CHAPTER 3
RESERVOIR SIMULATION

3.1 Introduction

In this chapter, the performance of intelligent well completion is evaluated based on the results from synthetic reservoir models which simulate the presence of heterogeneity distribution of the complex sedimentation. The utilization of these synthetic models is chosen to verify the efficiency of non-conventional well application in realistic scenarios in which distribution of petrophysical properties can influence well and reservoir performance. A recent study has investigated the effectiveness of different conventional multilateral well geometries in a wide range of heterogeneous and homogeneous reservoirs, in which permeability, anisotropicity of reservoir rock, and fluid properties were varied (Ferraro, 2003).

Productivity of multilateral and horizontal wells depends on many factors such as reservoir heterogeneity, the imperfect rectilinear trajectory of horizontal branch, and non-constant rate of fluid entrance. Heterogeneous models were created by assigning an appropriate distribution of petrophysical properties according to a fluvial depositional environment with high permeability channels of characterized preferential flux. The oil zone is bounded with an active aquifer.

The analysis was conducted using three different well geometries: traditional horizontal well, bilateral well, and fishbone geometry. Two different kinds of completion were chosen: openhole and intelligent. The study on intelligent completion is to evaluate the effective increment of achievable productivity, with a particular attention to utilize the downhole inflow control valves (the valves which automatically operate in order to control water production).

The flexibility of downhole inflow control valves used to control the production from each branch and real time data collected from downhole via downhole monitoring system, can effectively improve the efficiency of the well by reducing the total production of undesired fluid.

The intelligent completion comprises controllable valves (inflow control valves) located at appropriate positions in each section of the well to control water production by opening, shutting or controlling independently the valve on each productive branch. The well is simulated as a group of productive independent segments equipped with controllable valves to control liquid flow and separated from the adjacent zones using suspension packers and slotted liners to render realistic completion schematic.

In reservoirs where there is a water production problem, multilateral wells equipped with an intelligent system can be considered as one of the solution that provides more advantages by operating an automatic control to obtain more hydrocarbon recovery.

3.2 Reservoir Modelling

The dynamic modelling of reservoir performance is conducted using a numerical simulator called **ECLIPSE100**, commercialized by **GeoQuest Schlumberger**. The simulation requires several modules which are definition of geometric model (GRID), simulation of pressure loss in the well (VFPi), simulation of the dynamic behavior of the reservoir (ECL100), definition of thermodynamic characteristic of fluids (PVTi), graphical analysis of simulation results (FLOVIZ), and (OFFICE).

The models used in this study are three dimensional. The presence of well is simulated by defining the position of the well inside grids that the well passes through. The lateral branches are located in rectilinear segments at the centre of grid cells.

In the simulation, intelligent completions are defined through the option called **multi-segment well** of ECLIPSE100 program by adding the intelligent completion elements to the well with a simple definition that the well can operate and control by itself.

3.2.1 Reservoir Grid Model

The dimensions of reservoir model are 1,200 × 1,200 × 40 m. The reservoir is subdivided vertically into 10 grid block levels. The upper five levels are considered as an oil zone while the lower five levels are occupied by water aquifer. The net pay is then 20 m. The grid cells are 80 × 80 × 10 with the dimension of 15 × 15 × 4 m. in x, y, and z directions, respectively. Figure 3.1 represents the reservoir grid cell model with the upper five levels as oil zone and the lower five levels as water aquifer.

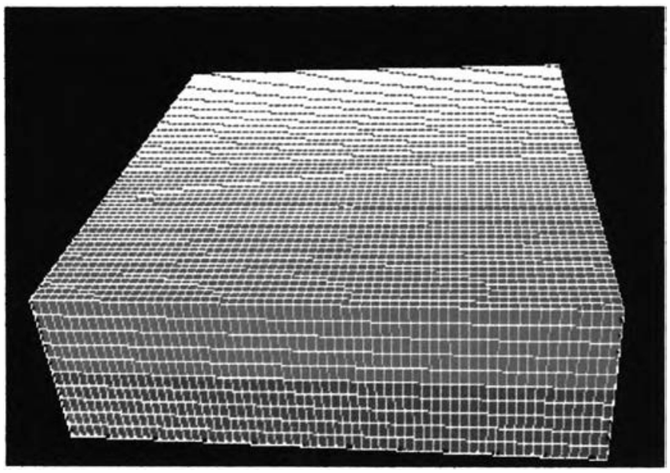


Figure 3.1: Reservoir grid cell model.

