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Complex Completion Design and Inflow Prediction Enabled by Detailed Numerical Well Modeling

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Abstract

An Operator was unable to model a potential new (additional) completion of a 330 m cased hole perforated sand screen and ICDs interval in a mature high water cut well which was originally completed with a 916 m open hole stand alone sand screen and Inflow Control Devices (ICDs) section in a multidarcy sand.

The potential opportunity to perforate this 330 m section presented significant potential reservoir drainage upside but could not be modelled using conventional well inflow prediction or reservoir simulation techniques. In order to determine if the recompletion was economically viable, the operator required a way to model the recompletion and the existing completion to determine the overall completion performance.

The complexity of the original open hole section completed with sand screens and ICDs and the new target to be completed with perforations, sand screens and ICDs was solved using computational fluid dynamics (CFD) modelling and high performance computing.

The existing and new reservoir intervals are characterised by unconsolidated high permeability sands. The reservoir conditions mobility ratio of oil to water is approximately 30:1. Due to high total liquid production rates, the existing open hole completion is producing at well above the economic oil rate cut off despite being at approximately 95% water cut and therefore the existing completion interval cannot be abandoned. The new recompletion perforation interval would initially produce at 100% oil. The key question was, what will the new recompletion interval add (if anything) to the overall well production rates and is the new recompletion economically viable. Conventional analytical or even 1D or 2D numerical models simply cannot handle the complexity of the geometry of this well's open and potential cased hole intervals, perforated intervals, sand screens and ICDs.

A 3D fully coupled well model was constructed and 2 phase CFD modelling undertaken in a combined model size of over 500 million cells each with unique properties. Through employment of what is thought to be the most comprehensive inflow model ever built, the contribution from the original open hole interval and the new interval were estimated and the optimum completion design investigated allowing the operator to determine the economic viability of the recompletion.

Introduction

The Wandoo oil field is located in the offshore Carnarvon Basin to the North West of Australia. The field lies in approximately 55 m of water and is located north west of Dampier, some 65 km from the coast in permit area WA-14-L. Prior to production, the field had a 22.1m oil column overlain by an 18m gas column. The oil is 19.5API gravity, 14.5cP viscosity, a GOR of 99scf/bbl and a low sulphur and wax content (-24°C-pour point). The field is drained by 15 horizontal wells (with the use of multilateral technology there are in fact, 19 reservoir wellbores) with gas injection being carried out through another horizontal well, all drilled from two platforms.

The B13 well is one of the horizontal oil production wells located in the Wandoo field. Production commenced in 2008 and the well is currently producing 470bopd and 8900bwpd (94.9% water cut).

If the assumptions about the log interpretation on B13 are correct then ~ 400 m of uncompleted pay exists from the wells intersection of the A3 sands to the current casing point.

These reserves could be accessed by perforating the casing and installing screens for sand control.

This paper summarises a study conducted to determine if recompleting the cased part of the well could result in increasing the oil production and recovery of the B13 well.

Modelling Objective.

The Wellscope™ modelling (Byrne et al 2009, 2010) was undertaken with the following objectives:

1. To quantify the productivity of 12 shots per foot (spf) vs 6 spf vs OH options. The open hole option here is included merely as a benchmark.
2. To determine the productivity of the cased and perforated interval when connected to the existing open hole section.

Well Modelling.

Senergy Wellscope System.

Wellscope™ is the Senergy process for modelling well inflow using computational fluid dynamics (CFD). CFD is the science of predicting fluid flow, heat and mass transfer, chemical reactions and related phenomena by solving numerically the sets of governing mathematical equations namely conservations of mass, momentum and energy.

Solvers used are based on the finite volumes method:

- The domain is discretised into a finite set of control volumes (cells)
- General conservation (transport equations for mass, momentum, energy etc.) are solved for each of these control volumes
- Partial differential equations are discretised into a system of algebraic equations.
- All algebraic equations are then solved numerically to render the solution field.

An overview of Wellscope™ is given in the following basic phases:

Problem Identification and Pre-Processing Phase.

This phase comprises the following steps:

- Define modelling goals
- Identify the domain to model
- Design and create the grid. Steps for a general model creation are listed:
- Geometry creation: involves creation of basic 2D or 3D models based upon actual dimensions
- Mesh generation: involves mesh setting for different domains under consideration.
- Mesh quality examination: Ensure mesh consistency across domains.
- Boundary zone assignment: Assign boundary type for domains in terms of pressure at the Inlet (matrix)/Outlet (well) and define continuum in terms of solid/fluid.

Solver Execution Phase.

Amongst the more important steps included in this phase are the following:

- Select appropriate physical model
- Definition of material properties: density, viscosity, fluid, solid, viscous & inertial resistance coefficient, permeability.
- Definition of boundary condition at all boundary zones assignment. Pressure at the inlet and outlet.
- Provide an initial solution
- Set up solver controls: convergence criteria
- Set up convergence monitors: continuity, velocities
- Compute and monitor the solution: iterations that are required to reach a convergence solution – Convergence is reached when changes in solution variables from one iteration to the next are negligible.
- Consider revisions of the model: Are physical model appropriate? Are boundary conditions correct? Is mesh adequate?

Post Processing Phase.

The steps during this phase include:

- Examine the results to review solution and extract useful data.

Model Input Data and Assumptions.

The model was built based on the following data provided by Vermilion and assumptions that were mutually agreed upon.

Reservoir:

Pressure	783psi
Permeability	10 D (B sand)
	5D (A sand)
	Sand distributions in the open holed interval are as per **Fig. 1**.

Saturation	100% water (OH interval) 100% oil (C & P interval)
Drainage radius	1 m
Kv/Kh	1

The reservoir between the recompletion section and the OH interval was not modelled except for a 10m interval on the C & P side.

WANDOO B-13H			
INTERVAL (mMDRT)	**FORMATION UNIT**	**SCREEN SIZE**	**PORTS OPEN**
1808.4 – 2195.1 (386.7)	B1 Sand	6-5/8"	1 port
2168 2171.6 2195.1	**B1/A3 Sand Boundary (Fault)** Swellable installed to isolate B1/A3 sand boundary Pip tag installed		
2195.1 – 2210.1 (15m)	A3 sand	6-5/8" + X-over	10 ports
2210.1 – 2502.9 (292.8m)	A3 sand	5-1/2"	10 ports
2500 – 2540 2502.9 2502.9	**A3 to B1 transition zone (B1 at 2540m)** Swellable installed to isolate A3/B1 sand boundary Pip tag installed		
2502.9 – 2595.8 (92.9m)	B1 sand	5-1/2"	1 port
2590 2595.8 2595.8	**B1/A3 Boundary (Fault)** Swellable installed to isolate B1/A3 sand boundary Pip tag installed		
2595.8 – 2619.1 (23.3m)	A3 sand	5-1/2"	1 port
2619.1	Swellable installed (contingency if screens not run all the way to planned setting depth)		
2619.1 – 2724.6 (105.5m)	A3 sand	5-1/2"	10 ports
2724.6 2724.6 – 2737.7	Swellable installed Blank 5-1/2" tubing joint c/w guide shoe.		

Fig. 1— Formation Unit Distribution in B13

PVT Properties:

Oil density at P_{res}	889 kg/m^3
Oil viscosity at $P_{res:}$	15 cP
Water density at $P_{res:}$	1016 kg/m^3
Water viscosity at P_{res}:	0.60 cP

Wellbore (OH):

Open hole Size:	9 in
Collapsed Annulus Permeability:	12.15 mD for the B Sand, 2.45 mD for the A Sand

ICD port configuration as per schematic	
FBHP @ OH heel	682 psi
Wellbore (C & P):	
9-5/8" Casing OD	244.475 mm
9-5/8" Casing ID	224 mm
Collapsed Annulus Perm	5 Darcy (base case)
Perforation Diameter	20 mm
Perforation length	270 mm
FBHP @ C & P heel	673 psi
No of ICD ports open	10
Screen:	
Jacket OD (5-1/2" SAS)	145 mm
Basepipe OD (5-1/2" SAS)	139.7 mm
Basepipe ID (5-1/2" SAS) 124mm	
Jacket OD (6-5/8" SAS)	173mm
Basepipe OD (6-5/8" SAS)	168.275 mm
Basepipe ID (6-5/8" SAS) 150.393 mm	
ICD Port Diameter:	3.175mm
Drainage layer height:	5mm

The assumptions that were made for the model were that the:

- Average drawdown of the B13 well was 100psi
- Downhole Fluid flow rate of the B13 well is around 8000 bpd at 100% water cut
- Formation damage "skin" effect will be captured by varying collapsed annular permeability in the open hole to match existing well performance
- Perforation interval will be across the B sand that has 100% oil saturation

Modelling Approach.

The final objective of ascertaining the feasibility and productivity of recompleting the 9-5/8" zone required an integrated model of the existing open hole and the cased and perforated (C & P) recompletion zone. Sector models of the existing open hole section and the recompletion interval were built to first capture all of the well geometry in detail (perforations, ICD, drainage layer, etc). This model was then checked for mesh quality and cell count before being run to analyze the flow characteristics in these sector models.

The ICD plays a crucial function in the inflow regulation of the fluids coming into the well. As such, the ICD flow characteristics were modelled and compared against the manufacturer's data as part of the validation process. In order to optimise the model efficiency, an appropriate drainage radius needed to be identified in constructing the final model. As such, models with two different reservoir drainage radii were also run to assist in selecting the appropriate size.

Upon completing the validation process and running some sensitivities with the sector model, the open hole section of the well was constructed and calibrated with the current performance of the well. The proposed completion interval was then added on to the model of the open hole section.

Sector Models.

Open Hole with Stand Alone Screens and ICDs.

As illustrated in **Fig. 2**, below, the sector model was 38ft in axial length and 2m in diameter. It consisted of the reservoir, wellbore annulus, 1 x SAS and 1 x ICD.

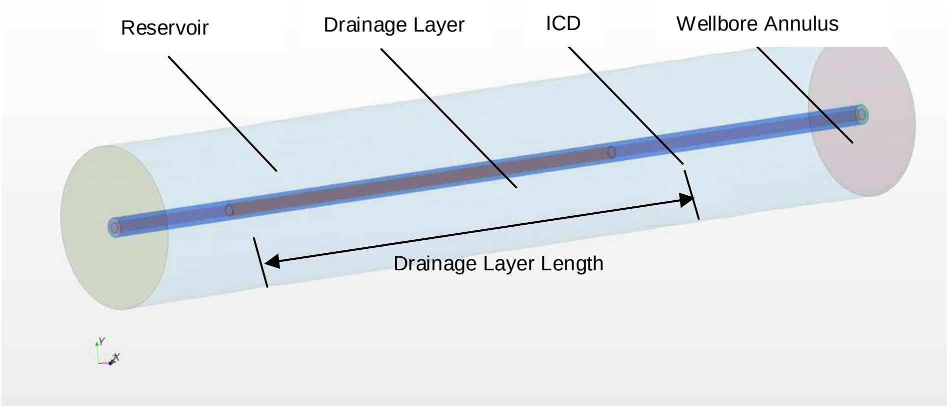

Fig. 2—38ft Open Hole Sector Model

The reservoir and the wellbore annulus were modelled as a porous medium assigned with viscous and inertial resistance values that corresponded to the provided permeability values. The screen was modelled as a pipe with six shots of ½” perforations inside the ICD housing and a 20ft long, 5mm thick, micro annulus that represented the screen drainage layer. The ICD design details are illustrated in **Fig. 3**.

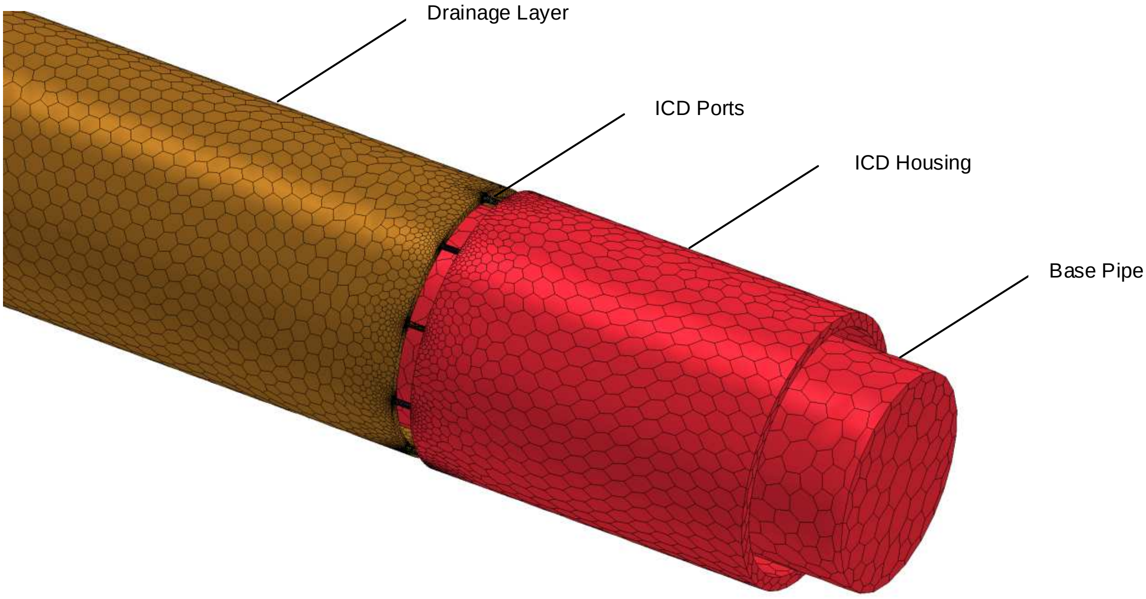

Fig. 3—Drainage layer and ICD configuration

Cased and Perforated (C & P) Section with Stand Alone Screens and ICDs.

