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An Effective Accelerated Pulsing Injection Method for Restoring Injectivity in Waterflood Fields with Selective Injection Systems with Side-Pocket Mandrels and Control Flow Valves

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Abstract

This paper presents the performance of three water injection wells, INJ-1, INJ-2, and INJ-3, at the Ecopetrol's Yarigui Cantagallo field re-completed with newly designed pulsing selective control valves (P-SCFV). The three wells originally had conventional selective control flow valves (C-SCFV) in side-pocket mandrels. While a total of 31 valves were replaced in seven wells, this paper will focus on the three wells where 12 P-SCFVs were installed and the injection data gathered and interpreted.

Enhanced Oil Recovery (EOR) and/or chemical methods are routinely used to improve oil recovery when production levels decline due to reduced formation pressure, poor displacement efficiency, and adverse mobility ratio. For decades, oil production companies with waterflood recovery schemes have employed various types of well completions for water injection, including selective completions with side-pocket mandrels.

When an injection zone loses its capacity to admit water, the optimal sweeping capacity will not be reached, and then the operator will not achieve sufficient oil production to maintain profitability. In the Yarigui Cantagallo field 12 P-SCFVs were installed (4 in each injector well), with the objective of overcoming the loss of injectivity in each injection zone due to blockages and permeability decay on the formation face, primarily as the result of calcium carbonate deposition. The new P-SCFVs were run to demonstrate that they could overcome the common problem of permeability decay with the objective that injectivity performance could be increased and sustained over an extended timeframe.

The 12 P-SCFVs have been in operation for 12 months, and the comparative results have shown performance optimization that conventional C-SCFVs could not achieve, such as, intervals previously not accepting injection water gradually (after ~ one month) accepting water from the P-SCFVs. The latter confirms the theoretical and practical efficiency created generated by a flow field that concurrently establishes a repeated pulsed water hammer effect and the creation of numerous vaporization zones, which result in the formation of cavitation bubbles. These vaporization cavities work in consort with the water hammer effect to clear detritus material from the mandrel and formation face giving rise to increased near wellbore permeability.

Introduction

The Yarigui Cantagallo oil field was discovered in 1942, and started its waterflood system in 2008 (**Fig. 1**). The field contains three stratigraphic units: B3 Sands, C Sands, and Cantagallo Sands, and two formations: Mugrosas and La Paz.

Fig. 1—Geographical Location of the Field

The lithology of the formation is Sandstone with pyroclastic sediments partially consolidated with a high clay content. The petrophysical characterization is as follows (see Table 1):

TABLE 1—PETROPHYSICAL CHARACTERIZATION

Porosity type	Primary
Average porosity	15 – 22 %
Horizontal permeability	205 mD (50mD – 350 mD)
Water saturation	30 %
Oil residual saturation	25 %
Compressibility of the rock	5 x 10-5 psi^{-1}
Net sand thickness	70 – 600 ft
Shale volume	< 50 %

The original formation pressure was 3250 psi @ -7000 ft TVDSS, with a current formation pressure measuring at 1000 – 3100 psi @ -7000 ft TVDSS. The average formation temperature is 140^{o} F. In regards to the hydrocarbons, the type is black-oil, with an original GOR of 350 SCF/STB, having a GOR today of 300 SCF/STB; the API gravity is 20.5^{o} (14^{o} – 21^{o}), with a viscosity of 21 cP (bubble pressure: 2,425 psia). The salinity of the water is 30,000 ppm Cl-. The specific gravity of the gas is 0.65 and GPM of 1.63.

When the oil production declines due to poor displacement efficiency and adverse mobility ratio, EOR is often utilized to improve oil production (Munisteri and Kotenev 2013). When an injection zone loses its capacity to admit water, the sweeping capacity will not be reached, and then the operators will not achieve sufficient oil production to maintain profitability.

