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Annular Flow Modelling and Advanced Well Completions Design Optimisation in Oil Rim Reservoirs

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Summary

The inflow control device completion has proved to be an effective solution to mitigate water and gas breakthrough and coning problems. One of the major parameters affecting the ICD completion's performance is annular flow, the flow of the fluid in the space between the base pipe and the sand-face. The importance of annular flow on the ICD completion was addressed by many researchers. However, there was lack of an analytical annular flow model to integrate the effect of all parameters important contributing to the annular flow. In this study a comprehensive annular flow modelling and ICD completion design using a reservoir simulation model are presented.

The results of the study show that ICD completions mitigate the heel-toe effect which is resulted from an improper well configuration. A sufficiently high strength ICD completion reduces the dependency of the annulus pressure to the flowing pressure along tubing itself i.e. reducing the heel-toe effect. This results in minimising the annular flow even with no need of annular flow isolation (AFI) tools like swellable packers. AFI installation would be less necessary in homogenous reservoirs when an appropriate ICD completion design, which could be determined by the analytical annular flow equations, was used.

Introduction

The growth of energy demand encourages oil companies to explore and create oil reserves where production was previously challenging by utilizing the complex well configurations including horizontal and multilateral wells. The wells provide a greater contact area with the reservoir resulting in a significantly increased well productivity compared to vertical wells. However, they are also characterized by an uneven drainage profile along the length of the completion due to variation in reservoir properties and/or a significant pressure loss along the wellbore (Heel-Toe effect).

Advanced well completion (AWC) has proved to be an effective solution to mitigate water and gas breakthrough and coning problems in these wells [1-3]. The design of advanced well completion is an important step in field development planning to optimise the production profile. This decision should, as far as possible, consider the full range of phenomena which would play an important role during the well and/or field's production lifetime [5].

The annular flow, which is the flow of the fluid in the space between the base pipe and the sand-face is one of the major parameters to be considered when designing advanced well completions. It is broadly accepted the inflow control device (ICD) completions can minimise annular flow in perfectly horizontal wellbores in perfectly homogeneous reservoirs. Note that no annular flow isolation (AFI) aka packers was used in the first ICDs completion in Norway in 1997.

The annular flow effect can be minimised or eliminated when the wellbore is segmented into a sufficient number of compartments by deploying AFIs as shown in Figure 1. AFIs have become an essential component of the completion in to improve the well performance since ICDs completion has introduced as a solution for sandstone heterogeneous reservoirs as well as carbonate [1-3]. The ultra-high permeability streaks or/and fractures, dominating the flow production, impair the whole production of the well. Therefore, number of AFIs should be increased substantially to control these layers.

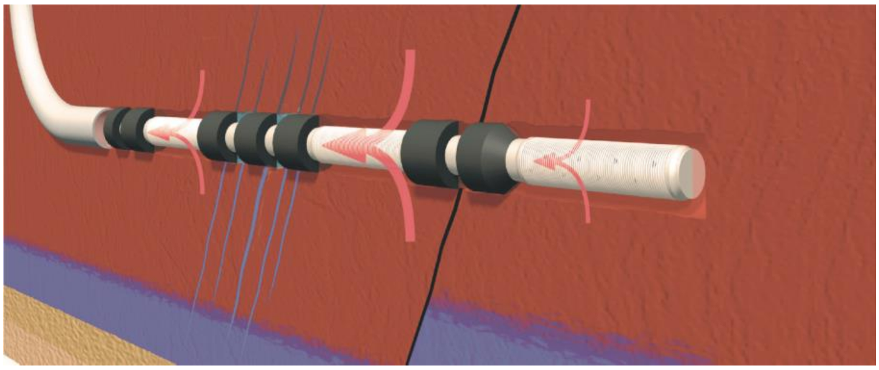


Figure 1 *Compartmentalization of wellbore [Courtesy of Tendeka].*

It is now generally accepted that AFI is a crucial component in an (A)ICD completion's design and installation [1, 2]. Therefore, the following analytical annular flow model to integrate the effect of the important parameters contributing to the annular flow was developed by the authors previously [4].

$$Q_{21} = Q_1' - Q_1 = \left(\frac{1}{\left(1 + \sqrt{\frac{\alpha_1}{F + \alpha_2}}\right)} - \frac{J_1}{J_1 + J_2}\right) Q_T \qquad \textit{Equation 1}$$

where Q21 is the annular flow rate. There are two terms in this equation describing the impacts of important parameters on the annular flow. The first term is the impacts of the wellbore configuration and the second is the reservoir heterogeneity effects on the significance of annular flow. The equation illustrates that annular flow happens due to 1) productivity index variations between two adjacent layers along the wellbore and 2) significant differences in the inner tubing's flowing pressure along the completed zones. This equation could be used to determine the ICD sizes and then whether is necessary to add AFIs in completion design.