Two sector models were created for the cased and perforated recompletion section. One sector was with a perforation shot density of 12 shots per foot (spf) and another with 6spf. Each perforation was modelled as a cylinder that extended from the 9-5/8” Casing ID into the reservoir. Final dimensions were based on the Halliburton 4-1/2” Millennnium Charge, type DP. The final dimensions of these perforations are listed previously in the section dealing with Model Input Data and Assumptions (Page 2). **Fig. 4**, **Fig. 5**, **Fig. 6**, **Fig. 7**, **Fig. 8** shows the geometry and mesh structures of these models.

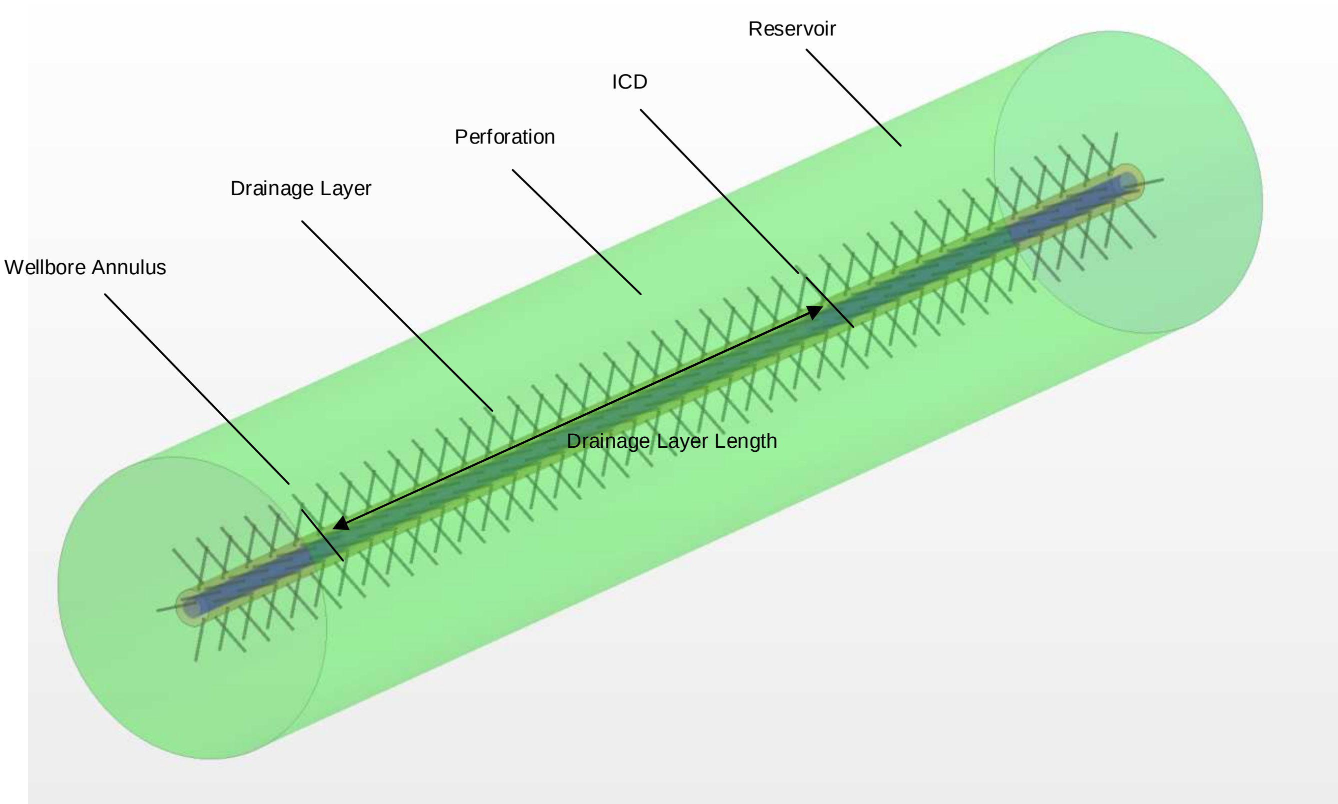

Fig. 4—The 12spf 38ft C & P Sector Model

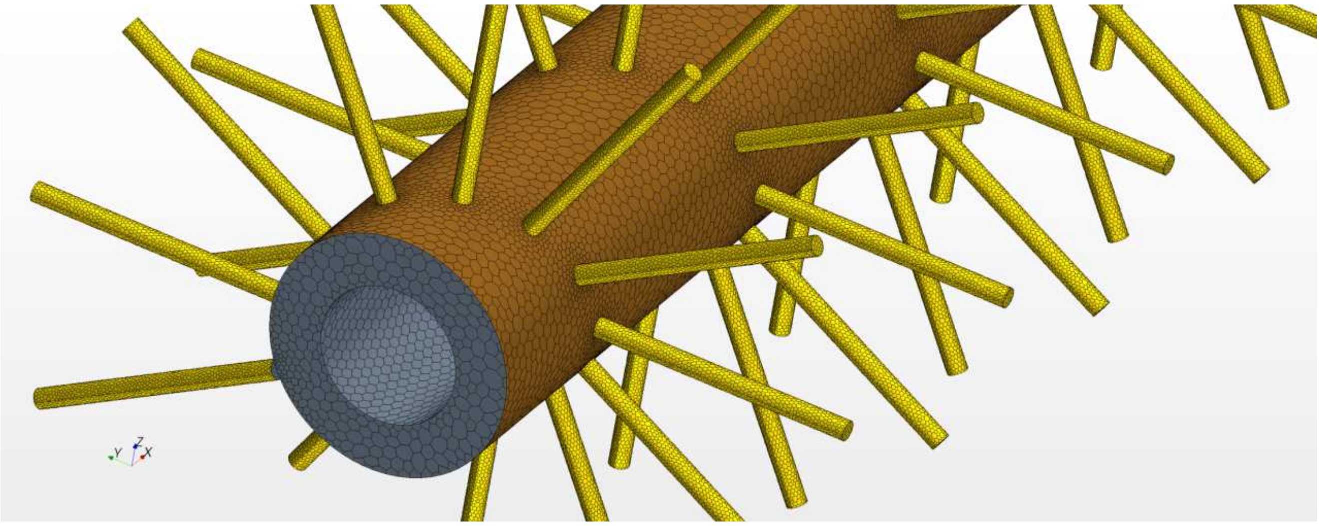

Fig. 5—Close up View of the Perforation and Wellbore Annulus for the 12 spf C & P Sector Model

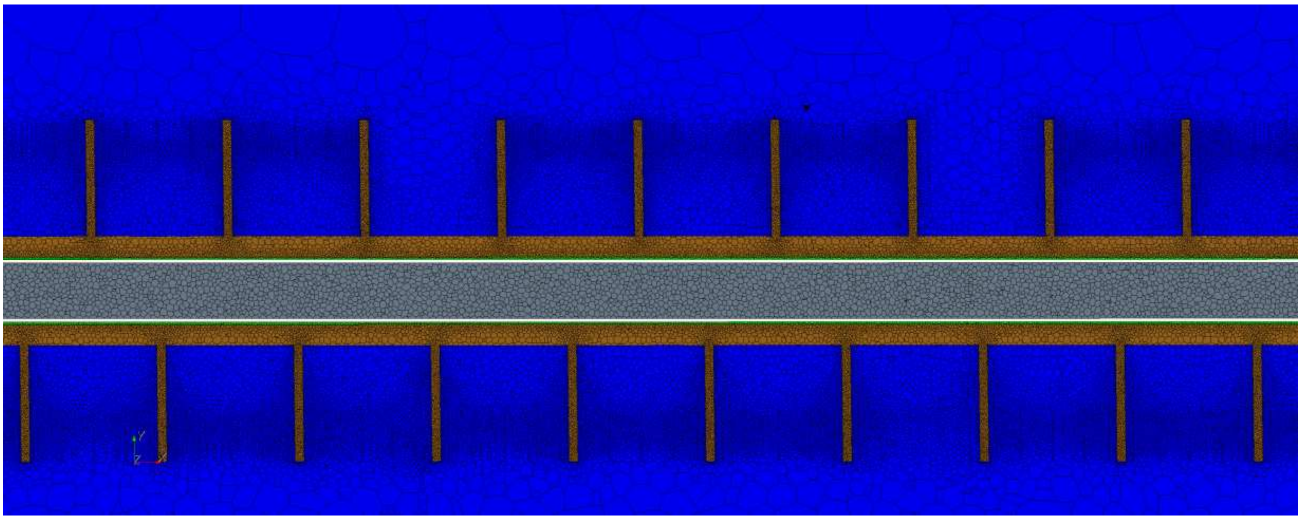

Fig. 6—A slice at the wellbore centre line, showing the perforation and the drainage layer for the 12spf C & P Sector Model

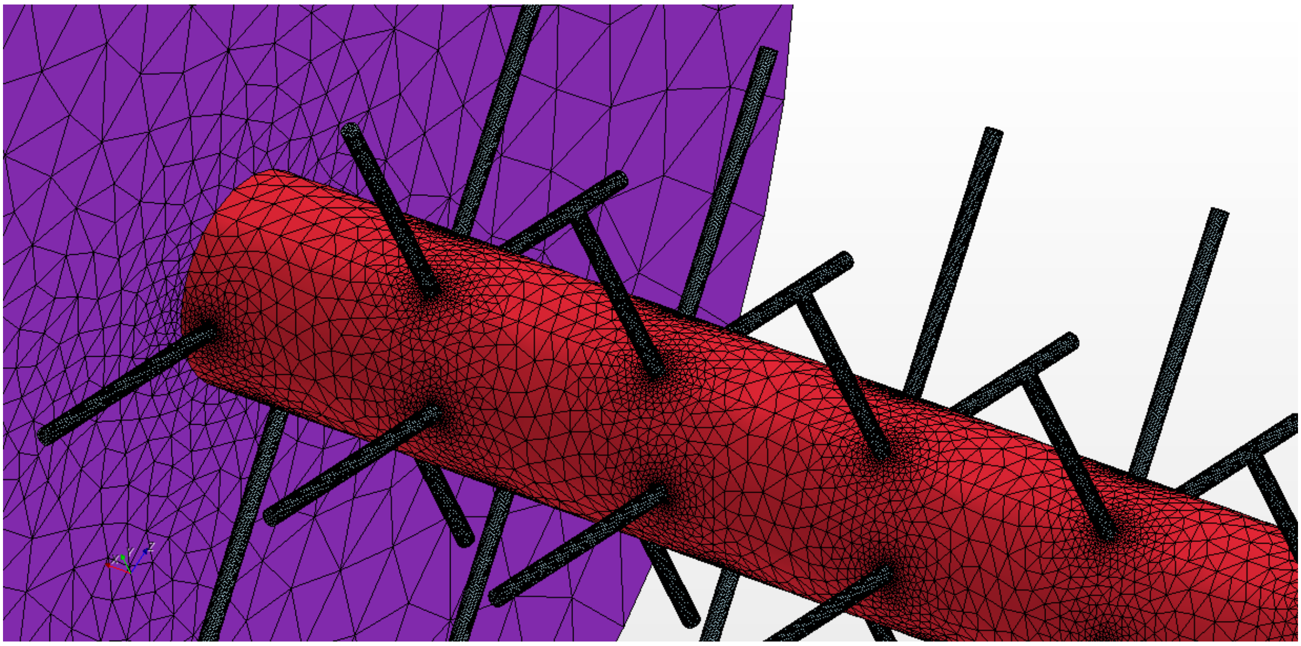

Fig. 7—Perforation and Wellbore Annulus of the 6 spf C & P Sector Model

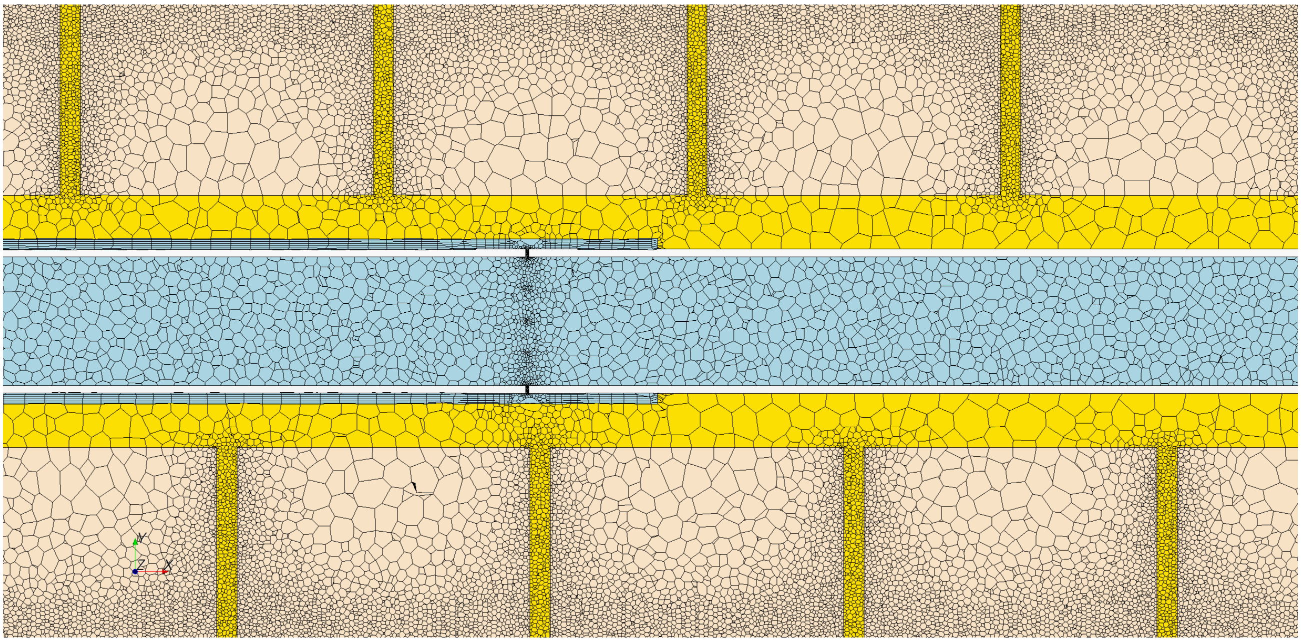

Fig. 8—Cross Sectional View of the perforation, the drainage layer and the ICD configuration for the 6spf C & P Sector Model

Final Model.

