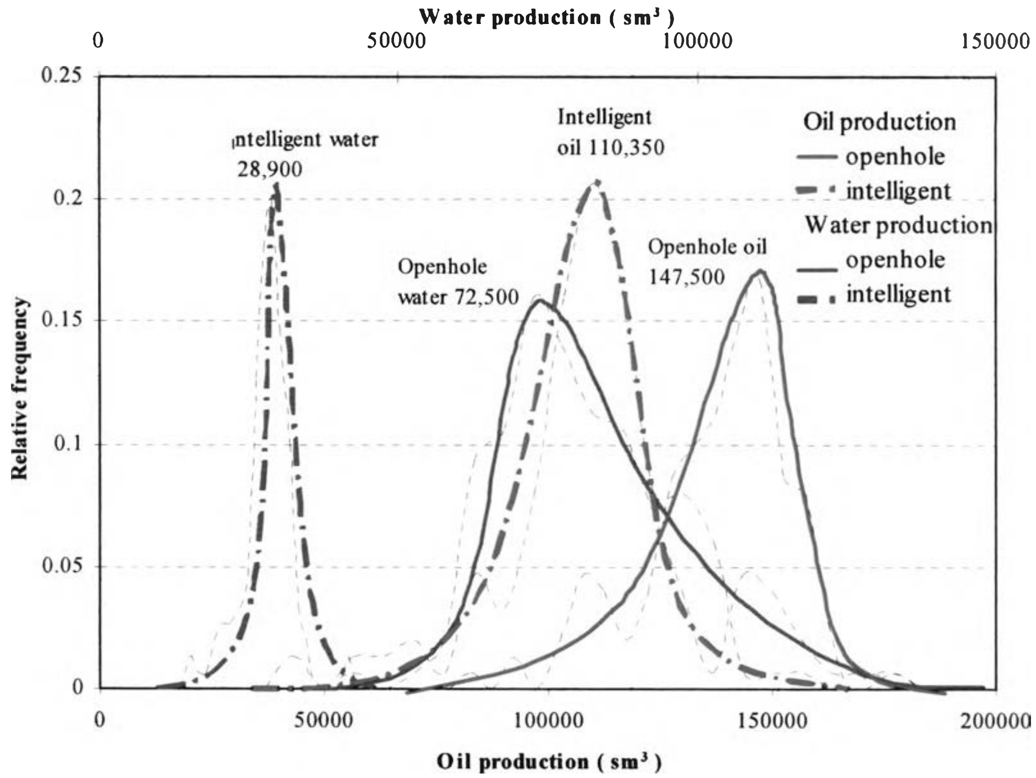

Figure 4.12: N_p and W_p distribution curves of fishbone well geometry.

Table 4.13: Relative differences between fishbone openhole and intelligent wells.

ΔN_p	ΔW_p	Δ Water fraction	Δ Total production	Distance fraction of oil	Distance fraction of water
-33.7 %	-150.9 %	-58.7 %	-58.0 %	-26.7 %	72.3 %

Table 4.13 shows the relative difference between fishbone openhole wells. As depicted in the Table, the total liquid production decreases by 58 % and oil production decreases by 33.7 % resulting from the mechanism of inflow control valves. An advantage obtained from this combination is the reduction of water production by 150.9 %. Moreover, water fraction reduces by 58.7 %. Considering the distance fraction of the most probable value, intelligent completion gives a moderate reduction of oil production by 26.7 % and an increment of water production by 72.3 %,

indicating that the application of intelligent completion worsens the favorable oil and water production values.

Table 4.14: Relative differences of statistics between fishbone openhole and intelligent wells.

$\Delta\,\delta$ N_p	$\Delta\,\delta$ W_p	Δ Relative frequency N_p	Δ Relative frequency W_p
53.0 %	-26.5 %	24.0 %	25.0 %

As seen in Table 4.14, the coefficient of variation of oil production increases by 53.0 % while the coefficient of variation of water production substantially decreases by 26.5 % relative to that of the openhole completion. For the water production, the reduction of data dispersion is obtained as the coefficient of variation decreases, indicating that more certain results can be obtained when intelligent completion is implemented.

The relative frequency for oil and water production increases by 24.0 % and 25.0 %, respectively, meaning that the results from intelligent completion cases are more reliable than those obtained from openhole case.

In order to summarize the results of openhole and intelligent completion cases for all three well geomtries, Tables 4.15 and4.16 are constructed. As shown in Table 4.15, oil production, water production, and total liquid production all decrease when intelligent completion is used. However, the reduction becomes smaller in the case of bilateral well and smallest in the case of fishbone well since the effective length increases.

Table 4.15: Relative difference between openhole wells and intelligent wells considering quantity aspect.

Well geometry	Δ N_p	Δ W_p	Δ Water fraction	Δ Total production	Δ Distance fraction N_p	Δ Distance fraction W_p
Horizontal well	-211.8 %	-525.0 %	-60.5 %	-289.4 %	-47.4 %	-45.9 %
Bilateral well	-103.7 %	-202.8 %	-31.1 %	-76.8 %	-37.8 %	5.0 %
Fishbone well	-33.7 %	-150.9 %	-58.7 %	-34.9 %	-26.7 %	72.3 %

Regarding oil production, the fishbone well geometry shows the best performance since it has the least reduction in oil production comparing with traditional horizontal and bilateral well geometries. On the other hand, water production which should be reduced as much as possible has the least reduction in the fishbone well geometry.

Water fraction does not show a clear trend as in other considerations. The value that is different from the rest is the bilateral case. This results from water fraction in intelligent completion case that is quite high (actually this value should be controled at 0.2 in this case) comparing with other well geometries. This results from the simulation step when the well is often shut and there is a large amount of water entering the well before the well is shut (inflow control valve is automatically shut in the first step after water cut is higher than 0.2).Considering on production, the application of intelligent completion gives the best result when it is applied with the fishbone well geometry. The fishbone well geometry combined with intelligent completion has the best reduction in oil production.

Considering the distance fraction of oil production, the fishbone well geometry has the least reduction in distance fraction. The water production shows an opposite interpretation since there is more water production where there are more laterals.

