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Research paper

Evaluating the performance of advanced wells in heavy oil reservoirs under uncertainty in permeability parameters

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ABSTRACT

Advanced wells play a crucial role in maximizing the efficiency of oil production. To achieve a successful design for advanced wells, several parameters must be considered and evaluated. Uncertainty in these parameters can have a significant impact on the performance assessment of the well in its lifetime. Absolute permeability, relative permeability, and permeability anisotropy are the parameters that determine reservoir permeability and are among the most important design parameters to be considered. This paper aims to assess the performance of advanced wells completed with passive and reactive downhole Flow Control Devices (FCDs) under uncertainty in the reservoir permeability parameters. The assessment is conducted through a case study on a synthetic heavy oil reservoir with a strong water drive. The Eclipse^{SM} reservoir simulator is used as a simulation tool and the Latin Hypercube Sampling (LHS) approach is applied as a sampling tool for uncertainty analysis in this study. According to the obtained results, under the presence of uncertainty, advanced wells with Autonomous Inflow Control Device (AICD) and Autonomous Inflow Control Valve (AICV) completions are able to mitigate the risk of water production by 53.20% and 71.12% respectively compared to conventional wells. However, Inflow Control Device (ICD) completion can only reduce the risk by 0.87%.

1. Introduction

In recent years, the advancement of drilling technology has enabled us to drill long horizontal and multilateral wells to improve oil recovery by maximizing the well-reservoir contact. One of the main challenges of using such wells is the early breakthrough of unwanted fluids due to the heel-toe effect and heterogeneity along the well. In order to solve this challenge, advanced (intelligent or smart) wells completed with downhole Flow Control Devices (FCDs), Annular Flow Isolation (AFI), Sand Control Screens (SCSs) as well as monitoring and control systems, are widely used today.

FCDs combined with AFI are the key elements in Advanced Well Completions (AWCs). FCDs are classified into three main types of passive, reactive, and active devices. Passive FCDs like Inflow Control Devices (ICDs) are mounted on the production tubing as a passive (fixed) flow restrictor to counteract the non-uniform inflow along the horizontal well. ICDs can passively reduce the production of unwanted fluids by postponing water or gas breakthrough; however, they are not able to restrict the production of unwanted fluids after the breakthrough. To solve this problem, Autonomous Inflow Control Devices (AICDs) and Autonomous Inflow Control Valves (AICVs) have been developed as robust alternatives. AICDs and AICVs are classified as reactive FCDs and are able to choke low-viscosity fluids (compared to oil) back after the breakthrough with no need for operating from the surface. Therefore, in addition to delaying the water or gas breakthrough, these technologies can reactively and autonomously restrict the production of unwanted fluids after breakthrough. AICDs and AICVs are self-adjusting fluid-dependent devices that are not controllable after the well completion. To achieve a flexible flow control, Interval Control Valves (ICVs) that fall into the category of active FCDs are used. These valves can be flexibly controlled from the surface through an electric, hydraulic, or wireless actuation system. As a result, by applying ICVs the production of unwanted fluids can be controlled both proactively and reactively. However, compared to other types of FCDs, ICVs are more expensive and due to the technical complexity of installation, the number of ICVs that can be installed on a long horizontal well is limited (Al-Khelaiwi et al., 2013; MoradiDowlatabad et al., 2015). Therefore, the performance of this type of FCDs is not evaluated in this study. ICDs and AICDs have been developed by different companies with various designs. The nozzle-type ICD, as well as the Rate-Controlled Production valve or RCP-type AICD, are widely used today and considered in this study. Fig. 1 shows the nozzle ICD, RCP AICD, and AICV designs.

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Fig. 1. Different types of passive and reactive FCDs (InflowControl, 2021; Tendeka, 2021a).

Evaluating the functionality and performance of passive and reactive FCDs in improving oil recovery by reducing water cut and/or gas/oil ratio (GOR) have been the subject of several studies. Henriksen et al. (2006) have demonstrated that ICDs are able to increase the efficiency of oil production by postponing gas breakthrough. The improvement of heavy oil production by using AICDs has been investigated by Guilmain et al. (2019), Tendeka (2021b, 2022), and Xiong et al. (2020). The performance of AICDs compared to ICDs in reducing GOR in light oil production has been studied by Mohammad Zin et al. (2020), Langaas et al. (2019), Triandi et al. (2018), and Halvorsen et al. (2016). In the same way, Moradi and Moldestad (2020) studied the water cut reduction potential of AICDs and ICDs in a mid-heavy oil reservoir. The advantages of AICVs over passive FCDs for achieving a reduced water cut and/or GOR has been shown by Aakre (2017), Kais et al. (2016), and Mathiesen et al. (2014). In these studies, the application of FCDs has been investigated without taking the uncertainty in the reservoir parameters into account. However, to fulfill a suitable design of advanced wells, the performance of advanced wells equipped with different types of FCDs under the presence of geological uncertainty must be carefully evaluated. To the best knowledge of the authors, so far a few studies have included uncertainty considerations for assessing the performance of advanced wells completed with different types of FCDs and AFI. For instance, Wehunt (2003) has presented an approach to evaluate the performance of conventional wells under reservoir and completion uncertainty, while also considering the impact of completion decisions and operating constraints. A decision analysis approach is suggested by Yeten et al. (2004) to determine whether or not to deploy smart completions under uncertain geology as well as the risk of failure of the control devices. Ouyang (2007) have proposed a procedure for evaluating the performance of advanced wells by considering the uncertainty of well completion parameters. The long-term benefits of advanced wells with ICD and ICV completions by reducing the impact of geostatistical uncertainty on the production forecast have been illustrated by Birchenko et al. (2008) through a probabilistic approach. Grebenkin and Davies (2010) have examined the performance of intelligent wells with ICV completion under the impact of uncertainty in dynamic parameters like fluid contacts, relative permeabilities, aquifer strength, and zonal skin. The capabilities of AWCs equipped with ICDs and AICDs compared to conventional wells under two production strategies with uncertainty in the geological parameters have been investigated by MoradiDowlatabad et al. (2015). Optimization of advanced wells under uncertainty has been studied by Ghosh and King (2013), Haghighat Sefat et al. (2016) and Eltaher et al. (2019).

Crude oil with the API gravity of less than 22° is classified as heavy oil. The oil recovery from a heavy oil reservoir with an aquifer or water injection is very challenging due to the unfavorable mobility of heavy oil compared to water. As a result, early water breakthrough and high water production are very important challenges for heavy oil recovery (Eltaher et al., 2014). Advanced wells completed with FCDs and AFI provide a robust practical solution to deal with these challenges. Therefore, the functionality of such wells in heavy oil recovery under different conditions and scenarios must be properly understood by further studies. This leads to finding suitable strategies for mitigating risks and maximizing profit. According to sensitivity analysis of oil production models to rock and fluid properties performed by Sharma et al. (2021), the well performance is noticeably sensitive to the reservoir permeability parameters. Therefore, uncertainty in these parameters including absolute permeability, relative permeability, and permeability anisotropy highly impacts the performance assessment of advanced wells. This paper aims to provide more insight into the performance of advanced wells completed with passive and reactive FCDs and AFI in heavy oil recovery under the uncertainty in the reservoir permeability parameters. The study is performed through near-well simulation of an advanced horizontal well with AFI and FCD completions in a synthetic heavy oil reservoir with a strong water drive. The Eclipse[SM] black-oil simulator (E100) coupled with MATLAB® are used for developing the simulation models.

Uncertainty assessment is commonly performed based on the Monte Carlo approach and requires a large number of simulation runs. This is a very time-consuming process by using physics-based reservoir simulators because they need to solve complex sets of Partial Differential Equations (PDEs) for describing the multiphase fluid flow from the reservoir pore to the production tubing. In order to speed up the process of uncertainty assessment, an efficient approach called Latin Hypercube Sampling (LHS) is used in this paper. Unlike the Monte Carlo approach which is based on a fully stochastic and memoryless sampling scheme, the LHS method is a pseudo-random sampling method based on stratification of the input probability distributions. By using the LHS technique the same level of accuracy can be achieved with fewer samples compared to the Monte Carlo approach (University of Oslo, 2021).

2. Theory

2.1. General mathematical model for nozzle ICDs

ICDs have been developed to delay the early water and gas breakthrough by balancing the inflow along the well through adding an extra pressure drop. The mathematical equation governing the behavior of nozzle-type ICD is described by Eq. (1) as (The Engeeniering Toolbox, 2021):

$$\dot{Q} = C_D A \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where $\dot{Q}$ is the volume flow rate of the fluid passing through the ICD and ΔP is the pressure drop over the ICD. In this equation, ρ is the fluid density, A is the cross-sectional area of the ICD nozzle, and C_D is called discharge coefficient that depends on the ICD design.