To construct the final model, the 929.3m open hole section was first constructed and correlated to achieve the target fluid rate of around 8000 bbl/d with a drawdown of 101psi. The collapsed annulus permeability was varied to achieve this target. No other parameters were changed.

Upon correlating the open hole model performance, the 12spf cased and perforated section was coupled to it and a base case model was run. The reservoir between the recompletion section and the OH interval was not modelled except for a 10m interval on the C & P side.

The complete C&P + OH completion, due to its 1,325 metre length, varied reservoir permeability and the number of ICD ports open, is split into 8 sections of reservoir as shown in **Table 1**. **Fig. 9** shows the start of the 12 spf perforated section.

Table 1: Reservoir Section Division

Reservoir Section	Length (m)	Start of mDRT (m)	Completion Type	Fluid
S01	332	1385	12 SPF	Oil
S02	20	1717	Casing Shoe	N/A
S03	71.4	1737	Casing Shoe	N/A
S04	386.7	1808.4	Open Hole	Water
S05	307.8	2195.5	Open Hole	Water
S06	92.9	2502.9	Open Hole	Water
S07	23.3	2595.8	Open Hole	Water
S08	118.6	2619.1	Open Hole	Water

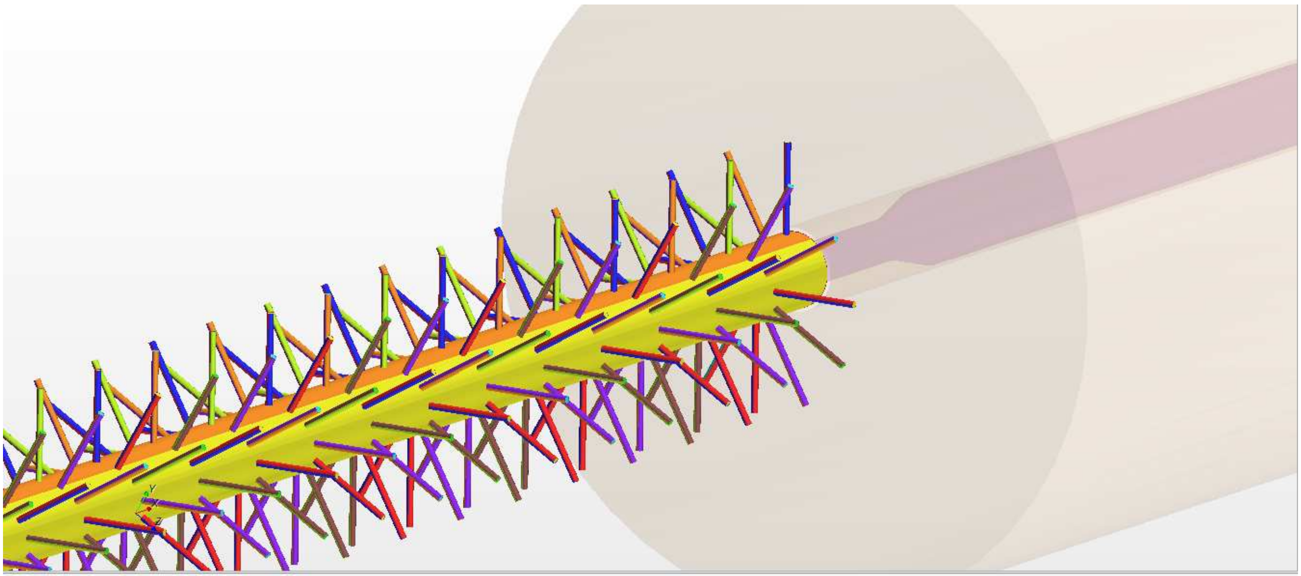

Fig. 9—Toe Section of the C & P Interval (Section S01)

Modelling Validation.

In order to optimise cell count and run time without compromising the accuracy of the simulation, an optimum reservoir drainage radius needed to be identified. Two models, one with an 11m radius and another with a 1m radius were constructed and run with the same configuration and inlet boundary pressure. The difference in the inflow rates was deemed negligible (Refer to **Fig. 10**). Subsequently, the sector models and final models were all constructed with a 1m drainage radius.

Res Perm (D)	Annulus Perm (D)	ICD Ports Open	Reservoir Radius (m)	Volume Flow Rate (bpd)
2	1	10	1	1,144
2	1	10	11	1,143

Fig. 10— Sector Model Inflow Performance vs Reservoir Drainage Radius

The ICDs play a crucial role in the regulation of the fluid inflow from the reservoir into the well. Although the ICDs were modelled as per the geometry and dimensions of the actual device, it was important to verify that the pressure drop characteristic was accurate. A virtual flow test was simulated with the ICD geometry with different flow rates and compared against data derived from published data (Jones et al, 2009). A 3D visualisation of the ICD is shown in **Fig. 11**. The setup of this virtual flow test is shown in **Fig. 12.**

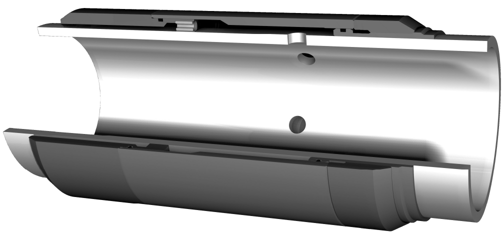

Fig. 11—3D Model of ICD Unit

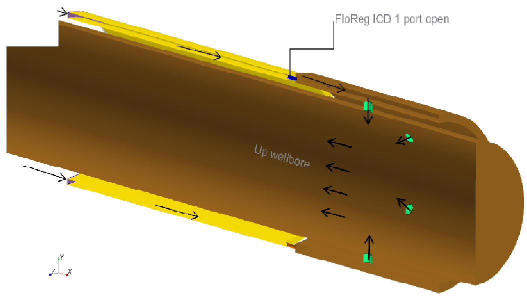

Fig. 12—CFD Model of Flow Test

Results of these tests are shown below:

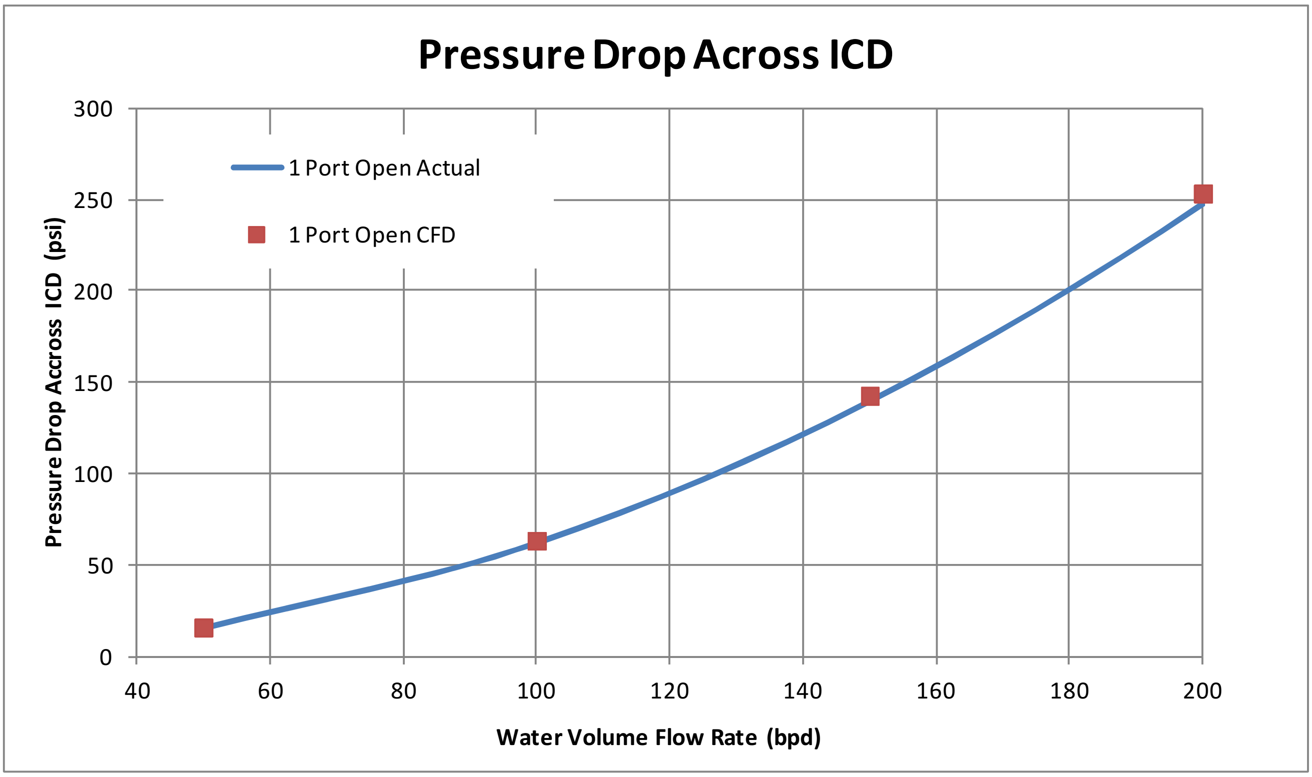

Fig. 13—Validation runs with water

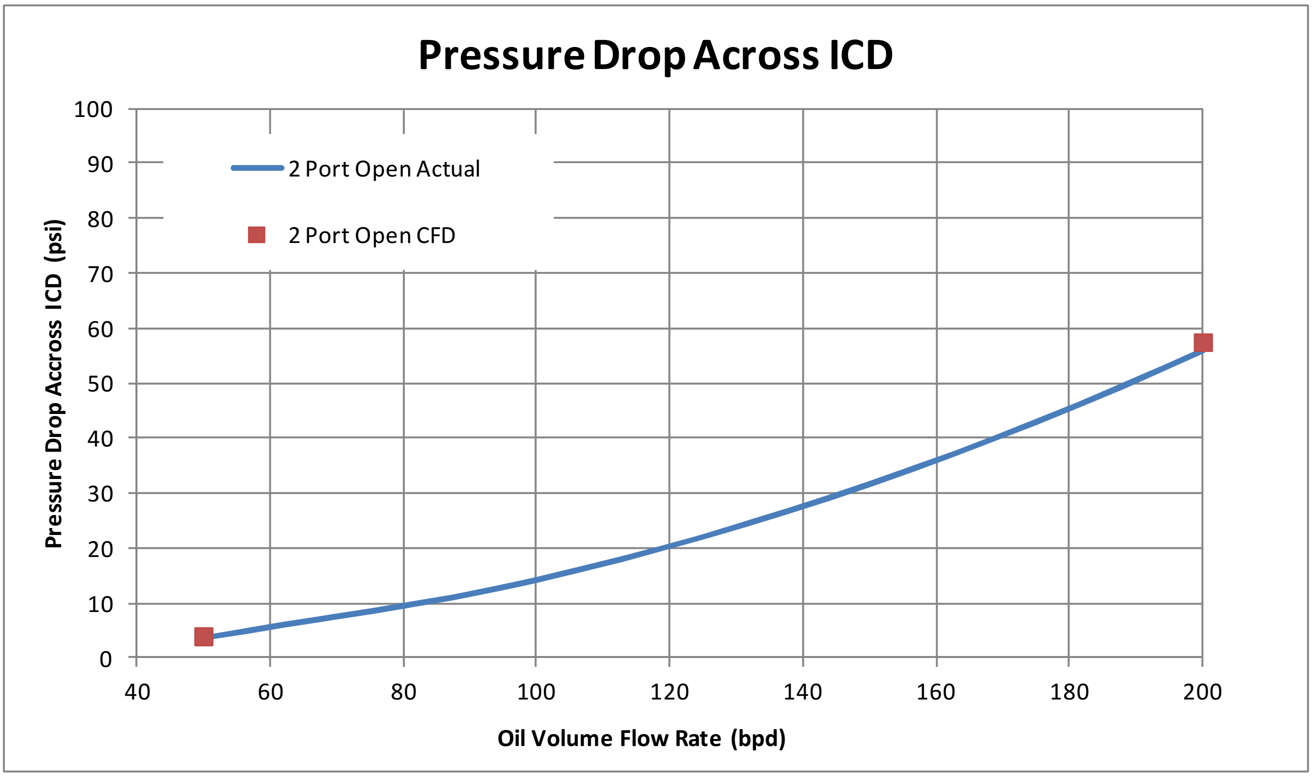

Fig. 14—Validation runs with oil

It is clear from Fig. 13 and Fig. 14 that the pressure drops across the ICD match the manufacturer data very well. **Fig. 15** shows the contour plot of pressure before and after the ICD nozzles, where it can be clearly seen that the pressure drops from 30 psi to 14 psi when 1 ICD port (nozzle) is open and 50 bpd of water is flowing.

This validation gives an excellent belief that the CFD-calculated pressure drop can be used, with high degree of confidence to simulate fluid flows across ICDs.

