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## Water Coning Attenuation - A Look at Intelligent Well Completion Approach

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**Abstract** Producing oil from bottom-water drive reservoirs usually result in production-related problems, one of it is water coning phenomenon. To ameliorate this production rate phenomenon, several control methods had been developed to prevent excessive water production and handling challenges at the surface during oil and gas production. The available water coning attenuation methods include: conformance technology, horizontal well technology, downhole oil-water separation technology, intelligent well completion technology, among others. To a large extent, some of these water coning attenuation methods have gained application in some Oilfields; even though they also have their respective drawbacks. Thus, this paper focused on use of intelligent well completion (IWC) as water coning control approach. Findings based on Field cases indicate that IWC seems robust, once the water breakthrough is sensed in the wellbore; the control valves shut-off the production interval(s). Additionally, the IWC technology is extended in some Fields to tackle other production-related problems like commingled production, sand production, etc. However, the technology adaptability requires improvement to predict water coning tendency in the reservoir, than rely on its control valves to sense presence of water in the wellbore to control the phenomenon. Furthermore, the use of IWC technology as water coning attenuation method is more effective in multilayered reservoir with single well. Hence, these advantages of IWC technology over other water coning methods can be exploited in the production of oil and gas from bottom-water reservoir(s).

**Keywords** Water coning, Bottom-water drive reservoir, Water coning control methods, Intelligent well completion

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### 1. Introduction

In the production of hydrocarbons, well completion involves preparing the bottom-hole to the required specifications, running production tubing and its associated downhole tools, perforating and stimulating as required [1]. In most reservoirs, production strategies are put in place to avert any oil production rate-sensitive problems, like coning and/or cusping depending on the encroached fluid (i.e., water and/or gas) into the production interval [2]. Yeten and Jalali [3] opined that the encroachment of gas/water from the gas cap/water aquifer coupled with the production of the oil is one of the major problems encountered in reservoir engineering. This encroached gas and/or water seriously impact the well productivity and influence the degree of depletion and the overall recovery efficiency of the oil reservoir [4]. Additionally, Shaibu *et al.* [5] noted that water coning often yield associated production problems, namely, reduced depletion mechanism efficiency, early abandonment of the affected well(s), reduced field recovery, reduced field profitability and extra cost for handling produced water. For instance, in the United States, it is estimated that on an average, eight barrels of water are produced for each barrel of oil [6]. Also, the world average is three barrel of water per day and the expenses incurred in the treatment of produced water in the US ranges between 0.20 – 8.5 USD per barrel while the cost of disposal falls between 0.07 – 1.6 USD per barrel [7]. Thus, the occurrence of water coning phenomenon in the production of oil cannot be underestimated in the Petroleum industry. Therefore, proper



field/well development strategies are *sine qua non* to forestall the occurrence of the mentioned production rate-sensitive phenomenon.

In bottom-water drive reservoirs, water coning is an intrinsic challenge which has seen several researchers worked assiduously to put forward solutions to mitigate and/or bring to its barest minimum, during oil production [8]. This involves the development of correlations to predict the occurrence of this phenomenon in the reservoir(s). These developed correlations basically predicts water coning breakthrough time (i.e., time the aquifer water enters the production intervals), critical rate (i.e., production rate to avoid simultaneous production of oil and water) and post-water performance after breakthrough. Okon *et al.* (2017b) added that these correlations' prediction in some cases can be used to delay the occurrence of water coning phenomenon in reservoir(s). However, they lack the potential to control the water coning tendency to its barest minimum. In this connection, numerous water coning control methods have been developed for bottom-water drive reservoirs. These control methods are: conformance technology, horizontal well technology, downhole oil-water separation technology, intelligent well technology, among others. Okon *et al.* [8] noted that some of these water coning control methods have successful field application and limitation(s). Therefore, this paper looks at the potentials of intelligent well completion, as water coning control method to handle excessive water production problems during oil production from bottom-water drive reservoirs.