3.2.2 Definition of Water Aquifer and Properties of Water Zone

The analytical water aquifer is treated as infinitively active aquifer zone. The definition is defined according to Carter Tracy (Fanchi, 1985) with the properties:

- Permeability (k_{aqui}) 200 mD
- Porosity (ϕ_{aqui}) 20 %
- Compressibility (c_{aqui}) 2×10^{-5} bar^{-1}

3.2.3 Reservoir Rock Properties in Oil Zone

The reservoir model is adopted from a complex fluvial environment with heterogeneous properties: permeability (k), saturation (S), and porosity (ϕ). The fluvial channel, located in the oil zone is 270 m. wide (cells 29 - 47 in the x direction), 1200 m. long (cells 1 – 80 in the y direction), and 20 m. deep (cells 1 – 5 in z direction) as shown in Figures 3.2, 3.3, and 3.4. The band of interest consists of high permeability channel stripes with permeability value of 100, 200, 300, 400, and 500 mD surrounded by 1 mD low permeability shale. The area outside the channel band has a unique directional permeability of 100 mD. However, permeability in each grid cell is assigned as the same value ($k_x = k_y = k_z$) for all the reservoir models. The example of permeability heterogeneity is illustrated in Figure 3.2.

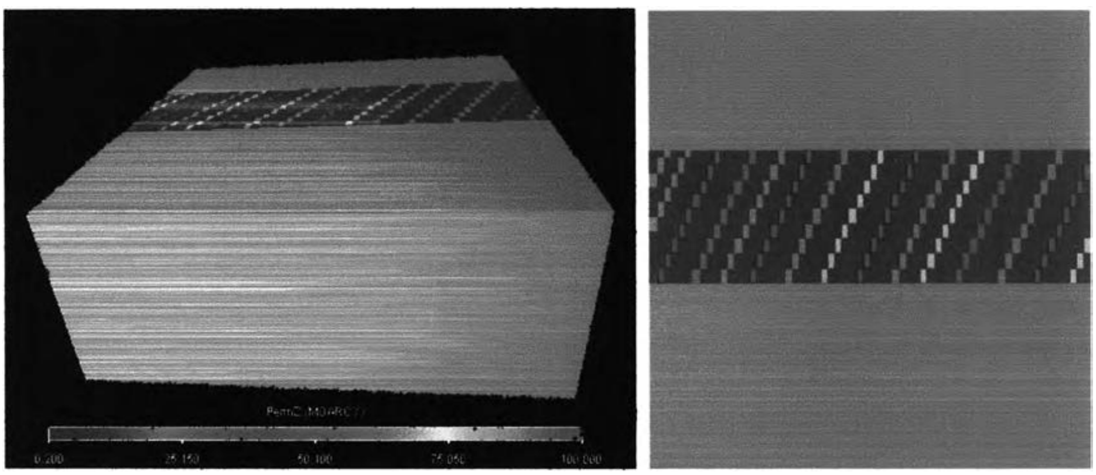


Figure 3.2: 3-D illustration and top view of reservoir model showing the heterogeneity of permeability.

Saturation and porosity maps were constructed from facies distribution maps. Saturation profiles were constructed in term of water saturation (S_w). Only two values were used; 1 for low permeability shale and 0.2 for oil channel stripes and the rest of the oil zone. Similarly, two values of porosity are applied to the reservoir model, 0.01 for low permeability shale and 0.2 for oil channel stripes and the rest of the oil zone. Nevertheless, porosity at the boundary of reservoir model was multiplied with a large number (illustrated in Figure 3.4) to represent a reservoir that has an infinite boundary, ensuring that the production is not disturbed by boundary effect. The examples of oil saturation and porosity heterogeneity are illustrated in Figures 3.3 and 3.4, respectively. The values of reservoir and fluid properties that are location dependent are summarized in Table 3.1.