2.2. General empirical equation for the RCP AICDs

Owing to the special design of AICDs, in addition to postponing the water and gas breakthrough, these valves can be partially closed for low-viscosity fluids like water and gas. The empirical mathematical function describing the performance of the RCP-type AICDs is represented by Eq. (2) as (Mathiesen et al., 2011):

$$\Delta P = a_{AICD} \cdot \left(\frac{\rho_{mix}^2}{\rho_{cal}}\right) \cdot \left(\frac{\mu_{cal}}{\mu_{mix}}\right)^y \cdot \dot{Q}^x \tag{2}$$

where $\dot{Q}$ is the volumetric flow rate of fluid passing through the AICD, and ΔP is the pressure drop over the AICD. In this equation

a_{AICD}, x and y are the user input parameters that depend upon the AICD design and fluid properties. ρ_{mix} and μ_{mix} are the density and viscosity of the fluid mixture, while ρ_{cal} and μ_{cal} are calibrating parameters. The density and viscosity of the mixed-fluid passing through AICDs are calculated by Eq. (3) as (Mathiesen et al., 2011):

$$\begin{aligned} \rho_{mix} &= \alpha_{oil}\rho_{oil} + \alpha_{water}\rho_{water} + \alpha_{gas}\rho_{gas} \\ \mu_{mix} &= \alpha_{oil}\mu_{oil} + \alpha_{water}\mu_{water} + \alpha_{gas}\mu_{gas} \end{aligned} \tag{3}$$

where α_{oil}, α_{water}, and α_{gas} are the volume fraction of oil, water, and gas in the fluid mixture respectively.

2.3. Principle equations for AICVs

Unlike the AICDs that are capable to partially close against unwanted fluids, AICVs can close almost completely when a low-viscosity fluid compared to oil, like water or gas, is the surrounding fluid. AICVs consist of a pipe-shape laminar flow restrictor and a turbulent flow restrictor in series and act based on the difference in pressure drop across the laminar and turbulent flow restrictors. The pressure drop across the pipe-shape laminar flow restrictor and a turbulent flow restrictor is expressed by Eqs. (4) and (5) respectively as (Mathiesen et al., 2014):

$$\Delta P = \frac{32\mu\rho v L}{D^2} \tag{4}$$

$$\Delta P = k\frac{1}{2}\rho v^2 \tag{5}$$

where ΔP is the pressure drop across the restrictor. μ, ρ and v are the fluid viscosity, density, and velocity respectively. L and D are the length and diameter of the laminar restrictor and k is a geometrical constant. According to Eq. (4), the pressure drop across a laminar flow restrictor depends on density and viscosity. Therefore, when a viscose fluid like oil passes through a laminar flow restrictor, it experiences a higher pressure drop compared to low-viscosity fluids like water and gas. Because of less pressure drop after the laminar flow restrictor, low-viscosity fluids have higher pressure in the chamber between the laminar and turbulent flow restrictors. Therefore, low-viscosity fluids move with higher velocity before passing through the turbulent flow restrictor. Based on Eq. (5), the pressure drop across a turbulent flow restrictor is proportional to density and velocity squared. As a result, low-viscosity fluids experience higher pressure drop across the turbulent flow restrictor compared to oil. Based on these principles AICVs are designed to remain open for oil and almost completely close for unwanted fluids (Aakre et al., 2013; Mathiesen et al., 2014).

2.4. Advanced well completion

The completion of the horizontal wells with nozzle ICDs, RCP AICDs, and AICVs is similar. The schematic of the advanced well completion with these types of FCDs as well as AFI in a heterogeneous reservoir is illustrated in Fig. 2.

Each production joint has a typical length of 12.4 m and is equipped with the FCD and sand screen. Practically, one FCD is mounted on each joint, but depending on the condition, up to four FCDs can be installed on a joint. With this type of completion, at first, the reservoir fluids enter the annulus and pass through the sand screen and then the fluids flow into the inflow chamber where the FCDs are installed and finally enters the production tubing. Water or gas breakthrough occurs faster in the locations with higher inflow like the heel section of the well or in high-permeability zones. Therefore, to avoid filling the annulus with unwanted fluids, such areas must be isolated by using AFI. Zonal isolation can also improve the oil recovery before water or gas break-through (Eltaher et al., 2014; Mathiesen et al., 2011).

2.5. Multisegment well model

The multisegment well model which is available in the Eclipse simulator contains several options for modeling advanced wells. In this model, the tubing and wellbore are divided into several one-dimensional segments. Each segment consists of a node and a flow path and has its own set of independent variables to describe the local fluid conditions. Each wellbore segment can be connected to none, one or more reservoir grid blocks. Moreover, specific segments can also be configured to model FCDs. Fig. 3 shows the schematic of a multisegment well model in the Eclipse simulator. As can be seen in the figure, one branch is used to model the production tubing and another branch is used to model the wellbore. Wellbore and the production tubing are connected via the FCD segments. Flow from the reservoir enters the annulus via the wellbore segments and passes into the tubing via FCDs (Schlumberger, 0000).

2.6. Black-oil correlations

In order to model oil production from a reservoir, it is necessary to know the physical properties and the phase behavior of the reservoir fluids over a wide range of pressure and temperature. For achieving this goal, one way is using the PVT data, which is determined experimentally. Since doing laboratory tests for determining the PVT data is difficult, several empirical correlations have been developed based on laboratory test results and available field data in recent years. Knowing the reservoir fluid composition is not required for using these empirical correlations due to the fact that in these correlations the reservoir fluids are considered as black oils. Therefore, these empirical correlations are called black-oil correlations (Moradi, 2020). The determination of solution gas–oil ratio (R_s), as well as oil and gas formation volume factors (B_o, B_g), and viscosities (μ_o, μ_g) at reservoir temperature as a function of pressure, is crucial for developing a model in the Eclipse simulator. The following black-oil correlations (all in the field unit except temperature which is in °R) are used to fulfill this aim.

2.6.1. Solution gas–oil ratio

R_s can be calculated by using Standing's (1947) correlation presented by Eq. (6) as (Bahadori, 2016):

$$R_s = \gamma_g\left[\left(\frac{p}{18.2} + 1.4\right)10^{0.00091(T-460)-0.0125\cdot \mathrm{API}}\right]^{1.2048} \tag{6}$$

where γ_g is the gas specific gravity, API is the gravity of stock tank oil, p is the reservoir pressure, and T is the reservoir temperature.

2.6.2. Oil and gas formation volume factors

B_o can be calculated as a function of the solution gas–oil ratio, the gas and oil specific gravities, and the reservoir temperature by Eq. (7) proposed by Standing (1947) as (Bahadori, 2016):

$$B_o = 0.9759 + 0.000120\left[R_s\left(\frac{\gamma_g}{\gamma_o}\right)^{0.5} + 1.25(T-460)\right]^{1.2} \tag{7}$$

For the calculation of B_g, Eq. (8) is used as (Bahadori, 2016):

$$B_g = 0.02829\frac{ZT}{p} \tag{8}$$

where Z is the gas compressibility factor.

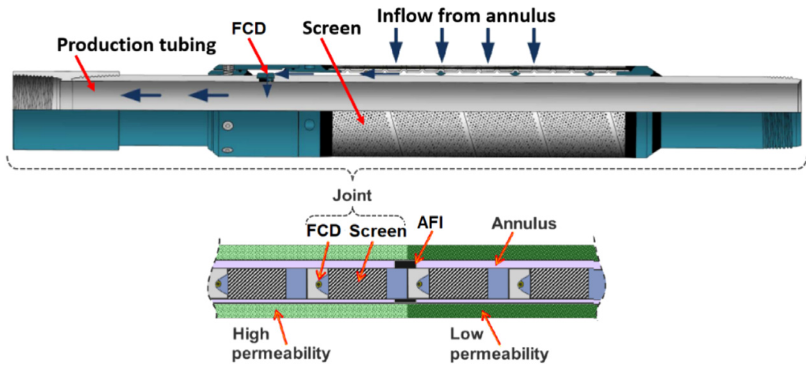

Fig. 2. Schematic of advanced well completion with the FCD and AFI in a heterogeneous reservoir (Halvorsen et al., 2012; Triandi et al., 2018).

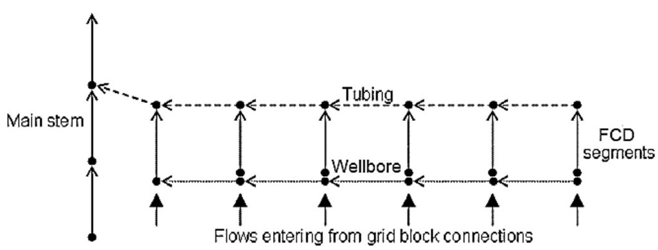

Fig. 3. Schematic of a multisegment well model in Eclipse (Schlumberger, 0000).