### 1.1. Water Coning Phenomenon in Bottom-Water Reservoirs

In bottom-water drive reservoirs, water coning is an inevitable challenge in partially perforated wells, that is, wells completed at the upper parts of the reservoir. During oil production, the pressure drop in the well vicinity tends to draw-up water from the aquifer towards the lowest completion interval at the well; as depicted in Figure 1. To large extent, this rising up of aquifer's water is caused by potential distribution near the wellbore. Okon *et al.* [2] noted that since the moment a well is produced, water cone is formed as a result of potential difference between the oil and water phase. Additionally, Gan [9] reported that the upward movement of water cone depends on vertical potential gradient, activity of aquifer, vertical permeability, fractional well penetration, drainage radius, well radius, and water-oil density contrast. Also considering that water is more mobile than oil, owing to its less viscosity, when the same potential gradient is applied to the fluids (i.e., oil and water), water velocity seems higher than that of oil. Consequently, the oil-water-contact below oil completion interval rises towards the perforation. In unbounded (i.e., infinite acting) reservoirs with inactive or weak aquifer, if the production rate ( $q$ ) is sufficiently low, the viscous force is offset by gravity contrast between the oil and water phase. Hence the water cone becomes stable and cease rising toward the completion interval. Nevertheless, when the production rate increases, the cone height above the oil-water contact (OWC) also increases. Over time, when the gravity contrast of water and oil cannot offset their mobility differences, water cone becomes unstable and rise towards the well perforation intervals. Thence, the coning water becomes pronounced at the wellbore and breakthrough (i.e., water production at the well) is unavoidable.

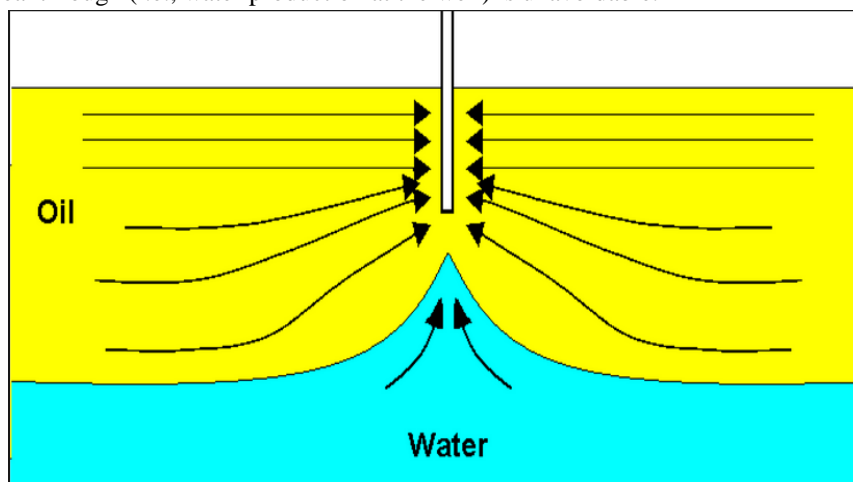


Figure 1: Schematic of Water Coning into a Vertical Well [10]



## 2. Water Coning Control Methods

In the petroleum industry, addressing the challenges of water coning during oil production from bottom-water drive reservoirs have taken different dimensions. Several correlations: critical rate, water breakthrough time and water cut performance after breakthrough had been developed to predict this phenomenon based on analytical, empirical and numerical approaches. These developed correlations in most cases indicate the occurrence and severity of this phenomenon in bottom-water drive reservoirs during hydrocarbon production. In lieu of the foregoing, several authors had developed methods to control water coning in bottom-water drive reservoirs. These methods include: selective water plugging [11]; chemical gelled baffles [12]; optimized perforations [13]; horizontal wells [14-16]; producing oil and water separately with downhole water sink (DWS) or downhole water loop (DWL) [17-18], among others. Additionally, Tu *et al.* [19] identified some of these methods as key production techniques used to control water coning during early production of oil and gas. However, these water coning control methods have their limitations on the bottom-water drive reservoirs or/and the wellbore vicinity. The comparison of some water coning controls methods as extracted from the work of Okon *et al.* [2] is presented in Table 1.