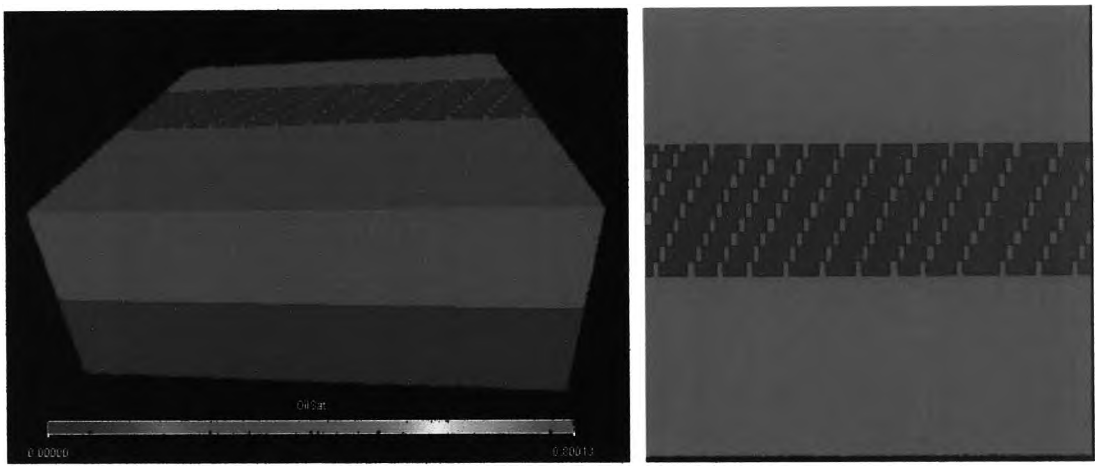


Figure 3.3: 3-D illustration and top view of reservoir model showing the heterogeneity of oil saturation (S_o).

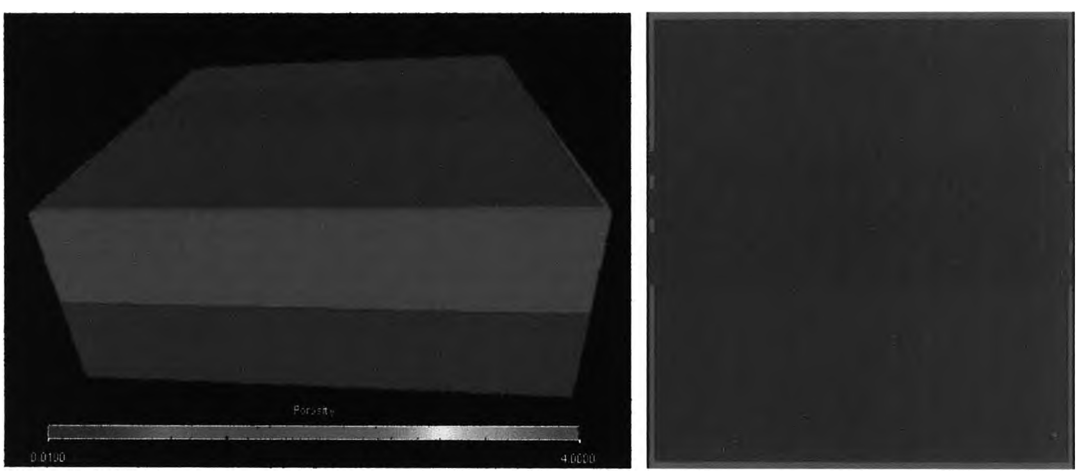


Figure 3.4: 3-D illustration and top view of reservoir model showing the heterogeneity of porosity.

Table 3.1: Reservoir and fluid properties that are location dependent.

Location	k_x, k_y, and k_z (mD)	S_{oi}	S_{wi}	ϕ
Shale stripes	1	0	1.0	0.01
Oil channel strips	100, 200, 300, 400, 500	0.8	0.2	0.2
The rest in oil zone	100	0.8	0.2	0.2

Since the reservoir grid cell model is referred from previous studies by Marescalco (2002) and Ferraro (2002), relative permeabilities for oil (k_{ro}) and water (k_{rw}) used in this study are the same as those used in the two studies as illustrated in Figure 3.5.

