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Water Coning Control: A Comparison of Downhole Water Sink and Downhole Water Loop Technologies

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Abstract In the petroleum industry, most active bottom-water drive reservoirs are completed strategically to handle produced water problems that may arise during the production of oil and gas. The water production may come in the form of a tongue, cone, cusp or a combination of all depending on the location, magnitude and direction of water movement. Thus, several attenuation methods have been developed to circumvent excessive water production as a result of water coning. Among these methods are selective water plugging, chemical shut-off, horizontal wells, downhole oil-water separation (DOWS) technology, etc. Recently, studies on DOWS technology have put forward two completions methods, namely, downhole water sink (DWS) and downhole water loop (DWL). Both completions approaches have mitigated water coning tendencies and improved oil recovery in bottom-water drive reservoirs. For DWS technology, the challenges of high cost of lifting fluids (i.e. oil and water) and handling huge volume of produced water at the surface is a concern. The DWL technology seems to surmount these limitations of the DWS technology, but lacks successful field application history unlike its DWS counterpart. Additionally, DWS completion is effective in large and active bottom-water (aquifer) while DWL completion is effective in both large and small aquifer with large reserves. Thus, oil companies should implement DWL completion as water coning control techniques to justify its theoretical robustness over DWS completion.

Keywords Water coning; Control methods; Downhole water sink (DWS) technology, Downhole water loop (DWL) technology

1. Introduction

In the exploration of hydrocarbons, reservoirs generally are considered alongside with the aquifers; which are usually beneath them. The presence of aquifer beneath hydrocarbon reservoirs serves as a two-edged sword with both positive and negative benefits. One major advantage of this water bearing body is that it serves as the drive mechanism (i.e., energy source) of the reservoir; which in turn increases the oil recovery potential of the reservoir. However, this water drive potential from aquifer becomes disadvantageous at a later production stage of the hydrocarbon reservoirs. The disadvantage comes in the form of production of water alongside oil; which to a large extent, cannot be avoided; especially in bottom-water drive reservoirs. If this oil production challenge is not mitigated, it can lead to less oil recovery and ultimately result in early abandonment of the hydrocarbon field(s) and/or well(s). Water production is a necessary evil in oil production, whose negative impact comes in several forms, one of which is water coning [1]. According to Okon *et al.* [2]**,** coning is a near-wellbore and rate-sensitive phenomenon which depends on production rates. Muskat and Wyckoff [3] described water coning as the gradual, frequent and sudden displacement of all or part of oil by water when a particular critical rate of production is exceeded. Also, they acknowledged the complexity of the flow system before water breakthrough and the period when bottom water was unperturbed as it forms the cone shape. Ozkan and Raghavan [4] identified two forces which tend to counterbalance themselves upon the oil-water interface. These forces are:

viscous force - which is a function of fluid production and gravitational force - which is as a result of the density differences between oil and water. Wibowo *et al.* [5] identified capillary force in addition to the aforementioned forces in their study of the influence and interaction of forces related to fluid flow mechanisms in a reservoir. They designed a physical scale model for an oil reservoir with bottom-water drive and the result supports the notion that these forces interactively have strong influence on production performances. However, Moawad *et al*. [6] emphasized that capillary forces are somewhat negligible in water coning studies especially in high permeable reservoirs.