**Table 1:** Comparison of some Water Coning Control Methods [2]

	<b>Control Methods</b>	<b>Completion</b>	<b>Advantage(s)</b>	<b>Limitation(s)</b>	<b>Candidate Reservoir</b>
i.	Conformance technology	Injecting polymers or gels to form a barrier between oil and water zones.	Delayed breakthrough time and reduce water cut.	The polymers or gels may plug the reservoir pore connectivity which can impaired fluid flow The well may damage when the polymer or gel barrier enters the oil completion.	Both water-drive reservoirs with inactive and active aquifer.
ii.	Horizontal wells	Drill horizontal well into the oil zone.	Compared to vertical well in the same oil zone, it provides delayed breakthrough time and high oil recovery potentials.	Horizontal wells are constrained by drilling technology. It is expensive than its conventional counterpart.	Conventional and thin-oil column reservoirs with both weak and active aquifer.
iii.	Downhole oil-water separation technology	Well completed with installed hydrocyclone and pumps to separate water from oil mixture.	Production of water free oil at the surface, reduce water handling at the surface, etc.	Hindered the minimum casing size requirement.	Conventional and thin-oil column reservoirs with both weak and active aquifer are candidate.
iv.	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	Conventional reservoir with large active aquifer



Control Methods	Completion	Advantage(s)	Limitation(s)	Candidate Reservoir
			high lifting cost Completion of dual zone is expensive than conventional (single) well	
v. 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
vi. 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.
vii. Intelligent or smart completions	Well completed with installed inflow control valves (ICVs), sensors, gauges, etc.	Monitor, regulate and measure reservoir and fluid parameters. Increase reservoir productivity.	Very expensive due to high cost of installed ICVs, etc. Reliability of the downhole valves and sensor are considerable factors for monitoring and control.	Conventional and thin oil column reservoirs with high recoverable reserves are possible candidate.

### 3. Intelligent Well Completion

In oil and gas production, completion techniques had advanced significantly over the last two decades. One of the most revolutionary inventions in production technologies was intelligent well completion (Arfaoui, online). Robinson [20] opined that intelligent completions involved completion system capable of collecting, transmitting and analyzing wellbore production, reservoir, and completion-integrity data, then enabling remote action to enhanced reservoir control and well-production performance. Therefore, it is characterized by the ability to collect and analyze data from the wellbore and allows the direct monitoring and control of reservoir, well and production processes using special equipment which are installed within the well completion. The installed devices in a typical intelligent well completion include: packers (i.e., sealing elements allowing



partitioning of the wellbore), pressure and temperature sensors, and downhole inflow control valves (ICV) on the production tubing [21]. Figure 2 shows a typical intelligent well completion schematic with some downhole installed devices. The first intelligent completion was installed in Saga Petroleum in Snorre tension leg platform in the Southern part of the Norwegian Sea in August 1997 [22]. Since then, intelligent well technology has been on the increase in different fields around the world. The application of this technology in several oil fields include: to control gas and water breakthrough, to select which zone can be brought to production, to solve sand production problems and to manage water injection for pressure maintenance. In addition, it can be used with submersible electrical pump in order to improve the well performance.