In this study, an example of application of the annular flow model to optimise advanced completion design in a homogeneous, Troll field like, reservoir model is described.

Case Study; A Troll like Model

A horizontal well with the length of 2250 meter has been placed in the middle layer of a Troll like homogeneous reservoir simulation model as shown in Figure 2. The oil rim reservoir is located between these with the thickness of 40 meters. A strong gas cap at the top and a weak water aquifer at the bottom of the reservoir provides pressure support. The optimal location of the well is chosen by a trial and error process to delay water/gas breakthrough, and increased the recovery factor compared to all other, alternative locations tested. The other well and reservoir properties are listed in Table 1.

The chosen production strategy for the well was to produce a maximum 5000 SM3/D of liquid and minimum bottom-hole flowing pressure (BHP) and top head pressure (THP) of 87 and 10 Bars respectively while GOR of the produced liquid does not exceed 200. The flow profile for the openhole completion, Figure 3, shows that as soon as the free gas breakthrough to the well occurs and GOR increases the well is choked back due to the applied GOR constraint. Although applying this limit results in a reduction in the liquid production from the well, it decreases the gas production significantly.

Table 1: *The model properties*

Parameter	***Description (Value)***
Permeability	*2000 (mD)*
Reservoir Dimension	*94*50 (m) in X, 26*200 (ft.) in Y, 51 (ft.) in Z*
Production Constraints	*Max Liquid rate: 5000.00 (SM3/D), Min BHP and THP: 87 and 10 Bars*
Well length	*2250 m*
Well Specifications	*Wellbore: 7.5 inch, Base pipe 5.5 inch*

Figure 2: *The reservoir and well schematic*

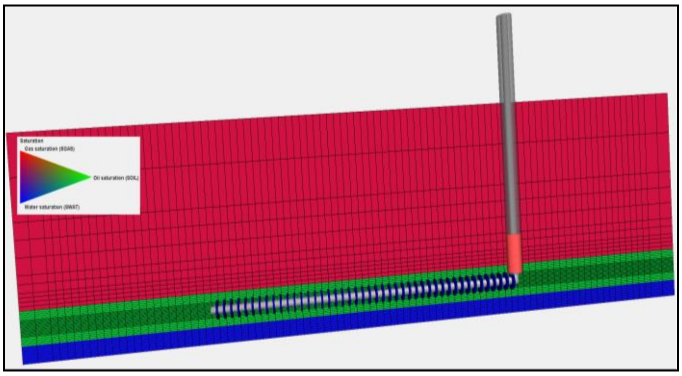


Figure a shows oil saturation profile after 9 months of production when the well was completed open hole. It shows that the well production profile is uneven and the well suffers a severe heel toe effect as the free gas is already broken through at the heel and a significant amount of oil was remained mostly at the middle and toe sections of the well. This is because the pressure drops due to the friction along the well (average of 2.53 Bar) is comparable with the drawdown of 1.80 Bar within the reservoir.

The Field Oil Efficiency (FOE) of the open-hole completion is 34% for the production period of 10 years. This uneven production profile could be mitigated by ICD completion.

Therefore, Equation 1 was used to determine that 4*2.5 mm is the optimum ICD (nozzle type) size for this application. Later, the production forecasts of various ICD designs are compared with 4*2.5 mm.