In a nutshell, water coning is an intrinsic challenge in the petroleum industry which has seen several researchers work assiduously to put forward solutions to mitigate and/or bring to its barest minimum, during oil production. Over the years, researches on water coning have led to the development of prediction models. These prediction models have basically been for predicting critical rate and breakthrough times [7]. These developed correlations for both vertical and horizontal wells include: Chaperon [8], Joshi [9], Yang and Wattenbarger [10], Recham *et al.* [11] whose research developed correlations for critical rate in horizontal wells. Papatzacos *et al.* [12], Ozkan and Raghavan [4], Bahadori [13] and Makinde *et al.* [14] developed correlations for breakthrough time in horizontal wells. On the other hand, Muskat and Wyckoff [3], Meyer and Garder [15], Chierici *et al.* [16], Wheatley [17], Chaperon [8], Abbas and Bass [18], Hoyland *et al.* [19], Guo and Lee [20], among others, presented critical rate correlations for vertical wells. Sobocinki and Cornelius [21], Bournazel and Jeanson [22], Recham *et al.* [11] and others, developed correlations for breakthrough time. While Kuo and DesBrisay [23], Yang and Watterbarger [10], Zamonsky *et al.* [24] presented correlations to account for post-water performance after breakthrough in vertical wells. Regrettably, the available water coning correlations only predict the phenomenon, which in some cases can be used to delay its occurrence. However, these correlations had not totally controlled the phenomenon to its barest minimum. Therefore, several water coning attenuation methods have been developed in the literature. These methods include: conformance technology, horizontal well technology, downhole oil-water separation technology, intelligent well technology, etc. Interestingly, some of these technologies have successful field application as reported in the literature. In this paper, two downhole oil-water separation approaches: downhole water sink (DWS) and downhole water loop (DWL) are critically looked at, as they seems to be the most effective and promising water coning control methods to handle excessive water production problems during oil and gas production.

1.1. The Physics of Water Coning

Prior to the production of oil and gas, the oil-water contact is supposedly flat, stable and practically distant away from the wellbore perforations [25]. Hence, the forces acting on the interface of the oil-water contact are at equilibrium. During oil production, the steady-state flow condition is prevalent as flow rate and pressure at the outer boundaries are constant which in turn leads to a constant pressure drawdown at every point within the reservoir boundaries [26]. Thus, there is a dynamic flow of oil towards the perforated interval aided by the break in equilibrium between the viscous forces and gravitational force.

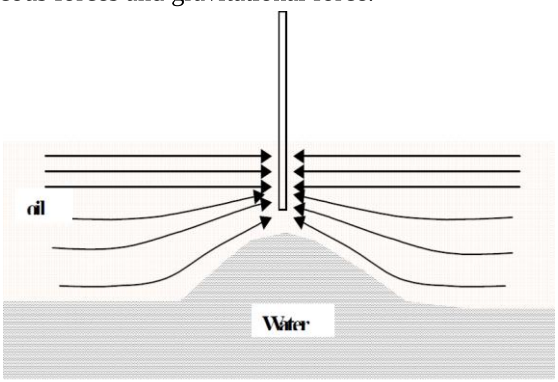

Figure 1: Schematic Representation Water Coning in Vertical Wells [27]

This imbalance in equilibrium between these forces favours the viscous force which leads to a sharp increase in flow rate and ultimately forming a cone-like shape [26]. Therefore, an increase in production rate initiates an increase in the height of the cone as it moves towards instability and results in water breakthrough. This instability of the cone is as a result of the strong upward dynamic force caused by high pressure drawdown which cannot be equaled by the weight of water. Tabatabaei *et al.* [26] alluded that water breakthrough occurs at a point above which the dynamic pressure gradient is greater than the hydrostatic pressure gradient. Thus, Figure 1 depicts the schematic of water coning in vertical well.

2. Water Coning Control Techniques

In a bid to address the recurrent challenges posed by water coning to the overall oil recovery from the reservoir, several techniques have been used to mitigate this production rate-sensitive phenomenon. Jin [28] categorized the evolution of water coning studies into three (3) eras: the Pre-1970; where the physical and experimental studies of the phenomenon were explored, the Post-1970; the era where theoretical and simulation studies of water coning were developed and the Post-1980; where the control approaches of water coning were initiated, developed and still being developed. In the early studies of water coning, the common goal of most studies was to develop correlations to predict the basic water coning parameters: critical rate, water breakthrough time and water cut performance after breakthrough using analytical, empirical and numerical approaches. However, these correlations have not totally eradicated the existence and challenges posed by water coning in the production of oil and1 gas. Rather, they predict the occurrence and severity of the water coning tendency in oil and gas production. Menouar and Hakim [29] maintained that the empirical approach for studying water coning cannot proffer solution to all its challenges, as a result of scaling some reservoir parameters. Also, Okon *et al.* [2] added that the analytical approach for predicting water coning parameters are mainly dependent on postulations that are impractical and unrealistic. Therefore, the development of water coning control method becomes a *sine qua non*. In this connection, several water coning control methods have been developed and they are gaining attention in the industry. Tu *et al.* [30] in their work identified some methods as key production techniques used to control water coning during early production of oil and gas. These methods include: selective water plugging [31]; chemical gelled baffles [32]; optimized perforations [33]; horizontal wells [34-36]; producing oil and water separately with downhole water sink (DWS) or downhole water loop (DWL) [37-38] etc. Nevertheless, these water coning control methods have their negative implications on the reservoir or/and the wellbore vicinity. Jin *et al.* [28] observed that the use of chemical gels to shut-off water is detrimental to the well integrity. This approach merely serves as delay-tactical method and not necessarily water coning control method. Therefore, intense studies on water coning control methods have resulted in downhole water sink (DWS) and downhole water loop (DWL) technologies; which are based on downhole oil-water separation technique.

