An Experimental Approach of Influences of Perforated Length and Fractures on Horizontal Well Productivity

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Abstract

Many simulation studies have been conducted regarding the importance of perforated well length on horizontal well performance. All of these studies suffered from their dependence upon theoretical models, which lack plausibility due to the lack of accurate experimental and/or field data. Therefore, there is a real need for experimental data to be used for tuning the single well simulation models before applying a full field simulation of oil reservoirs with horizontal wells. This experimental study was designed to investigate the influences of fractions of perforated length, total length, and fractures, which do not intersect with a well axis, on the productivity of horizontal wells. An experimental model (60 cm × 40 cm × 20 cm) was designed and used to achieve the study objectives. Carefully sized sandpacks were used to represent the homogeneous unconsolidated porous media while a perforated aluminum sheet was used as a horizontal fracture parallel (horizontal fracture) and perpendicular but not intersecting (vertical fracture) the horizontal well axis in the sandpack. Several runs were carried out using horizontal wells with different lengths and different perforation fractions of total length utilizing homogenous porous media with and without fracture systems.

The results indicated that an increase of perforated well length increases flow rate of the horizontal well for both homogeneous and fractured formations that do not intersect with the well axis. Furthermore, horizontally-fractured formations parallel to and vertically-fractured formations vertical to the well axis improve the productivity of horizontal wells for different perforation ratios. A single vertically-fractured porous medium provides a higher productivity ratio than a horizontally-fractured one for the same perforation length and intensity, when both fracture systems do not intersect with the well axis. Several empirical equations were developed to correlate the horizontal well productivity with perforated length for homogenous and fractured porous media.

Ignoring of the effect of pressure drop along horizontal well may have serious implications on perforated well length since proportionality of the productivity index to the well length is no longer valid.

Introduction and Literature Review

Recently, the economic feasibility of drilling a horizontal well improved drastically due to advances in drilling technology. Advantages of horizontal wells over vertical well applications have been confirmed by many scientists (1-4) and operators (5-7). Horizontal wells showed many distinct advantages over vertical ones such as improvement of well productivity, attenuation of sand production, and significant reduction of gas and/or water coning problems.

From reservoir and production engineering standpoints, the sole difference between vertical and horizontal wells was identified to be the contact area. For a partially penetrating vertical well, the reservoir disturbance due to a vertical well was limited to the close vicinity of the wellbore hole (8). Then, the choke diameter became the main parameter affecting the flow rate. For a horizontal well, the disturbance created by the well not only affected the vicinity of the wellbore, but also influences the whole reservoir due to the greater contact area of the pay zone penetrated by the well. In addition, in the case of a horizontal well, there was a non-uniform flow, which basically depends upon the ratio of pressure drop by friction through the horizontal section and pressure drop across the pay formation (9).

The adequacy of using the assumption of infinite wellbore conductivity to describe fluid flow in horizontal wells reveals an argument in the literature. If the pressure drop along the horizontal well was negligible in comparison to the reservoir pressure, this might be a good assumption. In practice, pressure drop along the horizontal section of the well was essential to maintain fluid flow within the wellbore, and therefore cannot be neglected.

Folefac et al. (10) pointed out that pressure drop along horizontal wells affected their inflow performance and in many circumstances led to over prediction of productivity index and deliverability of these horizontal wells. They showed in their simulation study that horizontal well parameters such as horizontal well length, diameter, and perforated intervals had the most significant effect on pressure drop level in the wellbore hole.

Al Qahtani et al. (9) performed a simulation study to investigate the effect of length and distribution of perforated intervals on horizontal well rates. This study was based upon the productivity index solution of perforation distribution and perforated lengths developed by Goode and Wilkinson (11). They coupled a computer program with a multiphase flow model to combine the inflow performance of the reservoir to the outflow performance of the horizontal well. This helped to obtain the overall performance of the horizontal well. The results indicated the important roles of length, distribution of perforated length, and also the existence of an optimum perforated length that yielded maximum production rate.

