WIERTNICTWO NAFTA GAZ • TOM 23/1 • 2006

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DOWN-HOLE WATER SINK TECHNOLOGY FOR WATER CONING CONTROL IN WELLS

1. INTRODUCTION

Several techniques have been used by the petroleum industry to solve the water coning problem; perforating the well as far above the initial oil-water contact (OWC) as possible; keeping production rates low (below critical rate), and creating a low- or non-permeable barrier by injecting resins, polymers or gels above the initial OWC. Although all these methods have shown limited (or no) field applications, they evidence the evolution of taught leading to the water sink technology. The new method, discussed here, increases critical rate by using two well completions with coordinated production rates to suppress water coning [1]. The method is fundamentally different to other techniques for water coning control.

In 1991, Wojtanowicz *et al*. [2] – using numerical model and field data – evaluated well performance for coning control using dual completion with "tailpipe water sink" – later dubbed: Downhole Water Sink (DWS). They concluded that the tailpipe sink would control water coning and produce more oil with less water than conventional wells. The first publication of DWS concept was followed with field trials, and analytical, experimental, and numerical studies to understand this technique and evaluate its performance in various petroleum wells.

2. DWS DEFINITION AND DESCRIPTION

Downhole Water Sink (DWS) is a completion/production technique for producing water-free hydrocarbons from reservoirs with bottom water drive and strong tendency to water coning. DWS eliminates water cutting the hydrocarbon production by employing hydrodynamic mechanism of coning control in-situ at the oil-water or gas-water contact. The mech-

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anism is based upon a local hydraulic drainage generated by a controlled downhole water sink installed in the aquifer beneath the oil or gas-water contact.

Figures 1 and 2 show principles of two basic variants of the DWS systems, drainage-injection (Fig. 1), and drainage-production (Fig. 2). In the system, a well is dual - completed in the oil and water zones and the two completions are separated by a packer set inside the well at depth of the oil-water contact. The water sink (bottom) completion comprises a submersible pump and the water drainage perforations. The submersible pump drains the formation water around the well and controls the water cone growth and it's breaking through the oil column into the oil-producing (top) completion. The fluids produced by the top completion are either free of water or have small water content – subject of the drainage rate adjustments. In the result, the well's productivity potential can be fully utilized to maximize oil production.

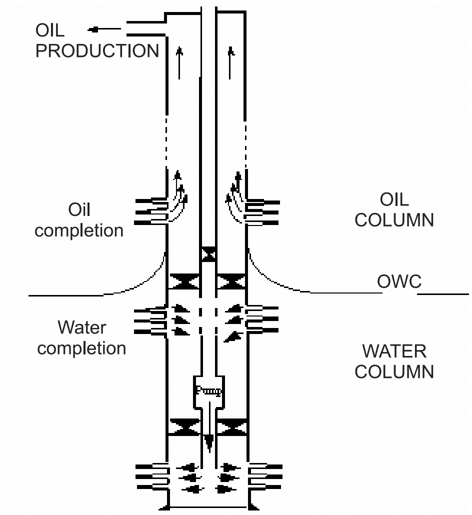

Fig. 1. DWS water drainage-injection

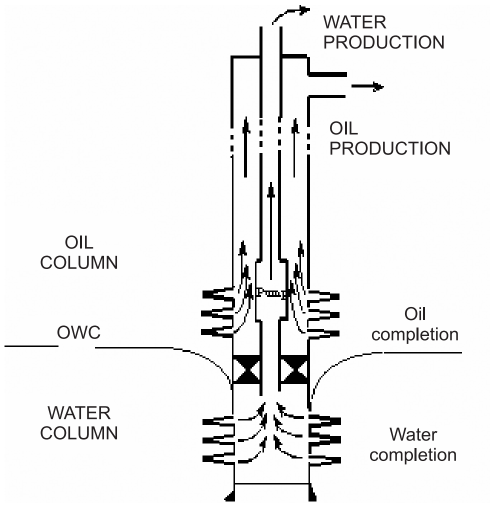

Fig. 2. DWS water drainage-production

Fate and quality of the drained formation water depend upon configuration of the DWS system. In the drainage-injection systems (Fig. 1) the drained water, free from oil contamination, is re-injected downhole into a deep injection zone. In the drainage-production systems (Fig. 2) the water is lifted to the surface for disposal or beneficial use – if applicable.The system applies to the offshore oil wells operating in the "clean water" range such that the drained water is free of oil and readily discharged overboard. The systems can also be used in gas wells with water coning problem to eliminate liquid loading and maximize gas production. In this application the top completion produces water-free gas and the bottom (water sink) completion drains the water with small amount of gas. The design involves inversing the water cone to create gas breakthrough into the water sink completion. At the completion, the liberated gas is produced to surface while the water pumped into a disposal zone.