2.1. Downhole Water Sink (DWS) Technology

This technology was first conceived and patented by Widmyer [39]. Pirson and Mehta [40] numerically tested this technology and concluded that, DWS might reduce the growth of water cone. Also, Driscoll [41] refined the idea by having multiple completions with the lowermost completion below the oil-water contact. However, little attention was paid to this technology at that time, the reasons might be that, industry had low confidence to install it and water coning problem was not as serious at that time as it is now [42]. The interest of the oil industry returned to the DWS technology after Wojtanowicz *et al.* [37] proposed completion with "tailpipe water sink". Basically, this technology is characterized by completion of a well through the oil-bearing zone to the underlying aquifer. Then, a packer is installed to separate the oil and water perforations. During production, oil flows into the upper completion being produced up the annulus between the tubing and the casing, while water is drained through the lowermost completion through perforations in the casing and then lifted up through the open tubing below the initial oil-water contact (OWC). As a result, the produced oil is water free and the drained water is oil free. A typical DWS completions schematic is depicted in Figure 2.

The water drained through the sink can be pumped to the surface or reinjected either into the same aquifer or into a different zone [43]. These two approaches of handling drained water distinguish the two ways of using DWS that are defined as Drainage-Production and Drainage-Injection technologies. In these completion methods, an oil well is drilled through the oil-bearing zone, to the underlying aquifer. Then, the well is dual-completed both in the oil zone (above OWC) for oil production and below OWC for water drainage. The downhole installation includes a submersible pump that is packed-off inside the well and placed below the drainage perforations. During production, oil flows into the conventional completion while the submersible pump drains the formation water from under the OWC. Pathak and Saxena [44] identified three types of DWS completions. The first completion is as shown in Figure 2, where oil is produced from the annulus between casing and production tubing, while water is produced from the production tubing. The second completion involves the water being produced from annulus and the oil produced from the production tubing; as shown in Figure 3a. Also, the third completion type involves the production of oil and water from two separate production tubing; Figure 3b presents this third completion type.

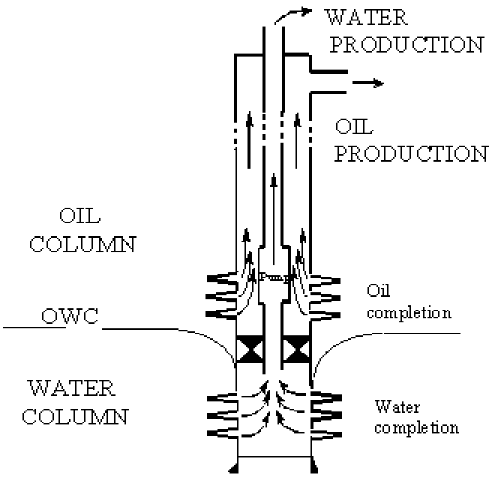

Figure 2: Schematic of Typical DWS Completions [45]