Table 4.16: Relative difference between openhole wells and intelligent wells considering reliability aspect.

Well geometry	Δ δ N_p	Δ δ W_p	Δ Relative frequency N_p	Δ Relative frequency W_p
Horizontal well	278.7 %	184.9 %	-12.5 %	-34.6 %
Bilateral well	140.8 %	85.4 %	0.7 %	0 %
Fishbone well	53.0 %	-26.5 %	24.0 %	25.0 %

As illustrated by the smallest relative changes in coefficients of variation of oil and water production and highest relative differences of the relative frequencies of oil and water production in Table 4.16, the fishbone well with intelligent completion gives the most reliable result. The coefficient of variation shows a decreasing trend from horizontal well to fishbone well for both oil and water production. This result indicates that data dispersion decreases when more lateral branches are added to the mainbore. Considering the coefficient of variation of water production for the fishbone well, dispersion of water production substantially decreases when intelligent completion is implemented. The relative frequencies of oil and water production show an increasing trend from horizontal well to fishbone well geometries. This signifies a higher possibility to obtain the most probable value.

4.1.4 Comparison between Openhole and Intelligent Completion Considering Water Cut Limit

Water production from certain wells need to be limited. These wells have to be shut when water production reaches a maximum allowance. This leads to the following study which assigns both openhole and intelligent wells to have the same water production limit.

In this phase of study, comparison between efficiency of openhole completion and intelligent completion with limited water production was investigated. Since control valves in intelligent completion are set to shut off when a water cut value of 0.2 is reached, the openhole wells are now constrained to be shut when the water cut reaches 0.2 (in order to make a comparison concerning water production constraint).

Figure 4.13 illustrates the probability curves of three well geometries completed openhole when the maximum water cut is set at 0.2. As seen in Figure 4.13, both oil and water productions of three well geometries skew to the left. This indicates that oil and water production both tend to be small.

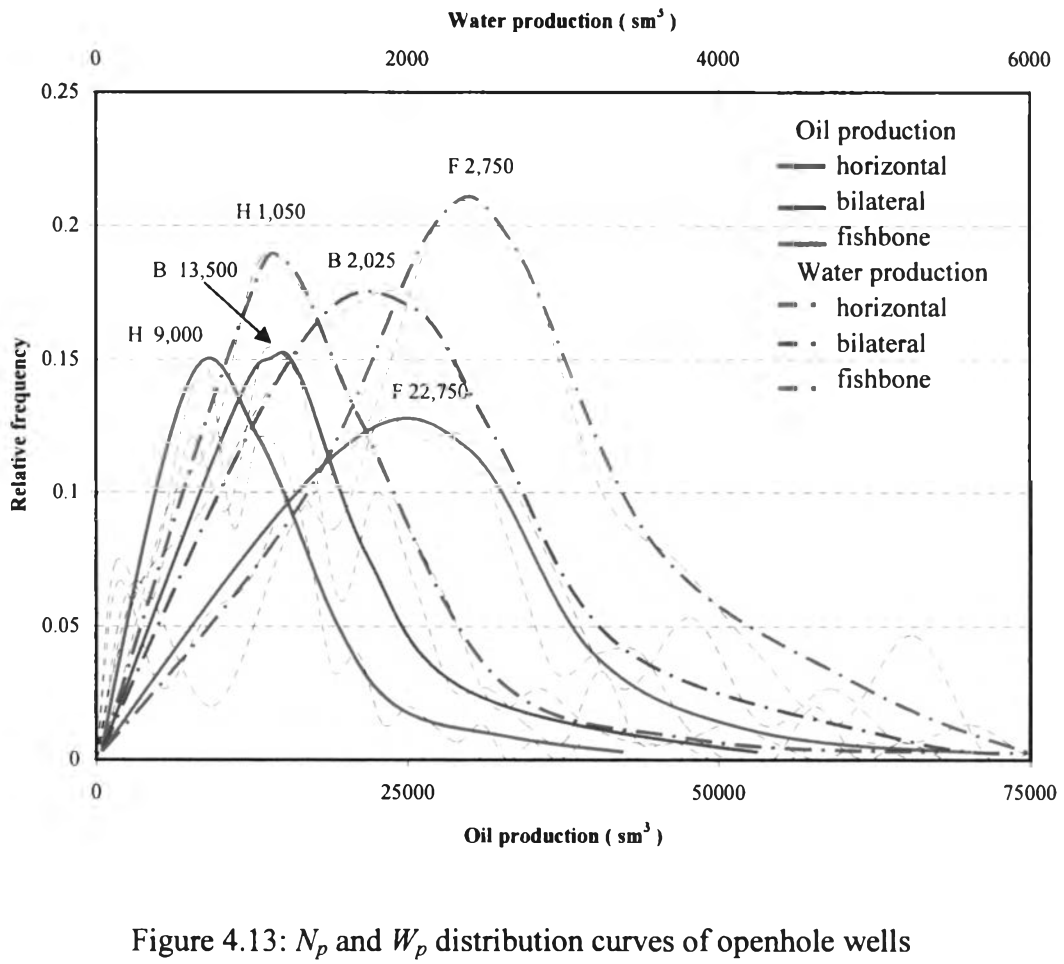

Figure 4.13: N_p and W_p distribution curves of openhole wells with a maximum water cut of 0.2.

Table 4.17: Simulation results of openhole wells with a maximum water cut of 0.2.

Well geometry	N_p (sm^3)	ΔN_p	W_p (sm^3)	ΔW_p	Total production	Water fraction	*RF*
Horizontal well	9,000	-	1,050	-	10,050	0.104	0.003
Bilateral well	13,500	50.0 %	2,025	92.9 %	15,525	0.130	0.004
Fishbone well	22,750	152.8 %	2,750	161.9 %	25,500	0.108	0.007

Table 4.17 summarizes the production data and some parameters obtained from Figure 4.13. As seen in Table 4.17, water production of each well reaches the maximum water cut of 0.2 very early. This results in a small amount of oil production. Comparing between well geometries, the fishbone well provides the best result due to its longest length. Water cresting phenomenon occurs the earliest in the horizontal well geometry, causing the well to shut early and produce less amount of oil. The fishbone geometry is the last one to shut, giving the highest oil production. Since the traditional horizontal well is kept as a reference case, the fishbone well geometry provides higher oil production by 152.8 % while the bilateral well gives higher oil production by 50.0 %.