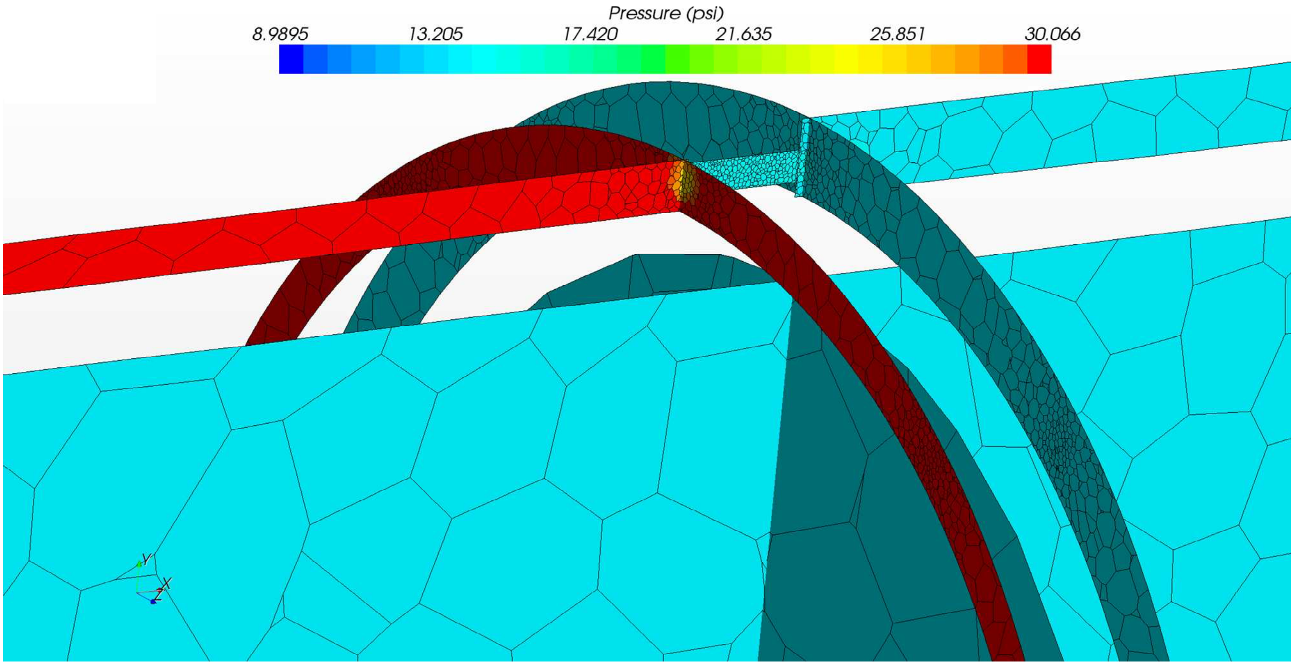

Fig. 15—Pressure drops from 30 psi to 14 psi; 1 Port Open, 50 bpd of water

Results.

Sector Model.

The first sector model that was constructed was a 39ft SAS with an ICD (10 Ports open) across the B3 sand. The results from this model gave a good insight into the areas at which pressure losses occurred in the open hole system as well as the influence of the drainage layer on the near wellbore pressure profile. These pressure profiles were also evident in the 12spf C & P sector model. From this observation, it can be deduced that for the C & P section, perforations located away from the drainage layers had minimal contribution to the well inflow. **Fig. 16, Fig. 17** and **Fig. 18** illustrate this. Only the perforations located directly across or near the drainage layer contributed to the inflow.

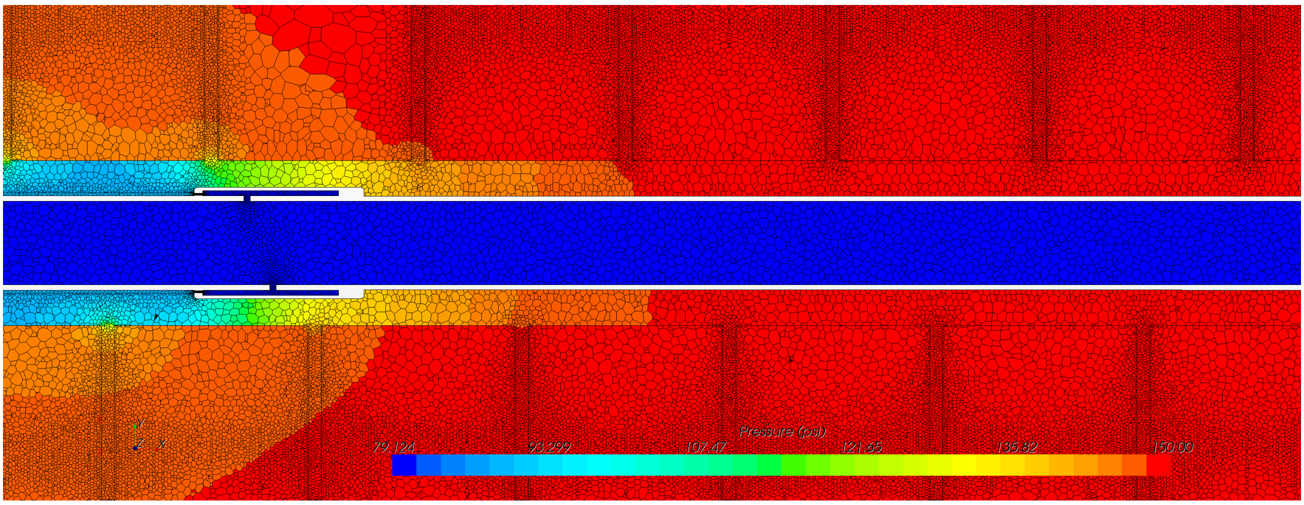

Fig. 16—Pressure profile (Near ICD)

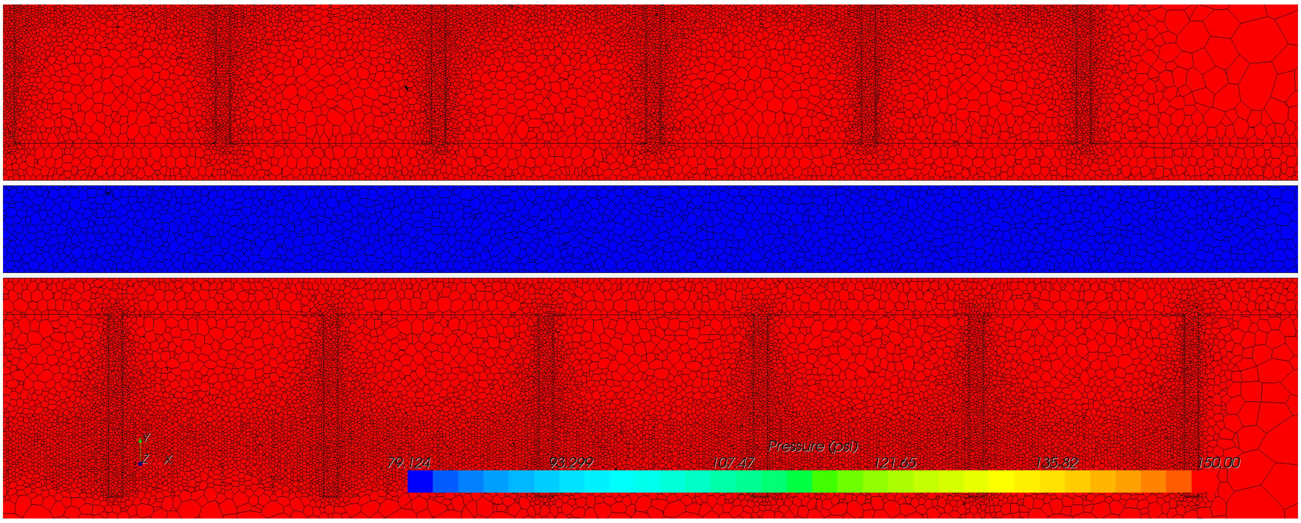

Fig. 17—Pressure profile (Pin End – “below” Screen)

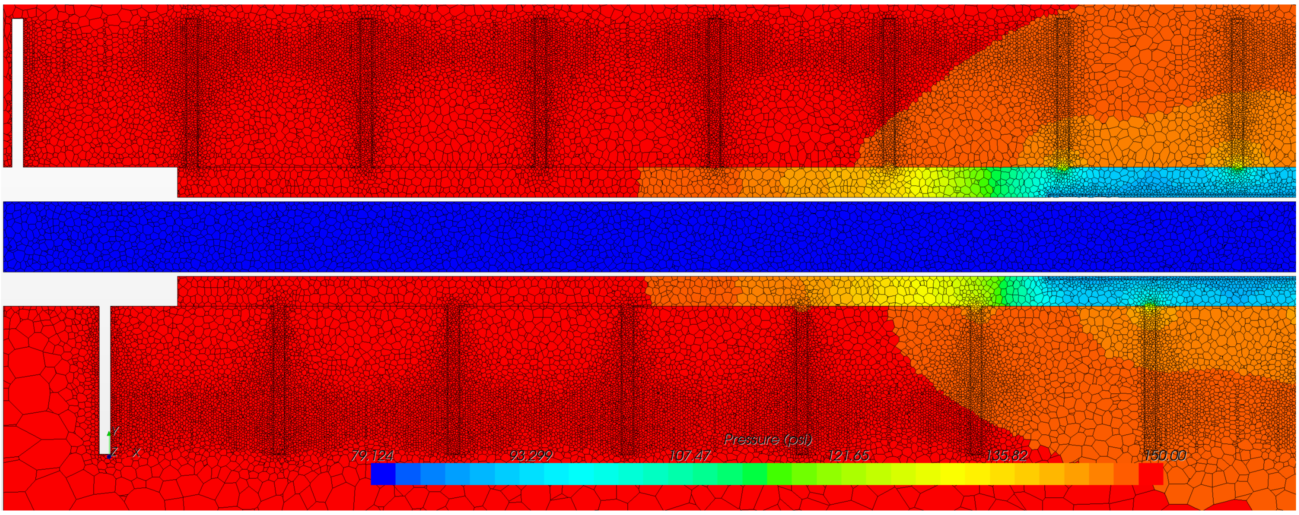

Fig. 18—Pressure (Box End – “above” screen)

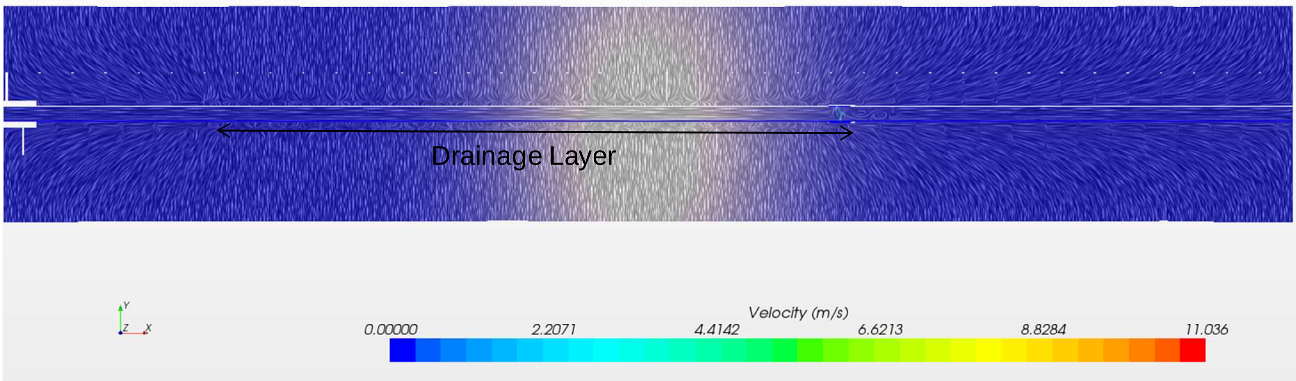

Fig. 19—Fluid Inflow Velocity

Fig. 19 summarises the pressure distribution pictures, where it can be seen that the fluids are drawn straight towards the drainage layer, which suggests that perforating to the left and to the right of the drainage layer would not be efficient.

Fig. 20 shows that, as expected, the major pressure loss component in the system is at the ICD, proving that the ICD is the dominant factor that influences the fluid inflow into the well.

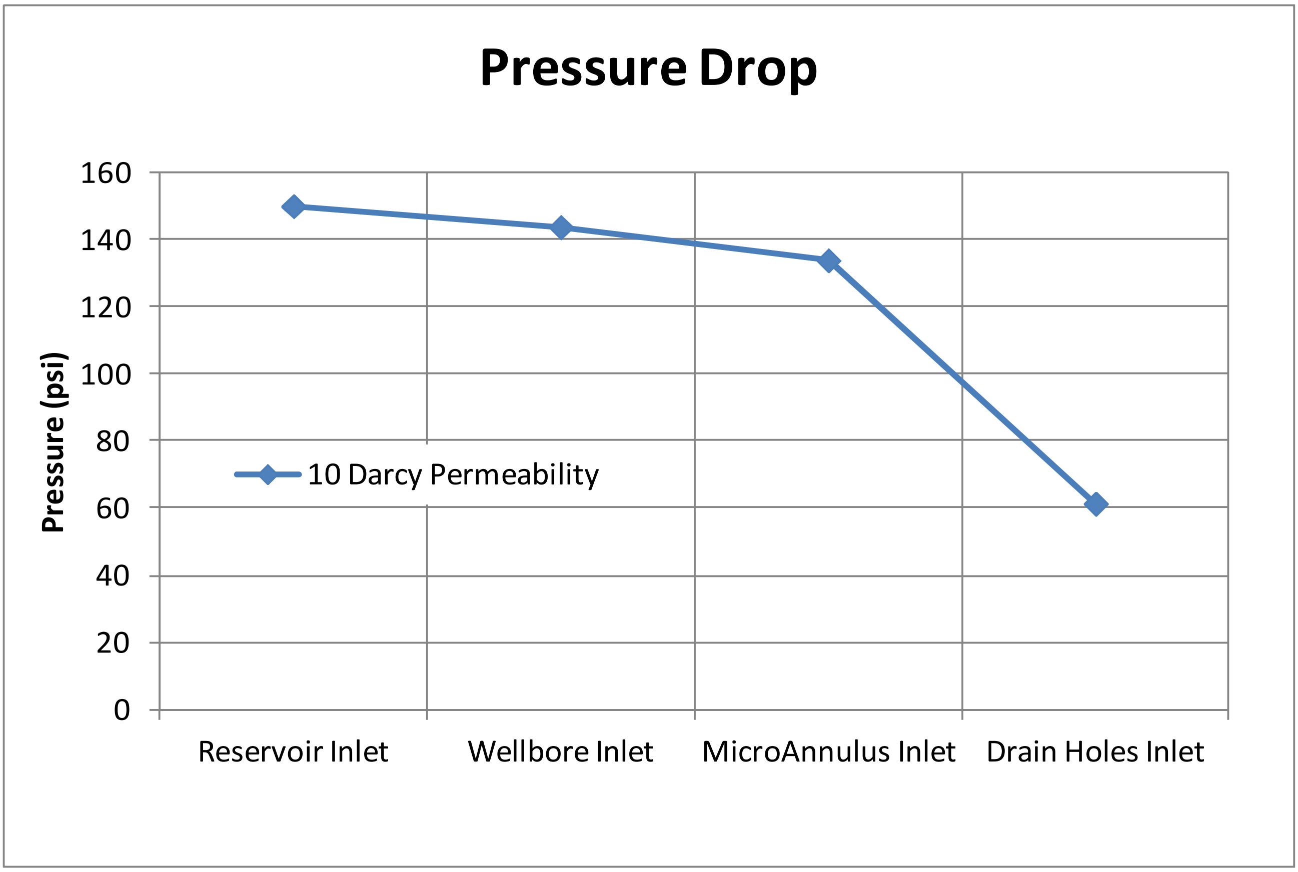

Fig. 20—Average Pressure of the Four Main Regions of the Well

The inflow performance was also compared between the OH, 12spf C & P and 6 spf C & P sector with a fixed drawdown of 130psi. The OH performance was found to be the best followed by the 12spf C & P and finally the 6spf C & P. This is graphically presented in **Fig. 21**. The pressure loss or "skin" effect present in the C & P models are due to the flow convergence in the perforations that connect the reservoir to the wellbore. The ICD in all three cases had 10 ports open to minimise its influence.