Field experience indicated that not only the perforated length of horizontal sections was a crucial parameter in determining the flow rate but also where these perforations were located (at heel or at toe of the horizontal section). Al Qahtani et al. (9) indicated that 20% of the horizontal length perforated at the heel yielded twice the production of the same fraction perforated at the toe side of the horizontal well. This pressure drop was expected to have an important impact on flow rate and productivity of the well. Ihal et al. (12) pointed out that the pressure-flow rate behaviour in the horizontal section was neglected, which was not true in many cases.

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facility to validate and improve a mechanistic model describing the accelerational pressure drop in the wellbore of horizontal wells penetrating non-fractured formations.

Joshi(13) concluded that performance analysis in horizontal wells requires knowledge of four parameters; namely, producing length, vertical to horizontal permeability ratio, horizontal permeability, and skin factor. In practice, estimation of these parameters was difficult and the number of unknowns normally exceeds the number of measurements, resulting in a highly subjective finding of well performance. Levitan et al.(14) developed a simple empirically-based correlation for predicting well productivity and productivity improvement factors for horizontal wells. The correlation provided an estimation of productivity for given values of average reservoir permeability, well length, and fluid properties. Yildiz(15) indicated that selective horizontal well perforation had been one of the most common completion methods for different well types to control sand production. It might also be needed to prevent wellbore collapse and to delay the production of unwanted fluids such as water and gas.

Calculation of pressure drop along the horizontal well is still a real problem in reservoir simulation for two main reasons: the difficulty of measuring these pressure drops and the limited data available to validate the degree of direct proportionality of horizontal well productivity index with perforated well length.

This experimental study is designed to investigate the influences of pressure drop across the horizontal well, fraction of perforated length of the horizontal well, and fractures (not intersecting with well axis) on well productivity. This study also provides a complete set of experimental data, which could be used to provide more understanding about the pressure drop-flow rate behaviour along the horizontal section of the well and to validate the plausibility of many single-well simulation models.

**Experimental Model and Procedure**

**Experimental Model**

The experimental model used is shown in Figure 1a. The schematic diagrams of the position of the vertical and horizontal fractures are shown in Figures 1b and 1c, respectively. The experimental cell is mainly a rectangular stainless steel box of 60 cm in length, 40 cm in width, and 20 cm in height. Two open holes are used in two opposite sides of the model to represent the injection inlet (to provide constant reservoir pressure) and the outlet hole (to control pressure and/or deliver the horizontal well production). Six horizontal wells are made of 6.0 mm inside diameter stainless-steel tube, and have a constant perforation intensity of 29 perforations per square inch.

To investigate the effect of fractions of perforated horizontal well, three wells (Well #1, #2, and #3) of 45 cm in length were perforated with different perforation fractions of 15% (6.75 cm), 30% (13.50 cm), and 60% (27 cm) of total horizontal length. Several similar tubes were used as horizontal wells, but with different imperforated and/or perforated lengths. To study the influence of total length of horizontal well on flow rate-pressure drop behaviour, three wells (Well #4, #5, and #6) of different well lengths of 14 cm, 24 cm, and 34 cm, respectively, were prepared and used. In addition, the results of these three wells were compared with Well #2, which has the same perforation intensity and the same perforation fractions of 30% of the horizontal well length, which is 45 cm.

Special reservoirs were used as containers for brine formation water and actual crude oil. Three pressure gauges (sensors) were inserted through the upper side of the box and connected to measure pressure drop along the horizontal well axis. In addition, inlet and outlet pressure gauges were used.