The water production obtained from the fishbone well geometry is the highest due to a longer period of production. It increases by 61.8 % comparing with horizontal well geometry. However, the average water fraction is simply 0.108 which is quite small. The recovery factor varies accordingly to the oil production. The fishbone well geometry gives the best result (0.007) while the horizontal well geometry gives the worst result (0.003).

Distance fractions of oil and water production of openhole wells with a maximum water cut of 0.2 are shown in Table 4.18. As depicted in the table, the distance fraction of oil production obtained from the fishbone well geometry is the best although the value is still less than 0.5. This means that the fishbone geometry has better ability to produce oil production closer to the highest value. The distance fraction of water increases as the total effective length increases. Since the horizontal well is the first to be shut, it has the smallest amount of water production. On the other hand, production period is extended in the fishbone well geometry. Thus, the most probable value of water production increases.

Table 4.18: Distance fraction of oil and water production of openhole wells with a maximum water cut of 0.2.

Well geometry	Distance fraction of oil production	Distance fraction of water production
Horizontal well	0.233	0.164
Bilateral well	0.231	0.218
Fishbone well	0.341	0.282

The oil and water production rate for all three well geometries is illustrated in Figure 4.12 in order to examine the production profile and water cresting phenomenon. Oil and water production rate from one of the 150 models is plotted in the figure.

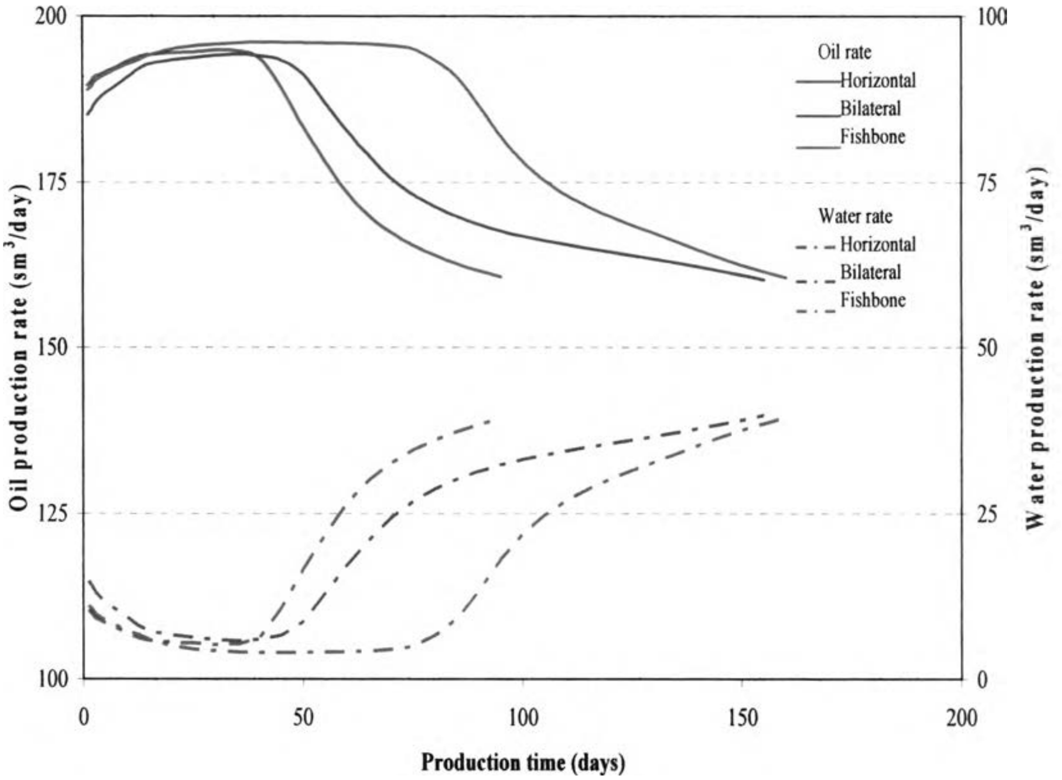

Figure 4.14: Oil and water rate of openhole wells with a maximum water cut of 0.2.

As shown in Figure 4.14, the oil rate reaches 160 sm^3/day when the well is shut because the water cut reaches 0.2 (water production rate is 40 sm^3/day). It can be seen from water rate curves that water crest arrives first in the horizontal well geometry. The well can be produced for approximately 90 days before it is shut in. In the case of bilateral well and fishbone well geometries, water crest arrives later and the well can maintain the production for a longer period.

For reliability study, Table 4.19 and 4.20 show the results in terms of average value, standard deviation, coefficient of variation, and relative frequency of oil and water production. As depicted in Table 4.19, the coefficients of variation of oil and water production do not show any clear trend due to a small period of production.

Table 4.19: Statistical values of oil and water production of openhole wells with a maximum water cut of 0.2.

Well geometry	Oil production			Water production		
	μ	σ	δ	μ	σ	δ
Horizontal well	12,687	6,912	0.545	1,551	913	0.589
Bilateral well	17,061	10,415	0.610	2,196	1,396	0.636
Fishbone well	23,783	12,603	0.530	2,687	1,471	0.547

Table 4.20: Relative frequency of oil and water production of openhole wells with a maximum water cut of 0.2.

Well geometry	Relative frequency of oil production	Relative frequency of water production
Horizontal well	0.147	0.307
Bilateral well	0.153	0.300
Fishbone well	0.127	0.207

As shown in Table 4.20, the relative frequency of oil production does not show a clear trend while a decreasing trend of relative frequency of water production can be found when the total effective length increases. Since the production period is extended, the range of possible production also increases, resulting in increased dispersion of results and the change in the curve shape.

In summary, the fishbone well geometry provides the best oil production due to its ability to retard water cresting phenomenon.

However, the above discussion is only concerned with comparison among well geometries. More important point is the comparison between openhole and intelligent completion when the water cut is constrained. As in the previous section, openhole completion is considered as reference case. Table 4.21 and 4.22 were constructed in order to compare openhole and intellignet completion for the same water cut value.