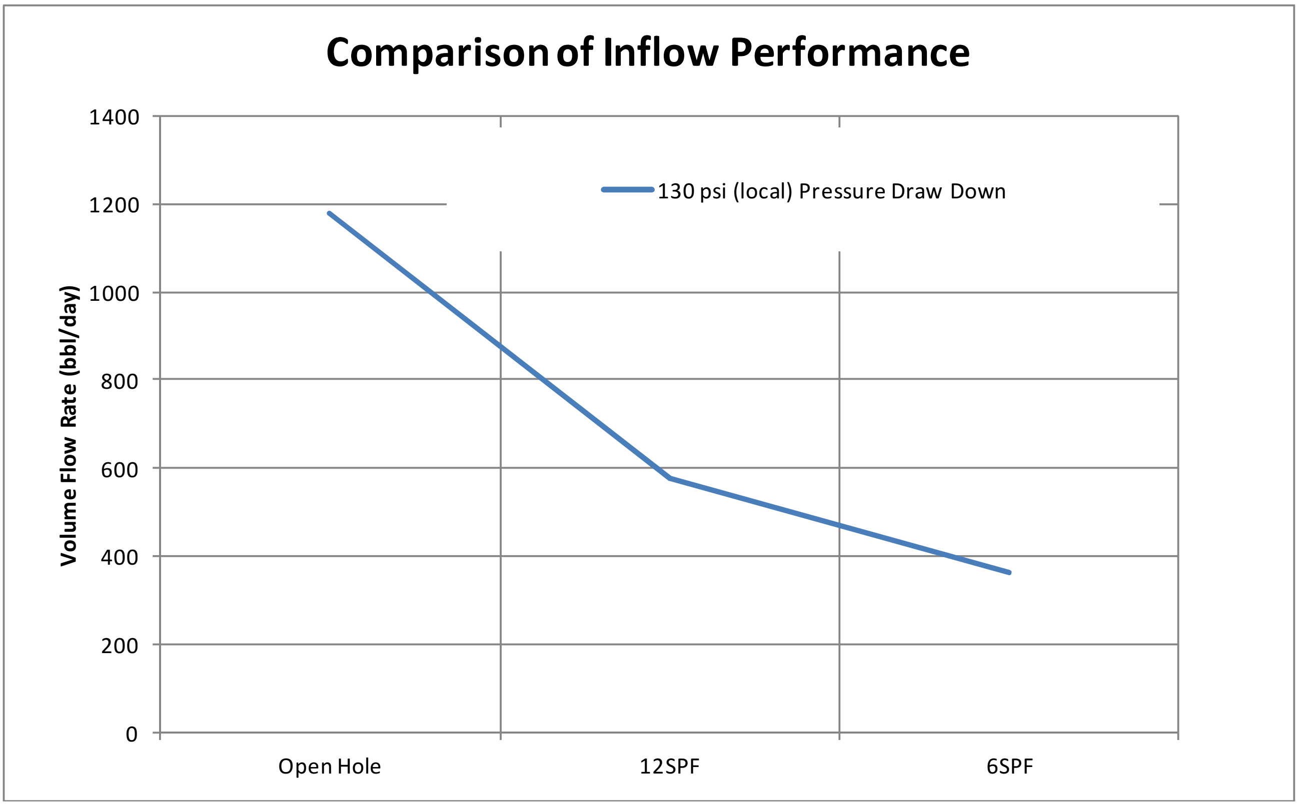

Fig. 21—Flowrate vs Drawdown for OH and C & P Sector Models

Different drawdown rates were also applied to the 12spf and 6spf model. With reference to

Table 2 & **Fig. 22**, at drawdown rates of less than 50psi, the influence of the drawdown on the flow rate between the two cases was apparent (65%-86%). However, at higher drawdown rates (above 50psi) the difference in flow rates between the models did not change much. This is because at these rates, the high pressure drop across the ICD completely dominates the fluid inflow from the reservoir for both the 6spf and 12spf case.

It is interesting to see in **Fig. 22** that for the 12 spf configuration, increasing the drawdown results in higher inflow compared to the 6 spf configuration. This results in higher Productivity Index, 4.278 bpd/psi for the 12 spf, compared to 2.707 bpd/psi for the 6 spf.

It is evident that the 12 spf configuration should be used to perforate the cased part of the well if possible.

Table 2—Sector Models Inflow rates vs Drawdown

Drawdown (psi)	Flowrate bpd		% Difference
	12spf	6spf	
10	75.7	40.7	86%
20	118.4	67.8	75%
30	161.1	94.8	70%
40	203.8	121.9	67%
50	246.5	149.0	65%
60	289.2	176.0	64%
70	331.9	203.1	63%
80	374.6	230.1	63%

Drawdown (psi)	Flowrate bpd		% Difference
	12spf	6spf	
90	417.3	257.2	62%
100	460.0	284.3	62%
110	502.7	311.3	61%
120	545.4	338.4	61%
130	588.1	365.5	61%
140	630.8	392.5	61%

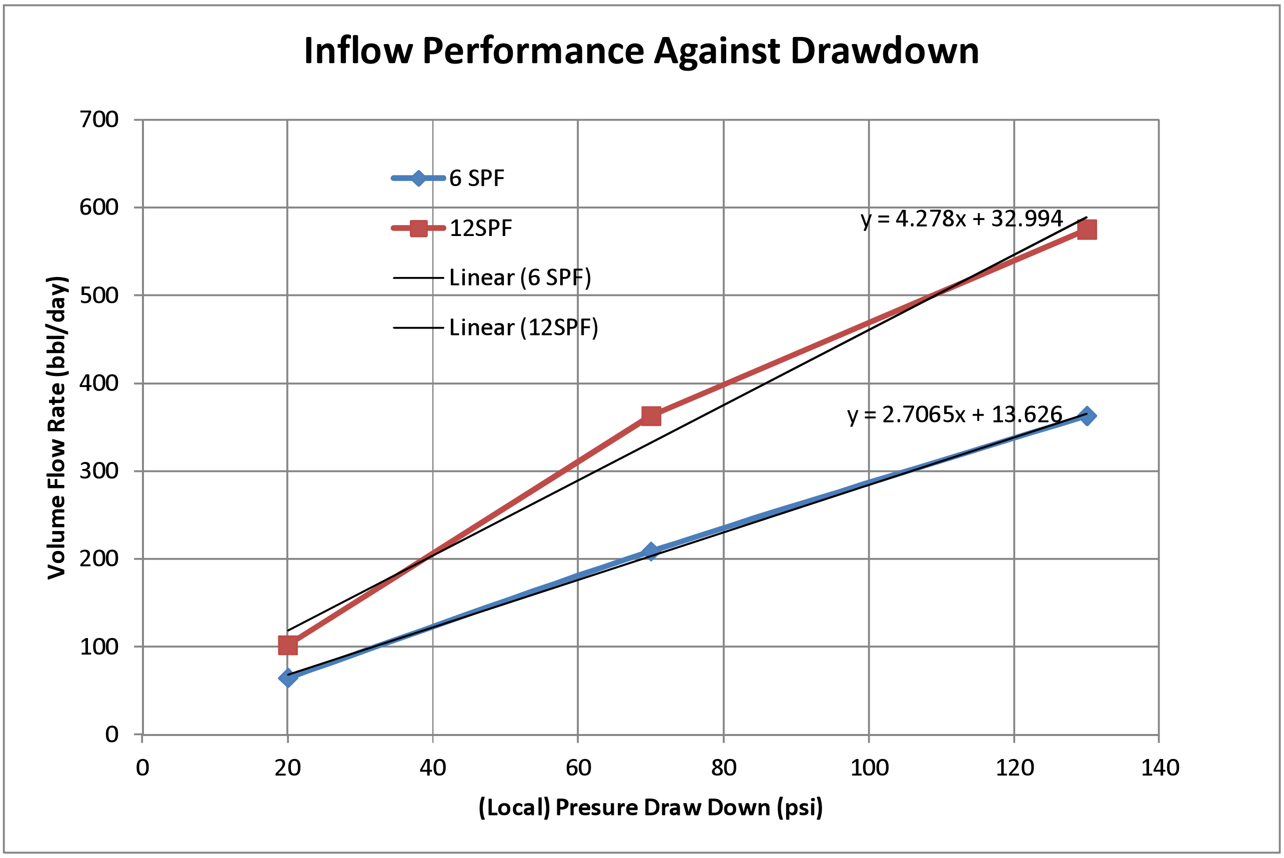

Fig. 22—Inflow Rates for 12spf and 6spf Sector model vs Drawdown

The Existing Entire Open Hole Completion.

As mentioned previously in the Final Model (Page 7), the existing open hole completion performance is adjusted to flow around 8,000 bpd of water. As we do not know the precise cause or causes of the "skin" in the existing open hole section, the collapsed annulus permeabilities were adjusted to produce around 8,000 bpd of water.

Reservoir Section	Length (m)	Start of mDRT (m)	Completion Type	Fluid	No of ICDs	No of ICD Ports Open	Reservoir Permeability (mD)	Annulus Permeability (mD)
S01	332	1385	12 SPF	Oil	28	10	10,000	5,000
S02	20	1717	Casing Shoe	N/A	N/A	N/A	N/A	N/A
S03	71.4	1737	Casing Shoe	N/A	N/A	N/A	N/A	N/A
S04	386.7	1808.4	Open Hole	Water	31	1	10,000	12.15
S05	307.8	2195.5	Open Hole	Water	26	10	2,000	2.45
S06	92.9	2502.9	Open Hole	Water	8	1	10,000	12.15
S07	23.3	2595.8	Open Hole	Water	2	1	2,000	2.45
S08	118.6	2619.1	Open Hole	Water	9	10	2,000	2.45

Fig. 23—Open Hole Collapsed Annulus Permeability

Fig. 23 shows the adjusted collapsed annulus permeability which gives 8,300 bpd of water.

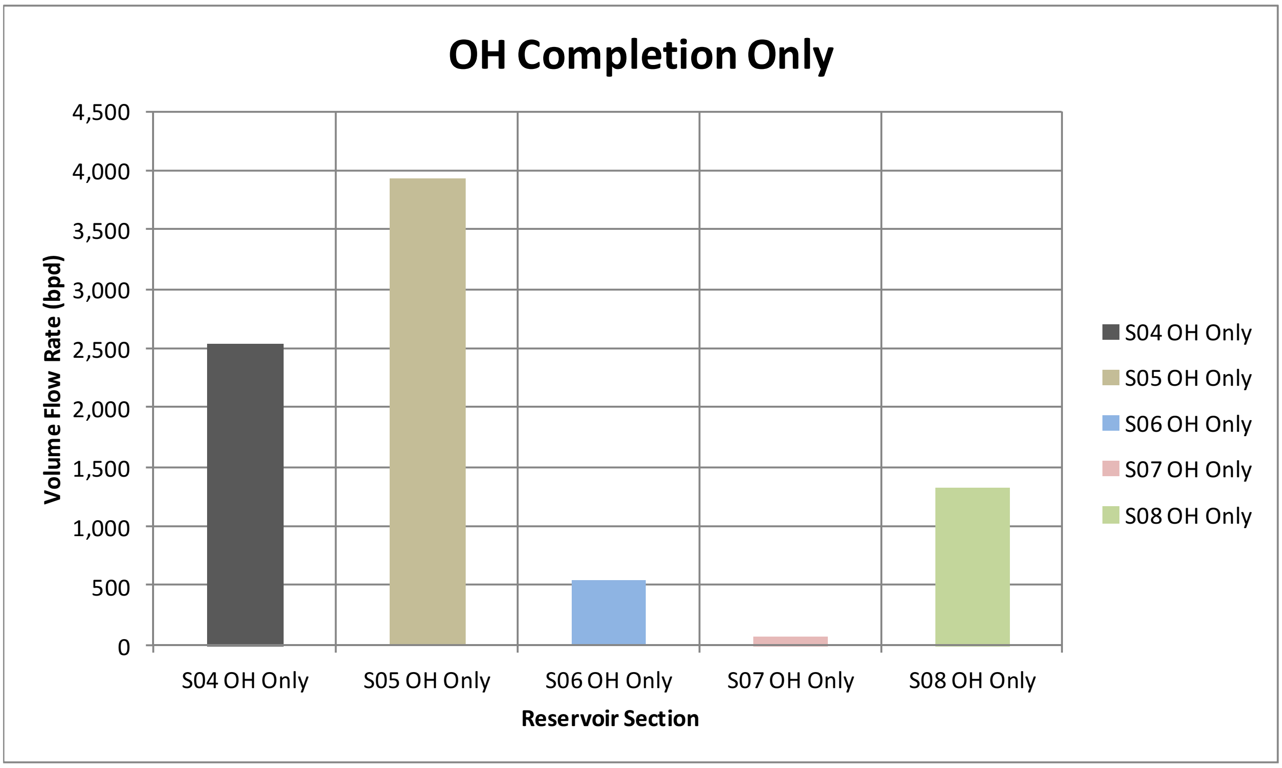

Fig. 24—Open Hole Completion Water Production

Fig. 24 shows that S05 section, despite having lower reservoir permeability (2 Darcy) than the S04 section (10 Darcy) produces most of the water, due to all 10 ICD ports being open, compared to just 1 port being open on the S04 section.