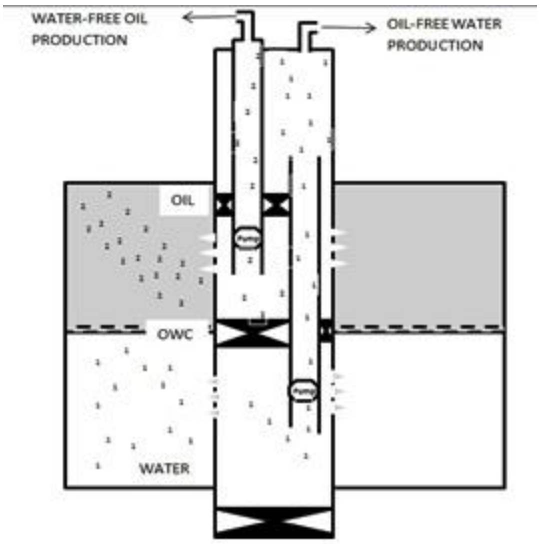

Figure 3a:Type of DWS Completions [44]

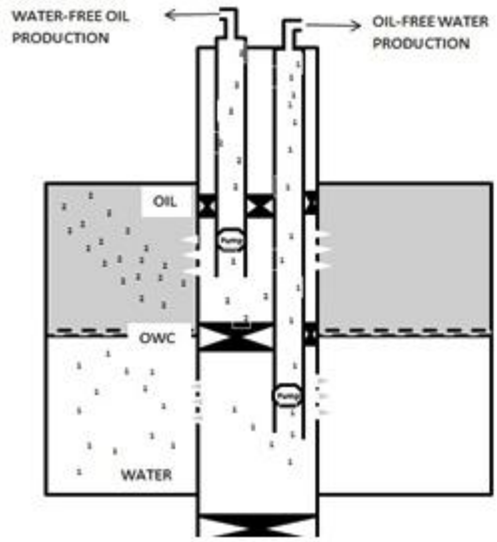

Figure 3b:Type of DWS Completions[44]

In addition, Shirman [43] maintained that, depending on the relative rates of oil production and water drainage, three different types of fluid inflow can be achieved:

i. segregated inflow, when oil flows toward the top completion and water to the bottom one;
ii. clean-water sink, which represents the case of controlled water breakthrough when oil is produced only through the top completion but water gets into both of them; and
iii. reversed coning presenting the situation of controlled oil breakthrough.

Thus, Figure 4 presents a generalized relation between different DWS implementations as a structural chart.

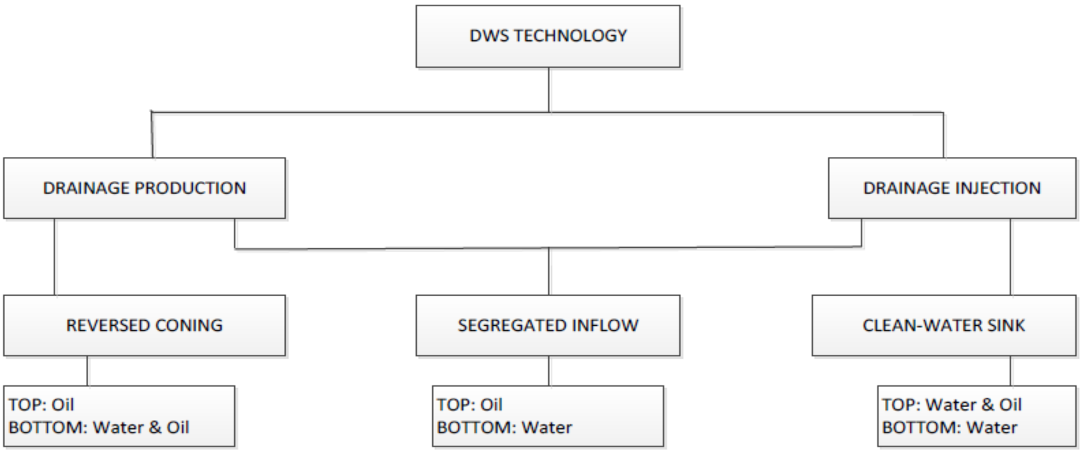

Figure 4: Downhole Water Sink (DWS) Technology Structure [43]