2.6.3. Oil and gas viscosities

The viscosity of dead oil, μ_{od}, undersaturated oil, μ_o, and saturated oil, μ_{ob}, can be calculated by using Standing's (1981) correlations given by Eqs. (9), (10), and (11) as (Bahadori, 2016):

$$\mu_{od} = 0.32 + \frac{18 \times 10^7}{\mathrm{API}^{4.53}} \left(\frac{360}{T - 260} \right)^{10^{0.42+\frac{8.332}{\mathrm{API}}}} \tag{9}$$

$$\mu_o = \mu_{ob} + 0.001(p - p_b)\left[0.024\mu_{ob}^{1.6} + 0.038\mu_{ob}^{0.56}\right] \tag{10}$$

$$\mu_{ob} = 10^a \mu_{od}^b \tag{11}$$

where p_b is the bubble point pressure and a and b are calculated by:

$$a = R_s(2.2 \times 10^{-7} R_s - 7.4 \times 10^{-4}) \tag{12}$$

$$b = 0.68 \times 10^c + 0.25 \times 10^d + 0.062 \times 10^e \tag{13}$$

$$c = -0.0000862 R_s, \;\; d = -0.0011 R_s, \;\; e = -0.0037 R_s \tag{14}$$

For prediction of the gas viscosity, Eq. (15) which is suggested by Lee et al. can be used as (Bahadori, 2016):

$$\mu_g = 10^{-4} k_v \exp\left[x_v \left(\frac{\rho}{62.4} \right)^{y_v} \right] \tag{15}$$

where ρ is the gas density. By using the molecular weight of the gas, MW, the parameters x_v, y_v, and k_v are calculated as:

$$x_v = 3.448 + 986.4 + 0.01009 \cdot \mathrm{MW} \tag{16}$$

$$y_v = 2.4 - 0.2 x_v \tag{17}$$

$$k_v = \frac{(0.379 + 0.0160 \cdot \mathrm{MW}) T^{1.5}}{209.2 + 19.26 \cdot \mathrm{MW} + T} \tag{18}$$

2.7. Generalized Corey model for relative permeability

One of the most accurate parametric models for the estimation of relative permeability for a two-phase system like gas–oil, gas–water, and oil–water systems is the generalized Corey model. Based on this model, for an oil–water system, the relative permeability of oil and water can be estimated by the following functions:

$$k_{ro} = k_{rocw} \left[\frac{1 - S_w - S_{ro}}{1 - S_{wc} - S_{ro}} \right]^{n_{ow}}, \; k_{rw} = k_{rwro} \left[\frac{S_w - S_{wc}}{1 - S_{wc} - S_{ro}} \right]^{n_w} \tag{19}$$

where S_w is the water saturation, S_{wc} is the irreducible water saturation, S_{ro} is the residual oil saturation, n_{ow} and n_w are the Corey exponents, k_{rocw} and k_{rwro} are the maximum relative permeability of oil and water respectively (Aakre, 2017).

2.8. Linear regression using the Least-Squares Method

If a function between two sets of corresponding variables, (x_1, x_2, …, x_n) and (y_1, y_2, …, y_n), can be described by a linear model as $y = \varphi^T(x) \cdot \theta$ where θ is the vector of unknown parameters of this model, θ^* which is the vector including the optimum values for the unknown parameters of the model, can be calculated by (Wikipedia, 2021):

$$\theta^* = (\phi^T \phi)^{-1} \phi^T Y \tag{20}$$

where

$$\phi = \begin{bmatrix} \varphi^T(x_1) \\ \varphi^T(x_2) \\ \vdots \\ \varphi^T(x_n) \end{bmatrix}, Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}.$$

2.9. Differential sensitivity analysis

Differential sensitivity analysis is one of the common techniques for performing sensitivity analysis. In this method, the sensitivity of each input parameter is quantified by a sensitivity coefficient which is basically the ratio of the change in output to the change in input while all other parameters remain constant. The sensitivity coefficient, ϕ_i, for a particular independent input variable X_i, with respect to the desired output Y, is calculated by Eq. (21) as (Hamby, 1994):

$$\phi_i = \frac{\partial Y}{\partial X_i} \left(\frac{X_i}{Y} \right) \tag{21}$$

where the quotient, X_i/Y, is introduced to normalize the coefficient by removing the effects of units.

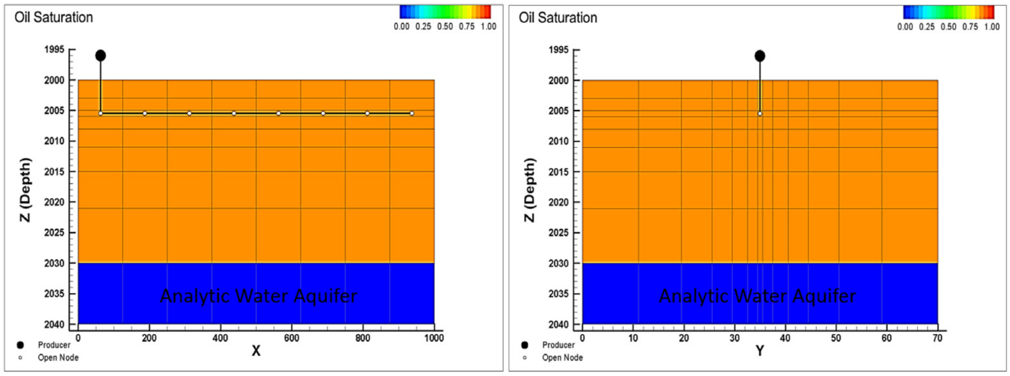

Fig. 4. The geometry of the reservoir near the well and the mesh resolution for simulation.

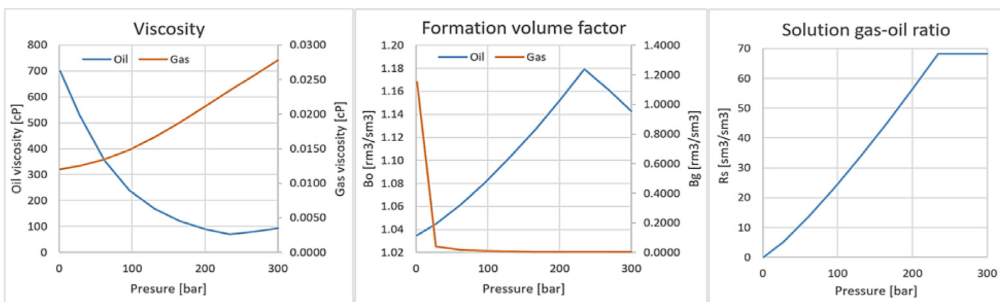

Fig. 5. Physical properties of oil and gas based on the pressure at the reservoir temperature.

3. Data and methods

3.1. Rock and fluid properties of the near-well reservoir

In this paper, the study is conducted through modeling and near-well simulation of oil production from an advanced horizontal well with different FCD completions in a synthetic reservoir with uncertain reservoir permeability parameters. It is assumed that a large water aquifer is located under the reservoir that maintains constant pressure at the bottom face of the reservoir. It is also assumed that the reservoir has a thickness of 30 m and a horizontal well with a length of 992 m is located 5.5 m below the top of the reservoir. For performing near-well simulation, the geometry of the reservoir near the well must be specified based on the dimensions of the drainage area of the well. The effective drainage area of a horizontal well has an ellipsoidal shape in reality. However, for simplicity, it can be assumed that the effective drainage area of a horizontal well has a rectangular shape. In this case, the length of the drainage area is the same as that of the horizontal well and the thickness of the drainage area is the same as that of the reservoir. The width of the drainage is assumed to be more than twice as big as the thickness of the drainage area. Therefore, the dimensions of the reservoir near the well are chosen to be 992 × 70 × 30 m. The cross-section of the drainage area is located in the Y–Z plane and the well is in the X-direction. Since the variation of fluid pressure in the Y and Z directions is higher than that of the X direction, the mesh configuration is considered to be nonuniform (finer mesh near the wellbore) in the Y and Z directions, and uniform in the X-direction. The geometry of the near-well reservoir and the mesh resolution is illustrated in Fig. 4.

The rock and fluid properties of the reservoir are given in Table 1. The reservoir contains live heavy oil with a viscosity of 90 cP at the reservoir pressure and temperature. Moreover, for developing the model in the Eclipse simulator, the variation of R_s, B_o, B_g, μ_o, and μ_g as a function of pressure at the reservoir temperature is calculated by the black-oil correlations given by Eqs. (6) to (18) and illustrated in Fig. 5.

3.2. Description of uncertainty in the reservoir permeability

The reservoir permeability is specified by three parameters of absolute permeability, permeability anisotropy, and relative permeability. In order to include uncertainty in the reservoir permeability, it is assumed that absolute permeability varies from 10 mD to 5000 mD in the reservoir. Also, the minimum and maximum permeability anisotropy in the reservoir are 0.05 and 0.95 respectively. Moreover, the wettability state of the reservoir change from completely oil-wet to completely water-wet, and consequently there is large uncertainty in the relative permeability of the reservoir. To perform uncertainty assessment based on the LHS method, 10 equally probable values (samples) for each reservoir permeability parameter are chosen. The samples are chosen in such a way that they cover the range of uncertainty in each parameter. These samples can have 1000 (10 × 10 × 10) equally probable combinations and consequently, 1000 states for the reservoir permeability must be considered for doing uncertainty quantification. To achieve this, 1000 simulation runs for each method of the well completion are needed. Table 2 presents the 10 possible values (samples) that have been chosen for absolute permeability, permeability anisotropy, and relative permeability. For specifying the relative permeability, the generalized Corey model given by Eq. (19) is used and the oil and water permeability curves are illustrated in Fig. 6.

