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Classification of Well Test Models and Characterization of Opening Pressure for Water-Induced Fractures[#]

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ABSTRACT

For low permeability reservoirs, water-flooding development is usually adopted, which leads to induced fractures near the wellbore, increasing reservoir heterogeneity, making the residual oil distribution more complex, and significantly increasing development costs. This study focuses on low-permeability reservoirs. Based on well test pressure monitoring data from production sites and their characteristic patterns on log-log pressure response plots, and considering the characteristics of water injection-induced fracture composite zones, four typical models and their corresponding water flooding types were identified. Through analyzing the dynamic mechanisms of opening and closing of water injection-induced fractures, a new method for interpreting the opening pressure of these fractures was proposed. This method accurately characterizes the opening pressure thresholds of water injection-induced fractures under different classification models. Subsequently, several water injection wells in the J Oilfield were selected to verify the opening pressure thresholds and analyzed the opening pressure thresholds for water injection-induced fractures corresponding to different reservoir depths, permeabilities, and the four classification models. The results show that this method of interpreting the opening pressure of induced fractures based on well test pressure monitoring data exhibits high rationality and accuracy in characterizing the opening pressure thresholds of induced fractures. The opening pressure of induced fractures in Mode 2 and Mode 3 is higher than that in Mode 4; with increasing depth, the opening pressure of induced fractures tends to increase; and as the interpreted permeability from well testing increases, the opening pressure of induced fractures tends to decrease.

Keywords: low permeability reservoirs, well test pre -ssure monitoring data, water injection-induced fract ure, the opening pressure thresholds

1. INTRODUCTION

Water injection-induced fractures can significantly enhance the injectivity of injection wells in low-permeability reservoirs. However, due to the contradiction between the low permeability of the formation and the high conductivity of the induced fractures, the injected water rapidly channels along the fractures. This results in severe water flooding imbalances, exacerbating the dynamic heterogeneity of the low-permeability reservoir and complicating the water flooding development situation [1-4]. In view of the well test interpretation model for the formation of induced fractures in water injection wells, it is believed that due to the absence of proppant in water-injection-induced fractures, when the well is shut down for pressure test, the fracture will gradually close with the decrease of bottom hole pressure. The water previously stored in the fracture is squeezed into the formation, and the early pressure response after the well shutting down presents a straight line with a pressure derivative unit slope [5]. For water-flooding reservoirs, the injection of water changes the fluid flow in the formation from single-phase to oil-water two-phase flow. Consequently, well test data from injection wells must be interpreted based on a two-phase flow mathematical model, typically using the composite reservoir flow theory for well test analysis [6]. Considering the wellbore storage and skin effect, Li et al. [7] established a mathematical model of an oil-water two-phase unsteady flow well test considering the influence of water cut and drew a new typical curve chart of oil-water two-phase flow well test. Liu et al. [8] established a well test mathematical model of a two-zone composite reservoir with water injection wells considering the influence of water cut and solved it analytically. The effects of different water cut, water saturation, permeability ratio, water drive front radius, and other parameters on the well test curve were analyzed. Additionally, many researchers have studied the threshold pressure for the opening of natural and

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artificial fractures in low-permeability reservoirs [9-10]. However, most of these studies have employed rock fracturing experiments and field monitoring methods.

At present, there is a lack of a comprehensive and systematic set of log-log pressure response type curves for diagnosing and identifying water injection-induced fractures in low-permeability reservoirs. Moreover, there is no clear characterization method for the threshold pressure for the opening of these induced fractures. Therefore, accurately identifying the characteristics of different types of log-log pressure response curves in the reservoir, delineating typical water flooding patterns, characterizing the threshold pressure for the opening of induced fractures corresponding to these patterns, and effectively controlling and utilizing water injection-induced fractures are the key objectives of this study.

2. PRESSURE RESPONSE TYPE CURVE ANALYSIS

2.1 Four typical models

The typical characteristics of Mode 1 on the pressure response type curve include the early pressure and derivative curves coinciding, presenting a straight line with a slope of 1, indicative of the wellbore storage stage. After the curves diverge, the pressure derivative curve slowly rises and then falls, indicating a positive skin effect with no induced fractures from water injection. The pressure derivative curve then starts to extend horizontally. Due to the short testing time, the pressure wave affects the oil-water flow region around the injection well, indicating a large area of influence.

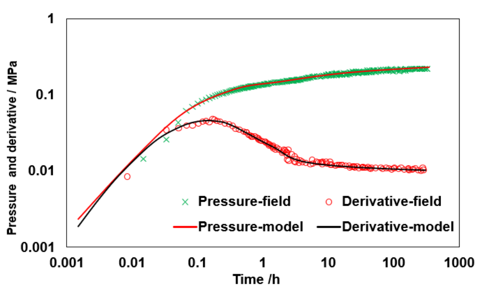

Fig. 1 Mode 1 well test pressure curve

Mode 2 features early pressure change and derivative curves coinciding, forming a straight line with a slope of 1, representing the wellbore storage stage. After the curves diverge, the pressure derivative curve gently rises with a slope of 1/2, indicating the linear flow phase caused by water injection-induced fractures. As testing continues, the pressure derivative curve exhibits a first horizontal segment, representing the inner zone radial flow, (i.e., the radial flow stage of the oil-water two-phase zone around the injection well.) Further on, the pressure derivative curve shows an upward trend, indicating the pressure wave has reached the water drive front, followed by a second horizontal segment, representing the outer zone radial flow, (i.e., the radial flow stage of the uninvaded zone (pure oil zone) far from the injection well.) The second horizontal segment of the pressure derivative curve is above the first, suggesting through analysis of flow coefficients and zonal radii that the well's composite zonal characteristics are "good inner, poor outer," meaning the reservoir properties in the inner zone are better than those in the outer zone.

