Petroleum xxx (2017) 1–9

Contents lists available at ScienceDirect

Petroleum

journal homepage: www.keaipublishing.com/en/journals/petlm

Wormholes propagation for fractured-vuggy formation: Laboratory tests, numerical simulation and field application

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ARTICLE INFO

Article history:
Received 15 December 2016
Received in revised form
2 May 2017
Accepted 27 May 2017

Keywords:
CT scanning
Digital core
Dolomite
Wormhole
Fractured-vuggy reservoir
Matrix acidizing
Acid fracturing

ABSTRACT

The propagation of wormhole is vital important for matrix acidizing and acid fracturing in carbonate reservoirs. While the formation of acid dissolved wormhole is derived from heterogeneous physical and chemical transportations and reactions. Alveolate dissolved pores, krast caves, and natural fissures are the major reservoir spaces for the Sinian dolomite formation in the Anyue gas field of the Sichuan Basin. There were four categories of formation, which are matrix dominated, inter-breccia dissolved pore dominated, dissolved pore and cave dominated, and fissure and cave dominated, based on the development intensity and connectedness of caves and fissures. The caves and fissures make the wormhole formation and propagation particularly complicated. Firstly, the 3-D topological structure of dissolved pores, vugs, fissures and throats inside cores is quantitatively scanned by CT imaging technology for its feature of vivid and damage-free. Secondly, 3-D patterns of wormhole are obtained with CT scanning after core flooding by acid. Additionally, the pore-throat network model is reconstructed with digital cores technology. Then, the size and ratio of pore and throat before and after core flooding by acid is analyzed and the absolute permeability of pore scale flow is numerically simulated to understand the fundamental influence of pores and vugs distribution and connectedness on wormhole propagation. Lastly, the wormhole pattern gained by CT scanning and simulating with two-scale model is compared. Meanwhile, the corrected two-scale model is utilized to simulate the wormhole propagation for matrix acidizing and acid fracturing of Sinian fractured-vuggy dolomite in Anyue gas field, Sichuan Basin. The optimized injection rate and volume were in agreement with the characteristic matrix acidizing operating curve, which indicates that the two-scale model was suitable for matrix acidizing optimization design of such formations. In addition, the simulated acid etched fracture length with considering the dynamic wormhole leakoff was consistent with the well testing interpreted result.

1. Introduction

The injected acids flow inside and dissolve the larger pores with less resistance selectively during matrix acidizing and acid fracturing for carbonate reservoirs. This heterogeneous physical and chemical transportations and reactions generate acid dissolved wormholes. The acid injection rate and volume should be optimized for matrix acidizing to ensure the acid dissolved wormholes breakthrough damaged zone exactly. While, the formation of wormhole causes excessive acid leakoff, which restricts the acid etched fracture length for acid fracturing.

The pattern and development of wormhole has been the focus of acid stimulation. The metal casting was initially used to investigate the patterns of wormholes [1]. The Computed Tomography (CT) scans with digital core analysis, which can accurately locate and quantitatively characterize the pore throat non-destructively [2,3], has been becoming the current main

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Peer review under responsibility of Southwest Petroleum University.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.petlm.2017.05.007

method in the form of wormhole [4]. In the terms of wormhole propagation, many scholars have conducted a large number of laboratory experiments [5–7] and theoretical simulation [8–10] aiming to obtain the optimal injection rate and the corresponding breakthrough volume, PV_{bt}, to guide acidizing design. The two-scale continuum model, in which the motion and continuity equations were solved by the Darcy scale and the physical parameters were calculated by the pore scale, has been widely used and extended in studying carbonate reservoir stimulation [10–12]. The wormhole development is influenced by mineral composition, spatial distribution of pore and throat, acid type and concentration, injection condition and temperature.

The Sinian dolomite formation of Anyue gas field is characterized by various storage types and strong heterogeneity [13]. The existence of dissolved vugs and micro fissures [14] complicated the propagation of acid etched wormholes. CT scan and digital core analysis has been used to study the development of acid etched wormholes. In addition, the two-scale model was calibrated with CT scanning and digital core analysis to simulate the wormhole propagation for matrix acidizing and acid fracturing in field scale.

2. Laboratory experiment

There were 6 cores of the Sinian formation with varying dissolved pores and vugs from three wells, as shown in Table 1. The cores were CT scanned firstly to quantitatively obtain the 3D topology of dissolved vugs, natural fissures, as well as pores and throats. Then, the core flooding experiment was carried out with varies injection rates, followed by CT scanning to analysis the 3D patterns of acid etched wormholes. Finally, the digital core analysis was used to analysis the influence of pores and vugs on wormhole propagation.