For both C-SCFVs and P-SCFVs, it is important that the quality of the water meet established domestic regulations; if the operator is injecting produced water, it is important that this water receive treatment to reduce the ppm of solids contained in the water (Boysen et al. 2013). Both conventional and pulsing valves will plug with debris if the solids content exceeds a certain level. However, the P-SCFVs are more resistant to plugging and can handle higher solids content than C-SCFVs due to the acceleration of the water and the hydraulic hammering effect created internally in the P-SCFVs.

This paper describes how the new P-SCFVs were run to demonstrate that they could overcome the common problem of permeability decay with the objective that injectivity performance could be increased and sustained over an extended timeframe.

Comparison between a C-SCFV and a P-SCFV

A C-SCFV is a tool that selectively controls the injection of water into a particular zone at a specific flow rate. Selective control flow valves improve the sweep efficiency by balancing the fluid flow at the upstream point, increasing oil recovery by 2%, and helping to reduce the water cut by approximately 20% (Abllah, Maulut, and Loong 2011). The valves incorporate orifices of different sizes to regulate injection rate into a particular interval based upon the injection parameters established by operating company engineers. Water is injected continuously and over time the particulates contained in the water deposit on the sandface and surrounding tools. Continual particulate deposition compromises the injection capacity of the reservoir by blocking or impairing permeability of the formation.

Alternatively, the P-SCFV injects the water as rapid pulses, hydraulically creating a water hammer effect on the formation face. In addition, the unique design of the pulsating tool creates an energized flow field that also produces vaporization cavities, which enables the formation of cavitation bubbles. In a hydrostatic medium these cavitation bubbles ultimately collapse releasing massive energy to assisting in altering the stress field of the formation and enhancing injectivity by increasing and maintaining permeability. The energized vaporization bubbles also act on all surfaces to remove detritus. The action of the pulsation and vaporization is sometimes refered to as a “Laundry Effect”.

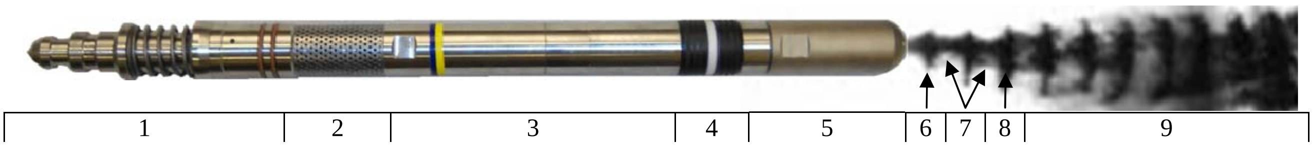

Fig. 2—Schematic of the P-SCFV and the Rapid Fluid Pulse Flow it Induces

Referring to **Fig. 2**, from sections 1 to 4, the P-SCFV is like a common C-SCFV. The major difference is section # 5, the pulsating chamber that creates rapid fluid pulses. This P-SCFV is available in two different configurations: bottom injection and lateral injection, with outside diameters for either configuration ranging from 1-1/4” to 2-1/4”. For this technical paper we refer to a bottom injection P-SCFV having an outside diameter of 1-1/5”. The segments of the tool showing in Fig. 2 above can be described as follows:

1. Hanger section
2. Inlet flow / filter
3. Control flow valve section
4. Seals
5. Pulsing resonance chamber
6. Pulse of fluid
7. Vaporization regions between pulses
8. Previous pulse
9. Continuation of rapid pulses creating the laundry effect around the mandrel and the formation face

P-SCFV Injection Head Operating Principle

The principles outlined in this section are primarily based on the studies of Spanos (2001) and Spanos et al. (2003). All P-SCFV tools share a common patented design and principle of operation: self-excited oscillation. **Fig. 3** is a simplified cross-sectional schematic of the tool. In essence, the tool consists of an inlet section of pipe attached to a resonance chamber along with an outlet section of pipe.