The homogeneous porous medium of unconsolidated formation was represented by a sandpack (well-sieved silica in the range of 300 to 450 microns in diameter). With respect to a single horizontal fracture, an aluminum foil sheet was placed parallel to the well axis and had the following properties: number of perforations is 532 perforations through an area of 2.257.60 cm² and located at 6.0 cm above the centred horizontal well. On the other side, a single vertical fracture not intersecting with the well axis was simulated by an aluminum foil sheet having the same properties of the previous sheet and was placed perpendicular to the well axis, 9.5 cm from the injection inlet side. The average effective porosity and permeability of the simulated homogeneous, horizontally-fractured, and vertically-fractured formations, but not intersecting with the well axis, are as follows: 34.42% and 0.69 darcy; 33.37% and 0.76 darcy; and, 34.22% and 0.77 darcy, respectively. The use of an aluminum foil with a sufficient number of perforations is a good fracture representation. The choice of this fracture design is based upon the following: a) the use of unconsolidated sand grains on an aluminum plate are expected to provide high conductivity due to it providing a leakage path for flowing water on the surface of this plane; b) perforating the foil increases its ability to permit water to flow through since water itself accumulated instantly in these perforations before flowing; c) the existence of perforated foil provides an almost continuous flow path across this foil plane; and, d) this fracture design was used before in the literature(16, 17). Sarwar and Islam(17) used a two-folded aluminum foil that contained 50 perforations before flowing; c) the existence of perforated foil provides an almost continuous flow path across this foil plane; and, d) this fracture design was used before in the literature(16, 17).

Experimental Procedure

In each experiment, the selected horizontal well with required specifications (total and perforated lengths) was inserted into the sandpack of the model. Sand particles were packed into the box...
and put under constant vibration for seven hours to ensure a good packing process. Then, pressure gauges were inserted and properly tested to measure the pressure drop just above and along the horizontal well axis.

The sandpack was evacuated, saturated with fresh water, and flooded with actual crude oil from one of the major UAE reservoirs to establish the initial oil-in-place condition. The weight difference between the evacuated pack and the water saturated one was used to calculate the porosity volumetrically. Then, crude oil of 5.0 cp viscosity (at 30°C) was injected until a steady-state condition was attained and secured. Finally, the pressure drops along the horizontal well were measured with their corresponding flow rate.

### Results and Discussion

#### Homogeneous Formations

**Effect of Perforated Length Fraction**

Three experiments (Runs #1, #2, and #3) were performed using three different horizontal wells of different perforation fractions of 15%, 30%, and 60% of total well length, respectively. All the three runs used constant perforation intensity of 29 perforations per square inch and a constant horizontal well length of 45 cm. Well properties and physical properties of the runs are presented in Table 1. The attained outlet flow rate was measured and graphically plotted vs. pressure drop along the horizontal well as shown in Figure 2. The data plotted in Figure 2 reveals good steady-state of single liquid flow condition, which is reflected in the existence of straight lines with good correlating coefficients (almost R² of 0.99), since the deviation from the straight line condition of Q_{friction} vs. ΔP is considered as a deviation to transient or unsteady-state flow regime. Figure 2 describes the increase of flow rate when the pressure drop along the horizontal well increases. The slope of each straight line plotted in this figure represents the productivity of the well (Q/ΔP). Figure 3 depicts well productivity (Q/ΔP) vs. fraction of perforated length to total well length (PL/L) for horizontal well length of 45 cm and under steady-state conditions. This figure shows the increase of horizontal well productivity with the increase of the PL/L ratio.

**Effect of Total Length**

Three experiments (Runs #4, #5, and #6) were performed using three different lengths of horizontal wells including 14 cm, 24 cm, and 34 cm, respectively, as shown in Table 1. The wells have the same perforation intensity of 29 perforations per square inch and the same perforation ratio (PL/L) of 30% of the horizontal well length. The data obtained from Run #2 was used with data from the three experiments (Runs #4, #5, and #6) to investigate the effect of total length on the performance of the horizontal well. Figure 4 shows that the increase of total horizontal well length increases the flow rate when both perforation ratio (PL/L = 30%) and perforation intensity (29 perforations per square inch) are constant. Horizontal well productivity (Q/ΔP) also increases when the total horizontal section increases more than 24 cm (or for PL/L > 52%), as shown in Figure 5.