3.3. Development of advanced well models with AFI and FCD completions

For modeling advanced wells with ICD and AICD completions as well as AFI in the Eclipse simulator using the multisegment well model, there are specific options (Eclipse keywords). Using the Eclipse keyword for modeling the ICD completion is quite

Table 1
The rock and fluid properties of the reservoir.

Property	Oil density	Oil viscosity	Water density	Water viscosity	Solution GOR	Porosity	Initial water saturation	Reservoir pressure	Reservoir temperature
Value	990	90	1050	0.46	68	0.25	0.12	200	60
Unit	kg/m^3	cP	kg/m^3	cP	sm^3/sm^3	–	–	bar	°C

Table 2
The values of reservoir permeability parameters for uncertainty analysis based on the LHS method.

Sample No.	Absolute permeability	Permeability anisotropy	Relative permeability parameters						Wettability
			nw	no	Swc	Sro	krocw	krwro	State
S1	10	0.05	1	6	0.15	0.05	0.775	1	Oil wet
S2	20	0.15	1.2	5.5	0.15	0.05	0.8	0.8	
S3	50	0.25	1.5	5	0.15	0.05	0.825	0.6	
S4	100	0.35	1.8	4.5	0.15	0.05	0.85	0.5	
S5	200	0.45	2	4	0.15	0.05	0.875	0.4	Mix wet
S6	500	0.55	3	3.6	0.15	0.05	0.9	0.35	
S7	1000	0.65	4	3.2	0.15	0.05	0.925	0.31	
S8	2000	0.75	5	2.8	0.15	0.05	0.95	0.27	
S9	3000	0.85	6	2.4	0.15	0.05	0.975	0.23	
S10	5000	0.95	7	2	0.15	0.05	1	0.2	Water wet

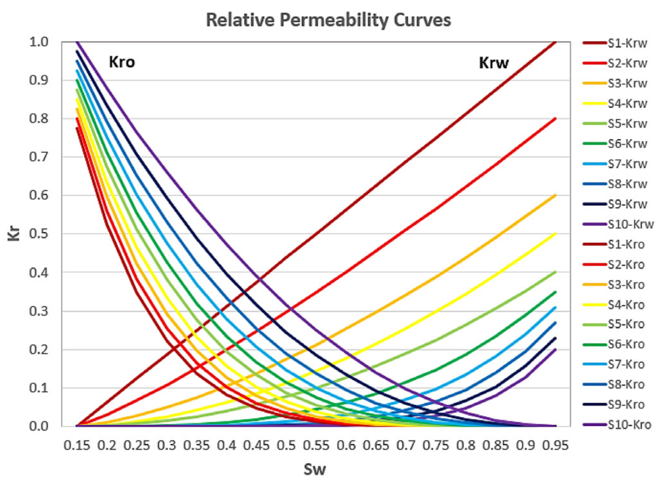

Fig. 6. The relative permeability curves used for uncertainty analysis based on the LHS method.

straightforward. However, in order to use the Eclipse keyword for modeling AICD completion, at first, a mathematical model in the format of Eq. (2) describing the autonomous behavior of AICDs must be derived. This can be fulfilled by performing linear regression on the available laboratory test data for the performance of AICDs (Moradi and Moldestad, 2021). Unlike ICDs and AICDs, there is not any specific Eclipse keyword for modeling the AICV completion. However, the Eclipse keyword for modeling AICDs can be used for modeling AICVs as well, if a mathematical model in the format of Eq. (2) describing the autonomous behavior of AICVs can be derived.

In order to develop the advanced well model with AFI and FCD completion, it is assumed that the production tubing consists of 8 segments, each 124 m long, completed with one equivalent FCD. The wellbore in the X-direction is also discretized into 8 uniform and isolated sections with the same length connected to the near-well reservoir. For comparing the performance of different types of FCDs, the size (strength) of FCDs used for developing the models must be the same. As a result, it is assumed that the flow area of the equivalent ICD is 7.85×10^{-5} m^2 (based on a nozzle diameter of 0.01 m), and the AICD and AICV have the same flow area when they are fully open. It is also assumed that the wellbore diameter is 8.5 inch and the production tubing has a diameter of 5.5 inch with a roughness of 15 µm.

There are some laboratory test data available in the literature describing the performance of AICDs and AICVs. Fig. 7 shows such experimental data for the similar size AICDs and AICVs. The experimental results for water and heavy oil with the viscosity of 90 cP for AICDs and 84 cP for AICV are used in this study. The exact values of the pressure difference based on the volumetric flow rate for these FCDs presented in Fig. 6 can be obtained by using photo digitizer software.

The mathematical functions for AICDs and AICVs in the format of Eq. (2) can be derived by doing linear regression on the obtained experimental values using the least-squares method presented by Eq. (20). This can be done by taking the logarithm from both sides of Eq. (2) and writing this equation in the matrix form as:

$$\log\left[\frac{\Delta P\cdot\rho_{cal}}{\rho^2{}_{mix}}\right]=\begin{bmatrix}1 & \log\left(\frac{\mu_{cal}}{\mu_{mix}}\right) & \log\dot{Q}\end{bmatrix}\begin{bmatrix}\log a_{AICD}\\ y\\ x\end{bmatrix}. \tag{22}$$

Eq. (22) can be presented in the form of $y=\varphi^T(x)\cdot\theta$ where:

$$y=\log\left[\frac{\Delta P\cdot\rho_{cal}}{\rho^2{}_{mix}}\right],\ \varphi^T=\begin{bmatrix}1 & \log\left(\frac{\mu_{cal}}{\mu_{mix}}\right) & \log\dot{Q}\end{bmatrix}, \quad \theta=\begin{bmatrix}\log a_{AICD}\\ y\\ x\end{bmatrix}. \tag{23}$$

Moreover, based on experimental data obtained from Fig. 7, ϕ and Y matrices, can be formed. Therefore, by using Eq. (20) the values of ρ_{cal}, μ_{cal}, a_{AICD}, y and x are calculated. By using this method, Eq. (24) is derived for AICDs (for the oil curve, $R^2 = 0.9950$, and for the water curve, $R^2 = 0.9841$). In the same way, Eq. (25) is derived for AICVs (for the oil curve, $R^2 = 0.9861$, and for the water curve, $R^2 = 0.9272$).

$$\Delta P_{AICD}=0.2875\cdot\left(\frac{\rho^2_{mix}}{1000}\right)\cdot\left(\frac{1}{\mu_{mix}}\right)^{0.6489}\cdot\dot{Q}^{2.6417}_{AICD} \tag{24}$$

$$\Delta P_{AICV}=0.4127\cdot\left(\frac{\rho^2_{mix}}{1000}\right)\cdot\left(\frac{1}{\mu_{mix}}\right)^{0.7532}\cdot\dot{Q}^{2.0115}_{AICV} \tag{25}$$

As can be seen in Fig. 8, the derived mathematical models for describing the performance of AICDs and AICVs have a suitable agreement with the laboratory test data and these functions are used for developing the advanced well models with AICD and AICV completions as well as AFI in the Eclipse simulator.

By using Eqs. (24) and (25), the performance of AICDs and AICVs in choking water in a heavy oil/water system can be compared. This can be done by considering an AICD and AICV as

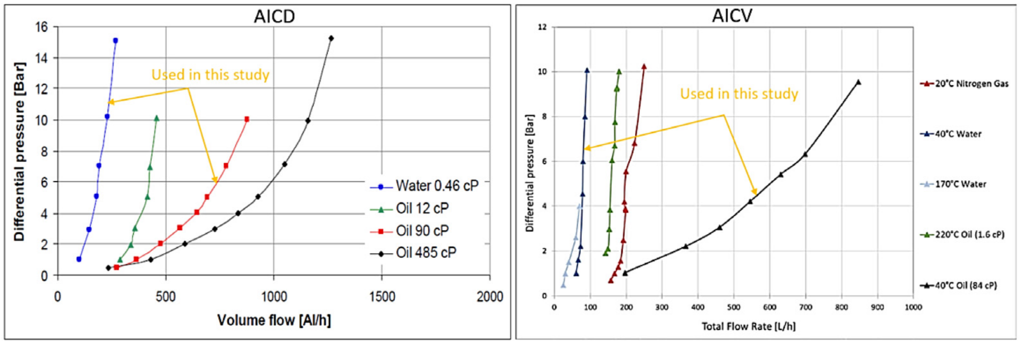

Fig. 7. Laboratory test data describing the performance of AICDs and AICVs (Mathiesen et al., 2011; Taghavi et al., 2019).