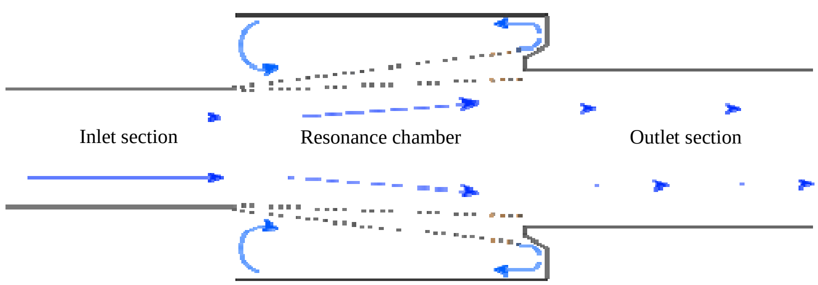

Fig. 3—Simplified Schematic of the Pulsing Chamber in Operation

A steady state turbulent flow of fluid enters the tool through the inlet pipe. When the fluid enters the chamber, it undergoes a sudden enlargement. The fluid flow in the corners of the chamber near the inlet is small, and consists of small eddies and vortices. A large shearing action and shear layer is induced by the difference in flow rate between the fluid in the chamber corners near the inlet and the fluid exiting the inlet. Consequently, vortex rings are created in the shear layer and travel from the inlet to the edge of the outlet pipe where it connects with the chamber. The collision of a vortex ring with this edge converts a large part of its energy into a wide range of pressure waves, i.e. the self-excited pressure oscillation. The remainder of the energy remains with the flow and is split between the flow towards the chamber wall and the flow into the outlet pipe. The large pressure oscillations of the pressure waves cause the output flow to be interrupted and subsequently converted into an oscillating or pulsating jet of fluid producing the water hammer and cavitational vaporization effects.

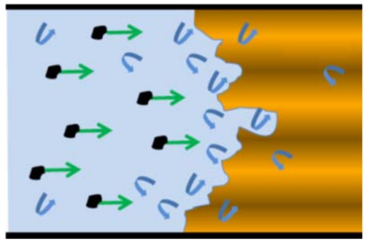

Fig. 4—The "Laundry Effect"

When the P-SCFV tool is deployed in a well, the repeated pulsed water hammer effect and cavitational vaporization zones produced by the tool enter the reservoir through the well perforations and impact the near well bore region. The strong oscillatory motions of the fluid in the near well bore zone are strongly coupled to deformations of the reservoir matrix in a complex non-linear manner. The net effect near the well bore is a strong agitation or "churning" effect—called the "Laundry Effect" (**Fig. 4**)—that breaks down sand bridges, loosens particles, and removes blockages from pore throats. Consequently, fluid injectivity is greatly improved.

Cavitation Effect Acting as a Wellbore Cleaning Process to Recover Injectivity

Cavitation occurs in the regions of the liquid (water) which are subjected to rapidly alternating pressures of high amplitude. The stress setup in the water molecule is caused by the friction forces generated by the relative movement of molecules and solids as a result of the collapse of cavitation bubbles in front of the formation face (**Fig. 5**).

