1. Introduction

A fracture system inherent makes fractured reservoirs seepage space more complicated. Large-scale fracture morphologies and strikes, etc. have been broadly investigated and deeper insights have been gained into the seepage law between the matrix and the fracture system. However, it is less likely to identify small-scale fractures (e.g., micro-fractures and potential fractures that are even closed in their virgin states). Consequently, such small-scale fractures have not been profoundly studied on and the influence of micro-fractures on development and production behavior is still not determined yet. In addition, some scholars believed that micro-fracture development could improve the formation seepage capability. Nevertheless, excessive productivity improvement may lead to rapid water cut rising and recoverable reserve declining. In this case, an optimal production production control condition of micro-fractured reservoirs should be furtherly studied on.

In this paper, the relative permeability experiment is firstly designed for the purpose of identifying seepage law of micro-fractured reservoirs under different displacement velocities conditions. Then, the dynamic performance affected by micro-fracture development is further analyzed. Based on a waterflooding performance prediction model, quantitative relationship is confirmed for recoverable reserve decline and pressure drop. Furthermore, a differentiated production control conditions for micro-fractured reservoirs development was proposed, which could be utilized for improving micro-fractured reservoirs development effect.


2.1 Oil-water relative permeability experiments in conditions of the same fracture width but different displacement velocities based on an un-steady state method

To explore seepage law of micro-fractured reservoirs and identify the optimal production control condition, oil-water relative permeability experiments are particularly designed based on an unsteady-state method in conditions of the same fracture width but different displacement velocities conditions [1,2]. In addition, the unsteady-state method is adopted, with the goal of reducing interference of other factors, to perform oil-water relative permeability experiments for the same core.

Experimental conditions: Confining pressure: 5MPa; Temperature: 35℃

Experimental fluid: Natural outcrop sandstone; Saturated formation water salinity: 226,000mg/L; Formation water density: 1.1723g/ml; Formation water viscosity: 1.28mPa.s; Oil viscosity: 3.42mPa.s;

Key experimental procedures:

Step1: Basic parameters (e.g., porosity and permeability) and relative permeability curves were tested before fracture generation;

Step2: Linear load was applied for micro-fracture generation in a direction along the core diameter based on the Brazilian splitting method; Considering that the fracture section was uneven, there may exist secondary fractures (More similar to the actual underground micro-fracture morphology); Both porosity and permeability were tested after fracture generation.

Step3: Relative permeability curves were tested in conditions of the same microfracture width but different seepage velocities (i.e., different displacement pressure differential).

2.2 Analysis on displacement law in conditions of the same fracture width but different displacement velocities
Five groups of relative permeability curves are listed in Table 1. It could be concluded that as the displacement velocity increasing, the oil relative permeability under $S_{wc}$ and the water relative permeability under $S_{or}$ show turning points while the corresponding displacement velocity reaches 1.6ml/min.

**Table 1. Experimental data summary for oil-water relative permeability in conditions of the same micro-fracture width and different displacement velocities based on an unsteady-state method**

<table>
<thead>
<tr>
<th>Displacement velocity (ml/min)</th>
<th>$S_{wc}$ (%)</th>
<th>Oil relative permeability under $S_{wc}$ (mD)</th>
<th>$S_{or}$ (%)</th>
<th>Water relative permeability under $S_{or}$ (mD)</th>
<th>$K_{rel}(S_{or})$ (%)</th>
<th>Displacement Efficiency (%)</th>
<th>Oil-water co-seepage area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>45.7</td>
<td>165</td>
<td>28.3</td>
<td>94</td>
<td>56.9</td>
<td>47.9</td>
<td>26.0</td>
</tr>
<tr>
<td>0.87</td>
<td>45.7</td>
<td>152</td>
<td>29.3</td>
<td>78</td>
<td>51.5</td>
<td>46.0</td>
<td>25.0</td>
</tr>
<tr>
<td>1.66</td>
<td>46.3</td>
<td>174</td>
<td>31.4</td>
<td>144</td>
<td>82.8</td>
<td>41.5</td>
<td>22.3</td>
</tr>
<tr>
<td>2.55</td>
<td>43.9</td>
<td>170</td>
<td>29.9</td>
<td>109</td>
<td>64.1</td>
<td>46.7</td>
<td>26.2</td>
</tr>
<tr>
<td>3.42</td>
<td>45.2</td>
<td>128</td>
<td>26.8</td>
<td>61</td>
<td>47.6</td>
<td>51.1</td>
<td>28.0</td>
</tr>
</tbody>
</table>

**Notes:** Porosity: 22.6%; Permeability before fracture generation: 80.7mD; Permeability after fracture generation: 303mD;