Table 4.21: Relative difference between openhole wells and intelligent wells considering quantity aspect with the same water cut of 0.2.

Well geometry	Δ N_p	Δ W_p	Δ Water fraction	Δ Total production	Δ Distance fraction N_p	Δ Distance fraction W_p
Horizontal well	372.2 %	1233.3 %	138.5 %	462.2 %	21.0 %	53.0 %
Bilateral well	400.0 %	1245.7 %	120.0 %	510.3 %	87.9 %	99.1 %
Fishbone well	385.0 %	950.0 %	92.5 %	446.1 %	53.1 %	85.1 %

As shown in Table 4.21, the values are around 380 - 400 % for oil production, 1000 - 1200 % for water production, 100 - 130 % for water fraction, and 450 - 500 % for total production. Even though the values are quite high, the significance can be found in fishbone well geometry by increasing the least water production and water fraction. This can be summarized that within three years of production, all intelligent wells produce oil around four times more than openhole well considering the same water cut while water production will increase around ten times. The distance fraction of oil and water production does not show any clear trend of the relative difference when the geometry is varied from horizontal to fishbone well However, he most probable values are higher than that of the horizontal well geometry. The differences between results of all well geometries can be found in the statistical analysis demonstrated in Table 4.22.

Table 4.22: Relative difference between openhole wells and intelligent wells considering reliability aspect with the same water cut of 0.2.

Well geometry	Δ δ N_p	Δ δ W_p	Δ Relative frequency N_p	Δ Relative frequency W_p
Horizontal well	-11.7 %	-16.8 %	-4.8 %	-67.4 %
Bilateral well	-50.7 %	-46.1 %	0.7 %	-49.0 %
Fishbone well	-66.2 %	-73.7 %	63.0 %	-3.4 %

As illustrated in Table 4.22, the relative differences of coefficients of variation for both oil and water productions show a decreasing trend from horizontal to fishbone geometries. This indicates that intelligent completion gives better results for both oil and water production than openhole completion when the effective well length increases.

The relative frequencies show an increasing trend when the well geometry changes from horizontal to fishbone well for both oil and water productions. This indicates that intelligent completion shows more certain results when there are more lateral branches.

In summary, all well geometries with intelligent completion produce around four times more oil and ten times more water than openhole wells with corresponding configuration. Concerning reliability of the results, the values of oil and water production from the fishbone well geometry with intelligent completion are the most reliable, having the smallest dispersions of data distribution and highest relative frequencies of the most probable values.

4.2 Vertical Permeability Study

Vertical permeability is one of the parameters that affect oil recovery, particularly, when there is a presence of aquifer. The fishbone well geometry, which gives the best result in all the previous cases, was chosen for the study of vertical permeability effect. In order to determine the best completion strategy, openhole and intelligent completions are applied to the fishbone well geometry. The values of vertical permeability were reduced by a factor of 0.5 and 0.2 in order to study this effect.

4.2.1 Openhole Completion

Results from running two sets of simulations using two new values of vertical permeability are compared with the original results. Figure 4.15 graphically illustrates oil and water productions. As seen in Figure 4.15, oil and water productions obtained from all well geometries show favorable results. Right-skewed curves for oil production and left-skewed curves for all water production can be seen in all the cases.

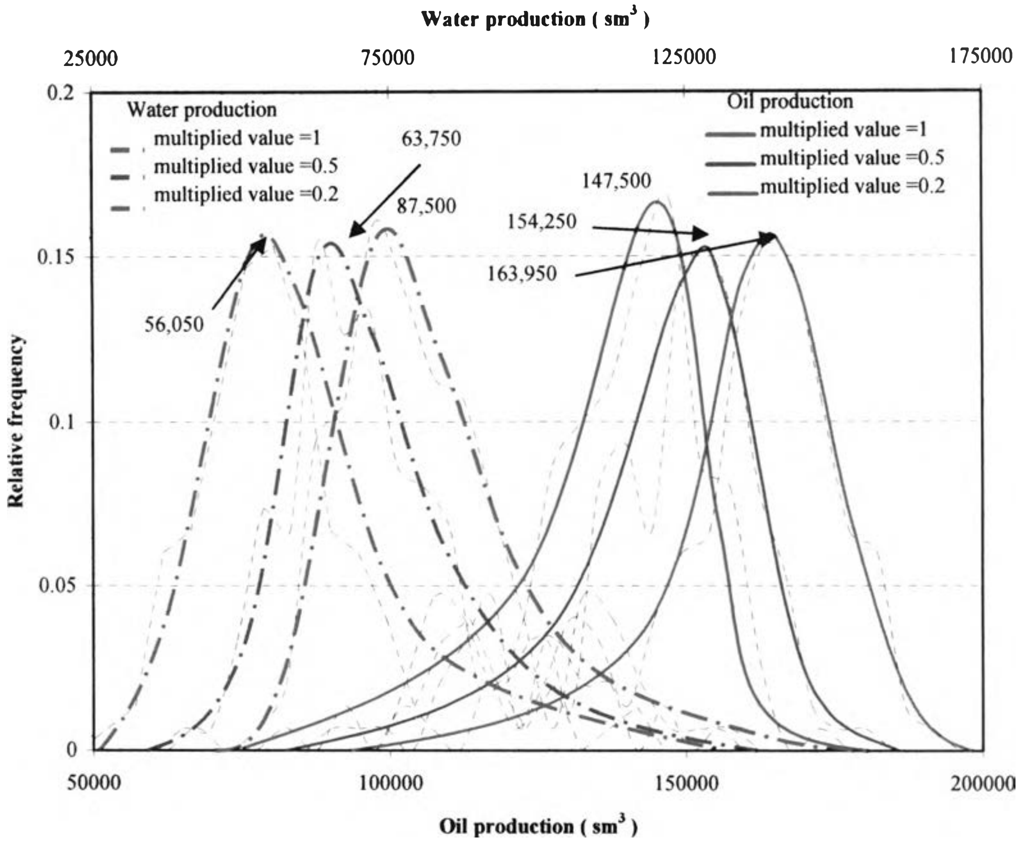

Figure 4.15: N_p and W_p distribution curves of fishbone openhole well for different vertical permeabilities.