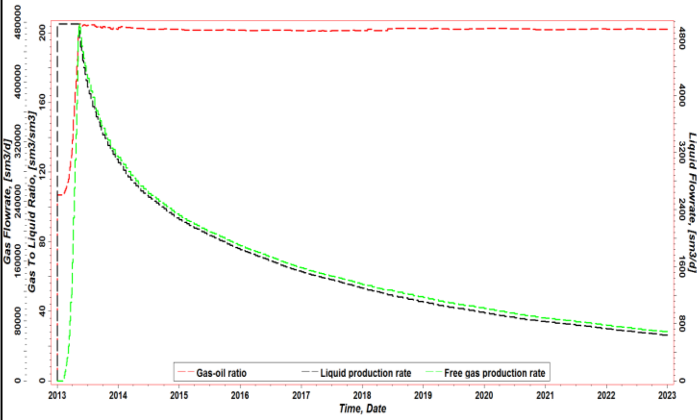
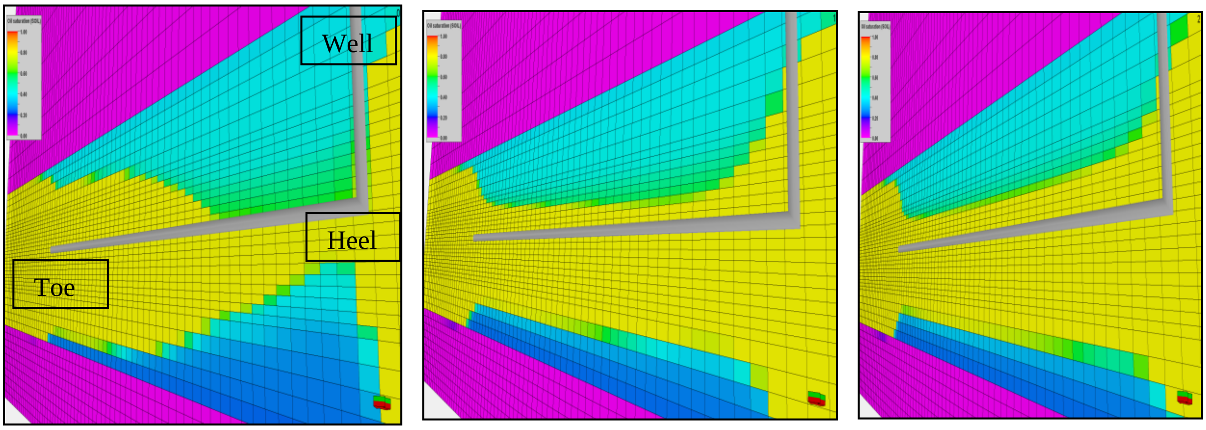


Figure 3 *The liquid, GOR and free Gas flow rates for the well with open hole completion.*

Discounted cumulative oil production (DISOil) with a discount rate of 0.1 was chosen as the objective function to entail the both impacts of early and total productions. Initially, the well was completed with 45 nozzle type ICDs and 44 swellable packers, assumed possible, as it is shown in Figure . One packer was installed at every single ICD joints to provide separate hydraulic ICD compartments. The maximum number of ICDs (45) is dictated by an Eclipse simulation limitation as only one ICD well segment can be connected to each reservoir grid block. Different ICD completion designs were installed to eliminate heel-toe effect and subsequently increase the oil production using available ICD sizes.

Figure b clearly shows the success of the ICD completions at providing more uniform inflow profiles as all zones have been encouraged to produce an almost same percentage of total oil production. Figure 4c shows that with No AFI an ideal uniform influx could be achieved that improves total oil production. Figure also shows that a small amount of fluid flows through the annuals and velocity of the fluid is lower than the critical velocity of 0.35 m/s that could cause erosion in the annulus.



a) Open hole completion *b) ICD (4*2.5 mm) with AFIs* *c) ICD (4*2.5 mm) with No AFI*

Figure 4 *Oil saturation profiles after after 9 months of production for three different completion.*

Table 2: *Indexes values for different ICD completion designs*

Completion	**DISOil**		**FOE**	
	(MM SM3)	**Relative (%)**	**%**	**Relative (%)**
Open-hole Completion	4.50		18.35	
ICD (2*2.5)-No AFIs	4.74	5.2	18.87	2.8
ICD (4*2.5)-No AFIs	4.77	5.9	18.90	3.0
ICD (4*4)-No AFIs	4.76	5.7	18.88	2.9
ICD (5*5)-No AFIs	4.68	4.0	18.71	2.0
ICD (2*2.5)-AFIs	4.52	0.3	17.83	-2.8
ICD (4*2.5)-AFIs	4.54	0.9	17.97	-2.1
ICD (4*4)-AFIs	4.41	-2.0	17.69	-3.6
ICD (5*5)-AFIs	4.06	-9.8	16.66	-9.2