3. FIELD TRIALS OF DWS

Following the first publication of the DWS concept, several field trials without rigorous design were carried out. These were short-term projects aimed at testing the principle and feasibility of DWS. Typically, operators would install DWS in old wells that had been producing with high water cut for a very long time. Also, the operators would restrict the information from these projects, so the reports and field histories are far from complete [1]. Some results from these field trials are presented below.

A DWS field test was performed in Canada in a completely watered out well that had been inactive for some time. The 2600-foot deep well produced from a sandstone reservoir comprising 60-foot thick oil column underlined by 23 feet of water column. (The reservoir permeability varies from 2 to 9 Darcy.) The well was re-completed for water drainage and re-injection. The re-completion project included squeezing most of the old perforations leaving 10-feet open to flow and perforating the 8-foot interval below the OWC. A bottom open-hole section of the well below the 51/2″-in production casing in the Leduc carbonate zone was used for water injection. Packers separated the three completed intervals. Completion also included two pumps – PCP and ESP, for oil production and for water drainage-injection, respectively. Even though the system was not rigorously designed – completions and pumping schedules were selected arbitrarily – the test was a technical success. The well was produced at the rate 250 BFPD with water drainage-injection rate 5400 BWPD. From the start, the well produced oil. Initially, the oil content in the produced fluid was 6% and it continued increasing daily at the rate of 0.1% per day for the whole duration of the test – three weeks.

A second DWS case history was reported from a well in East Texas, USA. After re-completion with DWS, the old, watered-out well was recovered and brought up to an average production rate of 24 BOPD - maximum recorded oil rate was up to 47 BOPD. The water drainage rate was 628 BWPD and the total (top and bottom completion) water cut (WC) was 97%.

Another case history concerns the first DWS trial in a well in Indonesia that was not a marginal producer. After a five-year long history of water coning and several unsuccessful attempts of water shut-off, the well was producing 240 BOPD with 84% water cut. The operator decided to add another (water sink) completion to this well and to try with ESP for water drainage and – possibly - production of additional oil by inversing the water cone. After re-completion with DWS installation comprising PCP and ESP at the top and bottom completions, respectively, the well's oil production rate increased to 298 BOPD (of which 20 BOPD came from the bottom water-sink completion. The test demonstrated the DWS potential for controlling water coning with the bottom water drainage. The inversion of the cone occurred at the rate of water drainage 2,550 BWPD.

4. THEORETICAL DEVELOPMENTS OF DWS TECHNOLOGY

A considerable number of R&D studies have been done to understand and evaluate DWS performance and its potential for different application. The work has included analytical modeling, physical experiments, numerical simulation of hypothetical and actual field reservoirs, and field projects with rigorous DWS design. The feasibility studies also addressed different well categories such as vertical oil wells, oil wells with gas lift, horizontal oil wells, and gas wells.

Feasibility of DWS for vertical oil wells was evaluated using analytical, numerical, and physical models [1, 3]. Evaluated in these studies was the DWS potential to reduce water cut in the produced fluids. The results demonstrate persistence and irreversible nature of water-cut in conventional wells compared to flexibility and ease to control with DWS installation. It was proved that DWS could reduce or eliminate water-cut at the top completion but it cannot reduce the total (top and bottom completion) water cut that includes the volume of drained water.

Recovery performance of DWS in oil wells was evaluated using physical and numerical models [4]. The study revealed that DWS could dramatically accelerate and increase oil recovery. A five-fold increase of the oil production rate resulted from increasing the drainage rate at the bottom completion without changing the rate at the top completion. A 70%, and 30% increase of oil recovery was obtained with the physical, and numerical models respectively.