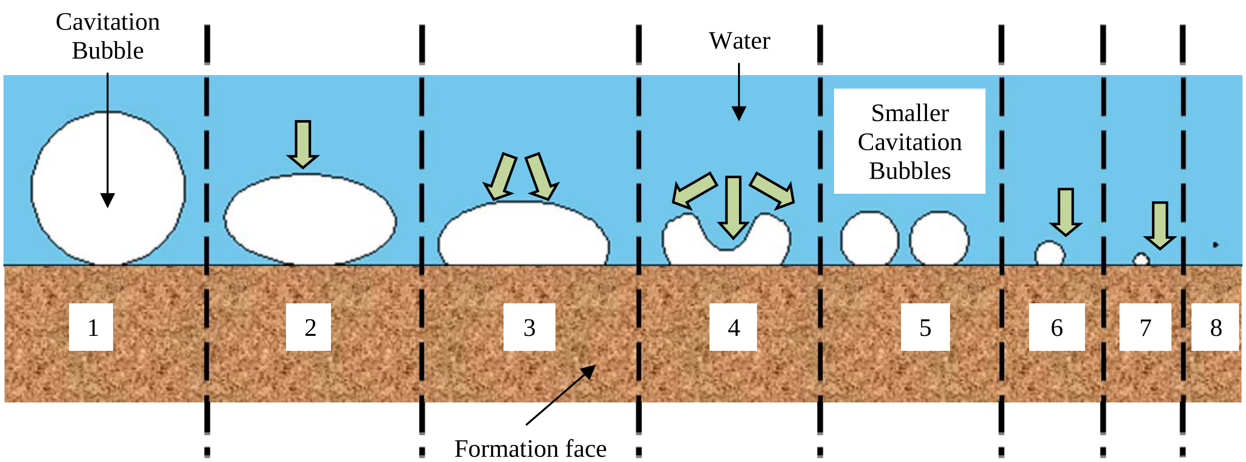

Fig. 5—Illustration of the Phases of the Cavitation Process

Description of the cavitation process created by the P-SCFV:

Steps:

1. Vaporization occurs in regions of lower pressure as fluid exits the tool; as a result vaporization bubbles form.
2. The vaporization bubbles expand and then are compressed by the surrounding fluid.
3. As the pressure of the fluid increases, the bubbles become more and more compressed.
4. Pressure inside the bubble reaches the point that it is not stable enough to support the external pressure of the surrounding fluid, starting the collapse of the bubble.
5. When the bubble finally collapses, a high velocity jet of fluid is formed, which impacts the surrounding surfaces including the formation face, as well as the mandrel, and exit ports of the mandrel.
6. After the original bubble collapses, creating a high-energy field, the cycle repeats until total collapse occurs.
7. The new smaller bubbles would repeat individually the steps from 1 to 5, creating smaller and smaller air bubbles as the 7th and 8th steps, bubbles which, in collapsing, each create their own high velocity jets of fluid which impact the surrounding surfaces, helping to remove the blocking damage on the formation face or around the exit port of the mandrel.

Some other tools may create cavitation as a by product of a jetting process, but the difference and benefits of the P-SCFV is that the tool is designed to create a large vaporization flow field with every pulse generated by the tool; each time the tool pulses, vaporization beds are created, as depicted in **Fig. 6** below.

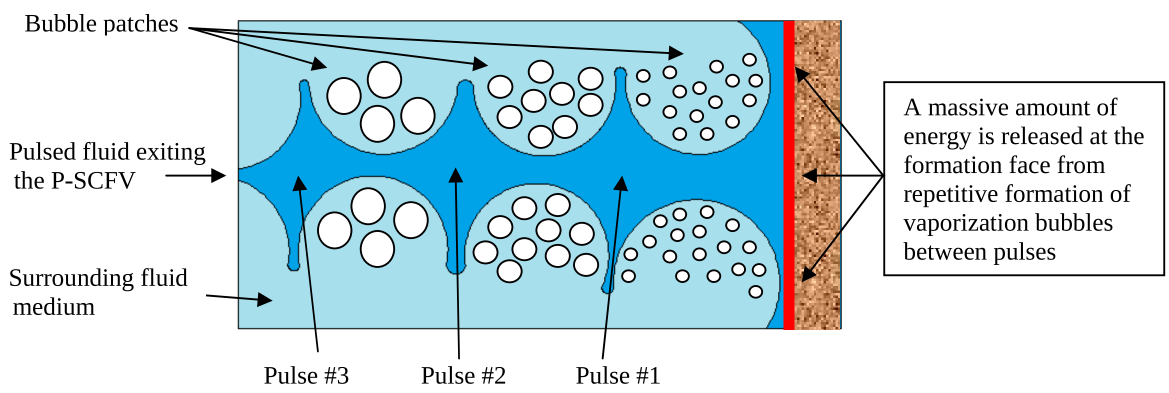

Fig. 6—Illustration of the Cavitation Process and Vaporization Beds as They Occur