Table 4.23: Simulation results of fishbone openhole wells for different vertical permeabilities.

Multiplied value	N_p (sm^3)	W_p (sm^3)	Water fraction	Recovery Factor
1	147,500	72,500	0.329	0.048
0.5	154,250	63,500	0.289	0.051
0.2	163,950	56,050	0.255	0.054

Table 4.23 summarizes the results obtained from three sets of reservoir simulations. As depicted in Table 4.23, oil production increases as the vertical permeability decreases. The total production rate is controlled to be 200 sm3/day while the water production is not controlled. Since the oil production increases, the water production has to decrease. Figure 4.16 illustrates the relationship between vertical permeability and oil and water production for the fishbone well geometry with openhole completion.

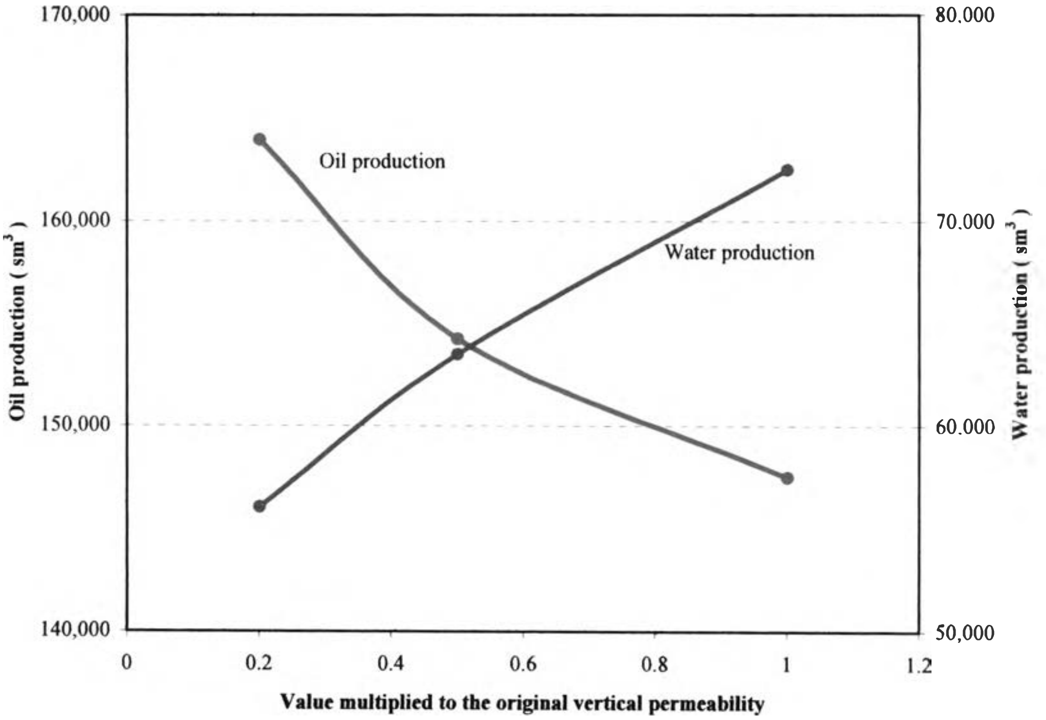

Figure 4.16: Relationship curves between vertical permeability and liquid production for fishbone openhole completion.

Since the well does not have a control on water production, the water fraction is quite high, especially in the case with a high vertical permeability which allows water to arrive early at the lateral wellbore during the water cresting phenomenon.

Table 4.24: Distance fraction of oil and water production of fishbone openhole wells for different vertical permeabilities.

Multiplied value	Distance fraction of oil production	Distance fraction of water production
1.0	0.697	0.303
0.5	0.720	0.280
0.2	0.695	0.303

Table 4.24 shows the distance fractions of oil and water production for different vertical permeabilities. As shown in Table 4.24, both distance fractions do not show any significant difference among the three well geometries.

In order to study the effect of water cresting, oil and water rates are plotted in Figure 4.17. The data from one of the models are used in this plot. As shown in Figure 4.17, oil rate for all values of vertical permeability start to drop at the same period which is around day 100^{th}. However, oil rate from a reservoir with a higher vertical permeability declines faster than that from a low vertical permeability reservoir. This happens because water from the aquifer reaches the laterals faster when the vertical permeability is high, seen as an increasing trend of the dash lines (water production rate) in Figure 4 17.