### Table 1: Horizontal well properties and petrophysical properties of homogenous formations.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Horizontal Well Length (L) (cm)</th>
<th>Perforated Well Length (PL) (cm)</th>
<th>Perforation Ratio (PL/L) (%)</th>
<th>Porosity (%)</th>
<th>Permeability (darcy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>6.75</td>
<td>15</td>
<td>32.75</td>
<td>0.73</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>13.50</td>
<td>30</td>
<td>35.79</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>27.00</td>
<td>60</td>
<td>36.38</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>4.20</td>
<td>30</td>
<td>31.82</td>
<td>0.45</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>7.20</td>
<td>30</td>
<td>34.67</td>
<td>0.39</td>
</tr>
<tr>
<td>6</td>
<td>34</td>
<td>10.20</td>
<td>30</td>
<td>35.09</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Average = 34.42 Average = 0.69

### Figure 2: Influence of perforated well length on flow rate-pressure drop behaviour of horizontal well through unconsolidated formation.

### Figure 3: Influence of portion of perforated well on productivity of horizontal well through homogeneous formations.

### Figure 4: Influence of horizontal well length on well productivity for constant perforated ratio (PL = 30% L)
Fractured Formations

A set of six runs was conducted to assess the effect of horizontal and vertical fractures on the productivity of horizontal wells. Well properties and physical properties of the runs simulating horizontal and vertical fractures are presented in Tables 2 and 3, respectively.

Horizontally-Fractured Formation

One of the main reasons for the success of horizontal well applications is the intersection with vertical fractures. Therefore, the influence of horizontal fractures parallel to the well axis has not been investigated. Figure 6 indicates the influence of perforated well length on flow rate-pressure drop behaviour for a fractured formation where a single fracture exists parallel to the well axis, i.e., horizontal fracture. It shows the increase in the attained flow rate as the perforated length of the horizontal well increases. Figure 7 shows the increase of the flow rate as the pressure drop along the horizontal well increases at a constant perforation ratio (PL = 30% L) and in the presence of a single horizontal fracture.

Vertically-Fractured Formation

In many cases, the drilled horizontal well does not intersect with all vertical fractures. For this reason, this study investigates the influence of a vertical fracture (which does not intersect with a well axis) on well productivity. Figure 8 shows a relationship between the flow rate of a horizontal well and the pressure drop along the horizontal well in the presence of a single vertical fracture for different perforation lengths of 15 cm, 30 cm, and 60 cm. It shows an increase in the attainable flow rate as the perforated length of the horizontal well increases. Figure 9 indicates that flow rate increases as the pressure drop along the horizontal well increases for a constant perforation ratio (PL/L = 30%) and in the presence of a single vertical fracture.

Comparison of Productivity Ratio

Figure 10 shows a comparison of the productivity of homogeneous, homogeneous with single horizontal fracture, and homogeneous with single vertical fracture porous media as a function of perforation ratio (PL/L). It indicates clearly that vertical fracture resulted in significant improvement of horizontal well productivity over horizontal fracture. Based on the results plotted in Figure 10, three different empirical correlations have been developed to predict the horizontal well productivity for homogeneous, single vertically-fractured, and single horizontally-fractured formations. These equations are presented in Appendix A. The main application of the derived empirical correlations are to: 1) provide a tool for the design of small-scale horizontal well experiments; (2) provide a suitable set of data for tuning the single well simulation models before applying to a full field simulation; 3) predict the horizontal well productivity ratio based upon perforated length when the horizontal well does not intersect fractured formations; and, 4) introduce a mathematical expression which can be applied for future scaling-up studies as a horizontal wellbore hole in a real reservoir/field. In general, the previous findings confirm the importance of the vertical to horizontal permeability ratio ($k_v/k_h$) for fractures which do not intersect with a well axis and its effects on the productivity of horizontal wells. In this experimental study, for