Description of the Well Candidates

Each of the three well injectors (see **Tables 2, 3 and 4**) was completed with four side-pocket mandrels per well:

TABLE 2—WELL INJECTOR INJ-1, WITH FOUR C-SCFVs	
Drilled depth	8,830 ft
Drilled	2007
Completed	2011
Casing	9.5” and 7”
Injection tubing	2-7/8”
Mandrel # 1 Top (ft)	8,606.80
Mandrel # 1 Bottom (ft)	8,615.70
Mandrel # 2 Top (ft)	8,530.60
Mandrel # 2 Bottom (ft)	8,539.30
Mandrel # 3 Top (ft)	8,470.30
Mandrel # 3 Bottom (ft)	8,479.10
Mandrel # 4 Top (ft)	8,356.20
Mandrel # 4 Bottom (ft)	8,365.00

Note: Before installation of the P-SCFVs, only mandrels #1, #2, and #3 contained a C-SCFV; mandrel #4 was empty, injecting water in an open-hole mode.

TABLE 3—WELL INJECTOR INJ-2, WITH FOUR C-SCFVs	
Actual depth	8,837 ft
Drilled	2008
Completed	2010
Casing	9.625” and 7”
Injection tubing	2-7/8”
Mandrel # 1 Top (ft)	8,116.40
Mandrel # 1 Bottom (ft)	8,126.00
Mandrel # 2 Top (ft)	7,996.40
Mandrel # 2 Bottom (ft)	8,005.80
Mandrel # 3 Top (ft)	7,875.90
Mandrel # 3 Bottom (ft)	7,885.50
Mandrel # 4 Top (ft)	7,839.00
Mandrel # 4 Bottom (ft)	7,844.50

Note: Before installation of the P-SCFVs, all C-SCFVs were found in a “Full-Open” mode, without flow control.

TABLE 4—WELL INJECTOR INJ-3, WITH FOUR C-SCFVs	
Drilled depth	8,837 ft
Drilled	2010
Completed	2011
Casing	9.625”
Injection tubing	2-7/8”
Mandrel # 1 Top (ft)	8340.70
Mandrel # 1 Bottom (ft)	8349.60
Mandrel # 2 Top (ft)	8173.30
Mandrel # 2 Bottom (ft)	8182.20
Mandrel # 3 Top (ft)	8091.50
Mandrel # 3 Bottom (ft)	8100.40
Mandrel # 4 Top (ft)	7960.90
Mandrel # 4 Bottom (ft)	7969.80

Note: Before installation of the P-SCFVs, all 4 C-SCFVs were flow controlled through an orifice.

Results from the Comparison of the C-SCFV and the P-SCFV (Before and After)

Constant injection to wells INJ-1, INJ-2, and INJ-3 could not be maintained due to operational issues (pump failures, sand invasion, power failure, service to the flow lines, etc.); therefore this project cannot be strictly analyzed based on the maximum injection capacity of each interval. To ensure that the P-SCFV maximizes injectivity capacity, the injection rate must remain constant. The most important factor in overall P-SCFV performance is water quality and specifically solids control. While dissolved solids play a minor role in permeability reduction, entrained solids can pack off the internal choke above the resonating chamber. Sufficient screens and filters should be incorporated downstream of the pumps with an effective quality assurance and quality control program to ensure optimal injection performance.