Effect of impermeable barriers on performance of conventional and DWS wells was studied using a scaled physical model (radial sand pack) and numerical simulator [5]. The study revealed that in homogeneous reservoirs, DWS would reduce water-cut by draining water from the bottom completion and producing more oil from the top completion. It was also shown that placement of a man-made impermeable barrier around the well bore would not stop the water cone from forming. Water would simply flow around the barrier. However, the barrier would effective eliminate benefits of dual completion with DWS. The study also showed that a continuous low-permeability layer at OWC across the reservoir would merely delay the development of water problem without eliminating it. Water breakthrough will be postponed, and the water-cut will be reduced, but DWS would not be effective.

Water coning creates a fluid saturation transition zone around the wellbore (with mobile oil and water). Because of that, sustainable drainage of oil-free water with DWS becomes somewhat difficult as the two completions (top and bottom) may receive co-mingled inflow of the two fluids. To understand the transition zone effect on well performance, a study was carried out using the numerical and pie-shaped physical models [6]. The results show that, in conventional wells with water coning, the transition zone is small and constant away from the well but enlarges towards the wellbore. This transition zone enlargement effect occurs in conventional wells due to diffusion resulting from pressure distribution around the well. In DWS wells the effect is more pronounced, and must be considered in DWS design, particularly when the oil-free water drainage is a desired objective of the design. The conclusions showed limiting application of analytical models for DWS well design and the need for developing reservoir simulator-based design tools.

Oil production and water drainage rates are important factors defining operational window for DWS in oil wells. An inflow performance method and software for evaluating DWS was created using VB-Microsoft Excel software coupled with a commercial reservoir simulator [7]. The software captured hydrodynamic interaction between the two completions of the well in terms of pressure interference, water saturation (coning), and producing water for any combination of top and bottom production rates in presence of heterogeneities, capillary forces, and relative permeabilities. Studies with the software showed that oil productivity index was mostly sensitive to mobility ratio and the bottom flowing pressure drawdown. It also revealed that DWS is most effective in wells producing at high-pressure drawdown from reservoirs with relatively thick water columns. Figure 3 shows a typical IPR curve for the DWS top completion generated by the software.

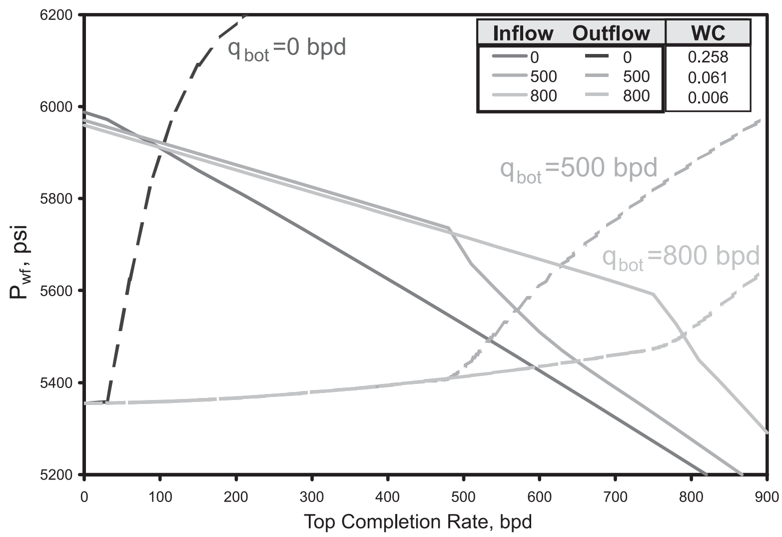

Fig. 3. IPR-Based Analysis for the Top Completion in a DWS well [7]

5. DESIGNED FIELD APPLICATIONS OF DWS

The first designed industrial installation of DWS in an oil well was made by Hunt Petroleum Co. in the Nebo Hemphill Field in Louisiana, USA [8]. The pay zone is clean sand located at 2500 ft with permeability between 1 to 4 Darcy. The reservoir has a very strong water drive at the oil-water contact from the bottom water column making up 10 to 90 percent of the reservoir height throughout the field.