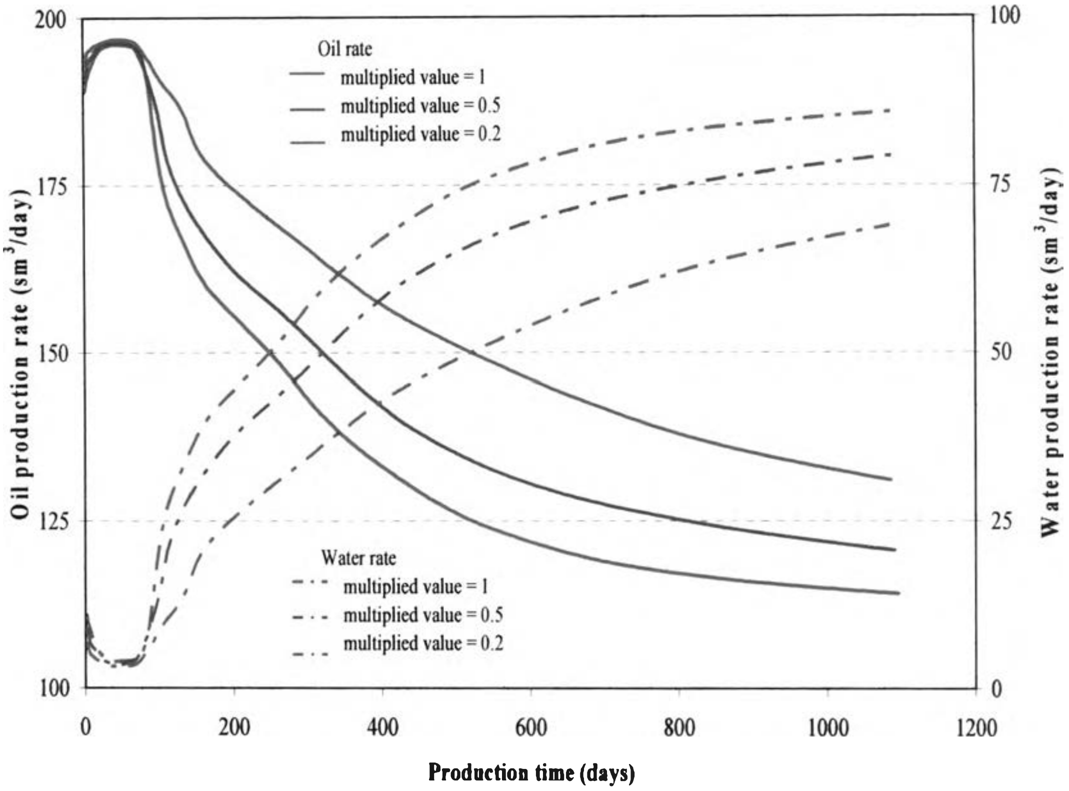

Figure 4.17: Oil and water rate obtained from fishbone openhole well for different vertical permeabilities.

In order to investigate reliability of the results, Tables 4.25 and 4.26 are constructed to compare important statistical values. As depicted in Table 4.25, the coefficient of variation for oil production slightly decreases as the vertical permeability decreases while that for water production substantially increases. This indicates that in low vertical permeability reservoir, the dispersion of water production is greater.

Table 4.25: Statistical values of oil and water production of fishbone openhole wells for different vertical permeabilities.

Multiplied value	Oil production			Water production		
	μ	σ	δ	μ	σ	δ
1.0	137,240	16,053	0.117	81,760	16,053	0.196
0.5	145,280	16,873	0.116	73,719	16,873	0.229
0.2	159,090	17,776	0.112	59,910	17,776	0.297

Table 4.26: Relative frequency of oil and water production of fishbone openhole wells for different vertical permeabilities.

Multiplied value	Relative frequency of oil production	Relative frequency of water production
1.0	0.167	0.160
0.5	0.153	0.153
0.2	0.153	0.153

Table 4.26 shows the relative frequencies for different vertical permeabilities. As shown in Table 4.26, the relative frequencies are slightly different. From Tables 4.25 and 4.26, it can be concluded that vertical permeability affects the dispersion of possible water production.

4.2.2 Intelligent Completion

Besides openhole completion, intelligent completion was also studied when the vertical permeability changes. In this case, the water cut is limited to 0.2. Figure 4.18 shows the distribution of fishbone well with intelligent completion in three reservoirs having vertical permeability of 1.0, 0.5, and 0.2 times the original vertical permeability. As seen in Figure 4.18, all curves do not show obvious skewness. However, it is slightly seen that favorable results are not obtained; left-skewed for oil production and right- skewed for water production.

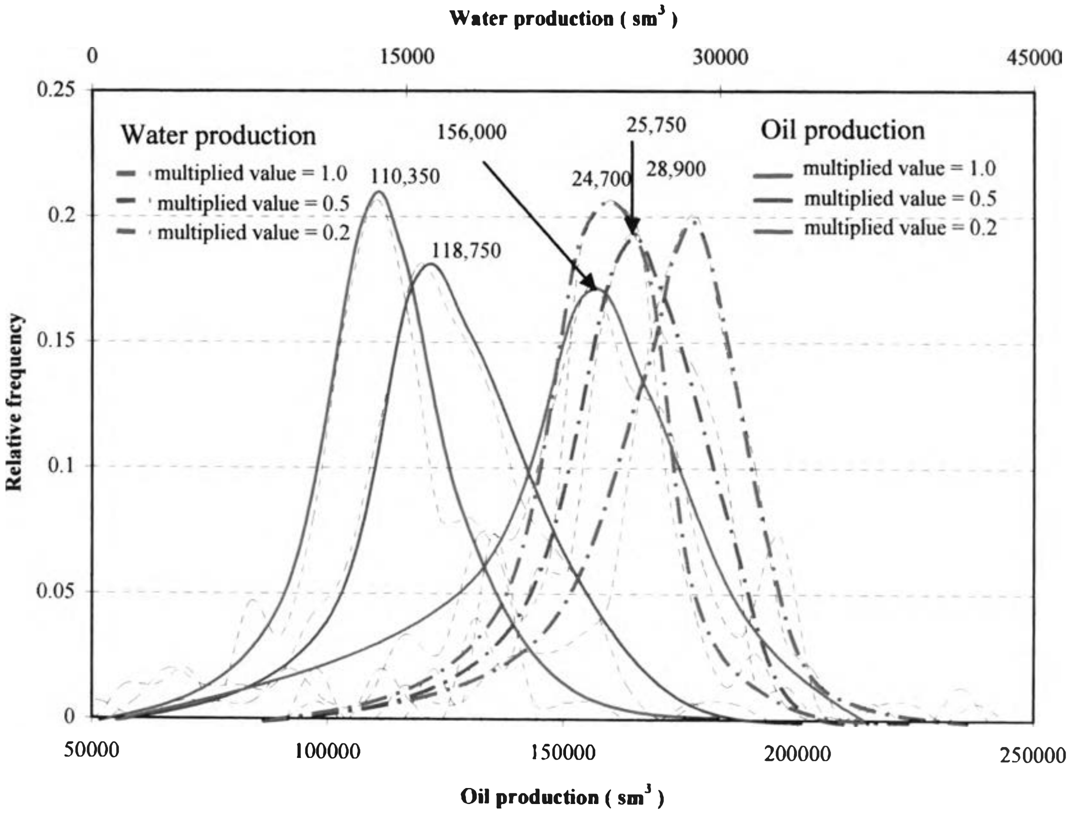

Figure 4.18: N_p and W_p distribution curves of fishbone intelligent well for different vertical permeabilities.

Table 4.27: Simulation results of fishbone intelligent well for different vertical permeabilities.

