Behavior of Water Cresting Under Horizontal Wells

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Abstract
Complex reservoir flow problems could be better understood through a study using physical models. The purpose of this paper is to present results of an experimental study of water crest behavior under horizontal wells. This work is made in an effort to better understand the formation and growth of water crest prior to and after water breakthrough. The physical model constructed differs from others in that variation in length and position of the horizontal well can be made. Eighteen different systems with varied oil column thickness and oil viscosity were run. Particularly in systems with viscous oil, the bottom water never reached the tip end of the well even at a producing water cut of almost 100 percent. The end effects defined as the unswept oil are pronounced as the well length is reduced and as the oil viscosity is increased. Also, at high water cut, the portion of the wellbore with low productivity increases with well length. These physical occurrences have not been previously reported. Postbreakthrough performance will be presented and discussed.

Introduction
Oil production from bottom water drive reservoirs is usually followed by water produced through the same well. This situation occurs when bottom water has broken through the well due to a high drawdown applied to the reservoir. The appearance of bottom water in vertical wells is in many cases observed in a relatively short time after the wells are put on production. Once the water enters the wells, a rapid increase in water cut may lead to low oil recovery.

The application of horizontal well technology has been widely used in many countries to improve oil recovery from water drive reservoirs. At a low drawdown, a horizontal well can have a larger capacity to produce oil as compared to a conventional vertical well. Thus, the critical rate, below which the flat surface of water-oil contact will not deform, in a horizontal well may be higher than that in a vertical well. But in practice, production rate is usually higher than the critical rate due to economic consideration. When this takes place, high mobility bottom water will invade into the overlying oil zone and moves toward the well. Water may be in the form of a cone for vertical wells and a crest for horizontal wells. Many publications relating to water coning phenomena have been available. The water cone beneath a vertical well is assumed to develop symmetrically with respect to the vertical well axis. This is true because no pressure gradient in the well system is accounted for and the well acts as a point source, eventually.

In the context of horizontal well producing oil from bottom water drive reservoirs, many researchers considered no pressure gradient exists along the horizontal wellbore. This implies that bottom water rises uniformly and the crest formed is symmetric with respect to a vertical plane passing through the wellbore axis. Later it has been shown that considerable pressure drops within a horizontal well may affect the production performance. Thus, the pressure gradients create varied potential fields beneath the wellbore. The first water would then break through the well at a point below which the potential is the highest. A numerical study has recently shown this phenomenon and also reported that neglecting pressure drop in the wellbore leads to overestimation of the rate of oil production. Unfortunately, no detailed information as to the fluids flow mechanism along and in the vicinity of the wellbore has been presented.

Complex mechanisms of fluids flow in a reservoir system containing a horizontal well and in the wellbore itself are not well understood. Tackling such problems through the use of physical models has been appreciated. Particularly, water cresting phenomena were recently investigated by Aulie et al. The physical system used is a Hele-
Shaw model similar to the one employed by Meyer and Searcy studying water coning behavior. The average gap between plates in the previous work was $2.4 \times 10^{-3}$ m while the horizontal well length designed was $2.5 \times 10^{-3}$ m. This study implies that pressure drop in the wellbore was neglected.

The purpose of the present work was therefore to study the formation of water cresting under various horizontal well lengths by employing a Hele-Shaw cell and varying oil viscosity and oil column thickness as well. The primary goal is to better understand the behavior of water cresting at various conditions.

**Experimental Setup**

**Model.** A well known Hele-Shaw cell was primarily used in the present work as the displacement medium. Although the Hele-Shaw cell does not consider the whole crest, we believe it can still provide meaningful and qualitative results analogous to the water coning problem. The cell is transparent and basically consisted of two pieces of glass plates installed vertically and parallel to each other, giving a narrow gap in between. The plates sat on a plexiglass reservoir employed to ensure uniform contact between the bottom part of the cell and the bottom water inlet. The schematic of the model is shown in Fig. 1. The plexiglass reservoir contained bottom water delivered from a constant level water source through a 0.25-in pipe. The front side of the cell was permanently marked with horizontal and vertical lines creating 10 cm x 10 cm squares which were further scaled down to 1 cm x 1 cm. The purpose of these scales was to mark down the data points of the water-oil interface for several time periods. The cell was clamped by small C-clamps whose stress was distributed by long pieces of 0.8 cm thick plexiglass. Additional large clamps were also used in the middle part of the cell to eliminate pressure acting on the inner walls and thus to obtain a uniform gap for the whole part of the cell. The horizontal well was placed at the top of the glass plates. The right and left edges of the cell were sealed using silicone gasket. Table 1 shows dimensions of the model.