C&P Recompletion on It's Own.

Prior to combining the 12 spf C&P recompletion with the existing OH completion, a simulation was run on the 12 spf C&P recompletion alone, to estimate the oil production. Below are the flow parameters along with the oil production.

- Reservoir permeability: 10 Darcy
- Annulus permeability : 5 Darcy
- Number of ICDs: 28
- Number of ICD Ports Open: 10
- Pressure draw down: 110 psi
- Horizontal well length : 332 m
- Oil Production: 14,667 bpd

It can be seen that the cased part of the well, when perforated with 12 shot-per-foot, would have produced around 14,667 bpd of oil on its own.

Combining the C&P recompletion and the existing OH Completion.

Following the results from the previous sections, the existing open hole completion is then connected to the 12 spf recompletion section, in order to ascertain the water & oil production, which is one of the main objectives of the study.

Prior to discussing the results, it is important to assess the convergence of the computational calculations, to ensure that the computational results have reached a converged condition. This is a complex model of significant size (more than 0.5 billion cells in the full model) and convergence is not trivial. For the full model (and several of the earlier models) simulations were run in a High Performance Computing (HPC) centre.

Fig. 25 shows the residuals convergence plot, which clearly indicates that the calculation was stable and has reached a converged condition.

The mass flow rate of oil and water has also reached a steady state condition, which is shown in **Fig. 26** and **Fig. 27** respectively. The mass flow balanced between the inlet and outlet is depicted in **Fig. 28**, which shows that the difference between the inlet and outlet mass flow rate is within 3% tolerance.

These plots give reassurance that the computational results have reached a steady state condition.

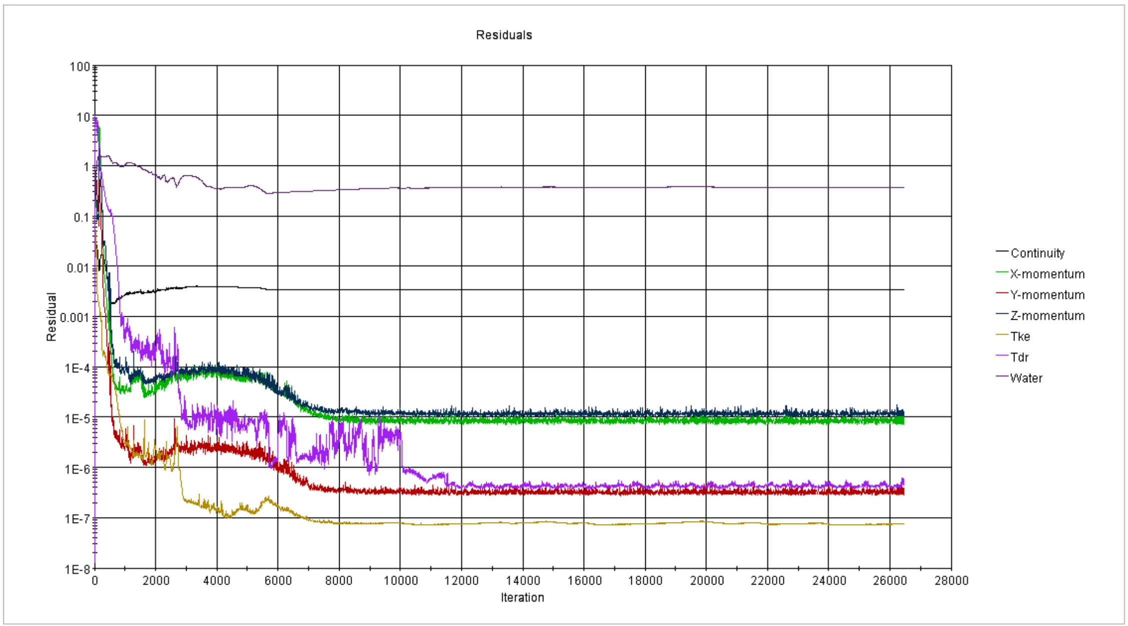

Fig. 25—Residuals convergence plot

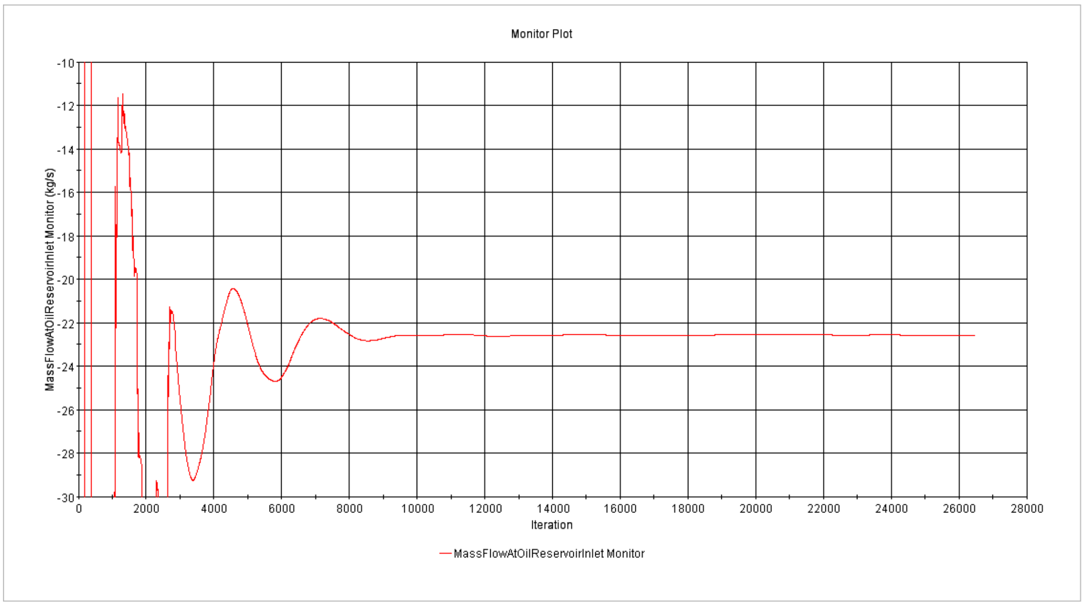

Fig. 26—Oil mass flow rate convergence

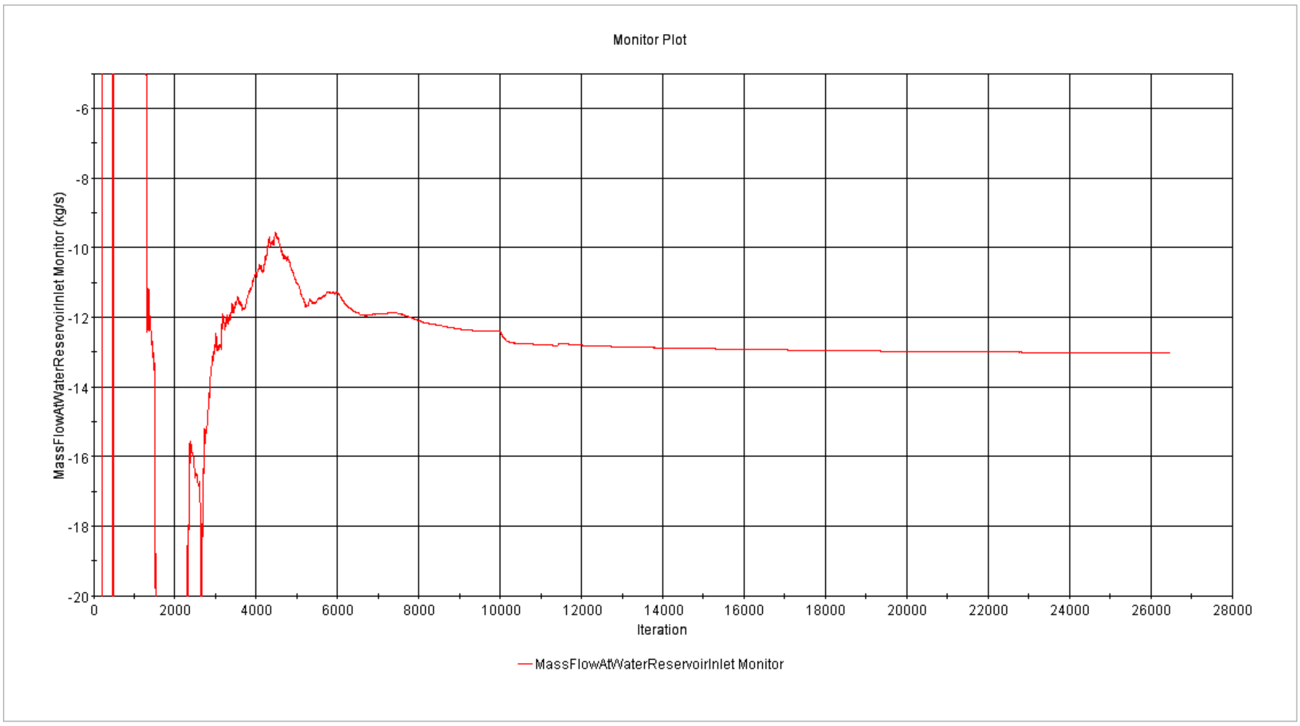

Fig. 27—Water mass flow rate convergence

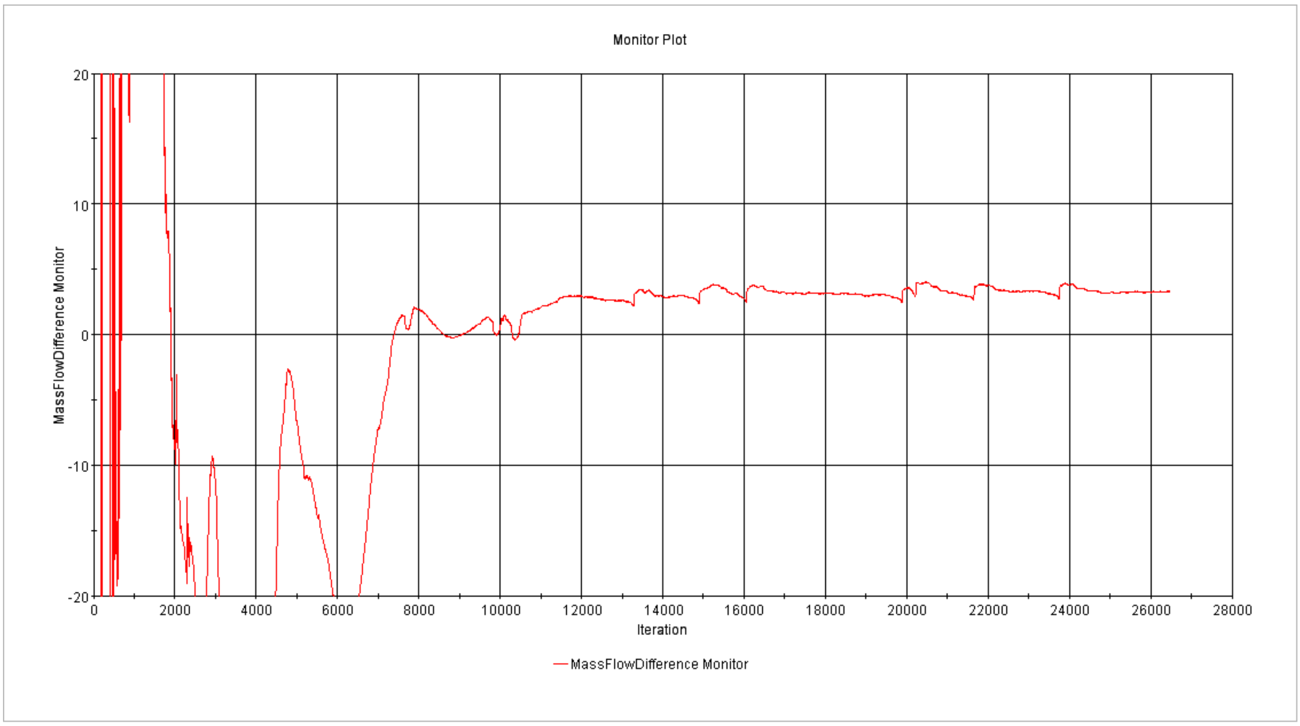

Fig. 28—Inlet - Outlet mass flow difference

When the C&P recompletion section is connected to the existing OH completion, there is reduction in both the water and oil production compared to OH and C&P on their own. This is illustrated in **Fig. 29**. This is expected as the water and oil flow would "work against each other". This suggests the importance of modelling the entire well as one system.