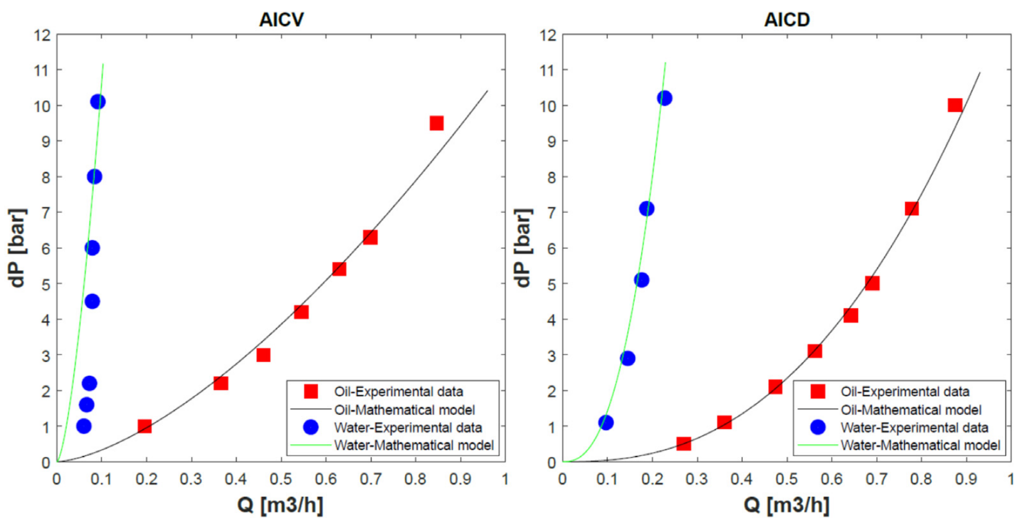

Fig. 8. The derived mathematical models of AICDs and AICVs against the laboratory test data for heavy oil and water.

a self-adjusting ICD with a flexible flow area, and combining Eqs. (24) and (25) with Eq. (1) for calculating the opening of AICDs and AICVs based on water cut. By using this method and assuming a pressure difference of 8 bar over the AICDs and AICVs, Eqs. (26) and (27) are obtained as:

$$a_1 = \frac{\left[\frac{8\times10^5}{10^5\times0.2875\cdot(\rho_{mix}^2/1000)\cdot(1/\mu_{mix})^{0.6489}}\right]^{\frac{1}{2.6417}}}{7.85\times10^{-5}\times3600\times0.61\cdot\sqrt{\frac{2\times8\times10^5}{\rho_{mix}}}} \tag{26}$$

$$a_2 = \frac{\left[\frac{8\times10^5}{10^5\times0.4127\cdot(\rho_{mix}^2/1000)\cdot(1/\mu_{mix})^{0.7532}}\right]^{\frac{1}{2.0115}}}{7.85\times10^{-5}\times3600\times0.61\cdot\sqrt{\frac{2\times8\times10^5}{\rho_{mix}}}} \tag{27}$$

where a_1 and a_2 are the parameters presenting the opening of the flow area of AICDs and AICVs respectively. Fig. 9, shows the performance of AICDs compared to AICVs for choking water in a heavy oil/water system by considering a pressure difference of 8 bar over these valves.

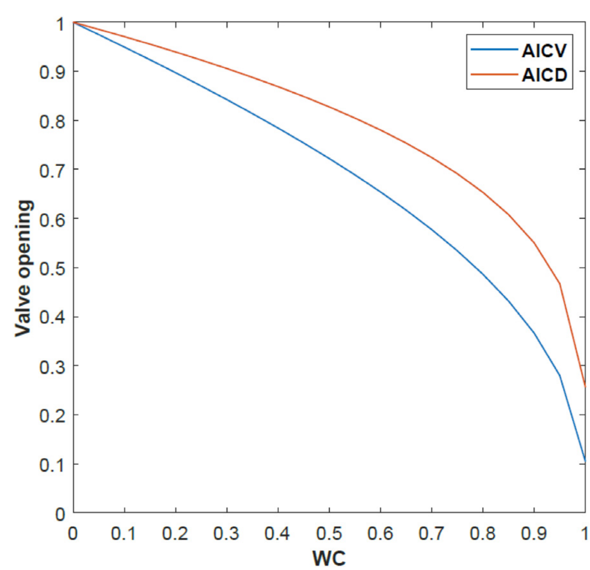

Fig. 9. Valve opening vs water cut for AICDs and AICVs in a heavy oil/water system.

3.4. Defining the strategy of production

The performance of advanced wells with different FCD completions highly depends on which production strategy is applied. There are two general strategies for oil production. In the first strategy, production is controlled by the Bottom Hole Pressure (BHP) or Tubing Head Pressure THP and constrained by the maximum allowed liquid production rate. In the second strategy, production is controlled based on the target liquid production rate and constrained by the minimum allowed BHP or THP. In this study, it is assumed that oil is produced according to the first general strategy in which the well is controlled by the minimum

BHP of 192 bar (the reservoir pressure is 200 bar) and constrained by the maximum liquid production rate of 500 m^3/day. In other words, in this strategy oil is produced with the constant pressure drawdown of 8 bar as long as the liquid production rate is below 500 m^3/day. When the liquid production rate exceeds 500 m^3/day, the pressure drawdown is decreased (BHP is increased) to keep the liquid production rate below 500 m^3/day.

4. Result and discussions

Sensitivity analysis is a widely used technique for quantifying how an input parameter affects the model outputs. Therefore, by using the sensitivity analysis, the contribution of the uncertainty of each model input to the uncertainty of the model outputs can be assessed and the most important parameters of the system can be identified. In this paper, a sensitivity analysis based on Eq. (21) has been performed to show how the uncertainty in reservoir permeability parameters (model inputs) can affect the performance of advanced wells in oil and water production (model outputs). According to the performed sensitivity analysis, the sensitivity coefficient for each reservoir permeability parameter with respect to cumulative oil and water production has been calculated and presented in Fig. 10. As can be seen in the figure, among the reservoir permeability parameters, relative permeability is the most, and permeability anisotropy is the least influential parameter on the performance of advanced wells. This means that uncertainty in relative permeability has the highest, and uncertainty in permeability anisotropy has the lowest contribution to the uncertainty in the performance of advanced wells. It can also be noticed that uncertainty in all reservoir permeability parameters has a higher impact on the uncertainty in water production than in oil production. Besides, Fig. 10 clearly illustrates that uncertainty in the reservoir permeability parameters has a noticeably lower impact on the performance of advanced wells with AICDs and AICVs compared to advanced wells with ICDs and open-hole wells. Therefore, by completing advanced wells with reactive FCDs (AICDs and AICVs) the effect of uncertainty in the reservoir permeability parameters on the well performance can be reduced.

In order to evaluate the performance of advanced wells based on different FCD completions, at first, the functionality of such FCDs in heavy oil production has been investigated without taking the uncertainty in the reservoir permeability into account. To achieve this, for a base model, the absolute permeability and permeability anisotropy of the near-well reservoir have been fixed to be 500 mD and 0.2 respectively. The relative permeability of the reservoir has also been specified using the Corey model for a mixed-wet reservoir.

Figs. 11 and 12 show the simulation results for oil and water production under the mentioned strategy from the advanced well with ICD, AICD, and AICV completions compared to the conventional (open-hole) well during 5000 days. Besides, oil saturation distribution in the reservoir after 1500 days for the open-hole well and advanced wells with different FCD completions is illustrated in Fig. 13.

Since basically with the same pressure drawdown, open-hole wells provide a more open area for the production of reservoir fluids, liquid production from such wells is higher than that of advanced wells. Therefore, as the results show, more oil and water are produced by using the open-hole completion. Moreover, AICDs and AICVs are fully open before water breakthrough and act like ICDs. However, as shown in Fig. 9, after water breakthrough these valves get partially closed by increasing the water cut. As a result, as Fig. 11 illustrates, less oil and water are produced from AICD and AICV completions compared to ICD completion. Due to the fact that AICVs have more capability for getting closed compared to AICDs shown in Fig. 9, liquid production from AICV completion is also less than AICD completion. According to Fig. 12, compared to the open-hole completion the cumulative oil production from ICD, AICD, and AICV completions is relatively reduced by 0.87%, 5.23%, and 13.85% respectively after 5000 days; however, the cumulative water productions considerably decrease by 4.17%, 22.73%, and 50.43% using these FCDs. Therefore, by using advanced wells with FCD completions the production of unwanted fluids is considerably reduced. Lifting, handling, and then disposing of unwanted fluids like water costs a lot of money. Therefore, controlling the water cut is one of the most important measures that must be taken to achieve cost-effective and improved oil production. Therefore, the functionality of FCDs is governed by their potential in maximizing profit by reducing the production of unwanted fluids per barrel of produced oil.

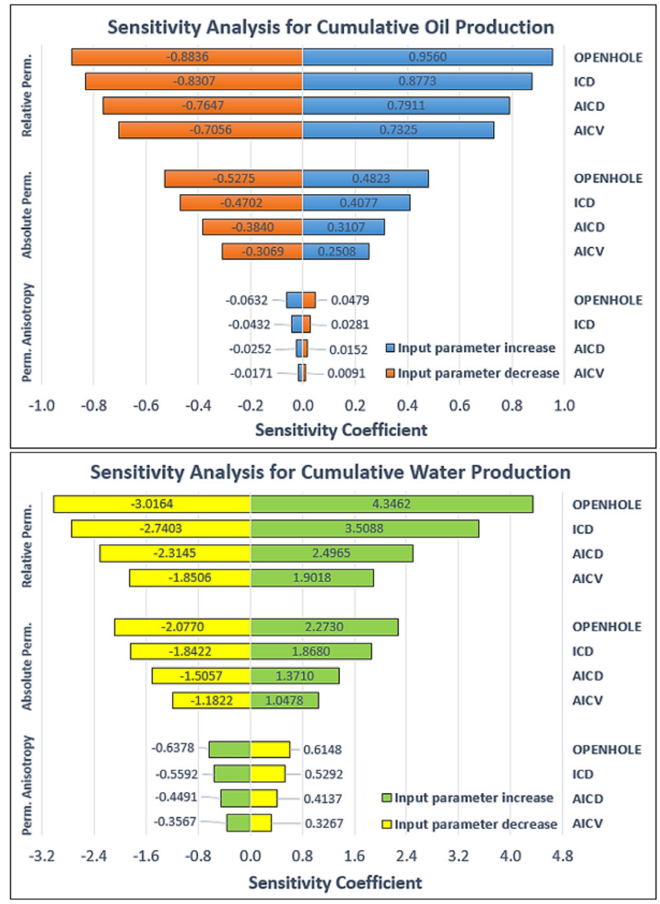

Fig. 10. Sensitivity analysis for reservoir permeability parameters with respect to cumulative oil and water production.