Initial oil production rate of the well completed with DWS was 30% higher than a typical well in the field. After 17 months of production, the well was making 57 BOPD comparing to 12–16 BOPD from conventional wells in this field. The top completion's water cut after two years of production was 0.1% compared with 92% for a typical well. However DWS well's bottom completion was draining 1900 BWPD so the total WC was 97% – pretty close to the WC value in the conventionally-completed wells in the same field.

Another DWS field deployment was performed in Bakersfield, California, USA, where the 10-year-old well was re-completed for separated production of oil and water [9]. Prior to re-completion, the well produced 6 BOPD with WC equal to 99%. In this well the pay zone is located at 4731 ft with 40-ft of net pay containing 32° API gravity oil. Permeability of the sand is approximately 1–3 Darcy and porosity is 31%. The reservoir pressure of 1750 psia is maintained by an active aquifer.

A numerical simulation model including actual reservoir data was used to design the DWS installation. After history matching the model was used to evaluate different DWS scenarios. The well was converted to DWS with a 10-ft long top completion located at the top of the oil zone (4731-ft to 4741-ft). Bottom completion was 5-ft long and located 5-ft below what was believed to be the current oil-water contact. Water was drained using a rod-pumping unit at rate of 900 BWPD, and the top perforated interval was produced at 25 BOPD with a WC of 58%. Production data indicates that the total WC for the well was 97.4%, which is close to the WC the well had before the re-completion.

Two DWS installations were placed in two wells in Venezuela in 2001 and 2002. The first installation was made by re-completing an old well located in La Victoria field. The reservoir contains undersaturated crude oil with low bubble-point pressure and low solution GOR. The major recovery mechanism is strong water drive from an immense Artesian aquifer supplied from the Andes. The rock is poorly consolidated shaly sand with high porosity (25–30%) and permeability (1000–3000 mD). The well was severely water out and DWS installation was used to reduce water cut at the top completion. Figure 4 shows the water cut results over the for the three-month long water drainage in their well. Note that the actual water-cut reduction was significantly higher than the one predicted theoretically. After three month of operation the well encounter mechanical problems (not related to DWS) and the test was terminated.

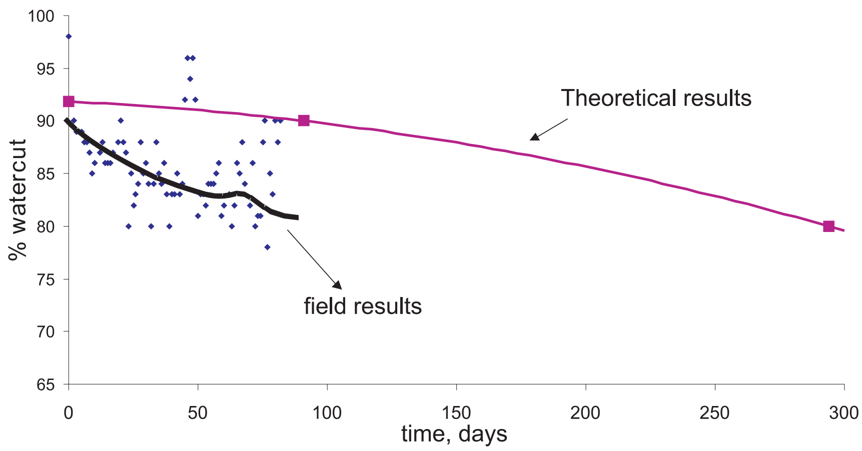

Fig. 4. DWS application for a well in La Victoria field, Venezuela

In 2002, another DWS installation was made in Venezuela in an oil well located in San Silvestre Field [10]. The well was initially a conventional producer with a single completion. However, in 2001, as the initial well production showed very high 96% water cut the well was soon shut-in while producing 100 BOPD. In January 2002 the well was re-completed and converted to DWS. Both completions were equipped with electric submersible pumps (ESP). Oil rate increased from 100 to 295 BOPD (175 BOPD from the top completion, and 120 BOPD from the bottom completion), water cut at the top completion decreases from 96 to 65%, and total water ratio was reduced from 25 to 12. After continuous and stable production with water drainage for several months, the well was returned to production as a regular DWS production well.