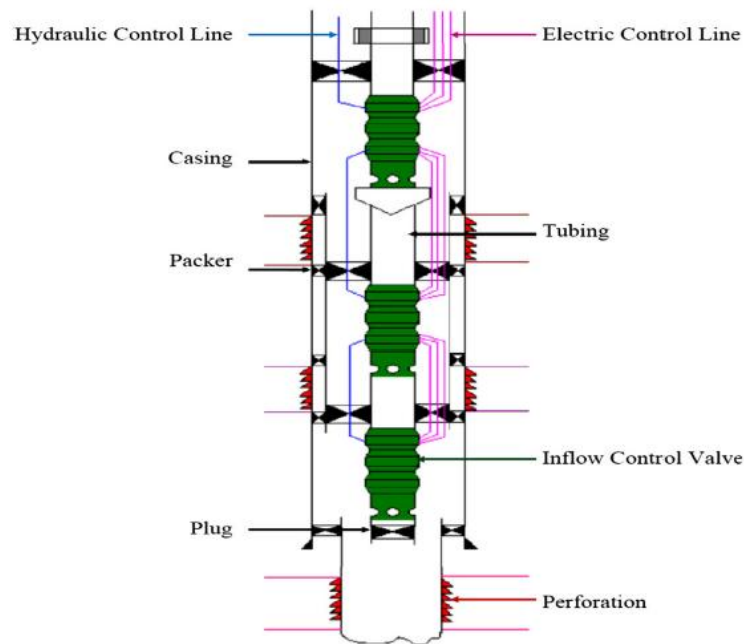


Figure 2: Intelligent Well Completion Schematic, showing packers, inflow control valves, hydraulic and electric control lines [23]

The design of an intelligent completion depends on the specific characteristics of the well, reservoir conditions (i.e., temperature, pressure etc.), reservoir zones, water-oil contact (WOC), other static and dynamic properties [24]. Earlier, Bernt and Geir [25] maintained that intelligent well design depends on the objectives: to improve the sweep efficiency/recovery, to optimize well performance or to maximize net present value (NPV), etc. Over the years, intelligent well completion (IWC) technology had been utilized in multiple fields under diverse environmental and reservoir conditions in different continents. Table 2 present some of the fields were IWC technology had been used to control production-related problem(s) to improve oil production/recovery from the reservoir(s). However, the fields presented in Table 2 are considered unique, as the method of IWC application differs based on individual field properties and requirements. Additionally, the desired benefits play a dominant role in the selection of the optimal IWC combination to be used.

### 3.1. Intelligent Well Completion in Water Coning Control

The uniqueness of intelligent well completion technology in controlling this production-related problem – water coning, is interesting; especially in layered reservoir(s) with multiple completions. No doubt, the benefits of intelligent completions have been demonstrated in practical applications, especially for multiple reservoirs where commingled production is the main production strategy [26]. The applicability of intelligent completions, however, is not confined to scenarios involving commingled production. Their potential benefits for production from a single reservoir have also been demonstrated. For instance, Figure 3 depicts a layered reservoir with water-drive and strong horizontal barriers drained with a single well perforated in each layer. From the figure,



water breakthrough in the layers does not take place simultaneously due to permeability differences in the reservoir. Using a completion with an on/off interval control valve (ICV) in each interval, well segments can be shut-off when water breaks through the production interval. This reduces the volume of water to be processed at the surface and prevents early lift-die out of the well.

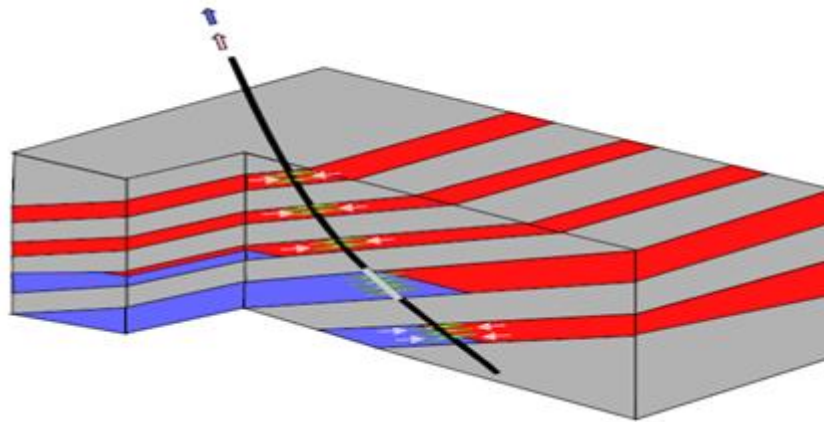


Figure 3: Control of Water Breakthrough in a Layered Reservoir [27]