The final production from the entire well is therefore:

- Water production : 6,976 bpd (water cut: 33.58 %)

- Oil production : 13,801 bpd

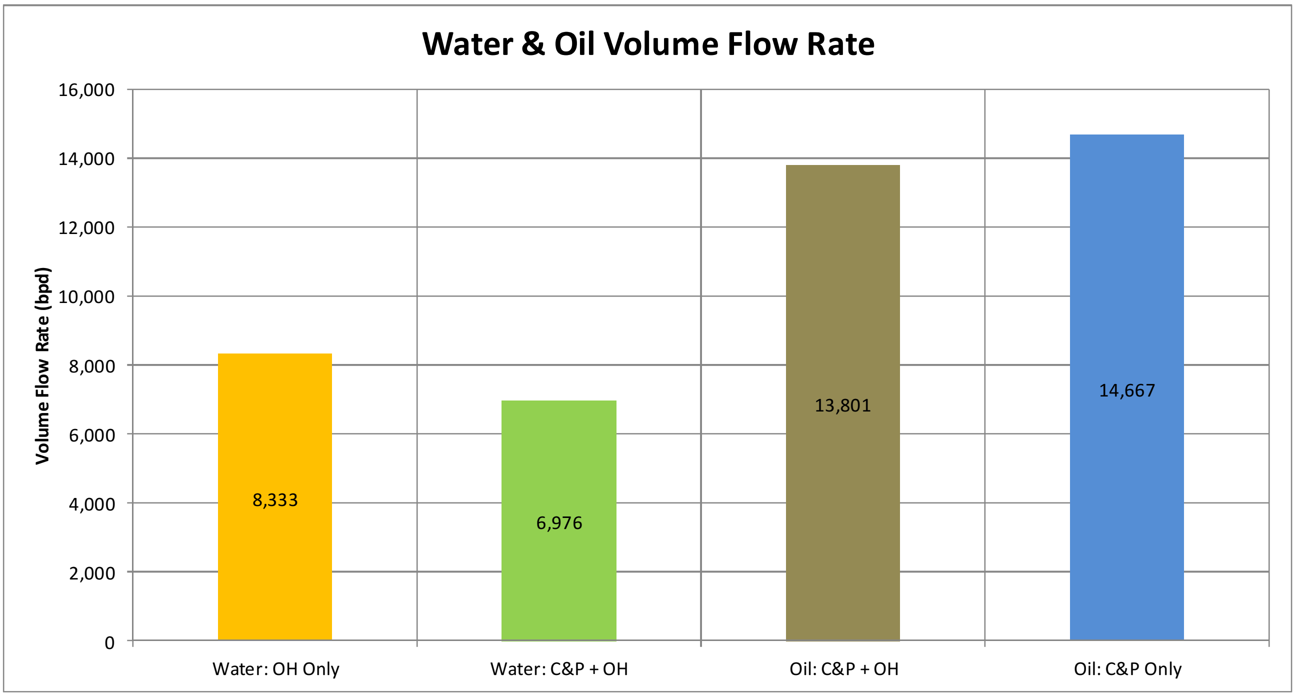

Fig. 29—Water & Oil Production

Most of the water production reduction, from OH only to OH + C&P, came from the reservoir section where 10 ICD ports are open, as shown in **Fig. 30**.

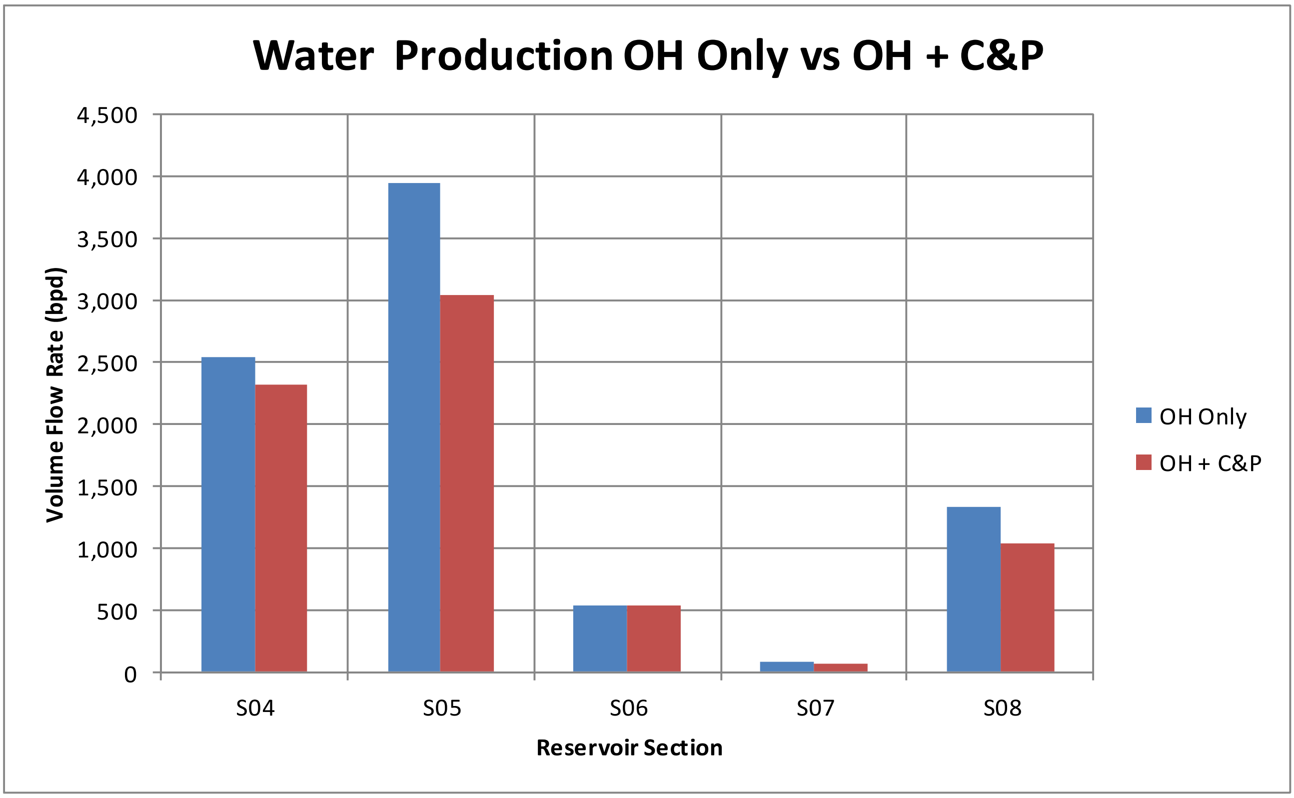

Fig. 30—Water Production from OH only vs OH + C&P

Sensitivity Study 1: Investigating the effect of very high damage.

It is seen in the section dealing with The Existing Entire Open Hole Completion (Page 15) that the collapsed annuli permeabilities were adjusted to produce around 8,300 bpd of water, which is the current liquids production rate in the open hole section.

The aim of this first sensitivity study is to investigate the effect of very low annulus permeability (e.g. due to very high damage or very high “skin”), 12 mD, on the inflow performance of the new completion sector model shown in **Fig. 21**. (where the base case collapsed annulus permeability was 5,000 mD).

Reducing the annulus permeability from 5,000 mD to 12 mD results in significant reduction in inflow. The Open Hole sector model flow rate drops from 1,179 bpd to 30 bpd, the 12 SPF flow rates drops from 575 bpd to 2 bpd and the 6 SPF flow rates drops from 363 bpd to less than 2 bpd. This comparison is illustrated in **Fig. 31**.

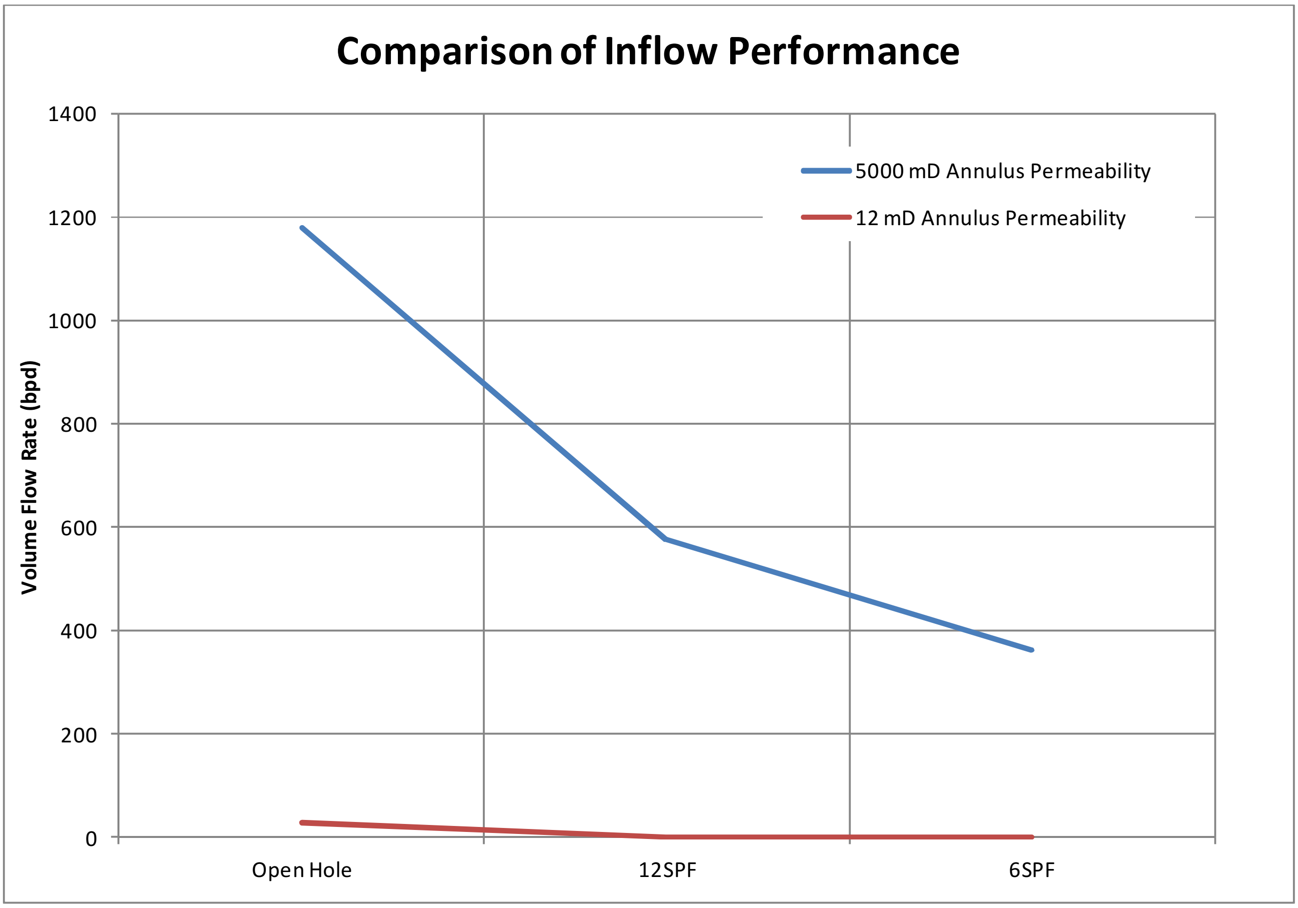

Fig. 31—Annulus Permeability Effect on Inflow Performance (Sector Model)

Sensitivity Study 2: 6 SPF with varying annulus permeability.

Based on the results shown in Combining the C&P recompletion and the existing OH Completion (Page 16) and Sensitivity Study 1: Investigating the effect of very high damage (Page 19), it is felt that the 5,000 mD annulus permeability is an optimistic value, and the 12 mD annulus permeability is too low to yield a sensible rate – there would have to be significant damage during the recompletion process to cause the 12 mD annulus permeability.

The aim of the second sensitivity study is therefore to ascertain the water and oil production when the recompletion is done using 6 SPF with two different collapsed annuli permeabilities, 500 mD and 1,000 mD.

It can be seen in **Fig. 32** that the highest oil flow rate from the recompletion part was achieved using 12 SPF with 5,000 mD permeability. It has been seen previously that for the same flow conditions, the 6 SPF flow rate is approximately 63% of 12 SPF flow rate due to the reduced contact between the wellbore and the reservoir. When the annulus permeability is reduced, there is an additional significant reduction in the oil flow rate. This is what causes the significant oil flow rate reduction from 12 SPF + 5,000 mD annulus permeability to 6 SPF + 1,000 mD annulus permeability. A further reduction in the oil flow rate is seen when the 6 SPF annulus permeability was reduced to 500 mD.

It is interesting to see that the water production from the existing open hole completion is not significantly affected by the reduction in the oil production. The water cut however rises due to the reduction in the oil production, as shown in **Fig. 33**.