6. OTHER POTENTIAL APLLICATIONS OF DWS

6.1. Horizontal oil wells with DWS

Primary advantage of horizontal wells is long penetration and small pressure drawdown. Thus, horizontal wells have been used for developing reservoirs with severe coning problems. Several field reports, however, indicate that horizontal wells are also not free from the problem of water coning. In some reports, water breakthrough into horizontal wells could be quite dramatic and tend to erode the merit of high deliverability [11].

Evaluation of two possible DWS configurations in horizontal wells has been done using numerical simulator models [11]. The study evaluated two innovative concepts of "smart" completions for controlling water cresting in horizontal wells: "tail pipe water sink" (TWS), and "bi-lateral water sink" (BWS). TWS comprises a vertical well extension into the water zone and an upper horizontal section targeted at the top of the oil pay. BWS includes two horizontal parallel wells drilled laterally on top of each other with the upper section targeted at the top of the oil zone and the lower section targeted a few feet below the original oil-water contact.

The results have shown that the BWS variant outperforms the TWS variant by increasing oil recovery. It was also found out that the water sink (bottom) leg could be much shorter than the production (top) leg of the bilateral well. A horizontal section in the water zone equal to one third of the horizontal section in the oil zone was adequate to control water-cresting with BWS.

6.2. DWS oil wells with gas lift

Feasibility study and a design method for dual gas lifting in DWS wells were performed using a two-tier nodal analysis, and a numerical simulator model [12]. The study was done using data from actual wells in Venezuela. The results indicate that it is possible to use dual gas lift combined with DWS. Performance of DWS, however, would be controlled by the gas lift design since the water-lifting rate limits the oil inflow rates. Other factors controlling DWS performance included well geometry, gas injection rate, and injection gas pressure. Figure 5 depicts a conceptual design of DWS with dual gas lift.

Figure 6 shows an example case for designing a dual gas lift well. The plot presents the family of water cut isolines (for different combination of the top/bottom completion rates) combined with the water-lifting limit (Maximum GL rate) at the bottom completion (horizontal lines) for two different water tubing sizes 3″, and 2 7/8″. Superimposed are also three isolines of pressure drawdown (at the top completion, 1000 psi, 1150 psi, and 130 psi) and the dotted line representing gas-lifting limit for 2 1/16″ oil plus water tubing string.

Maximum oil rate occurs at the point where the horizontal GL limit line intercepts either the pressure drawdown line or maximum GL top completion line – whichever gives smaller rate at the top completion. The point determines gas lift volume requirements.