Oil-water displacement efficiency changes with certain rules instead of a monotone function under various displacement velocities. At a micro-scale, synergistic interaction comes into play preferably once a balance is achieved between the displacement velocity and imbibition velocity. In this case, better displacement efficiency could be generated. In the case of a low displacement velocity, imbibition plays a leading role; and favorable displacement efficiency is achieved considering that relevant fractures are all single fractures on the whole. Under the circumstance that displacement velocity rises to a level above the imbibition velocity, the displacement effects become poor. When the displacement velocity is further elevated to a certain level, matrix-fracture displacement pressure differential climbs; and, residual oil that cannot flow originally begins to move, which is embodied in residual oil saturation decline and displacement efficiency improvement. Situations described above are all specific to cases of single fractures. In the context of complex secondary fracture development or fracture systems, corresponding behavior variation rules are also rather sophisticated. Therefore, rapid development should not be conducted, because it may lead to entrapment of residual oil in matrix by fractures, recoverable reserve decrease and poor development effects.

3. Quantitative Relationship of Recoverable Reserve Reduction and Production Control Condition for Micro-fractured Reservoirs

Based on modified Welge equation and material balance equation, a new waterflooding prediction model was proposed as follows.

$$N_p = N_R = \frac{A}{(L_p + C)^n} \quad (1)$$

Taking well A-31 as an example as shown in Figure 1, it becomes clear that slopes of curves significantly changes after liquid increasing; In addition, water cut increase accelerates, while the corresponding recoverable reserve decreases. Therefore, there is an optimal production control condition for micro-fractured reservoirs development.
Figure 1. Dynamic performance comparison before and after liquid increasing under the influence of micro-fracture development

The proposed model is utilized to respectively predict recoverable reserves before and after liquid increasing; and the quantitative relationship is confirmed for recoverable reserve decline and pressure drop differential subsequent to liquid increasing producers where micro-fractures are developed in oilfield A, as shown in Figure 2.

Figure 2. Quantitative relationship of producing pressure drop differential and recoverable reserve reduction

The proposed differentiated production control condition could be proposed as follows.

i. Regarding large-scale fractures development: Tectonic fractures are developed in this area. In three wells 100m away from the fault, the fracture scale is rather large. As revealed by relevant trend lines, the interval of such three wells differs from that of other wells which suffer the influence of fracture development. Moreover, no intersection point where the recoverable reserve is zero is found. In other words, pressure drop should be under strict control as far as large-scale fractures are concerned. For this reason, liquid increasing could not be conducted blindly for the purpose of avoiding sudden water influx.

ii. Regarding micro-fractures and potential fractures development: A quantitative tendency chart of producing pressure differential and recoverable reserve reduction signifies that a zero point of recoverable reserves obtained under the influence of micro-fracture development lies between 400Psi and 800Psi. In other words, a reasonable producing pressure drop should be controlled below 400-
800Psi. Clearly, the reasonable producing pressure drop could vary within a certain range, which indicates that micro-fractures are developed to diverse degrees and different micro-fracture development levels correspond to different producing pressure drops.

iii. Regarding formation with no micro-fractures development: Liquid incrasing may be fulfilled. Considering that potential fractures may be developed, it is suggested that no blind liquid incrasing should be carried out. Corresponding liquid incrasing could be gradually completed at a small scale to observe dynamic variation rules. Here, it is highly recommend not to perform large-scale liquid incrasing.

4. Conclusions

(1) According to relative permeability experiments of fracture-matrix coupling subjected to the same micro-fracture width but different seepage velocities (i.e., different pressure drops), the optimal displacement velocity is defined for micro-fractured reservoirs. To be specific, synergistic interaction is best exerted when a balance is achieved between displacement and imbibition velocities, generating the best development effect.

(2) A quantitative relation is established between recoverable reserve reduction and producing pressure drop of micro-fractured reservoirs. Under the circumstance that the recoverable reserve reduction is zero, the corresponding producing pressure drop is deemed to be reasonable. Besides, a differentiated production control condition is also proposed so as to prevent rapid water cut increase and recoverable reserve reduction. In details, different fracture development levels correspond to different producing pressure drops.

(3) Considering that micro-fractures (or potential fractures) with a small scale cannot be identified easily, their behavior may be observed to analyze the dynamic performance. Here, the proposed method could be utilized to analyze a rational production control condition of micro-fractured reservoirs based on actual dynamic performance data, which has certain reference significance for micro-fractured reservoir development.

Acknowledgements

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>A, C, m</td>
<td>Coefficients</td>
<td></td>
</tr>
<tr>
<td>S_{wc}</td>
<td>Irreducible water saturation (%)</td>
<td></td>
</tr>
<tr>
<td>K_{rw}(S_{or})</td>
<td>Water relative permeability under residul oil saturation (%)</td>
<td></td>
</tr>
<tr>
<td>L_{p}</td>
<td>Cumulative liquid production(cm³)</td>
<td></td>
</tr>
</tbody>
</table>

Recoverable reserves(cm³)

Residul oil saturation (%)

Cumulative oil production(cm³)

References