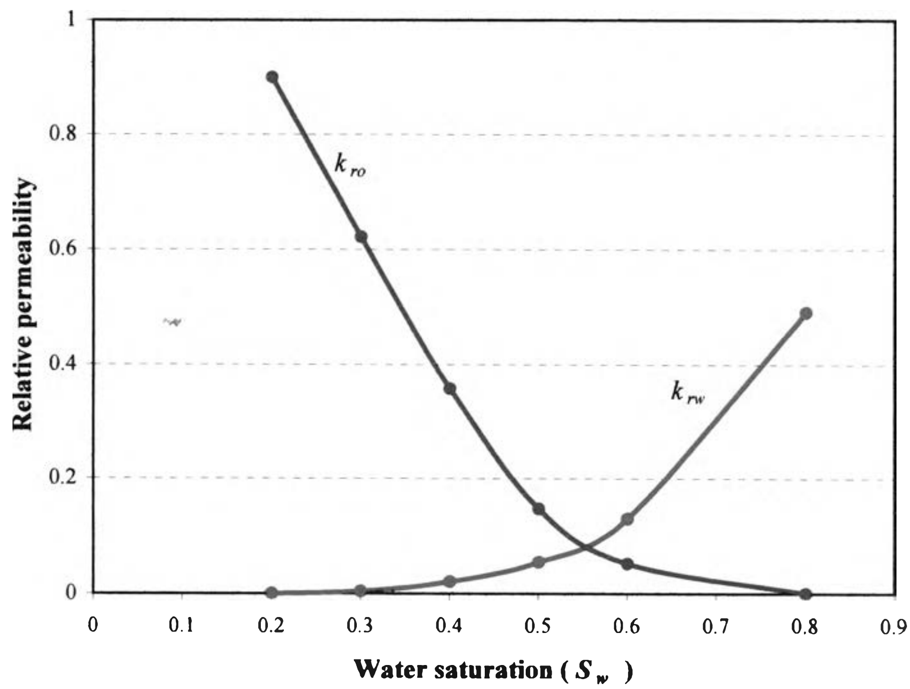


Figure 3.5: Relative permeability respect to water saturation.

Other constants of rock property are shown below:

- Rock compressibility (c_r) 2×10^{-5} bar^{-1}
- Connate water saturation (S_{wc}) 0.2
- Maximum water saturation (S_{wmax}) 1.0

The capillary effect from capillary pressure (p_c) is considered to be small and can be neglect.

3.2.4 Thermodynamic Properties

The initial pressure (p_i) has to be assigned at a fixed reference depth (datum plane) which is 3,035 m. The value of static pressure at the datum depth equals to 304 bar with the reservoir temperature of 100 °C. The initial water-oil contact is located at the depth of 3,020 m.

3.2.5 Reservoir Fluid Properties

The formation volume factor (B), viscosity (μ), and density (ρ) of reservoir fluids were borrowed from previous studies by Marescalco and Ferraro as shown below:

- Oil formation volume factor (B_o) 1.7 rm^3/sm^3 (ref. at 350 bar)
  1.7798 rm^3/sm^3 (ref. at 1 bar)
- Oil viscosity (μ_o) 0.35 cp
- Oil density (ρ_o) 35.8 °API
- Water formation volume factor (B_w) 1.003 rm^3/sm^3 (ref. at 140 bar)
- Water compressibility (c_w) 10^{-5} bar
- Water viscosity (μ_o) 0.35 cp
- Water density (ρ_w) 1,064 kg/m^3

Nevertheless, the effect from infinitively active water aquifer maintains the pressure of the reservoir fluid to be constant. Therefore, fluid properties are generally constant.