**Liquids.** Immiscible liquids, oil and water, were used here to study the behavior of water cresting under horizontal wells. Two refined oils with different viscosity are used as indicated in Table 2. The viscosity differed quite large between the two oils, 7.1 and 24.6 centipoises. Assuming that both effective permeabilities of the cell to the oil and to the water were the same, the mobility ratios were 7.8 and 27, respectively. In order to clearly observe the water-oil interface movements during experimental runs, the water was colored with red dyes. In addition, toluene and benzene may also be used to fasten draining and to clean the cell. In order to keep the cell clean, the produced fluids were always discarded.

**Experimental Procedure.** In all experimental runs, the water level in the water tank was kept constant at height of 1.40 meters above the horizontal well. The opening of the production valve No. 1 was never changed. No effort was done to set a constant rate in all cases. The range of production rate was 2 to 4 cc/second, depending on well length, oil column thickness, and oil density. The rate increased with well length and oil column but it decreased as the density of oil increased. The parameters well length and oil column, however, were dominant. It was assumed that the influence of rate of production, within this range, on the behavior of water cresting would not be qualitatively significant so that the results would still be meaningful as will be shown in the next section.

Before running each experiment, the cell was initially saturated with water by allowing water to enter the cell from the aquifer (i.e., plexiglass reservoir). At this step, valves No. 2 and No. 4 were at closed position. When the water reached valves No. 5 and No. 6, these valves were closed while production valve No. 1 was still opened. As the wellbore was filled fully with water and some water run out through production line, valves No. 1 and No. 3 were then closed and valve No. 2 was opened to permit oil flowing down into the cell by slowly opening valve No. 4. At this stage, the oil was displacing water down until a certain oil column thickness was obtained as desired. Valves No. 4 and No. 2 were then immediately closed.

An experiment was then run by opening valves No. 1 and No. 3. Observations of water crest development and measurements of fluids production were performed every 15 minutes until producing water cut mostly was close to 100%. The breakthrough time for water was recorded by using a stopwatch. The water crest development was manually recorded by marking down the water-oil interface on the front side of the cell with an erasable whiteboard pen. As previously described, the front side has scales and therefore the data points of each water-oil interface position at specified time period could be drawn.

Another experimental run can be performed with the same oil by following the steps described above. When different oil will be employed, the used oil left in the cell can be drained through valves No. 5 and No. 6. Toluene or benzene may also be used to fasten draining and to clean the cell. In order to keep the cell clean, the produced fluids were always discarded.

**Results and Discussion**

As can be inferred from Tables 1 and 2, a total of eighteen different experimental runs have been conducted. As there is no outer source of oil, it is assumed that the oil layer is the size of reservoir. The main purpose of the present work was to study the behavior of water cresting under horizontal wells at various schemes. It would be more valuable, however, to present typicals of production performance in terms of water cut and oil recovery as the fluids produced were measured. For convenience, therefore, this section is divided into two main subsection.