Multiplied value	N_p (sm^3)	W_p (sm^3)	Total production (sm^3)	Water fraction	Recovery Factor
1	110,350	28,900	139,250	0.208	0.036
0.5	118,750	25,750	144,500	0.178	0.039
0.2	156,000	24,700	180,700	0.137	0.051

As depicted in Table 4.27, oil production obviously increases as vertical permeability becomes lower. However, water production decreases since it is harder for the water to flow from the aquifer to the laterals through a low vertical permeability zones. The inflow control valves operate less frequently in a low vertical permeability reservoir. Low water production and water fraction can be obtained in a lower vertical permeability reservoir in which water cresting phenomenon has the the least effect.

In order to explain production rate during the productive life, oil and water rates from one of the models are shown in Figures 4.19 and 4.20, respectively. As shown in Figures 4.19 and 4.20, we can see that water from the aquifer arrives first in the case of high vertical permeability around the 70th day. In the other two cases, water reaches the laterals on the 100th day and 150th day. In the case of lowest vertical permeability, there are two production trends: the trend from the first day of production and the trend starting from the 400th day. This can be described that in very low vertical permability reservoir, lateral flow has more effect to the well production than vertical flow. Intelligent well is produced by mean of lateral flow in the first period. Before water arrives, oil rate starts to drop which is seen in the first trend. After that, an enormous amount of oil from outside oil channel stripes arrives at the well which is represented the second trend (starting at day 400th). At the same time, water from the aquifer vertically arrives, resulting in decline of oil production in the second trend. This production behavior can also be found when the vertical permeability is multiplied by 0.5 but less pronounce. It should be noted that this behavior cannot be found in openhole production cases because the wells produce continuously without automatic shutting and opening of flow control valves.

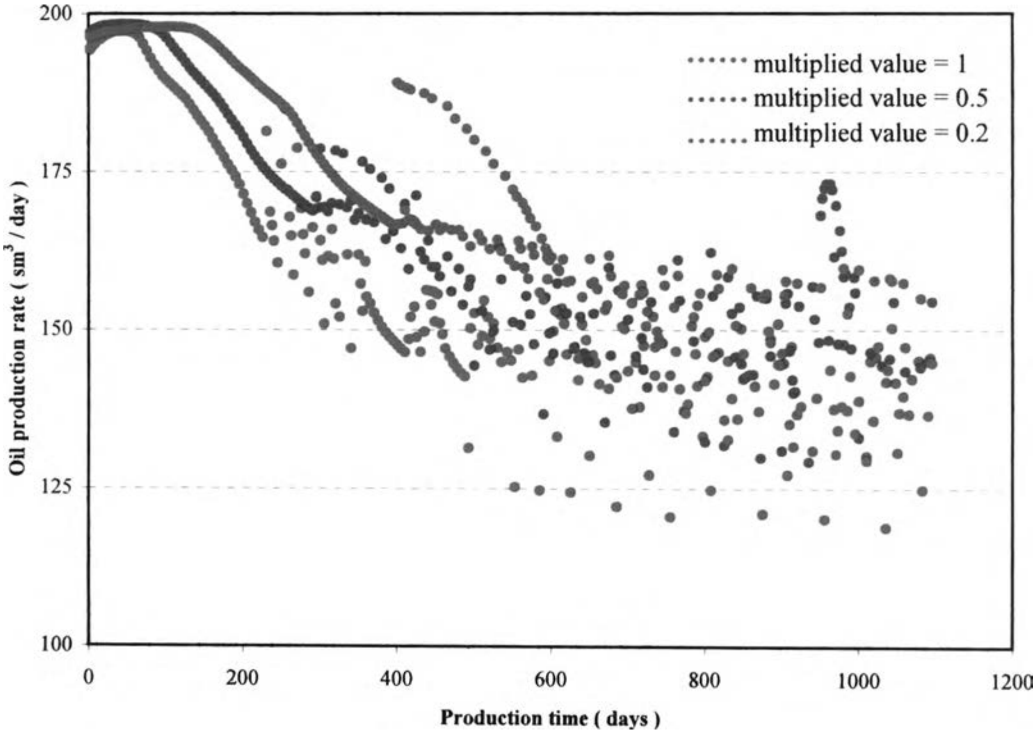

Figure 4.19: Oil rate obtained of fishbone intelligent wells
for different vertical permeabilities.