3.3 Well Modelling

3.3.1 Well Geometry

Three well models were investigated: traditional horizontal well, bilateral well, and fishbone well geometries. The wells are centrally placed in the reservoir with the vertical mother bore at location (30,40) in the x-y coordinate with a wellbore radius (r_w) of 0.16 m. The geometries of the three wells are described below:

- **Traditional horizontal well**

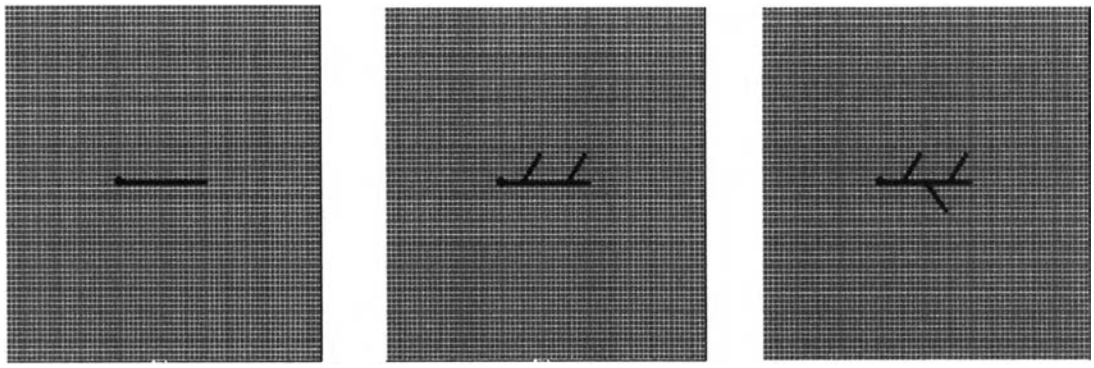
The horizontal mainbore deviates horizontally from the mother bore at depth 3,021 m (at the centre of the grid block in layer 2) with a total effective horizontal well length of 300 m. as shown in Figures 3.6a and 3.7.

- **Bilateral well**

The well consists of one horizontal mainbore and two parallel branches. The configuration is similar to the traditional horizontal well but with an addition of two 90-meter laterals branching out horizontally from the horizontal mainbore at depth 3,021 m at coordinate (35,40), and (45,40) at 60° angle with the horizontal mainbore as displayed in Figures 3.6b and 3.8a.

- **Fishbone well**

The well consists of one horizontal mainbore and three parallel branches. The configuration is similar to the bilateral well with an additional 90-meter lateral branching out in the opposite direction as the other two laterals as depicted in Figures 3.6c and 3.8b. Two lateral branches deviate horizontally from the horizontal mainbore at depth 3,021 m. at coordinate (35,40) and (45,40), and another branch deviates horizontally in the opposite direction at location (40,45) at 60° angle with the horizontal mainbore.



a.Traditional horizontal well   b. Bilateral well   c. Fishbone well

Figure 3.6: Top views of well location for three well geometries.

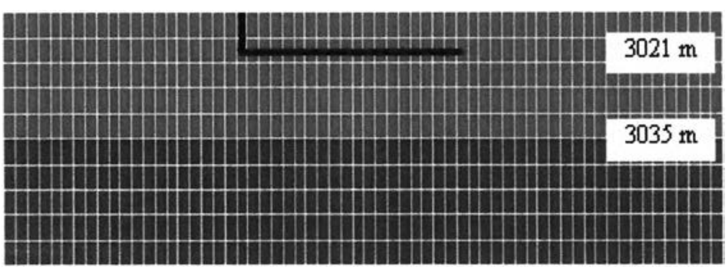
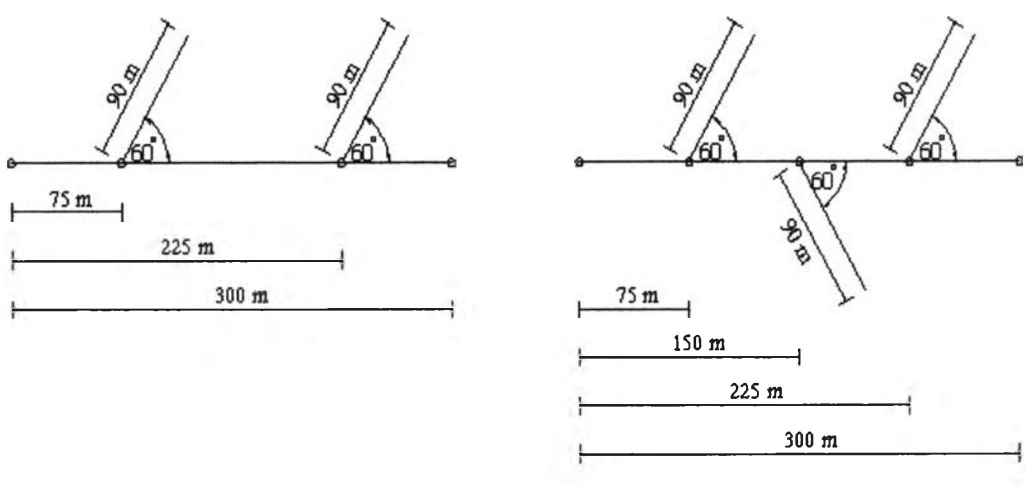