2.1.1. Evaluation - Field Application of DWS Technology

Wojtanowicz and Bassiouni [46] used an analytical model to show that water drainage keeps the water-oil interface (WOI) below the oil perforations and prevents water breakthrough. Their model was based upon the substitution of the oil and water completions with spherical sinks. The theory behind this new completion method is relatively simple. Since water cones upward due to the pressure drop caused by oil production, an equal pressure drop in the water zone will keep the water from rising. Swisher and Wojtanowicz [47] described the first field application of DWS wells in the Nebo-Hemphill Field, LaSalle Parish, Louisiana. The DWS well could not only prevent water coning, but also reverse the water cone after breakthrough. Thus, the well greatly increased oil production rate compared with conventional wells. In addition, Bowlin *et al.* [48] reported another field application of the DWS technology by Texaco Inc. with the name of in-situ gravity segregation in Kern County, California. The well was installed in a location with 10 years of previous water coning problems. The results showed that this installation successfully controlled the water coning problem, and the oil production rate was doubled. After that, considerable efforts have been put into the research of DWS worldwide [7, 38, 49 etc]. Until now, DWS completion has been field tested in numerous reservoirs all over the world with good results. Some of these fields are presented in Table 1. According to Shirman and Wojtanowicz [50], DWS technology can on the average reduce water cut by 40 percent or more. With respect to oil recovery, Wojtanowicz *et al.* [51] reported five-fold increase of oil production rate due to the improved drainage at the bottom completion with DWS technology. In addition, Zaidi *et al.* [52] affirmed the effectiveness of the DWS technology in stopping water coning and also improve oil recovery. However, DWS technology has its major drawback with respect to the economic cost of lifting huge volume of water to the surface, use of separate tubing strings for oil and water and the pressure drop due to weak bottom water drive [52].

Table 1: Some Fields where DWS Technology was used for Water Coning Control [2]

Source	Field Name	Location	Reservoir Type
Swisher and Wojtanowicz [47]	Nepo-Hemphill Field	LaSalle Parish, Louisiana	N/A
Bowlin *et al.* [48]	Kern River Field	California	N/A
Shirman and Wojtanowicz [53]	N/A	Indonesia	N/A
	Bakers Field	California	N/A
	East Texas Field	Texas	Sandstone
	N/A	Canada	

2.2. Downhole Water Loop (DWL) Technology

In order to overcome the challenges of lifting to, and handling massive volume of water at the surface due to the use of DWS technology, Wojtanowicz and Xu [54] proposed a concept of Downhole Water Loop (DWL) technique to cut back the volume of formation water produced by an oil well from reservoir underlain by active bottom water (aquifer). Okon *et al.* [2] opined that the DWL technology was developed to solve the problem of producing unwanted fluid (water) which DWS technology could not handle.The technology used dual completion of the well inside the water zone, below the OWC to install the water loop equipment (separated by a packer) in addition to the conventional completion in the oil zone (above the OWC). In other words, unlike the DWS, DWL technology is characterized by triple-well completions: the top (oil) completion, the middle completion for water drainage and the bottom completion for water injection; as shown in Figure 5. The water loop installation included a submersible pump, the upper (water sink) perforations and the lower (water source) perforations. A submersible pump would drain the formation water around the well from the water sink, and then would re-inject the same water back to the water zone through the water source perforations.

Some simulation studies performed to determine the hydrodynamics of the OWC in the well's vicinity indicated that, the DWL technology could effectively control the oil production rate to 2-4 times higher than the critical rates obtained when using conventional completion. In addition, DWL technology has an advantage which is its potential to become a solution to the environmental compliance problem associated with produced water disposal. Also, from the standpoint of the reservoir engineering theory, the formation water could be kept away from oil-production perforations to improve the oil recovery per well with DWL technology [28]. While DWL technology looks promising based on the analytical and simulation studies, unfortunately, no field application of this technology has been reported in the literature.