The presented results in Figs. 11–13 illustrate the performance of advanced well with different FCD completions just for the base case in which specific values have been considered for the reservoir permeability parameters. However, such wells may have different performances in reservoirs with other values of permeability parameters. There is huge uncertainty in the reservoir permeability parameters and consequently, to evaluate the performance of advanced wells this uncertainty must be taken into account. For achieving this goal, based on the values of permeability parameters specified by the LHS approach in Table 2, 1000 simulations have been run for open-hole, ICD, AICD, and AICV completions for 10 years. These 1000 simulation runs

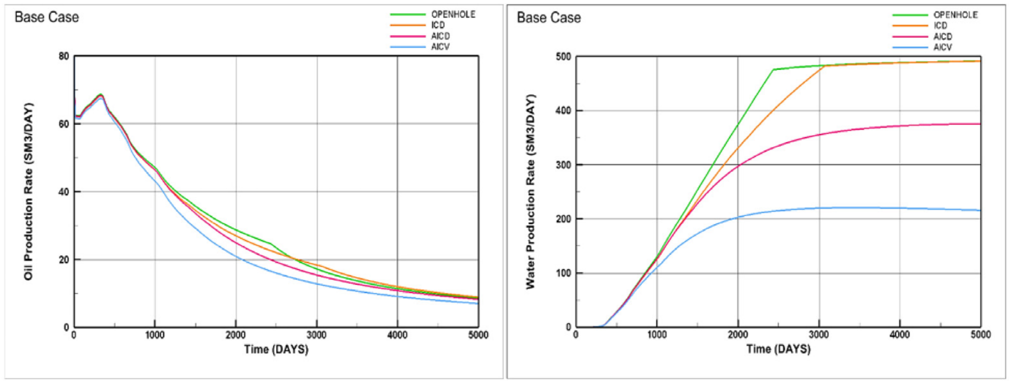

Fig. 11. Volumetric oil and water production rate from open-hole and advanced wells with different FCD completions.

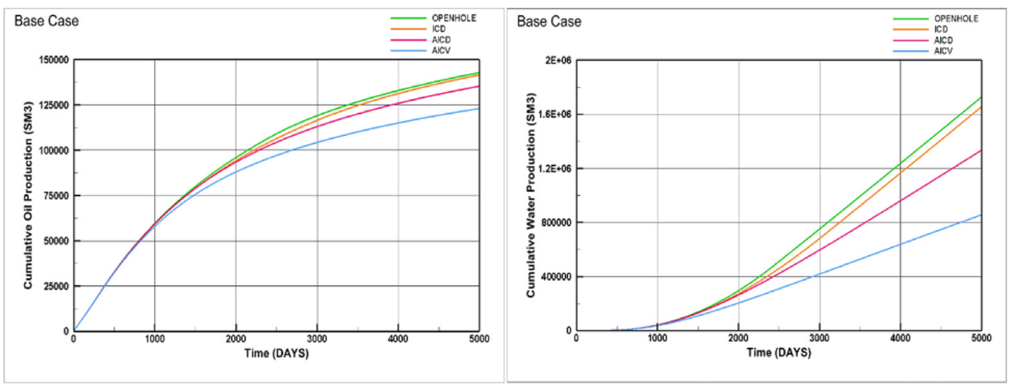

Fig. 12. Cumulative oil and water production from open-hole and advanced wells with different FCD completions.

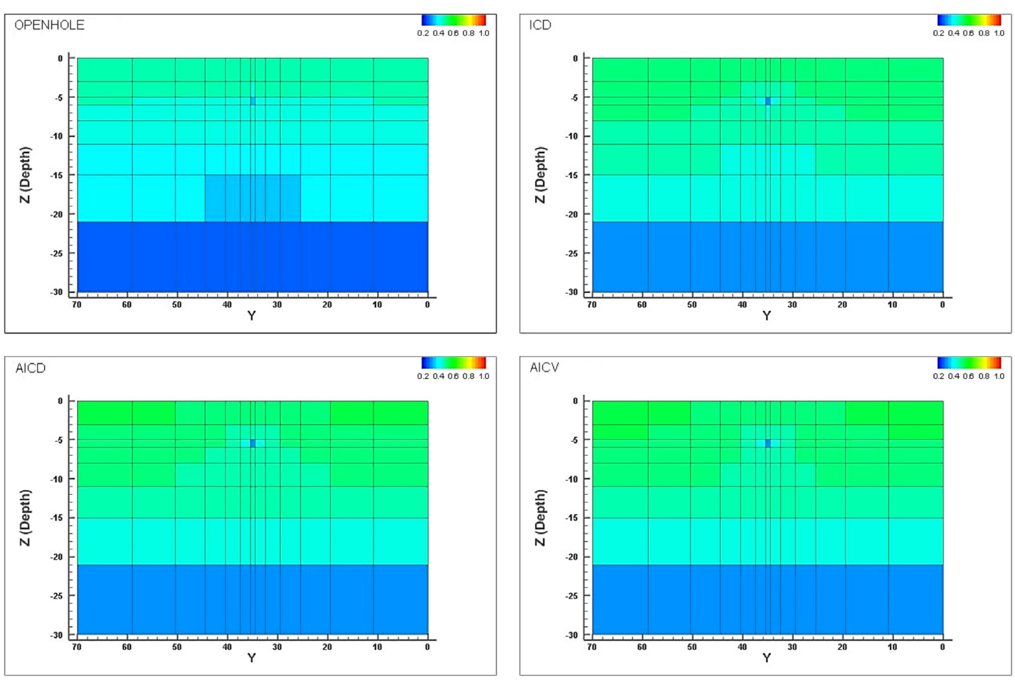

Fig. 13. Oil saturation distribution in the reservoir after 1500 days for the open-hole well and advanced wells with different FCD completions.

cover all possible combinations of the considered values of reservoir permeability parameters and believed they maintain enough accuracy for doing uncertainty quantifications. Based on the obtained results from these simulations, the probability distribution for cumulative oil and water production after 10 years has been determined and presented in Fig. 14.

As can be seen in the figure, under the presence of uncertainty in the reservoir permeability, the mean value of cumulative water

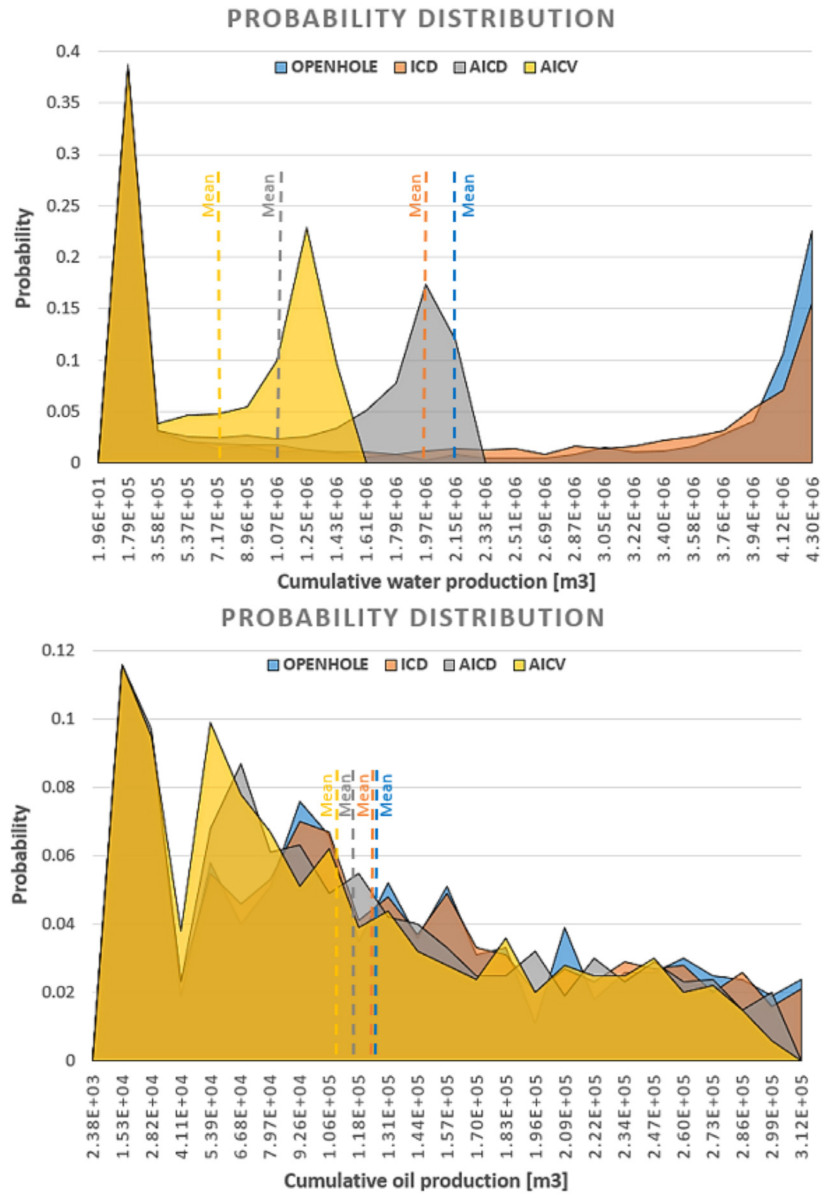

Fig. 14. Probability distribution of cumulative oil and water production for open-hole and advanced wells with different FCD completions.