### TABLE 2: Horizontal well properties and petrophysical properties of horizontal fractured system.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Horizontal Well Length (L) (cm)</th>
<th>Perforated Well Length (PL) (cm)</th>
<th>Perforation Ratio (PL/L) (%)</th>
<th>Porosity (%)</th>
<th>Permeability (darcy)</th>
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<tbody>
<tr>
<td>1</td>
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<td>15</td>
<td>29.83</td>
<td>0.91</td>
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<td>32.17</td>
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<td>33.72</td>
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<td>34</td>
<td>10.20</td>
<td>30</td>
<td>36.71</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Average = 33.37 Average = 0.76

### TABLE 3: Horizontal well properties and petrophysical properties of vertical fractured system.

<table>
<thead>
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<th>Run #</th>
<th>Horizontal Well Length (L) (cm)</th>
<th>Perforated Well Length (PL) (cm)</th>
<th>Perforation Ratio (PL/L) (%)</th>
<th>Porosity (%)</th>
<th>Permeability (darcy)</th>
</tr>
</thead>
<tbody>
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<td>31.98</td>
<td>0.73</td>
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<td>10.20</td>
<td>30</td>
<td>34.86</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Average = 34.22 Average = 0.77
the systems without fractures, vertical and horizontal permeabilities were equal \((k_v/k_h) = 1.0\) as a result of using sand pack with small variations in mesh number.

Conclusions

In this experimental study, the influences of perforated length and total length of a horizontal well on flow rate-pressure drop behaviour are investigated and the following conclusions are obtained:

1. The increase of perforated well length and/or total well length of a horizontal well increase(s) flow rate and well productivity under steady-state flow conditions in homogenous reservoirs and fractured formations, which do not intersect with a well axis;

2. Formations of vertical and horizontal fractures, which do not intersect with a well axis, yield higher well productivity than homogeneous ones penetrated by horizontal wells;

3. Analysis of the performance of the fractured formations indicates that vertically-fractured formations provide higher productivity than horizontally-fractured ones through horizontal wells when both fractures do not intersect with a well axis; and,

4. Different empirical correlations have been developed, based upon a small-scale model, to predict the horizontal well productivity using perforated lengths for homogenous, single vertically-fractured, and single horizontally-fractured formations.

NOMENCLATURE

\[K\] = rock permeability, md

\[\Delta P\] = pressure drop along horizontal section of horizontal well, kPa

\[L\] = total horizontal well length, cm

\[PL\] = perforated length of total horizontal well length, cm

\[PR\] = well productivity ratio = \(Q/\Delta P\), cm\(^3\)/min/psi

REFERENCES


Appendix A

Developed Empirical Correlations for Horizontal Well Productivity Ratios

Homogenous Formation

\[ PR = 0.1731 \ln(PL) - 0.0888 \]
\[ R^2 = 0.9796 \]  
A-1

Single Horizontally-Fractured Well

\[ PR = 1.2984 \ln(PL) - 1.0495 \]
\[ R^2 = 0.9959 \]  
A-2

Single Vertically-Fractured Well

\[ PR = 1.4355 \ln(PL) + 0.181 \]
\[ R^2 = 0.903 \]  
A-3

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Professor A.Y. Zekri received his B.Sc., M.S., and Ph.D. degrees from the University of Southern California. He has spent more than two decades in the petroleum industry. Professor Zekri worked as a consultant to the management committees of Waha Oil Co., Agip Oil Company, and the Petroleum Research Centre of Libya. He has authored or co-authored more than 90 papers on new developments and technical issues in the areas of improved oil recovery, flow through porous media, and petroleum contracts. He has edited and refereed technical papers in widely respected journals. Professor Zekri is currently working as a professor of petroleum engineering at the United Arab Emirates University.