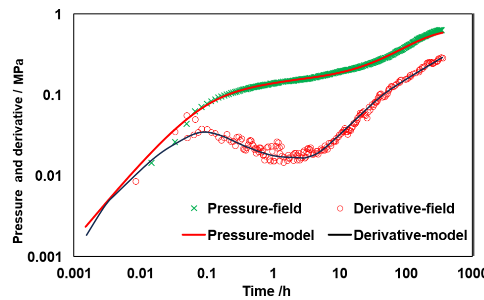

Fig. 2 Mode 2 well test pressure curve

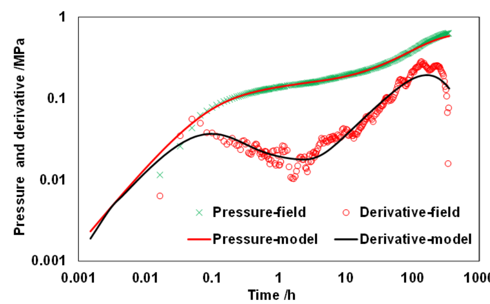

Fig. 3 Mode 3 well test pressure curve

Mode 3 is similar to Mode 2, with the only difference being that the pressure derivative curve starts to drop at the end, indicating a constant pressure boundary. This boundary effect might be due to the pressure wave influence from surrounding injection wells, causing inter-well connectivity and water flooding, preventing effective displacement between injection and production wells, significantly impacting later oilfield development.

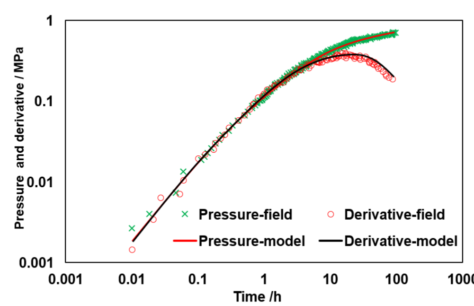

Fig. 4 Mode 4 well test pressure curve

Mode 4 is characterized by a large wellbore storage coefficient and a long well storage duration, considered to be due to fracture storage. The pressure recovery at the end of this storage phase can be used to determine the opening pressure of the water injection-induced fractures.

2.2 The opening pressure thresholds of water-induced fractures

In well test interpretation, the determination of induced fracture occurrence relies on the presence of a linear flow line with a slope of 1/2 in the pressure drawdown log-log plot. Mode 1, characterized as a matrix porosity type, generally does not induce fractures. Mode 2 represents water-induced fractures-water drive zonation, while Mode 3 represents inter-well connectivity due to water injection. In both these modes, the linear flow line with a slope of 1/2 in the pressure drawdown log-log plot is not prominent, and the pressure at the secondary fracture opening is inevitably lower than the pressure corresponding to the initial opening pressure. Consequently, it can be considered that the opening pressure of induced fractures in these two modes lies between the average reservoir pressure and the initial fracture opening pressure.

Mode 4 is characterized as a fracture storage type. When the injection well starts a shut-in pressure test, the induced fractures gradually close. The end of the fracture storage period (indicated by the divergence of the pressure and pressure derivative curves) signifies the complete closure of the fractures. At this point, the pressure recovery can be used to represent the opening pressure of the water-induced fractures.

3. RESULTS AND DISCUSSION

The theoretically derived induced fracture opening pressures for Mode 2, Mode 3, and Mode 4 are validated using the historical production data of the corresponding injection wells. Since water-induced fractures occur after the first injection in the respective wells, the induced fracture opening pressure must be lower than the initial opening pressure. By analyzing the production dynamics of the injection wells during the corresponding well test periods, we can validate the induced fracture opening pressure. If the induced fracture opening pressure derived from well testing is lower than the wellhead pressure recorded in the injection well's production data (after converting the well test pressure from bottomhole to wellhead for verification), the theoretically derived induced fracture opening pressure is considered relatively accurate. This method of interpreting induced fracture opening pressure based on well test pressure data has been found to be highly reasonable and accurate in characterizing the limits of induced fracture opening pressure.

For Mode 2 and Mode 3, the induced fracture opening pressure obtained falls within a range. This is because both types belong to the induced fracture zoning category, where the presence of distinct linear flow lines with a slope of 1/2 in the pressure derivative log-log plot is not prominent. However, for Mode 4, the induced fracture opening pressure is definitive. It corresponds to the point where the pressure curve and the pressure derivative curve first diverge in the log-log pressure response plot. Therefore, the opening pressure is a singular value, not a range.