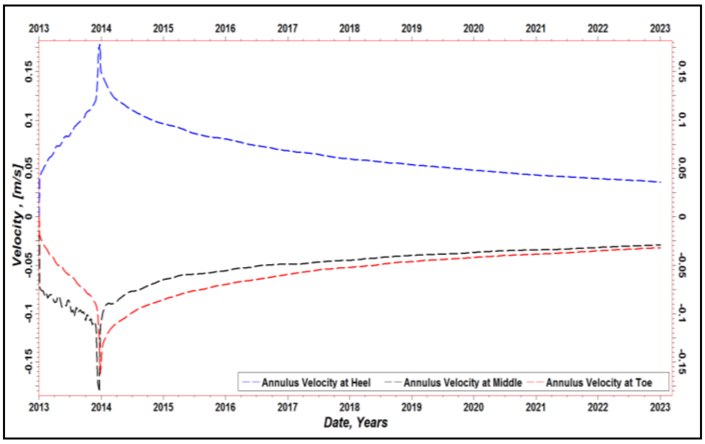


Figure 5 *Fluid velocity profiles in annalus for the well with ICD (4*2.5 mm) & No AFIs Completions.*

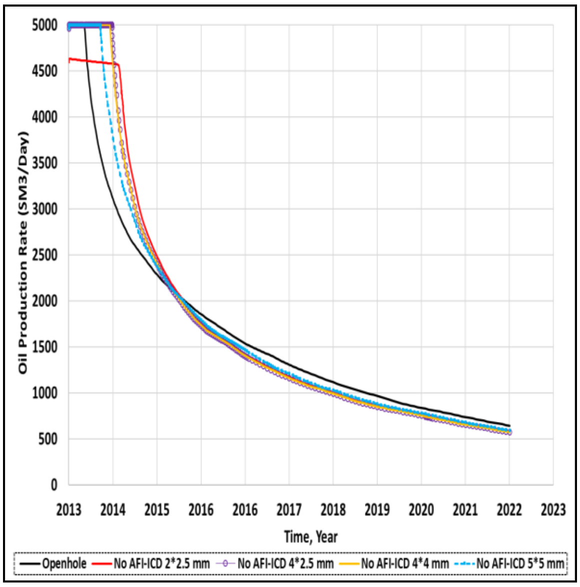


Figure 6 *Cumulative free gas production profiles for various ICD completions with no AFIs.*

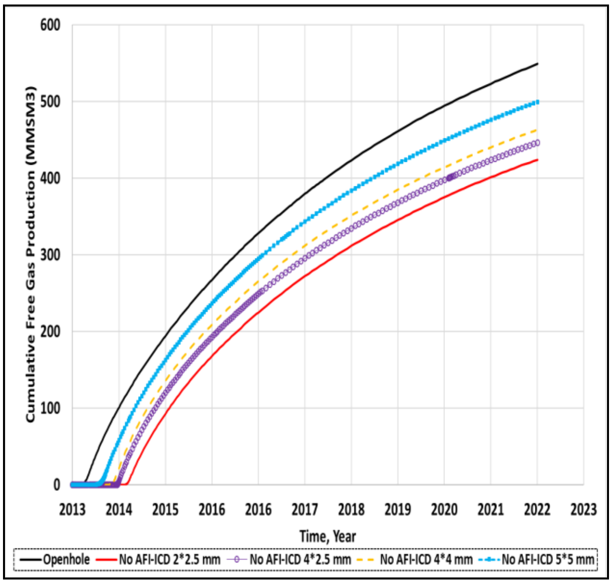


Figure 7 *Oil production rate profiles for various ICD completions with no AFIs.*

These observations suggest that a uniform inflow from the reservoir (i.e. eliminating the heel-toe effect) can be obtained with the installation of ICD completions if the annular flow is minimised i.e. eliminating the dependency of reservoir influx from the reservoir to the flowing pressure along the tubing. The uniform could be achieved by installing a sufficient strength ICD only even with no AFI. In fact, installing AFIs could impair ICD completion performance greatly if inappropriate ICD size was deployed.

Conclusions

1. The results of the study show that ICD completions mitigate the heel-toe effect which is resulted from an improper well configuration.
2. A sufficiently high strength ICD completion reduces the dependency of the annulus pressure to the flowing pressure along tubing itself i.e. reducing the heel-toe effect.
3. The application of the first analytical formula to address the annular flow for an ICD completion was performed. The recommended ICD size by the equation could deliver an optimised well performance.
4. The application along with the equation illustrate why a sufficient strength ICD design could reduce the need for AFIs by minimising annular flow in homogeneous reservoirs. It also helps to obtain an appropriate strength of (A)ICD completion in such reservoirs.

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