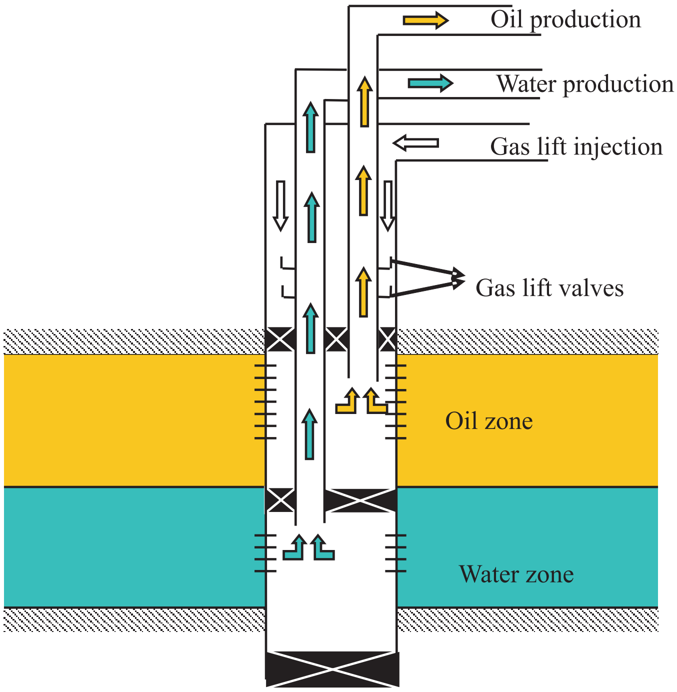

Fig. 5. DWS with dual gas lift wells

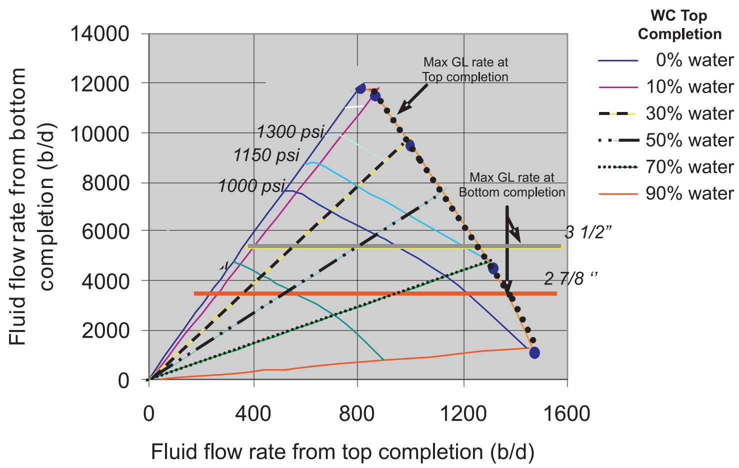

Fig. 6. Example case design for DWS with dual gas lift wells [12]

A field trial using DWS with dual gas lift well was performed in a depleted oil field in the coastal region of South Louisiana, USA. The pay zone is homogeneous sand located at 7,339-ft. The pay zone is about 18-ft thick with an underlying 88 feet of the water column. Permeability of the zone is 573 md. Top and bottom completion are located at 7339-ft and 7357-ft, respectively. After the DWS installation, the well produces 20% more oil than a typical well in the field.

6.3. Gas wells with DWS

Gas wells are more sensitive to water inflow than oil wells because small inflow may cause liquid loading and kill the well [13]. Conventional techniques for water un-loading enhance water removal mechanism inside the well either by increasing tubing lifting performance (chemical injection, concentric pipes, thermal, gas lift) or by directly removing water from the well's bottom (pumps, plungers, and Downhole Gas Water Separation – DGWS). All these techniques do nothing to prevent gas-inflow reduction due to water inflow. They merely improve tubing performance relationship (TPR) without tackling inflow performance relationship (IPR). On the other hand, DWS technique increases tubing performance, while controlling water inflow and, in principle is applicable to the gas wells.

Feasibility study of DWS for gas wells was performed using reservoir simulator models [14]. The study qualified the use of DWS in gas reservoirs by comparing simulated performance of the conventional, and DWS wells. The simulation runs were made over a broad range of the initial reservoir pressure and permeability values for a gas reservoir with large associated aquifer.

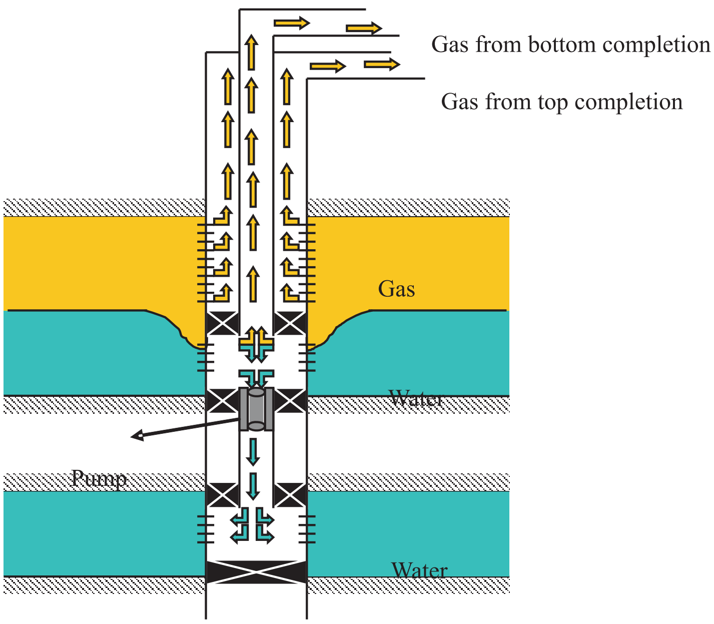

Fig. 7. DWS configuration for gas wells including dual completion with gravity gas/water separation [14]

The results reveal considerable advantage of dual completion over conventional wells in low-pressure (subnormal) tight (1 mD) reservoirs – a 2.6 – fold recovery increase before killing the well with water. The advantage, however, reduces to 10% for reservoir with normal pore pressure gradient and permeability 10 mD.