As a result of operational challenges encountered, an “Injectivity Index (II) method” was applied. Reservoir engineers analyzing the performance of injection wells commonly apply this method. For analysis purposes, the following formula was used:

$$\text{Injectivity Index} = \text{Total Surface Injection Rate} \div (\text{Surface Injection Pressure} \times \text{Total Length of the Injection Zones})$$

TABLE 5—WELL INJECTOR INJ-1: INJECTIVITY INDEX BEFORE AND AFTER		
Total flow before:	2,946	bwpd
Injectivity index (II) before:	0.00319	bwpd/(psi-ft)
Total Flow (peak) after:	3,540	bwpd
Injectivity index (II) after:	0.00384	bwpd/(psi-ft)
Injectivity Index change:	+ 0.00065	bwpd/(psi-ft)
Injectivity Index benefit:	+ 20.55	%

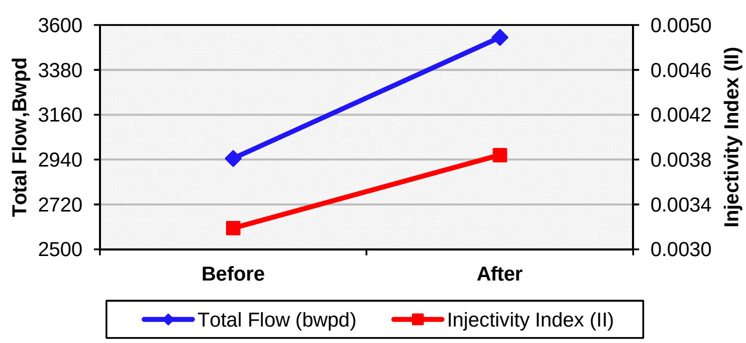

Fig. 7— Well Injector INJ-1: Flow and Injectivity Before and After

Overall, injector INJ-1 recorded an increased injectivity index of 20.55% following the installation of P-SCFVs. (See **Table 5** and **Fig. 7**). Because in this particular injector, previous to the project, the fourth mandrel was injecting water in an open-hole mode (as noted above), one might expect, with a valve now installed on the fourth mandrel controlling the amount of flow, that the flow would decrease in the injector overall. Instead, however, the injector reached a significantly higher peak level compared to historical levels.

TABLE 6 – Well injector INJ-2: INJECTIVITY INDEX BEFORE AND AFTER		
Total flow before:	1,583	bwpd
Injectivity index (II) before:	0.00233	bwpd/(psi-ft)
Total Flow (peak) after:	2,150	bwpd
Injectivity index (II) after:	0.00351	bwpd/(psi-ft)
Injectivity Index change:	+ 0.00119	bwpd/(psi-ft)
Injectivity Index benefit:	+ 50.89	%

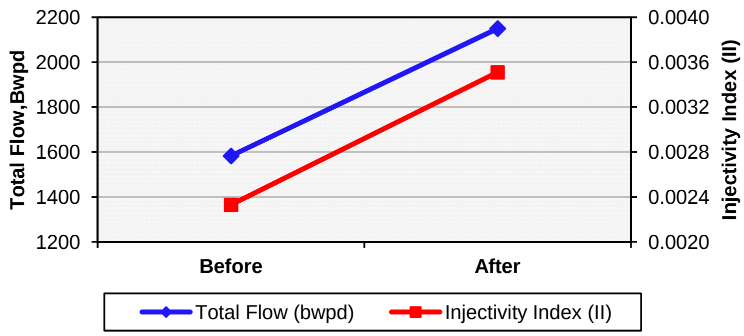

Fig. 8— Well Injector INJ-2: Flow and Injectivity Before and After

Overall, injector INJ-2 recorded an increased injectivity index of 50.89% following the installation of P-SCFVs. (See **Table 6** and **Fig. 8**.) Because in this particular injector, all the C-SCFVs previously installed were found in a fully open mode (as noted above), again one might expect, with all four pulsing valves controlling the amount of flow, that the flow would decrease in the injector overall. Instead, however, the injector again reached a significantly higher peak level compared to historical levels.