2.1. Spatial distribution of pores and vugs

The highest resolution of nanoVoxel-2700 CT scanner, with characterization of second optical amplification, was up to 500 nm. The 3D images intuitively show the spatial distribution of pores, dissolved vugs, throats, and natural fissures, while the 2D slices showed the size and connectivity of pores and throats. Some of the core CT scan results are shown in Fig. 1.

Sinian dolomite reservoir is a low porosity and permeability reservoir with temperature varied from 144 to 156 °C and buried depth varied from 4900 to 5800 m, in Anyue gas field, Sichuan Basin. The reservoir space is mainly composed of karst caves, alveolate dissolved pores, and fissures. There were four categories of formation, which are matrix dominated, inter-breccia dissolved pore dominated, dissolved pore and cave dominated, and fissure and cave dominated, based on the development intensity and connectedness of caves and fissures. The last two categories are mainly the favorable reservoirs developed in the platform margin. However, the CT scanning images reveal that the cores contain large numbers of dissolved pores and vugs with little micro-fissure.

The cores were drilled from well A, well B, and well C, respectively. The No.1 and No.2 cores were characterized by large dissolved caves, strong heterogeneous and good connectivity. While the No.3 and No.4 cores were characterized by small dissolved pores with much more uniform spatial distribution. Note that there were massive alveolate dissolved pores developed at the core face, but it is considerable tight inside the No.5 and No.6 cores.

Table 1
Datum of cores for laboratory experiments.

No.	Length mm	Diameter mm	Porosity %	Permeability md
1	45.00	24.60	2.97	0.1908
2	48.84	24.66	3.74	0.0427
3	45.80	24.60	1.60	0.7965
4	46.20	24.60	2.24	1.0126
5	48.10	24.60	3.05	0.2081
6	46.20	24.60	2.70	0.0013

2.2. 3D patterns of wormhole

The core flooding tests were carried out with viscoelastic surfactant acid at the temperature of 130 °C. The adjacent cores were drilled from the same full-hole rock sample to minimize the influence of core heterogeneous on wormhole development.

According to the results of the experiments, only the cores, which are drilled from well A and characterized by large connected vugs, were penetrated by acid etched wormhole. The corresponding breakthrough volumes were 19.6 and 5.35, as shown in Fig. 2, for constant injection rate of 5 ml/min and 10 ml/min, respectively.

The cores drilled from well B were characterized by small dissolved pores with much more uniform spatial distribution. While the cores drilled from well C were characterized by massive alveolate dissolved pores at the core face but tight inside. Unfortunately, the displacement pressure rocketed up to the pressure limit of 40 MPa in the core flooding tests. Then, the constant pressure of 40 MPa at the inlet condition was hold. The injection rates for the No.3, No.4 and No.5 core were about 0.3 ml/min, 0.6 ml/min, and 0.3 ml/min, respectively. And the acidizing experiment for the No.6 core was failed for failure of core holding unit. It is observed that there is no acid etched wormhole formed but face dissolved for the No.3 and No.4 cores, and that the acid etched wormhole was terminated for the No.5 core.

In addition, the acid leakoff curve can be treated with the core flooding tests. Fig. 3 shows the cumulative acid leakoff volume versus leakoff time.

It is apparent that the cumulative acid leakoff volume is quadratic to $\sqrt{t}$ and linear to t for cores with wormhole, which is contrary to classical Carter leakoff theory. The presence of acid etched wormhole would increase the acid leakoff significantly. In contrast, the cumulative acid leakoff volume is linearly proportional to $\sqrt{t}$ for cores without wormhole, which is consistent with classical Carter leakoff theory. Interestingly, the slope of the fitting line was increased from 0.5682 to 4.277 for cores with non-penetrated wormhole, which indicate the formation of wormhole changed the leakoff coefficient. The slopes of fitting lines increase from 0.5682 to 5.2976, which suggest that the leakoff coefficient increased from 5.61×10^{-4} $m\sqrt{min}$ to 5.23×10^{-3} $m\sqrt{min}$ for cores without wormhole and with non-penetrated wormhole. Apparently, a single leakoff coefficient is unable to represent the acid leakoff along the whole artificial fracture face, whether the acid etched wormhole was formed or not.

The CT scanning results after acidizing are shown in Fig. 4, which clearly shows the pattern of acid etched wormholes.

The CT scanning images for 6 cores before (Fig. 1) and after (Fig. 4) acid treatment were compared. It is observed that the acid etched wormhole developed and penetrated the core at the connected macroscopic vugs for the No.2 core, which is flooding with viscoelastic surfactant acid. And there is no obvious change inside before and after acidizing for the No.4 core. The acid

Please cite this article in press as: F. Liu, et al., Wormholes propagation for fractured-vuggy formation: Laboratory tests, numerical simulation and field application, Petroleum (2017), http://dx.doi.org/10.1016/j.petlm.2017.05.007