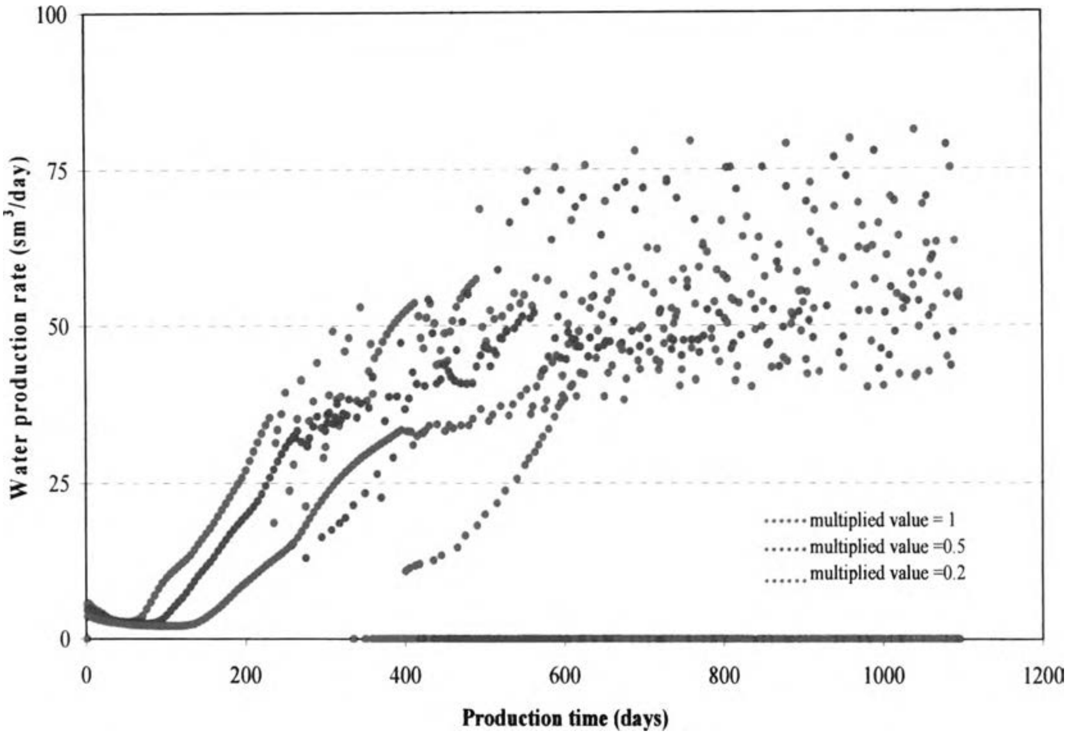

Figure 4.20: Water rate obtained of fishbone intelligent wells for different vertical permeabilities.

Table 4.28: Distance fraction of oil and water production of fishbone openhole wells for different vertical permeabilities.

Multiplied value	Distance fraction of oil production	Distance fraction of water production
1.0	0.511	0.522
0.5	0.525	0.484
0.2	0.714	0.547

As shown in Table 4.28, the distance fraction of oil production increases as the vertical permeability decreases. An outstanding value of 0.714 can be obtained in the case when the vertical permeability is multiplied by 0.2. This means that the most probable value is closer to the highest value. Nevertheless, the distance fraction of water production does not show favorable results. They are more or less constant around 0.5. Thus, the most probable values in all the three cases are located at the middle of their respective distribution curves.

The reliability of the results was also investigated by analyzing the coefficients of variation (Table 4.29) and relative frequencies of the most probable values (Table 4.30) for both oil and water productions. As illustrated in Table 4.29, the coefficients of variation of oil and water production do not show any trend when the vertical permeability decreases. This means that vertical permeability does not have any effect to the reliability of results from intelligent well.

Table 4.29: Statistical values of oil and water production of fishbone intelligent wells for different vertical permeabilities.

Multiplied value	Oil production			Water production		
	μ	σ	δ	μ	σ	δ
1.0	110,009	19,678	0.179	27,842	4,001	0.144
0.5	122,698	23,036	0.188	25,863	4,349	0.168
0.2	153,712	28,065	0.183	24,286	3,740	0.154

Table 4.30: Relative frequency of oil and water production of fishbone intelligent wells for different vertical permeabilities.

Multiplied value	Relative frequency of oil production	Relative frequency of water production
1.0	0.207	0.200
0.5	0.18	0.193
0.2	0.173	0.207

The relative frequency of oil production has a decreasing trend when the vertical permeability decreases. This indicates that there is less dispersion in high vertical permeability reservoir than in low vertical permeability reservoir. The relative frequency for water production shows almost the same value around 0.2.

In summary, the simulation results show that intelligent completion exploited in reservoirs with different values of vertical permeability have different values of oil and water production. The oil and water productions increase as the vertical permeability decreases (by means of more lateral flow and less water from vertical flow).

Anyway, in extremely low vertical permeability case in which cresting phenomenon does not have any effect on water production, the installation of intelligent completion does not provide any advantages. On the other hand, the cost of installation and intelligent elements tends to be a big disadvantage.

4.2.3 Comparison between Openhole and Intelligent Completion

In this phase of study, openhole cases are kept as reference cases as in other studies. Tables 4.31 and 4.32 illustrated the relative differences between simulation results from openhole and intelligent completions for the fishbone well geometry for different vertical permeabilities.

Table 4.31: Relative differences between fishbone openhole wells and intelligent wells for different vertical permeabilities considering quantity aspect.

Multiplied value	ΔN_p	ΔW_p	Δ Water fraction	Δ Total production	Δ Distance fraction N_p	Δ Distance fraction W_p
1.0	-25.2 %	-60.1 %	-36.8 %	-36.7 %	-48.9 %	72.3 %
0.5	-23.0 %	-59.4 %	-38.4 %	-34.3 %	-27.1 %	72.9 %
0.2	-4.8 %	-56.0 %	-46.4 %	-17.9 %	3.2 %	80.5 %

As depicted in Table 4.31, there is less reduction in oil and water production when the vertical permeability decreases. However, there is a greater reduction in water production than oil production in each respective case.

The water fraction shows a slightly decreasing trend when vertical permeability decreases while the total production shows a slightly increasing trend. These result from water production that is reduced more in low vertical permeability reservoir.

Regarding the distance fraction of oil production, the oil production from openhole and intelligent wells in the case in which the vertical permeability is multiplied by 0.2 are almost the same while the difference in other two cases can be remarkably seen. This can be explained that intelligent well is interrupted in a fewer times in the case of very low permeability due to high lateral flow and less water cresting effect. On the other hand, the distance fraction of water production increases by approximately 80 % in all the cases.

Table 4.32: Relative differences between fishbone openhole wells and intelligent wells for different vertical permeabilities considering reliability aspect.

Well geometry	$\Delta\,\delta$ N_p	$\Delta\,\delta$ W_p	Δ Relative frequency N_p	Δ Relative frequency W_p
1.0	53.0 %	-26.5 %	24.0 %	25.0 %
0.5	62.1 %	-26.6 %	17.6 %	26.1 %
0.2	63.4 %	-48.1 %	13.1 %	35.1 %

As seen in Table 4.32, the coefficient of variation of oil production is constant for all three cases when intelligent completion is used. The coefficient of variation of water production reduces around 26 % for multiplied values of 1.0 and 0.5 while it reduces by 48.1 % for multiplied value of 0.2 when intelligent completion is implemented. This reduction occurs since the water production is limited by inflow control valves. Small increment of relative frequencies of oil and water production around 10 – 30 % can be found when intelligent completion is applied in all cases.

In this set of studies on vertical permeability, oil production from intelligent completion is still lower than that from openhole completion due to automatic shutting and opening of inflow control valves corresponding to a prescription to control the water cut. However, if the water cut constraint is imposed on the openhole cases, we should see a big improvement in oil production when intelligent completion is used.