Regrettably, the approach of using intelligent well completion to control coning tendency in the reservoir waits for the problem(s) (i.e., water and/or gas coning) to occur, before it then reset the instrumentation (devices) to mitigate the problem(s). In other words, intelligent well completion technology does not prevent the occurrence or suppress water coning tendency, rather, it controls the severity of the phenomenon when it has occurred and breaks into the wellbore. Yeten *et al.* [26] were of the opinion that an approach that would use downhole inflow control devices in conjunction with a predictive reservoir model will be a better option for the control of this production rate-sensitive phenomenon. Nevertheless, intelligent well completion technology in water coning control has practical field application. Its comparison with downhole water sink (DWS) technology will demonstrate the superiority of the intelligent well completion over DWS, in terms of water handling problems at the surface [2]. Meaning, IWC prevents the huge volumes of water from being produced at the surface; as a result of water coning, to remain in the reservoir(s). However, the oil recovery potentials of these two water coning control approaches will favour DWS over IWC. This assertion is because IWC technology will shut-off the interval(s) immediately water breaks into the production interval, this in turn limits the recoverable reserves of the reservoir. Be that as it may, IWC technology for water coning control would be more innovative if the inflow control device incorporates water coning prediction model(s) for its coning control. This move would allow for the optimization of the reservoir performance rather than just prevention of the coning problem that have already occurred.

### 3.2. Field Cases of Intelligent Well Completion Application

Earlier approaches like horizontal impermeable barriers, conformance technology, horizontal well technology etc. to control water coning tendency have its field application challenges. However, the use of horizontal well technology as water coning attenuation method is not totally rolled-out in the Petroleum industry. Intelligent well completion (IWC) technology in the Petroleum industry had attempted to handle numerous production related problems, namely, commingled production, reservoir characterization and surveillance, unwanted gas and water production (coning), sand production, among others. From Table 2, two fields: Gullfaks and Tern in Norway and United Kingdom respectively have used IWC to handle commingled production successfully. This represents 18.18% of the fields with IWC technology looked at in this paper. Also, the Table indicates that IWC technology had been used successfully in Aconcagua, Camden Hills and King's Peak fields (all in Gulf of Mexico), Ghawar field (Saudi Aramco), Agbami field (Nigeria) and Kitanoil field (Australia) to tackle water production problem. In KE38 (Indonesia) and Azeri-Chirag-Gunashli (Azerbaijan) fields, IWC technology had been used to enhance the performance of gas lift systems. In the Okporhuru field (Nigeria) intelligent completion provided the solution to sand production challenges encountered in the field. Thus, Figure 4 shows





the distribution of the IWC technology as used to tackle the various production related challenge; as presented in Table 2.

**Table 2:** Field Case Histories of Intelligent Well Completions

S/N	Field(s) / Source	Location	Reservoir / Field Description	IWC Application(s)	Result(s)
i.	Gulfaks field, North sea [28]	Norway	Sandstone reservoir with unconformity and tilted faults.	Downhole sensors were used to collect data, increase reservoir characterization; commingled production was possible and need for new well(s) was eliminated.	Successful
ii.	Tern field, North sea [29]	United kingdom	Reservoir consists of lower Ness/Etive and Broom/Rannoch/Upper Ness formations. Development of these reserves was by sequential of the lower and then the upper regions.	IWC controlled commingling of the lower and upper formations. It enabled production from the wellbore to be switched between the lower Ness/Broom and Triassic formations.	Successful; an accelerated oil production of 430,000bbl was recorded.
iii.	Aconcagua, Camden Hills and King's Peak fields [30]	Gulf of Mexico	These fields have wells each penetrates up to 4 distal turbidite sand reservoirs producing gas. The reservoirs are commingled and located on 6200ft to 7200ft of water.	The reservoirs are completed with IWC equipment installed in 9 to 10 development wells. Permits water shut-off from each reservoirs and potential choking to optimize production without intervention.	Successful
iv.	Ghawar field [31]	Saudi Aramco	The largest conventional oil field in the world, reservoir surrounded by faults/fractures. Water reaches the wellbore via fractures, which leads to coning.	Intelligent multilateral well was drilled with 3 packers, 3 hydraulic flow control valves and portable multiphase flow meter to curtail water coning.	Successful, maintained water cut below 5% and production rate at 5Mbbbl/day.
v.	Nakika fields [32]	Gulf of Mexico	Reservoirs are highly faulted, compartmentalized and difficult to image due to high salt presence.	Installed downhole pressure and temperature sensors with ICVs helped to increase reservoir characterization, eliminate costly subsea well intervention and optimize production.	Successful, IWC provided high quality reservoir surveillance data.
vi.	Kwale field	Nigeria	Reservoir consists of stacked	An electro-hydraulic	Successful