The study also identified a DWS completion design suitable for gas wells – shown in Figure 7. In the design, the top completion is used only for gas production, and the bottom completion for water drainage, inverse gas coning, gravity separation and water injection.

A comparison of DGWS and DWS well performance has been made for a few selected scenarios (14). (In DGWS wells water is separated and re-injected after entering the well. The DWS gas wells are different from DGWS by inclusion of a second bottom completion that controls water outside the well and prevents commingled inflow of gas and water to the top completion.) The results show that when compared to DGWS wells, the final gas recovery of DWS wells is the same, but DGWS takes 50% more time than DWS to produce the gas.

6.4. DWS in oil reservoirs with edge-water drive

In the edge-water-drive oil reservoirs with unfavorable mobility ratios, water tongues may under-run oil. The water tongue commonly conforms to strike far from the well, and then forms a salient (or areal tongue) as it approaches the well; finally, a water cone may form atop the tongue when it reaches the well. The water tongue, salient, and coning interact to affect water breakthrough time and post-breakthrough production, and therefore influence ultimate recovery [15]. To date, the effects of coning and tonguing on production behavior have already been alleviated by placing short well completions at the top of the oil pay zone, letting the well water out, shutting the well and continue production from the next well–up dip the reservoir. DWS could delay water invasion to wells, prolong wells life and increase recovery.

Recently, a combined effect of water tonguing and water coning on oil recovery in dipping structures has been evaluated [15]. Reservoir simulation model was used to identify well and reservoir conditions that lead to early water production and bypassed oil in comparison with common analytical solutions. (Comparison of simulation results with analytical models for diffuse and segregated flow assesses the severity of tongues, salients, and cones; analytical models cannot consider these mechanisms simultaneously.) The results reveal that displacement conditions with low dipping angle, low vertical to horizontal permeability ratio, high mobility ratio, and low gravity number, leads to bypassed oil when the well attains to its economic limit due to high water cut. Partial penetration delays water breakthrough time and slightly improves recovery factor by postponing water cone buildup and water take over the well. The results demonstrate active water coning and DWS promise for side-water system.

Incremental oil recovery with DWS in a side water system was assessed theoretically for a well located in a mature oil reservoir (KE-KF) in Louisiana, USA. [16]. Reservoir simulator model was used in this work. The dipping reservoir has been water-flooded and the well has had a long history of severe water problem resulting on well shut-in when water cut was 90%. The results revealed a two-fold increase in oil recovery when DWS is in place comparing to the case without using DWS.

7. CONCLUSIONS

1. Downhole Water sink (DWS) technology is a completion/production technique for controlling water inflow to oil and gas wells in reservoirs with water drive and strong tendency to water coning.
2. DWS may reduce or eliminate water from oil/gas production stream by hydrodynamic effect of water drainage in-situ below the oil-water or gas-water contact.
3. DWS also applies to oil wells with gas lift where it requires optimized dual gas lift design.
4. Analytical, numerical, and physical experiments reveal that DWS increases petroleum rates, and enhances/accelerates recovery. The rate increase effect has been demonstrated in the field. The recovery advantage still remains to be seen in field operations.
5. DWS could be used in horizontal oil wells with water cresting problems by adding another short-bilateral section below the long horizontal well and using it as water sink. Simulation studies show enhanced recovery with bilateral water sink completion (BWS).
6. A modified DWS is feasible for low productivity gas reservoir with bottom water. In this case, maximum advantage of DWS can be achieved when the top completion is short (penetrating top 20–40% of the gas zone), bottom completion is long (penetrating the bottom part of the gas zone, or even the top of the aquifer), and the completions are as close as possible. Furthermore, water drainage should be postponed until water breakthrough occurs at the top completion. Then, water should be drained at maximum achievable rate even if an initial inverse gas coning to the bottom completion occurs.
7. The mechanism of water coning is also at work in dipping reservoir structures with side-water invasion due water flooding or structural water drive.
8. Simulation of improved water flooding in a dipping mature reservoir shows a significant two-fold increase of incremental oil from a well recompleted with DWS.

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