production by using AICDs and AICVs is significantly decreased compared to ICD and open-hole completion. However, the mean value of oil recovery from AICD and AICV completions is slightly lower than that of ICD and open-hole completions. The mean values of cumulative oil and water production are given in Table 3. According to these results, the mean value of cumulative water production is reduced by 8.28%, 49.96%, and 65.90% using ICDs, AICDs, and AICVs compared to open-hole completion. In the same way, the figure for mean oil recovery is decreased by 1.37%, 8.87%, and 13.42% respectively.

To perform uncertainty analysis, by using the probability distribution curves presented in Fig. 14, the cumulative probability distributions of water and oil production have been determined and illustrated by Fig. 15. Moreover, for cumulative production of water and oil, the low estimation (P10), median or best estimation (P50), and the high estimation (P90) based on open-hole, ICD, AICD, and AICV completions has been calculated and given in Table 3.

According to the presented results, P50 or the most probable (best) estimation for water production is sequentially 21.63%, 40.57%, and 59.20% lower when the advanced wells are completed with ICDs, AICDs, and AICVs compared to open-hole completion. Besides, P50 for oil production based on ICD and open-hole completions is almost the same although it is 12.07%, and 19.79% lower for AICD and AICV completions. P10 for both water and oil production based on all types of completions is almost the same. However, P90 for water production by using AICDs and AICVs significantly decreased compared to ICD and open-hole completions. This means that by completion of advanced well with AICDs and AICDs the risk (P10 through P90) of water production is considerably decreased. According to obtained results, under the presence of uncertainty in the reservoir permeability, the risk of water production is decreased by 0.87%, 53.20%, and 71.12% using ICDs, AICDs, and AICVs compared to open-hole completions. According to obtained results, under the presence of uncertainty in the reservoir permeability, the risk of water production is decreased by 0.87%, 53.20%, and 71.12% using ICDs, AICDs, and AICVs compared to open-hole completions.

These simulation results are reasonably comparable with the results of heavy oil recovery by using advanced wells in real cases.

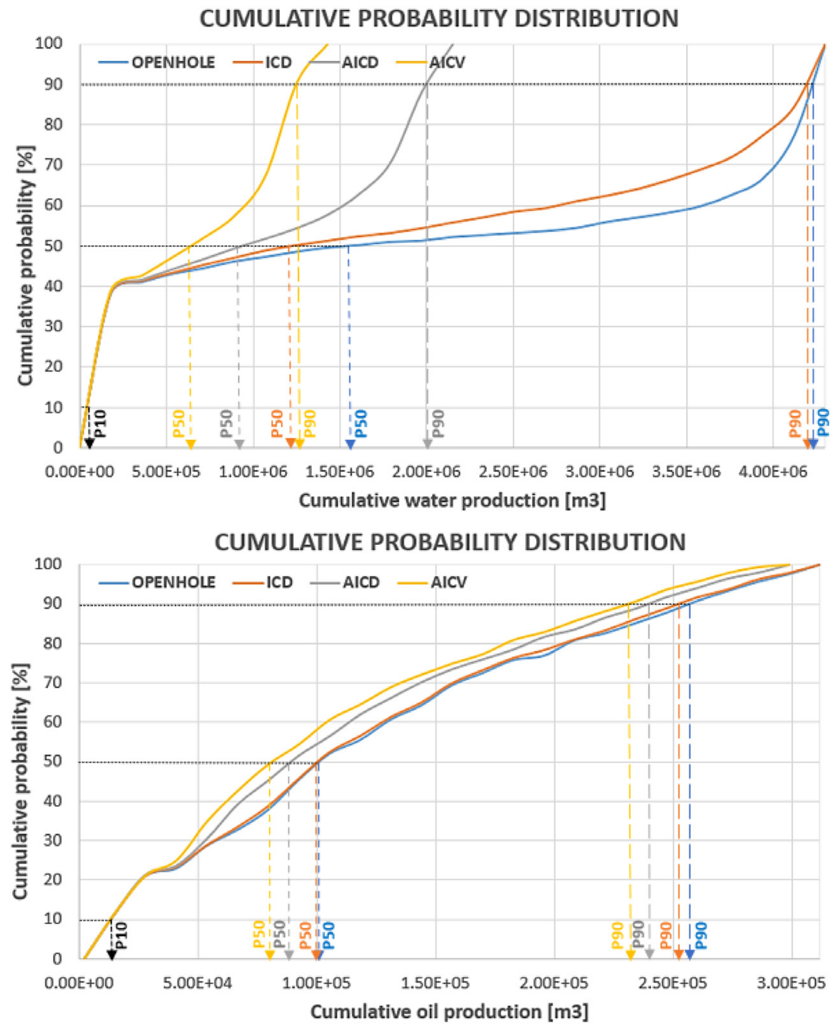

Fig. 15. Cumulative probability distribution of cumulative oil and water production for open-hole and advanced wells with different FCD completions.

Table 3
Mean, low estimation (P10), median or best estimation (P50), and high estimation (P90) of cumulative water and oil production based on open-hole, ICD, AICD, and AICV completions under uncertainty in the reservoir permeability.

Parameter	Cumulative Water Production [m^3]				Cumulative Oil Production [m^3]			
	Openhole	ICD	AICD	AICV	Openhole	ICD	AICD	AICV
Mean	2.13E+06	1.95E+06	1.06E+06	7.25E+05	1.26E+05	1.24E+05	1.15E+05	1.09E+05
P10	4.70E+04	4.70E+04	4.62E+04	4.63E+04	1.36E+04	1.36E+04	1.34E+04	1.35E+04
P50	1.58E+06	1.24E+06	9.41E+05	6.46E+05	1.02E+05	1.01E+05	8.93E+04	8.15E+04
P90	4.22E+06	4.18E+06	2.00E+06	1.25E+06	2.57E+05	2.52E+05	2.39E+05	2.31E+05

The first real example is heavy oil recovery from a reservoir in Western Canada by using a well with AICD completion. According to the reported results, water production has been reduced by 40%–50% using an advanced well with AICD completion (Tendeka, 2022). This is close to the obtained simulation results that show AICD completion can reduce the risk of water production by 53.2%. The second real example is heavy oil recovery from a reservoir in the Middle East using six wells completed by AICVs. According to the field operator, water cut has been reduced by 68% using advanced wells with AICV completion (InflowControl, 2022). This is also comparable with the obtained results from the simulation that show AICV completion can reduce the risk of water production by 71.12% in heavy oil recovery. These two real examples can roughly prove that the obtained simulation results are reasonable and realistic.

5. Conclusions

The performance of advanced wells with AFI and different FCD completions compared to conventional wells in heavy oil recovery under uncertainty in the reservoir permeability parameters has been evaluated in this paper. The evaluation was conducted for a synthetic reservoir with a strong water drive under a production strategy based on controlling the minimum BHP constrained by the maximum allowed liquid production rate. According to the performed sensitivity analysis, among the reservoir permeability parameters, uncertainty in relative permeability has the highest, while uncertainty in permeability anisotropy has the lowest impact on the performance of advanced wells. Besides, uncertainty in the reservoir permeability parameters has a noticeably lower impact on the performance of advanced wells with AICDs and AICVs compared to advanced wells with ICDs and open-hole wells. Therefore, by completing advanced wells with AICDs and AICVs the effect of uncertainty in the reservoir permeability parameters on the well performance can be reduced. According to the obtained simulation results, almost the same amount of oil is produced by using an advanced well with passive FCD (ICDs) completion compared to an open-hole well in heavy oil recovery. However, by applying reactive FCD (AICDs and AICVs) completions, oil production is slightly decreased compared to open-hole completion. This is due to the fact that reactive FCDs get partially closed by increasing water cut and consequently with the same pressure drawdown, liquid production (both oil and water) from such wells is less than that of an open-hole well. According to the performed uncertainty assessment, under the presence of uncertainty in reservoir permeability, reactive FCDs compared to passive FCDs have a much better performance in mitigating the risk of water production in heavy oil recovery. AICD and AICV completions can significantly reduce the risk of water production by 53.20% and 71.12% respectively compared to open-hole completion while by using ICD completion the risk of water production is only reduced by 0.87%. Lifting, handling, and then disposing of water costs a lot of money and also have a huge carbon footprint. Therefore, using advanced well completed with reactive FCDs as well as AFI can be a valuable measure for achieving cost-effective and environmentally friendly heavy oil recovery.