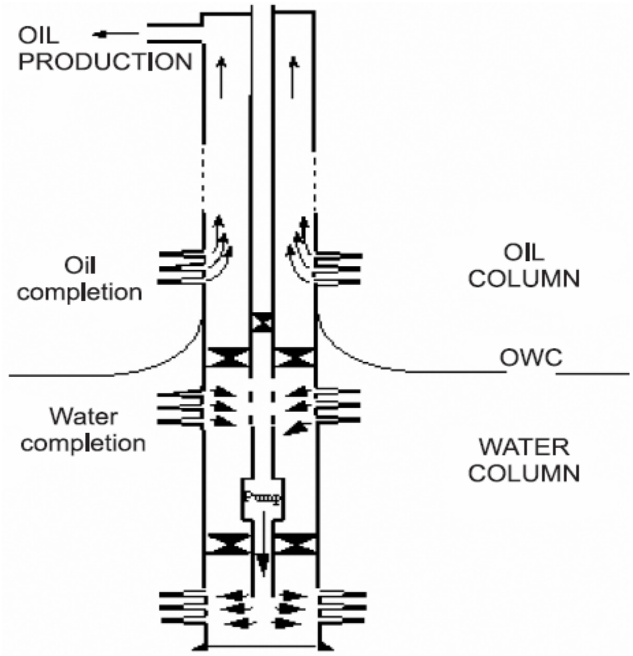

Figure 5: Schematic of Typical DWL Completion [45]

2.2.1. Evaluation of DWL Technology

Downhole water loop (DWL) technology studies have shown that it has the potential to improve oil recovery [28], but good results may not be obtained except the DWL system is carefully designed [55]. Jin *et al.* [56] performed series of design models for DWL and established that some well and reservoir properties influence the performance of DWL technology. These properties include: drainage-injection spacing, anisotropy ratio, penetration length, perforation length, formation damage effect, oil-water viscosity ratio etc. However, Gan [55] observed poor performance by a DWL system in a reservoir with active aquifer and limited oil reserve. Hence, he proposed the concept of Twin-Horizontal Downhole Water Loop (THDWL) completion. The THDWL completion is a quadruple-completed well with two symmetric horizontal sections for drainage water re-injection below the water drainage interval as shown in Figure 6. According to Gan [55], the THDWL completion is more potent in displacing oil in a more efficient manner, as it adds two more injectors to increase oil recovery. However, this proposed THDWL completion is still at its early stage of study, as no detailed analysis of the model nor its field scale application have been provided in the literature. In all, DWL technology seems promising than its DWS technology counterpart, based on the analytical and simulation studies. Unfortunately, no field application of this DWL technology has been reported in the literature to support it development as water coning attenuation method in the petroleum industry.

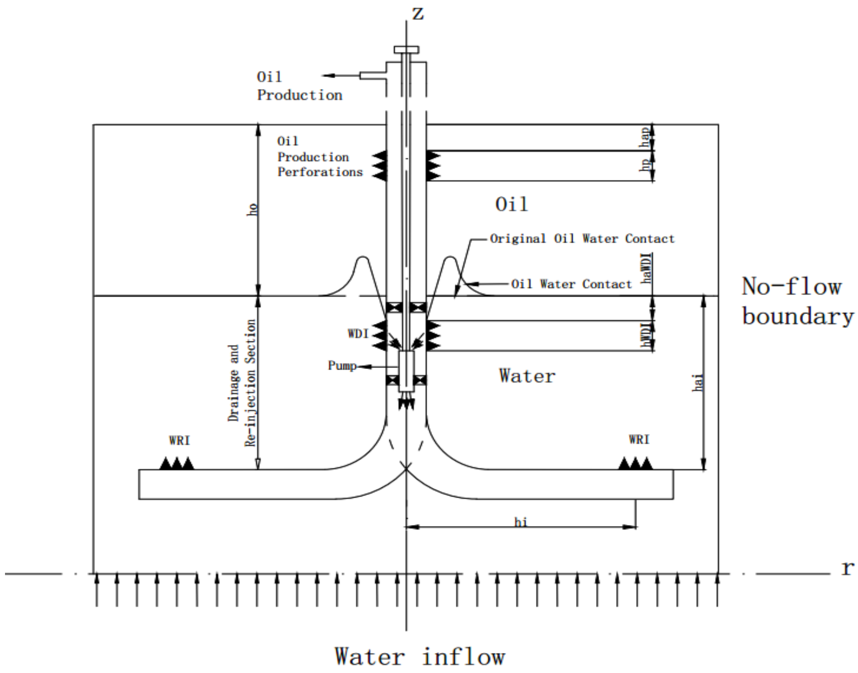

Figure 6: Schematics of THDWL Completion [55]