Figure 3.7: Side view of the traditional horizontal geometry.



a. Bilateral well   b. Fishbone well

Figure 3.8: Top view of bilateral well and fishbone well geometries.

3.4 Well Completion

Two types of well completion were investigated: openhole and intelligent completion. Both well completion systems are classified as level 1 according to **TAML Multilaterals Classification System** (Hogg, 1997). In intelligent completion, slotted liner is set up in cooperation with suspension packers in each branch and the horizontal mainbore. In order to control the flow from each lateral, an inflow control valve is placed at each junction. However, the toes of all the branches are kept openhole in order to facilitate the flow of fluid into the branches. Figure 3.9 depicts a schematic of intelligent completion system.

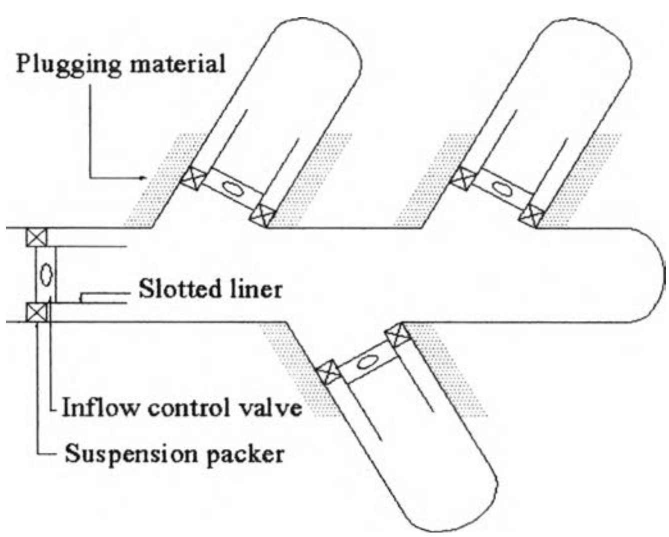


Figure 3.9: Intelligent completion system.

Bilateral and fishbone geometries have a better possibility efficiency to drain oil from oil stripes. For this reason, the lateral branches can be targeted to penetrate oil channel stripes. The braches are packed with the plugging material at the junction (first three cells starting from the horizontal mainbore) in order to avoid water cresting effect. Therefore, the branches are extended in intelligent completion case in order to have the same productive length comparing to openhole wells.

3.5 Production Modelling

All the simulation cases were set up to have fluid production rate of 200 m^3/day. Since intelligent completion has a high initial cost, it is economically competitive only if the cost of investment can be paid in short a period. For this reason, a production period three years was chosen for every simulation case.