**Water Cresting Phenomena.** Results shown in Figs. 2a, 2b, and 2c demonstrate formation of water crest under horizontal wells of three different lengths, 1.0, 0.75 and 0.5 m, at several time intervals for systems containing 7.1 cp oil. The total length of time for observing the development
of water crest in all systems was mostly 120 seconds at which producing water cut achieved was at least 97%, unless otherwise indicated. These three figures are resulted from systems with the same initial 40 cm thick oil column. As described in the previous section that the longer the well the higher the rate of production. Prior to breakthrough, these systems produced oil at an average rate of 2.2 cc/sec for 0.5 m long well, 2.8 cc/sec for 0.75 m well, and 4.0 cc/sec for the longest well. For further discussion, we call these wells as the short, intermediate, and long wells, respectively. The breakthrough time is defined as the time needed for water to reach the wellbore. The first contact point is either at the heel end or at the point near the heel end. For the short, intermediate, and long wells, the breakthrough times were 35, 41 and 53 seconds respectively. This indicates that high pressure gradients within wellbores of these particular systems exist because the fluid particles or bottom water under the heel end moved upward faster than that in other position. The same breakthrough phenomenon was shown in a study of numerical simulation when pressure losses within the wellbore system were considered.31

Inspecting carefully the three figures mentioned above, the right and left flanks of the water crest were more steeper in the system with a short well. Although the rate of production in the short well is the lowest but water breakthrough in this well was earlier, indicating that the velocity of water under this well was the highest. The development of water crest under this well, however, halted sooner, leaving more oil left above water-oil interfaces. In this study, portions of oil column unswept is called the end effects caused by the water in the wellbore blocking oil from entering the well. At this late production period, when the water cut was higher than 97%, there was still considerable portion of the wellbore producing small amount of clean oil. The point of intersection between wellbore and water-oil interface moved to the tip end direction very slowly at this stage. Even, extending production period to reach water cut of 99% did not let water reaching the tip end for these systems.

Figs. 3a, 3b, and 3c show the developments of water cresting for systems containing 24.6 centipoise paraffin oil, 40 cm thick oil column, and different well lengths. These systems had larger end effects when compared with the previous corresponding systems. It means that oil left would be more in systems with more viscous oil caused by higher mobility ratio. Therefore, it is of importance to note particularly for systems with long horizontal wells that a large portion of horizontal well section was unreached by bottom water even at water cut of higher than 95%. This is of practical interests in that well completion and perforation distribution should be correctly designed for horizontal wells producing oil from bottom water drive reservoirs such that a uniform influx along the wellbore can be obtained in order for bottom water to displace the oil more efficiently. Some other experimental runs were also performed using different initial oil column thickness, 30 and 20 cm, as shown, respectively, in Figs. 4a and 4b for 7.1 centipoise oil and Figs. 5a and 5b for 24.6 centipoise paraffin oil. In these cases the well length was 100 cm. Water breakthrough times observed for the systems shown in Figs. 4a and 4b, respectively, were 45 and 36 seconds; while the average rate of production prior to breakthrough was 3.2 cc/second for 30 cm oil column and 2.6 cc/second for the other one. The difference in rate is obviously due to the difference in water head acting initially on the original water-oil contact. Same performance is shown by the paraffin oil systems. The influence of oil column thickness on the shape or formation of water crest for systems containing same oil and having same well length is hardly differentiated. But it is interesting to note that the portion of the wellbore that still produced small amount of clean oil was quite long for this long well at late period of production. For example, see Figs. 2a, 4a, and 4b. The development of water crest halted sooner in the system with thinner oil column. Since the rate of production was lowest in this system, the pressure gradient within the wellbore should also be lowest so that after breakthrough bottom water could enter most portion of the wellbore. It seems that, at late period (or producing water cut is higher than 95%), the oil left is directly proportional to the initial oil column. By observing Figs. 3a, 5a, and 5b, it can be seen that the thickest initial oil column in the system with more viscous oil yielded the longest low productivity section, which is again the section that still produces small amount of clean oil, at late period.

Although the rest of the experimental results for systems with well length of 75 cm and 50 cm are not shown here, we may conclude the cresting behavior for all the systems studied that bottom water always appeared for the first time at the heel end of the wells, breakthrough time for water decreases as the length of a horizontal well and/or the thickness of initial oil column are reduced, and as the oil viscosity increases. Also, the longer the horizontal wellbore, the thicker the initial oil column, and the higher the oil viscosity, the longer the wellbore section with low productivity at producing water cut of, in general, higher than 90%.

Production Performance.