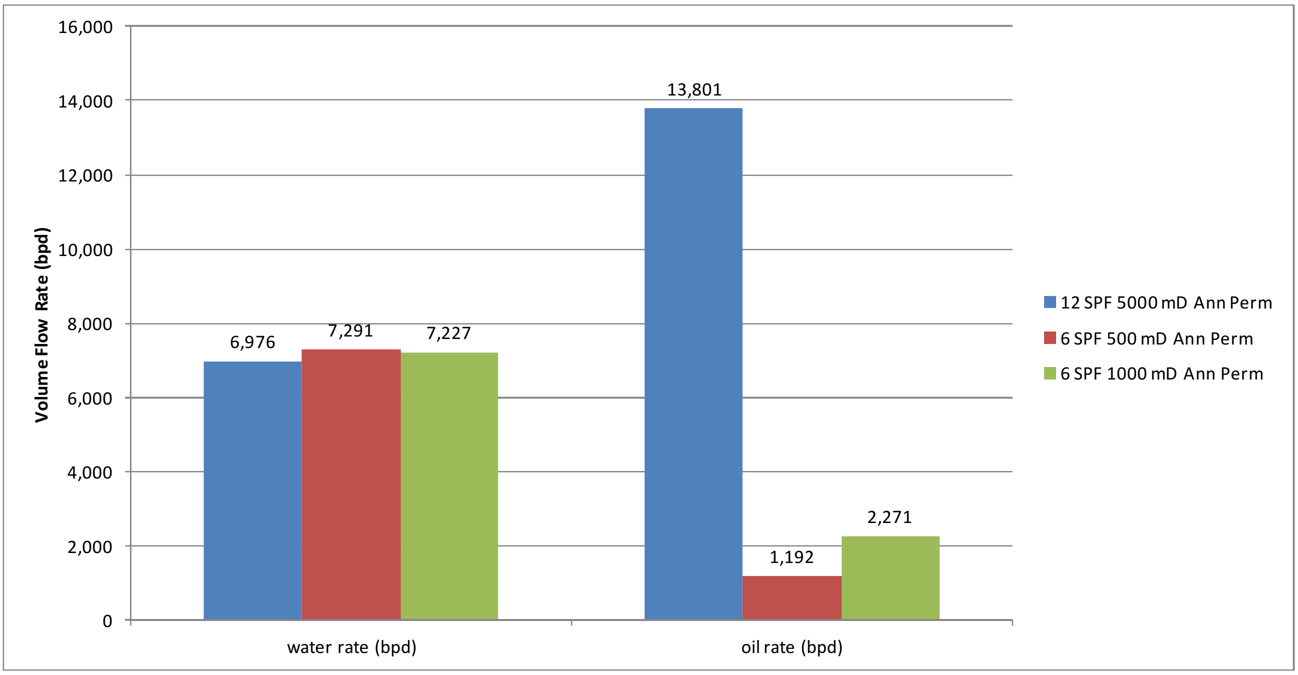

Fig. 32—Water and oil flow rate due to three different recompletion scenarios; the complete well: OH + C&P

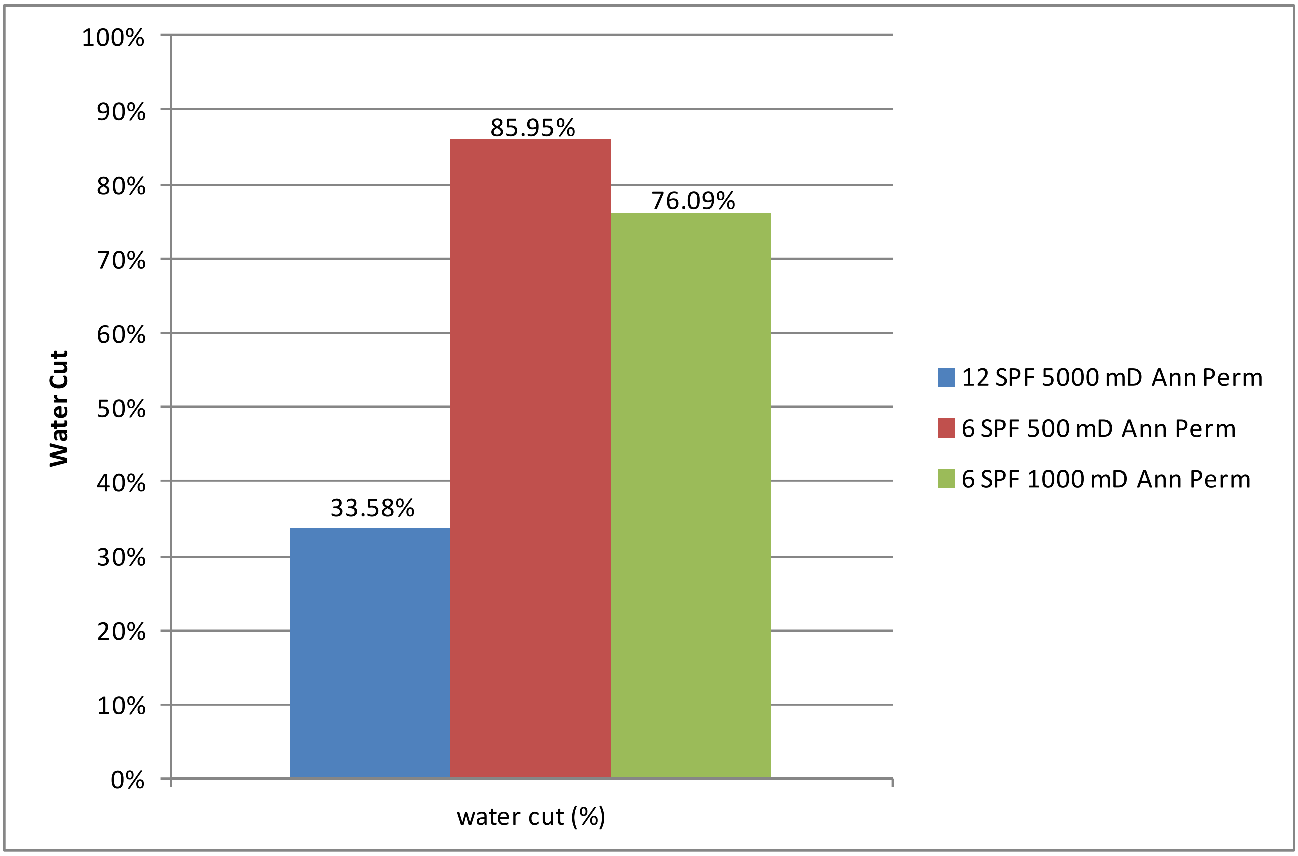

Fig. 33—Water cut due to three different recompletion scenarios; the complete well: OH + C&P

Flow structures around the ICD and the base-pipe outlet.

This section outlines the flow structures around the inflow control device (ICD) and the base-pipe outlet, to show how the water and oil mix together.

Fig. 34 shows a contour plot of Volume Fraction of Oil around an ICD; red indicates 100% oil, blue indicates 100% water, and the colour between blue and red indicates a mixture of water and oil. It can be seen in the picture on the left that oil, through the ICD drainage holes, is entering the base-pipe where the water is flowing from right to left (indicated by the arrow in the picture), the oil then starts to mix with the water. **Fig. 34a** shows a cut through the ICD and the base-pipe cross section, also depicting oil 'penetrating' the water with relatively higher velocity induced by the ICD.

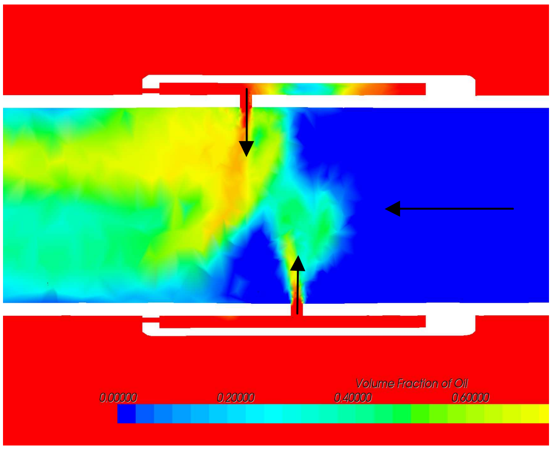

Fig. 34—Oil entering the base-pipe through ICD

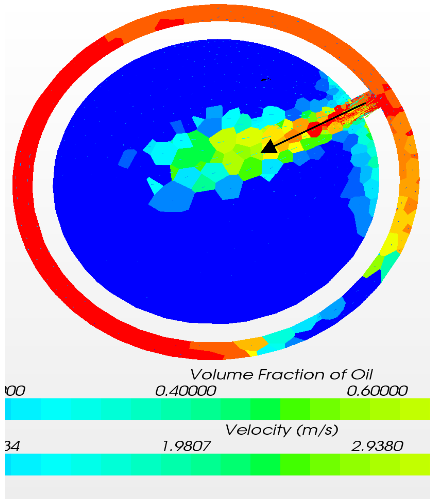

Fig. 34a cut through the ICD and the base-pipe cross section

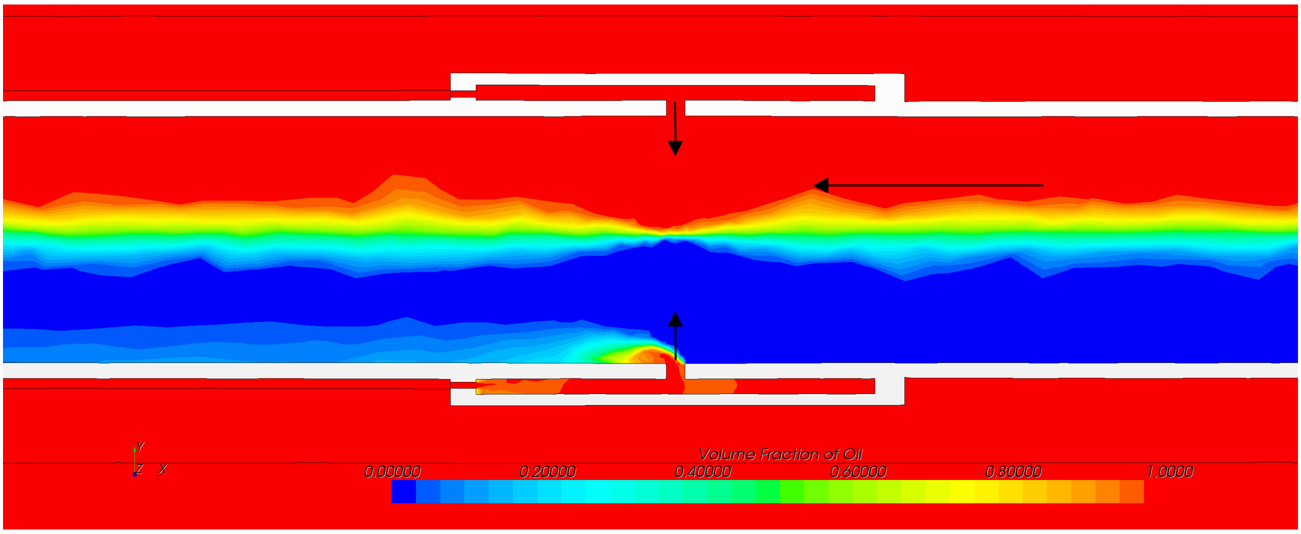

Fig. 35—Oil entering the base-pipe through an ICD near the toe of the completion

Similar phenomenon can be seen in **Fig. 35**. However in this picture, since the ICD is located near the toe of the well, water, being the heavier fluid, has been flowing at the bottom of the base-pipe. At the top of the base-pipe oil enters the base-pipe and continues to flow with the oil which has been flowing at the top of the base-pipe. At the bottom of the base-pipe however, the oil mixes with the water after it enters the base-pipe and continue to flow to the left.

Fig. 36 depicts the view of the base-pipe outlet, showing the oil (red) flows at the top and water (blue) flows at the bottom of the base-pipe.

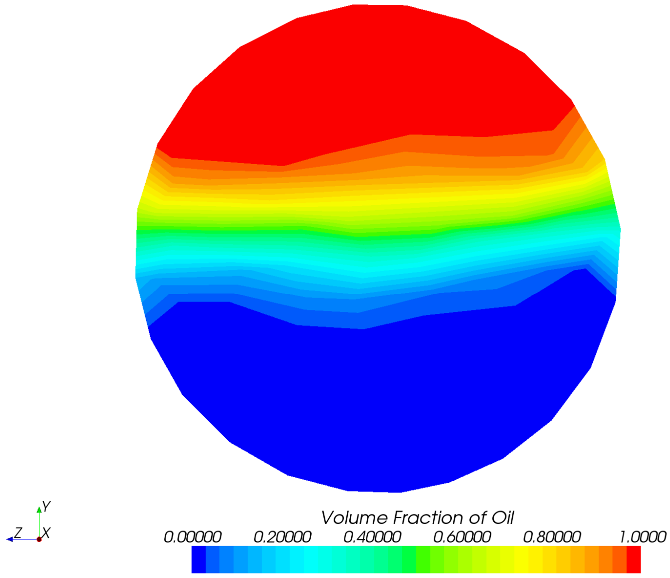

Fig. 36—Volume Fraction of Oil at the base-pipe outlet

Conclusions

The sector model sensitivity runs proved that the perforations located away from the drainage layer of the screens had minimal contribution to the well's productivity. This information inferred two things; firstly, perforating the entire length of the C & P section was not necessary in order to achieve the target flow rate. Secondly, to maximize the well PI, the drainage layer should be as long as possible, in this case, close to 28ft (assuming average pipe length of 38ft) as opposed to the modelled length of 20ft.

The sector models also proved that in terms of productivity, the OH ranked the best followed by the 12spf and 6spf completion. The difference in productivity was more apparent at lower drawdown rates. This was because at higher rates, the pressure drop across the ICDs was the dominating factor that governed the inflow of fluid from the reservoir into the well.

Prior to modelling the complete C&P + OH completion, the OH part and the C&P part of the well were simulated as standalone wells. Since no other information were available for the existing open hole completion, the collapsed annuli permeabilities were adjusted such that around 8,300 bpd of water flows in this part of the well. The C&P recompletion part on its own produces around 14,667 bpd of oil, and when both the C&P and OH are connected to each other, there is reduction in both the water and oil production compared to OH and C&P on their own. This suggests that it is important to model the entire well as one system.

Three different recompletion scenarios were studied and the water and oil production rates are summarised in **Fig. 37** below:

Recompletion scenario	water rate (bpd)	oil rate (bpd)	water cut (%)
12 SPF 5000 mD Annulus Permeability	6,976	13,801	33.58%
6 SPF 1000 mD Annulus Permeability	7,227	2,271	76.09%
6 SPF 500 mD Annulus Permeability	7,291	1,192	85.95%

Fig. 37— Summary of water, oil production for three different recompletion scenarios

Recommendations

Based on the results of this study, it is recommended to recomplete the cased part of the well with as many perforations as possible, and minimise damage during and post perforating. It is not necessary to perforate the entire joint; the critical area to perforate is near the ICD location. Of course perforating only the intervals across which the drainage layers will sit requires precise positioning of perforations and screen and is likely to carry significant risk. The screen drainage layer should be made as long as possible.

The addition of well connected new perforations in the recompletion reduces production from the original completion but not by a significant amount (maximum modelled reduction of approximately 16%). This indicates that the recompletion can achieve one of the primary objectives i.e. preserving production from the original completion whilst adding significant additional oil production.

The quantity of additional flow restriction in the new completion has a significant impact on the oil production from this zone. Every effort should be made to increase reservoir contact (higher density of clean perforations) and reduce any formation damage during or post perforation.

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