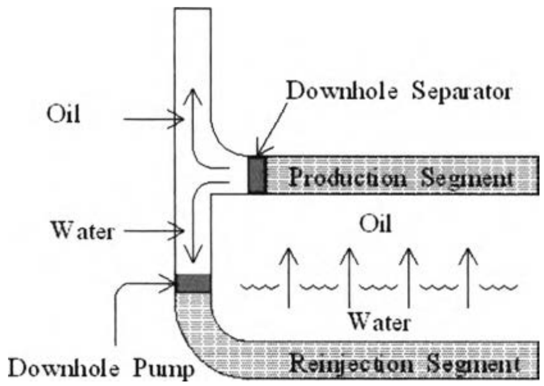
3.6 Flow Control Modelling

3.6.1 Multi-Segment Well Model

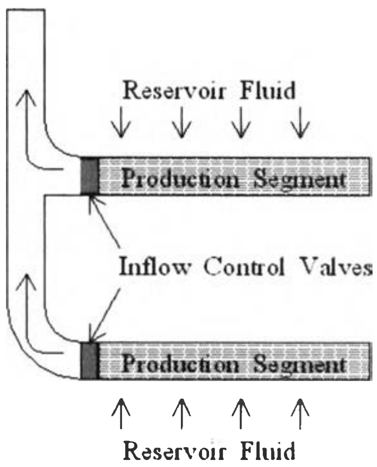
The multi-segment well model is one of special options available in ECLIPSE100. It is used to obtain detailed description of mass flow in the well from a single part or multiple branches. It is adopted for both horizontal and multilateral wells.

The description of fluid flow is obtained by subdividing the well into an appropriate number of segments in which geometric, characteristic, and completion properties are assigned. Each segment can be constructed as one or more blocks with total flow rate (q_T), fractional flow of water and gas (f_w and f_g), and pressure (p) as block variables. These parameters are evaluated by solving the mass balance equation for each phase in the system and the pressure loss equation considering the pressure loss due to hydrostatic pressure, friction, and acceleration. The pressure loss can be calculated using a homogeneous mass flow model (every phase flows at the same velocity) or slippage between phases. It is moreover possible to calculate the pressure loss using an appropriate well efficiency table (vertical flow performance), constructed from experimental data.

In intelligent completion, it is necessary to simulate the effect from the presence of valves in the well. Specific models for mass flow control can be applied. With the multi-segment option, it is possible to model a presence of valves in order to limit flow rate by imposing the pressure loss due to friction. Furthermore, downhole separators can be simulated with this option, allowing water and separated gas to be re-injected directly to the formation through an appropriate injection drain. The schematic diagrams of the application of downhole separator and inflow control valves are illustrated in Figure 3.10a and 3.10b, respectively.



a. Downhole separator



b. Inflow control valves

Figure 3.10: Schematic diagrams of multi-segment option.

Each segment consists of a node and a vector allowing the flow connection from adjacent nodes (it is necessary that all segments are connected). The geometrical properties of segments needed to be identified are node depth location, length, diameter, and orientation as shown in Table 3.2.

Table 3.2: Geometrical properties of horizontal mainbore and lateral branch.

Geometrical properties	Horizontal mainbore	Lateral Branch
Depth	3,021 m.	3,021 m.
Length	300 m.	90 m.
Diameter	0.16 m.	0.16 m.
Orientation	x direction	x direction

Normally, each segment should be defined as a single grid cell in order to compare relative productions from the surrounding blocks. The defined segments can be connected along the well, in particular, the location in which reservoir properties are different or there is a deviation of well profile. Additional segments can be further defined to represent inflow control valves in order to control water entrance.

Initially, it is necessary to define the most suitable option for intelligent completion. Several options used to simulate mass flow control system are described in the following paragraphs.

3.6.2 VFPi Module

The module VFPi is an instrument that evaluates the pressure loss in the wellbore using an appropriate equation. The pressure loss is a function of fluid properties and characteristics of each segment. The fluid properties which are function of pressure and temperature can be obtained from a table or can be calculated from empirical correlations.

The fluid temperature, in this study, was assigned as a constant for all the profile along each lateral. Pipe characteristics needed in the calculation of pressure loss are length, diameter, inclination, and roughness.

Besides the need for pressure loss calculation for vertical and horizontal sections, the pressure loss calculations in lateral branches are also required. A section of the well model can be visualized in two dimensions. As it is impossible to define some parts of well, only vertical and deviated horizontal wells were defined for VFPi table construction. The well characteristics consist of temperature profile, initial pressure, necessary geometrical characteristics, wellbore volume, and exact position in a plane.