CRediT authorship contribution statement

Ali Moradi: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Nastaran A. Samani:** Methodology, Formal analysis. **Amaranath S. Kumara:** Supervision, Methodology. **Britt M.E. Moldestad:** Supervision, Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ali Moradi reports financial support was provided by University of South-Eastern Norway. Ali Moradi reports a relationship with University of South-Eastern Norway that includes: employment.

Data availability

Data will be made available on request.

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References

Aakre, H., 2017. The Impact of Autonomous Inflow Control Valve on Increased Oil Production and Recovery (Ph.D. thesis). University College of Southeast Norway, Faculty of Technology, Natural Sciences and Maritime Sciences.

Aakre, H., Halvorsen, B., Werswick, B., Mathiesen, V., 2013. Smart well with autonomous inflow control valve technology. In: SPE Middle East Oil and Gas Show and Conference. OnePetro.

Al-Khelaiwi, F.T.M., et al., 2013. A Comprehensive Approach to the Design of Advanced Well Completions (Ph.D. thesis). Heriot-Watt University.

Bahadori, A., 2016. Fluid Phase Behavior for Conventional and Unconventional Oil and Gas Reservoirs. Gulf Professional Publishing.

Birchenko, V.M., Demyanov, V., Konopczynski, M.R., Davies, D.R., 2008. Impact of reservoir uncertainty on selection of advanced completion type. In: International Petroleum Technology Conference. European Association of Geoscientists & Engineers.

Eltaher, E., Muradov, K., Davies, D., Grassick, P., 2019. Autonomous flow control device modelling and completion optimisation. J. Pet. Sci. Eng. 177, 995–1009.

Eltaher, E.M.K., Sefat, M.H., Muradov, K., Davies, D., 2014. Performance of autonomous inflow control completion in heavy oil reservoirs. In: International Petroleum Technology Conference. OnePetro.

Ghosh, B., King, P., 2013. Optimisation of smart well completion design in the presence of uncertainty. In: SPE Reservoir Characterization and Simulation Conference and Exhibition. OnePetro.

Grebenkin, I.M., Davies, D.R., 2010. Analysis of the impact of an intelligent well completion on the oil production uncertainty. In: SPE Russian Oil and Gas Conference and Exhibition. OnePetro.

Guilmain, M., Fipke, S., Konopczynski, M., et al., 2019. Aicd technology reduces water cut and improves oil recovery in Colombian heavy oil field. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

Haghighat Sefat, M., et al., 2016. Proactive Optimisation of Intelligent Wells under Uncertainty (Ph.D. thesis). Heriot-Watt University.

Halvorsen, M., Elseth, G., Nævdal, O.M., 2012. Increased oil production at troll by autonomous inflow control with rcp valves. In: SPE Annual Technical Conference and Exhibition. OnePetro.

Halvorsen, M., Madsen, M., Vikøren Mo, M., Isma Mohd, I., Green, A., 2016. Enhanced oil recovery on troll field by implementing autonomous inflow control device. In: SPE Bergen One Day Seminar. OnePetro.

Hamby, D.M., 1994. A review of techniques for parameter sensitivity analysis of environmental models. Environ. Monit. Assess. 32 (2), 135–154.

Henriksen, K.H., Gule, E.I., Augustine, J.R., 2006. Case study: The application of inflow control devices in the troll field. In: SPE Europec/EAGE Annual Conference and Exhibition. OnePetro.

InflowControl, 2021. Autonomous inflow control valve. https://www.inflowcontrol.no/. (Accessed 10 November 2021).

InflowControl, 2022. 68% Water cut reduction: 6 AICV® wells within a mature heavy oil field. https://www.nsenergybusiness.com/wp-content/uploads/sites/3/2020/10/Case-Study-3-AICV%C2%AE-Water-Shut-off_Control_2020_A4.pdf.

Kais, R., Mathiesen, V., Aakre, H., Woiceshyn, G., Elarabi, A., Hernandez, R., 2016. First autonomous inflow control valve AICV well completion deployed in a field under an EOR water & CO2 injection scheme. In: SPE Annual Technical Conference and Exhibition. OnePetro.

Langaas, K., Jeurissen, E.J., Abay, H.K., 2019. Combining passive and autonomous inflow-control devices in a trilateral horizontal well in the alvheim field. SPE Prod. Oper. 34 (03), 446–460.

Mathiesen, V., Aakre, H., Werswick, B., Elseth, G., 2011. The autonomous RCP valve-new technology for inflow control in horizontal wells. In: SPE Offshore Europe Oil and Gas Conference and Exhibition. OnePetro.

Mathiesen, V., Werswick, B., Aakre, H., 2014. The next generation inflow control, the next step to increase oil recovery on the norwegian continental shelf. In: SPE Bergen One Day Seminar. OnePetro.

Mohammad Zin, Z., Khairuddin, M.S., A Manaf, M., Mohammad, S.M., Yap, B.C., Ahmad, M.Y., Shafie, S.H., Dang, L.L., et al., 2020. Improved recovery through optimum well design using autonomous inflow control device in complex brown field reservoir. In: Offshore Technology Conference Asia. Offshore Technology Conference.

Moradi, A., 2020. Cost-effective and safe oil production from existing and near-future oil fields. University of South-Eastern Norway.

Moradi, A., Moldestad, B.M.E., 2020. Near-well simulation of oil production from a horizontal well with ICD and AICD completions in the Johan Sverdrup field using OLGA/ROCX. In: Proceedings of the 61st SIMS Conference on Simulation and Modelling, Virtual Conference, Finland.

Moradi, A., Moldestad, B.M.E., 2021. A proposed method for simulation of rate-controlled production valves for reduced water cut. SPE Prod. Oper. 1–16.

MoradiDowlatabad, M., Zarei, F., Akbari, M., 2015. The improvement of production profile while managing reservoir uncertainties with inflow control devices completions. In: SPE Bergen One Day Seminar. OnePetro.

University of Oslo, 2021. Sampling methods. https://www.uio.no/studier/emner/matnat/math/STK4400/v05/undervisningsmateriale/Sampling%20methods.pdf, (Accessed 10 November 2021).

Ouyang, L.-B., 2007. Uncertainty assessment on well performance prediction for an oil well equipped with selected completions. In: Production and Operations Symposium. OnePetro.

Schlumberger, 0000. Eclipse technical description.

Sharma, B., Moradi, A., Moldestad, B.M.E., 2021. Sensitivity analysis of oil production models to reservoir rock and fluid properties. In: The First SIMS EUROSIM Conference on Modelling and Simulation, Finland. Scandinavian Simulation Society.

Taghavi, S., Aakre, H., Swaffield, S., Brough, R.B., 2019. Verification of autonomous inflow control valve flow performance within heavy oil-SAGD thermal flow loop. In: SPE Annual Technical Conference and Exhibition. OnePetro.
Tendeka, 2021a. Inflow control. https://www.tendeka.com/technologies/inflow-control/, (Accessed 10 November 2021).
Tendeka, 2021b. Case study: FloSure autonomous inflow control device (AICD) installed to increase oil production in China. https://www.tendeka.com/wp-content/uploads/FloSure-AICD-installed-to-increase-oil-production-in-China-1.pdf, (Accessed 10 November 2021).
Tendeka, 2022. Case study: FloSure AICD improves heavy oil cold production in Western Canada. https://www.tendeka.com/wp-content/uploads/AICD-Heavy-Oil-Canada-update-2019.pdf, (Accessed 11 May 2022).
The Engeeniering Toolbox, 2021. Orifice, nozzle and venturi flow rate meters. https://www.engineeringtoolbox.com/orifice-nozzle-venturi-d_590.html, (Accessed 10 November 2021).
Triandi, M., Chigbo, I., Khunmek, T., Ismail, I.M., 2018. Field case: Use of autonomous inflow control devices to increase oil production in a thin oil rim reservoir in the Gulf of Thailand. In: Abu Dhabi International Petroleum Exhibition & Conference. OnePetro.
Wehunt, C.D., 2003. Well performance with operating limits under reservoir and completion uncertainties. In: SPE Annual Technical Conference and Exhibition. OnePetro.
Wikipedia, 2021. Linear regression. https://en.wikipedia.org/wiki/Linear_regression, (Accessed 10 November 2021).
Xiong, S., Li, F., Wei, C., Luo, D., Moradi, M., 2020. Sand production management while increasing oil production of a gravel packed well equipped with RCP autonomous inflow control devices in a thin heavy oil reservoir in offshore China. In: Offshore Technology Conference Asia. OnePetro.
Yeten, B., Brouwer, D.R., Durlofsky, L.J., Aziz, K., 2004. Decision analysis under uncertainty for smart well deployment. J. Pet. Sci. Eng. 44 (1), 175–191.