Water Cut. The fluids produced during experimental runs were measured for all systems studied. Typical results in terms of water cut are presented in Figs. 6, 7, and 8 for systems with varied well length, different oil viscosity, and various initial thicknesses of oil column, respectively. The effect of well length on water cut is clearly shown in Fig. 6. The increase in water cut started from breakthrough until, say, 80% was about the same. But afterward, the increase was slower for shorter well. This is because the formation of water crest completed faster in the short well system, while the intermediate and long wells still drained some more oil and the water-oil interface moved to the right. Eventually, the increase was the same when water cut reached a value of about 97% and tended to be constant at about 98%. Similar results are also obtained for systems with different oil column thicknesses (see Fig. 7). In this cases, the well length was 75 cm and the oil viscosity was 7.1 cp. The production time required to reach a water cut of 90% tends to be longer as the thickness of oil column is in-
creased, but afterward the time is shorter to achieve a water cut of 97%, leaving more oil.

As described above, water breakthrough occurred earlier in the system containing more viscous oil but the crest in the system with thinner oil developed faster, reaching a high water cut sooner as indicated in Fig. 8. Since the development of water crest was slower in the more viscous system, the increase in water cut was also slower in the system. However, it must be remembered that more viscous oil resulted in longer well section that produced small amount of clean oil at late period. This behavior might be identical with the ones employing significant difference in production rate because the controlling factor here was viscous force. Therefore, producing oil applying horizontal wells requires serious completion design. In order to have a uniform water crest under a horizontal well, perforation design as described by a previous study should be considered because uniform crest might result in better sweep efficiency.

Oil Recovery. The two subsections above describe the displacement mechanisms taking place in two-dimensional systems under horizontal wells. Figs. 9, 10, and 11 show the effects of horizontal well length, oil viscosity, and oil column thickness, respectively, on oil recovery. The end effects caused by water acting as an obstacle to the flow of oil are more pronounced in systems with short wells and/or more viscous oil, resulting in more oil left in the cell. Thus, as can be seen Figs. 9 and 10, the oil recovery obtained is the highest for the longest well and less viscous oil. Unlike these occurrences, systems with the same well length and oil viscosity but different oil column thicknesses gave relatively the same oil recovery as shown typically in Fig. 11. The controlling factor in producing fluids in these systems was gravity, which was due to different oil column thickness. The rates were 2.2, 2.7, and 3.2 cc/second, respectively, for the systems with original water-oil contact of 20, 30, and 40 cm measured from the top edge of the cell. These mean, for a given well length, that as long as the rate of production is about directly proportional to the oil column thickness then oil recovery, particularly, would not much different.

Conclusions
1. In all the systems studied here, in which water crest developed, water breakthrough occurred at or very close to the heel end of the wells, indicating the existence of pressure gradient inside the wellbore. The point of intersection between water-oil interface and the wellbore moved slowly in the opposite direction of fluids flow within the wellbore.
2. In most of the cases studied, when the production period was extended to achieve water cut of close to 99%, the bottom water never reached the tip end of the well, leaving some portion of the wellbore with low productivity. This portion increased with well length and oil viscosity but slightly decreased as the initial oil column thickness decreased. These phenomena suggest that non-openhole completion should be the right choice for horizontal wells with expected water or gas cresting problems in order to perform future remedial work easier. One may try to perforate more holes toward the end of a horizontal well.
3. The rate of increase in water cut, starting from water breakthrough to the end of production period, was slower in the systems with the longest well and in those with the thickest oil column.
4. The right and left flanks of water crest were steeper in the systems with shorter wells, yielding lower oil recovery. Similar results were obtained for systems containing the more viscous oil. For the same oil and a given well length, the oil recovery was not significantly influenced by the initial thickness of oil column, although the breakthrough time for water was quite earlier in the system with thinner oil column. In these cases, the average rate of production prior to breakthrough was about directly proportional to the initial thickness of oil column.
5. For the purpose of a qualitative comparison, Table 3 demonstrates the overall production performance of the systems studied here.