In this study, the well was constructed from two and three lateral branches. It is not possible to set up pressure loss tables for lateral branches. However, we cannot assume that the pressure loss happens only in the mainbore.

Fortunately, it is possible to simulate the presence of downhole chokes which also create pressure loss. This available tool was used to construct VFP tables for constructing additional VFP tables (one for pressure loss along the well and others for valves or other elements installed in a completion system). However, this method cannot verify the accuracy of pressure loss in lateral branches.

For this reason, the VFP table for multilateral well combined with intelligent completion cannot be defined in this study due to a complexity of well geometry.

3.6.3 Control System of Fluid Entrance

Control system of fluid entrance allows the imposition of limited fluid flow rate. This system can be used to limit water production and associated gas from oil, control the production or injection at different branches of a multilateral well or avoid cross flow between branches in the same well.

This option is used in this study by setting water production limit in each segment. After a segment is shut due to water production limit, the simulator will redistribute the flow rate in the rest of the segments of the well.

3.7 Application Option from Simulator

3.7.1 GROUP Option

GROUP option is an available item provided by ECLIPSE100. This option is used to add up connected cells as a segment. For example, in the fishbone well geometry, the lateral mainbore and three horizontal branches are treated as four wells. The point which represents the wellhead of the well is identified in order to collect the production from every segment. Nevertheless, it is not possible to treat single branches as independent elements.

3.7.2 LUMPED Connection Option

LUMPED connection is an available option provided by ECLIPSE100. This option is used to link connected segments together. This option allows the operators to control production periodically (for small time interval, the water cut checking happens at the initial of each time step simplifying the flow-equation calculation and reducing the total convergence problem). This real time control system can fix the operation condition of connected group. In this study, the maximum fraction of producible water is fixed. The connection will be shut when the water cut reaches the pre-set maximum value, and the well will re-open automatically again if the amount of the undesired fluid decreased. Moreover, this option is suitable for a complex well geometry especially multilateral well which needs to control water entrance.

This option reflects a real time control, for example, a control of the water fraction respect to total liquid flow rate. The system regulates production from particular critical connections that will be closed if they do not produce water at the rate lower than the limiting rate.

3.8 Numerical Simulation

The optimal multilateral well geometry has to be based on sufficient reservoir detail (Ehlig-Economides *et al.*, 1996). In this study, reservoir properties such as fluid and petrophysical properties are sufficiently known. However, fluvial environment has very complex geological structure, i.e., location and orientation of channel stripes may have a high degree of uncertainty. Therefore, statistical study has been investigated in previous research by Marescalco, 2003. In this study, 150 fluvial reservoir models were created with different geological structures. They were generated with different locations, numbers, and angles of oil stripes, local variations of permeability, fluid saturations, and porosities. The models were created with high permeability channels in order to represent deltaic sedimentary location alternating with shale stripes which are low permeability zones. Vertically, the channels were also constructed differently in terms of distribution and inclination orientation.

The analytical study conducted by Marescalco demonstrated the stabilizations of statistical values such as mean, P50, P10, P90, P30, and P70 of oil and water production is obtained with the use of 150 random reservoir models.

This study consists of two main parts: multilateral well efficiency and effect of vertical permeability on oil production. In the first part, three well geometries were investigated in order to find the most suitable well geometry for the chosen reservoir model and constrained conditions. The openhole well was simulated first, then, intelligent completion was applied in every case to study achievable recovery. The intelligent completion was studied in two manners:

- **Time limitation study**

Results obtaining by intelligent well were compared with results from openhole case simulated with the same production period (three years) without considering water production limitation.

- **Production constraint study**

This case represents the exploitation area in which a limit in water production is imposed such as an environmentally sensitive area. Results from intelligent completion were compared with openhole case at the same limit of water cut value which is 20 %.

The second part of this study deals with the effect of vertical permeability since it has an influence on water cresting phenomenon. In general, the well with longer effective length and more lateral branches tends to give better results; therefore, the fishbone well geometry was chosen for the study in this phase. The values 0.5 and 0.2 were multiplied to the existing vertical permeability in order to see how variation in vertical permeability affects oil recovery.