TABLE 7—Well injector INJ-3: INJECTIVITY INDEX BEFORE AND AFTER		
Total flow before:	2,951	bwpd
Injectivity index (II) before:	0.00350	bwpd/(psi-ft)
Total Flow (pick) after:	6,837	Bwpd
Injectivity index (II) after:	0.00474	bwpd/(psi-ft)
Injectivity Index change:	+ 0.00124	bwpd/(psi-ft)
Injectivity Index benefit:	+ 35.52	%

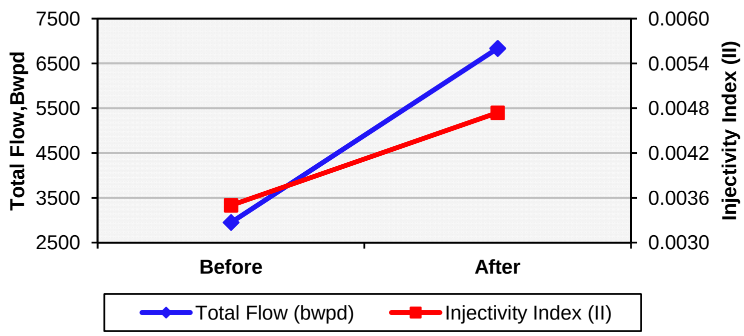

Fig. 9—Well Injector INJ-3: Flow and Injectivity Before and After

Overall, injector INJ-3 recorded an increased injectivity index of 35.52% following the installation of P-SCFVs. (See **Table 7** and **Fig. 9**.) This particular injector provides the best comparison of flow before and after since, previous to the project, there were four C-SCFVs installed controlling the flow, which were replaced during the project with four P-SCFVs also controlling the flow. Of the three wells, this one, therefore, reflects most accurately the increase possible in flow with the P-SCFVs.

TABLE 8—FINAL RESULTS: INJECTIVITY INDEX CHANGE FOR ALL 12 VALVES COMPILED

P-CSV Benefit – 12 valves		
Injectivity index (II) before:	0.00902	bwpd/(psi-ft)
Injectivity index (II) after:	0.01209	bwpd/(psi-ft)
Injectivity Index change:	+ 0.00307	bwpd/(psi-ft)
Injectivity Index benefit:	+ 34.04	%

The compiled results show the injectivity index benefit for the project as 34.04%, illustrating the benefit of the P-SCFVs in recovering injectivity. (See **Table 8**.)

Conclusions

The project aimed to improve and restore water injection volumes hence restoring sweeping efficiency. The increase in injectivity index ranged from 20% to 50% dependent on reservoir characteristics and permeability variations. It is worth mentioning that the increase in injection flow ranged from 20% to more than 100%, indicating the addition of new injection paths. The fluid pulsating technique was proven to be effective in improving injectivity and contributed greatly to enhancing the productivity and economics of the field development.

The performance of the twelve P-SCFVs varied from well to well, in part because the water injection was variable. This finding is also in line with several testing and predictive models of formation damage due to impairment related to solids invasion. Performing pre-operational checks on water quality and wellhead data gathering (injection pressure and rate) are deemed necessary to ensure that operational related controls are met. Water quality has been often found to have multiple effects on P-SCFV performance with respect to plugging the inlet flow and creating an excessive pressure drop at the orifice intake. Monitoring of surface parameters plays a major role in pre/post job evaluation and technology assessment.

It was recommended to continue injecting in the three successful wells while addressing operational challenges in the other four wells by replacing the P-SCFVs while monitoring and controlling water quality. Since the scope of the project was improving and maintaining water injectivity, it may be worth further study to evaluate the impact P-SCFVs have on oil production through rigorous monitoring and measurement of static reservoir pressure. Based on Abllah, Maulut, and Loong’s case study (2011) in which C-SCFVs increased oil production 2%, one might expect a further increase in production with the higher performing P-SCFVs and their increase in injectivity.

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