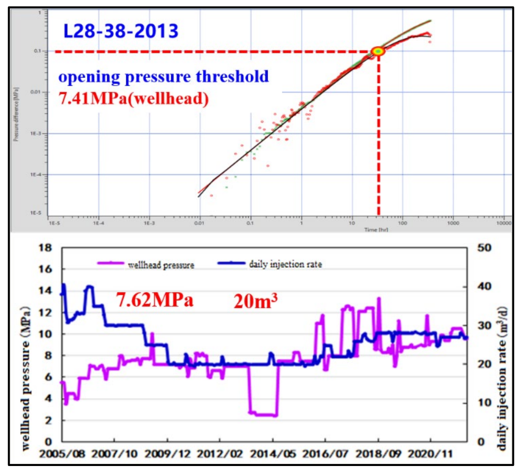

Fig. 5 Mode 4 induced fracture opening pressure threshold validation

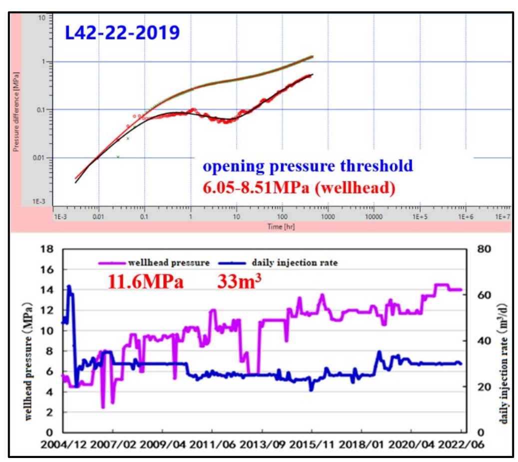

Fig. 6 Mode 2 and mode 3 induced fracture opening pressure threshold validation

Under certain pressure conditions, water-induced fractures begin to expand and open, influenced by factors such as reservoir depth, permeability, and reservoir fluid pressure. Building upon previous methods for characterizing the opening pressure threshold, this study further analyzes the impact of varying reservoir depths and permeabilities on the opening pressure thresholds of water-induced fractures corresponding to different modes.

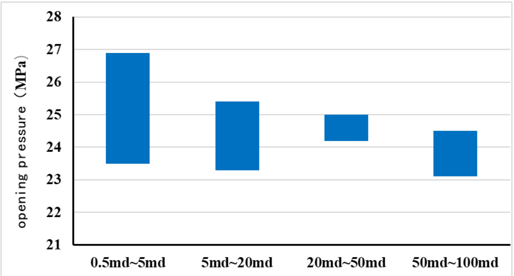

Fig. 7 Distribution of opening pressures for different permeabilities

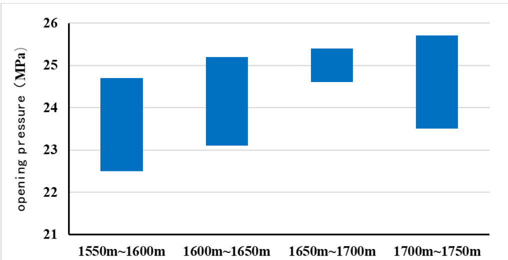

Fig. 8 Distribution of opening pressures for different reservoir depths

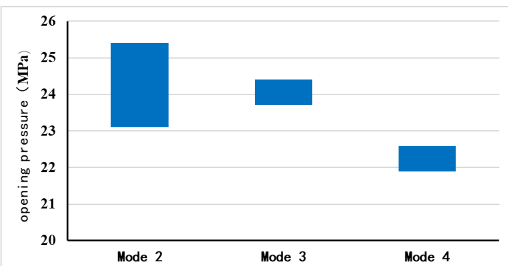

Fig. 9 Distribution of opening pressures for different modes

4. CONCLUSIONS

Through the interpretation and analysis of pressure data during the shut-in phase of water injection wells in low permeability reservoirs, the pressure response graphs can be categorized into four modes. Mode 1 is the homogeneous type, with no induced fractures, where pressure propagates within the water-invaded zone, and the pressure derivative curve is a horizontal line. Mode 2 involves water-induced fractures with zonation, where induced fractures open, and after the pressure wave reaches the water drive front, the pressure derivative curve shows an upward trend. Mode 3 is characterized by inter-well connectivity due to water injection, where induced fractures open, and the pressure derivative curve declines in the later stage. Mode 4 is the fracture storage type, where induced fractures open, and the pressure derivative curve displays high storage characteristics with a slope of 1. These modes provide a comprehensive framework for understanding the pressure behavior in different scenarios of water injection in low permeability reservoirs.

The opening pressure thresholds for induced fractures vary among different water injection wells. For Mode 2 and Mode 3, the opening pressure threshold is a range, while for Mode 4, it is a specific value. When compared with injection dynamics, the opening pressure thresholds show a high degree of accuracy. Additionally, the opening pressures exhibit different trends with changes in reservoir depth, permeability, and mode.

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