Acknowledgments
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References


SI Metric Conversion Factors

\[ \begin{align*}
& \text{cp} \times 1.0^\prime = \text{E–03} = \text{Pa-s} \\
& \text{ft} \times 3.048^\prime = \text{E–01} = \text{m} \\
& \text{md} \times 9.894 233 \text{E–04} = \mu \text{m}^2
\end{align*} \]

*Conversion factor is exact.

**TABLE 1–DATA OF EXPERIMENTAL SETUP**

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<th>Parameter</th>
<th>Value</th>
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<tr>
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<tr>
<td>Height of glass plates, ( m )</td>
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<tr>
<td>Length of glass plates, ( m )</td>
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<tr>
<td>Gap between plates, ( m )</td>
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<tr>
<td>Cell permeability, ( m^2 )</td>
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<tr>
<td>Length of horizontal well, ( m )</td>
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<td>Diameter of the wells, ( m )</td>
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<td>Thickness of oil column, ( m )</td>
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<td>Water head measured from the well, ( m )</td>
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**TABLE 2–DATA OF FLUIDS USED**

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<th>Fluid</th>
<th>Viscosity (cp)</th>
<th>Density (g/cc)</th>
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<tbody>
<tr>
<td>SAE-10 Oil</td>
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<tr>
<td>Paraffin Oil</td>
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<td>0.86</td>
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<tr>
<td>Dyed Water</td>
<td>0.91</td>
<td>1.012</td>
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**TABLE 3–A QUALITATIVE COMPARISON OF HORIZONTAL WELL PERFORMANCE IN BOTTOM WATER DRIVE RESERVOIR**

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>low viscosity oil</th>
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<tr>
<td>Breakthrough time</td>
<td>early</td>
<td>late</td>
</tr>
<tr>
<td>Water cut</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Unsept oil</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Breakthrough time</td>
<td>long well</td>
<td>short well</td>
</tr>
<tr>
<td>Water cut</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Unsept oil</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Breakthrough time</td>
<td>thick oil layer</td>
<td>thin oil layer</td>
</tr>
<tr>
<td>Water cut</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Unsept oil</td>
<td>high</td>
<td>low</td>
</tr>
</tbody>
</table>

**TABLE 4–A QUALITATIVE COMPARISON OF HORIZONTAL WELL PERFORMANCE IN BOTTOM WATER DRIVE RESERVOIR**

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>Unsept oil</td>
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Fig. 1—Schematic experimental set-up showing (a) front view and (b) side view.

Fig. 2—Development of water crest under horizontal wells. Lengths of horizontal section are (A) 100 cm, (B) 76 cm and (C) 60 cm. The oil viscosity and oil column thickness are 7.1 cp and 40 cm, respectively.

Fig. 3—Development of water crest under horizontal wells. Lengths of horizontal section are (A) 100 cm, (B) 76 cm and (C) 60 cm. The oil viscosity and oil column thickness are 24.6 cp and 40 cm, respectively.
Fig. 4—Development of water crest under a 100-cm-long horizontal well with oil column thickness of (A) 30 cm and (B) 20 cm, and oil viscosity of 7.1 cp.

Fig. 5—Development of water crest under a 100-cm-long horizontal well with oil column thickness of (A) 30 cm and (B) 20 cm, and oil viscosity of 24.6 cp.

Fig. 6—Water cut versus production time for systems with 7.1 cp oil, 40 cm thickness oil column, and three different well lengths.

Fig. 7—Water cut versus production time for systems with 7.1 cp oil, a 75-cm-long horizontal well, and three different thickness of oil column.

Fig. 8—Water cut versus production time for systems with a 100-cm-long horizontal well, 40 cm thickness oil column, and two different oil viscosity.
Fig. 9—Effect of horizontal well length on oil recovery for a system containing 7.1 cp oil and 40-cm-thick oil column.

Fig. 10—Effect of oil viscosity on oil recovery for a system with a 100-cm-long horizontal well length and 40-cm-thick oil column.

Fig. 11—Effect of oil column thickness on oil recovery for a system containing 24.6 cp oil and employing a 100-cm-long horizontal well.