S/N	Field(s) / Source	Location	Reservoir / Field Description	IWC Application(s)	Result(s)
	[33]		barrier and point-bar sandstones. The sand thickness is variable with water saturation between 52.5 - 88.5% and permeability 3.2 - 28md.	level intelligent well system was installed in the field. The system helped displace annular fluid when necessary.	
vii.	KE38 field, East Java Basin [34]	Indonesia	The reservoir is composed of reef carbonate structure within the Kujung formation with several domes. It has large gas cap support and oil column between 60ft - 300ft.	Production complications using conventional gas lift completions and high cost associated with surface equipment, intelligent well technology known as Auto Gas Lift (AGL) was used to enhanced oil and gas production.	Successful
viii.	Agbami field [35]	Nigeria	Agbami field located offshore has varying properties of zones, infill drilling was used and the field later experienced excess water influx.	Direct hydraulic flow control valves were used to choke back zones with unwanted gas and water production and increase production from other zones.	Successful, approximately 10million BOPD was added due to IWC application.
ix.	Kitan oil field [36]	Australia	The field is located at a water depth between 305m to 335m, North West of the existing Gas condensate field. The reservoir is at 3300m subsea depth and is produced through deep-water subsea completion; susceptible to water coning and commingling.	The IWC design consist of 2 multi-stage hydraulic downhole flow control valves and 3 downhole gauges to control and monitor two different production zones. The lower flow control valves close to shut-off water production from the lower zone.	Successful, low water cut was achieved and hydrocarbon production was optimized.
x.	Okporhuru field, Niger Delta [37]	Nigeria	Stacked reservoirs, Marginal field due to limited data, low first pass initial oil volume.	Application of a compact modular multi-zonal smart completion solution (IZC) and use of unique sand control technique in the appraised field to increase production.	Successful
xi.	Azeri-Chirag-	Azerbaijan	The field located 120km of the coast of Azerbaijan in	Distributed Temperature Sensors	Successful





S/N	Field(s) / Source	Location	Reservoir / Field Description	IWC Application(s)	Result(s)
	Gunashli (ACG) field [38]		120m of water and contains 5.4 billion barrels of recoverable oil. The main challenge is lack of simultaneous production logging and drilling for the ACG platform.	(DTS) and Distributed Vibration Sensors (DVS) were used to enhance detection of injection, crossflow of shallow gas and gas lift design.	

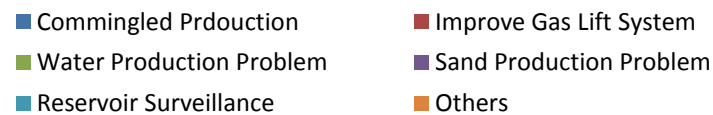


Figure 4: IWC Technology as used to tackle various Production related problems

The highlight of this study is that IWC technology is not limited to tackling one particular production related problem. In some cases, it can be explore to handle more than one production-related problem; as observed in Table 2. Therefore, the adaptability of the IWC technology would give it an edge over other water coning control approaches, if its mentioned limitation is improved upon.

#### 4. Conclusions

The review of the application of intelligent well completion (IWC) in the handling of production-related-problems indicates that:

- most Oilfields use IWC for the purpose of controlling water coning and any other production-related problem(s);
- IWCs as water coning attenuation method only prevent/reduce the handling of produced water at the surface when the water had breakthrough into the wellbore;
- they would be more effective water coning control approach in multilayered reservoirs with single production well; and
- the adaptability of the IWC control valves should be improve to predict water coning tendency and then suppress the phenomenon in the candidate reservoir(s).

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