3. Comparison of DWS and DWL Technologies

The DWS and DWL share similar technological concept which mainly focuses on improved oil recovery by preventing water coning amongst others. Thus, DWL design is based on the DWS and it can be referred to as an improvement on DWS. Yet, there seems to be several reasons or factors why either of them is unique. In as much as the DWS is very effective in handling water coning tendency, its major drawback lies in high lifting cost and produced water handling at the surface. Moreover, it is not advisable to apply the DWS technology in reservoirs with relatively small aquifers as it may result to large pressure drawdown and thus, do the opposite of what is expected (i.e. insignificant increase oil recovery). On the other hand, the DWL's performance has been proven to be better theoretically; as no field case application is available in the literature to support the assertion. It will not only solve the challenges of high lifting cost and produced water handling at the surface, it is environmentally friendly and economical than its DWS counterpart. Additionally, the DWL technology serves as an internal reservoir pressure maintenance mechanism. However, DWL is not effective for a reservoir with active aquifer with limited oil reserve [55]. Thus, Okon *el al.* [2] x-rayed and presented the various downhole oil-water technologies for water coning control; as shown in Table 2.

Table 2: Comparison of some Downhole Oil-Water Technologies for Water Coning Control [2]

S/N	Control Methods	Completion	Advantage(s)	Limitation(s)	Candidate Reservoir
1.	Downhole oil-water separation technology	Well completed with installed hydrocyclone and pumps to separate	Production of water free oil at the surface, reduce water handling at	Hindered the minimum casing size requirement	Conventional and thin-oil column reservoirs with both weak and

		water from oil mixture	the surface, etc.		active aquifer are candidate
2.	Downhole water sink (DWS)	Dual completion; above and below the oil-water contact (OWC)	Increase critical rate and low water cut. Delayed or breakthrough time	Production of water and handling problems. More energy consumption and high lifting cost Completion of dual zone is expensive than conventional (single) well	Conventional reservoir with large active aquifer
3.	Downhole water loop (DWL)	Triple completion; one above oil-water contact and two below OWC (i.e., one completion at DI and other at DWI)	Increase critical rate and low water cut, with delayed breakthrough time; Better performance at reservoir pressure maintenance; No production and handling of water at the surface, Less energy and consumption cost of water pump	Due to complexity and water coning dynamic, it requires careful design of the production system; Limited by the thickness of the aquifer; Completion of three intervals is expensive	Weak (inactive) bottom-water drive reservoirs
4.	Thin-horizontal downhole water loop (THDWL)	Quadruple (four) completion; one above OWC for production of oil and three below OWC.	Handling the drawback observed in the DWS and DWL. Less or low water cut than DWS and DWL	Very expensive than DWS and DWL completion approach	Both water drive reservoir with weak and active aquifer.

4. Conclusion

One major production related problem in oil and gas production that has received a lot of attention is water coning; especially in bottom-water drive reservoirs. The developed correlations available in the literature to predict water coning parameters are adequately prolific to establish its occurrence and severity in the reservoir during oil production. Notwithstanding, these correlations' prediction provides a window of operation to avert early occurrence of water coning. However, most predicted water coning parameters; especially critical rate, if implemented would be uneconomical for any company to operate. Therefore, water coning control methods that would suppress or mitigate coning tendency and improve oil recovery is a consideration. There are several water coning control methods in the literature, however, downhole water sink (DWS) and downhole water loop (DWL) completions handle the challenge of water coning and improve oil recovery as well. Thus, this paper reviewed the DWS and DWL technologies, and the following conclusions were drawn:

i. DWS is effective in reservoir(s) with large and active aquifer, and with proven field(s) case applications;

ii. in DWS completion, the challenge of high cost of lifting fluids (i.e. oil and water) and handling huge volume of produced water at the surface is a concern;

iii. DWL technology is effective in reservoir(s) with large and small aquifer, but the technology lacks field(s) case history to support its requisite proliferate application in the petroleum industry; and
iv. also, the challenge of lifting huge volume of water is averted with DWL completion; rather the water serves as pressure maintenance approach to boost the reservoir pressure.

Therefore, theoretically, DWL technology seems more promising than the DWS technology; however, it requires field(s) case application to support its robustness as water coning control approach over DWS technology.

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