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ScienceDirect
Natural Gas Industry B xx (2016) 1—7
www.elsevier.com/locate/ngib

Research Article

Determination of water-lock critical value of low-permeability sandstones based on digital core☆

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Received 14 January 2016; accepted 9 May 2016

Abstract

Research and development of water lock inhibiting measures is very crucial in verifying the link mechanism between the internal factors of water lock and its extent of damage. Based on conventional water-lock physics experiments, however, only the consequence of macro water lock damage can be investigated, while the microscopic mechanism cannot be studied. In this paper, 3D digital cores of low-permeability sandstones were prepared by means of high-resolution micro-CT scan, and their equivalent pore network model was built as well. Virtual "imbibition" experiments controlled by capillary force were carried out by using pore-scale flow simulation. Then the link mechanism between the microscopic internal factors (e.g. wettability, water saturation and pore—throat structure parameters) and the water-lock damage degree was discussed. It is shown that the damage degree of water lock reduces gradually as the wettability transits from water wet to gas wet. Therefore, the water lock damage can be reduced effectively and gas-well productivity can be improved so long as the capillary environment is changed from strong water wettability to weak gas wettability. The more different the initial water saturation is from the irreducible water saturation, the more serious the water lock damage is. The damage degree of water lock is in a negative correlation with the coordinate number, but a positive correlation with the pore—throat ratio. Based on the existing research results, water lock tends to form in the formations composed of medium-sized throats. It is concluded that there is a critical throat radius, at which the water lock is the most serious.

Keywords: Low-permeability sandstone; Digital core; Pore network model; Water lock; Wettability; Water saturation; Pore—throat structure parameter; Critical throat radius

A low-permeability sandstone gas reservoir is generally characterized by low porosity, low permeability, complex pore structure, abundant secondary pores, small throats and high capillary pressure; thus, water blocking is likely to occur in the process of well drilling, completion, fracturing and workover. The damage of water blocking to a reservoir could be quantitatively evaluated through lab tests now [1—7], but there are no unified criteria and proved techniques due to the complexities of pore structures and water blocking damage process itself. In a physical experiment [8—21], water would be injected homogeneously into a core; how to establish water saturation and corresponding permeability is crucial to the

☆ Project supported by the National Natural Science Foundation of China for the Youth, "Study on the Effect of Shale Bedding Architecture on Features of Ultrasonic Wave and Its Application" (No. 41502287), the S&T Program of Chongqing Land and Resources Bureau "Evaluation on Gas Saturation in Shale based on Digital Core Technology" (No. CQGT-KJ-2015018), and Sinopec Key Geophysical Laboratory Open Fund Project "Apparent Characteristics of Shale Reservoir and Digital Rock Physics Laboratory Study" (No. 33550006-15-FW2099-0015).
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Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2016.05.010

experiment. Due to small pore space and extremely low permeability, it is hard to complete such an experiment with credible results for a low-permeability sand core. A number of typical cores would be used in a water-blocking test, but the results are uncontrollable because it is difficult to measure the relative permeability accurately in such a tedious two-phase experiment. The most important is that physical experiments could show us the consequence of water blocking rather than the micro mechanism. Gas flow in a low-permeability sandstone reservoir is dependent on many factors, such as rock wettability, water saturation and pore—throat structure; whereas it is a great challenge to quantitatively delineate the relationships between these micro factors and water blocking through conventional physical experiments.

This paper uses the technique of digital core; a digital model based on CT data would first be built to characterize the pore structure of low-permeability sandstone and then virtual spontaneous imbibition experiments would be performed. This technique correlates wettability, saturation and pore—throat structure, which are difficult to be measured through a conventional physical experiment, with the damage of water blocking. The objective is to find solutions to water blocking for low-permeability sandstone gas reservoirs and to improve the ultimate gas recovery.

1. Pore structure digital modeling

An accurate digital pore-structure model is a prerequisite for virtual imbibition experiments. The so-called model here comprises a digital core model integrated with pore network. A digital core model would be built through micro-CT scanning, which is generally used for nondestructive examination of interior structures and could differentiate between pores and solid matrix of a rock because absorption coefficient of X-ray is dependent on density. This method is the most accurate direct method for digital modeling at present. MicroXCT-400 scanner (Fig. 1-a) set in the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University was employed in 3D imaging of low-permeability sand cores to generate 3D gray-level images of microstructures with high resolution (Fig. 1-b). After a series of treatment such as filtering, binarization segmentation and surface reconstruction of the raw gray-level images with such software as Matlab and Avizo, a 3D digital core model for low-permeability sand was established (Fig. 1-c, in which rock matrix is plotted in blue and pores in black).

If the pore structure is extremely complicated, numerical simulations based on an actual digital core would consume significant computer resources; thus, a pore-network model

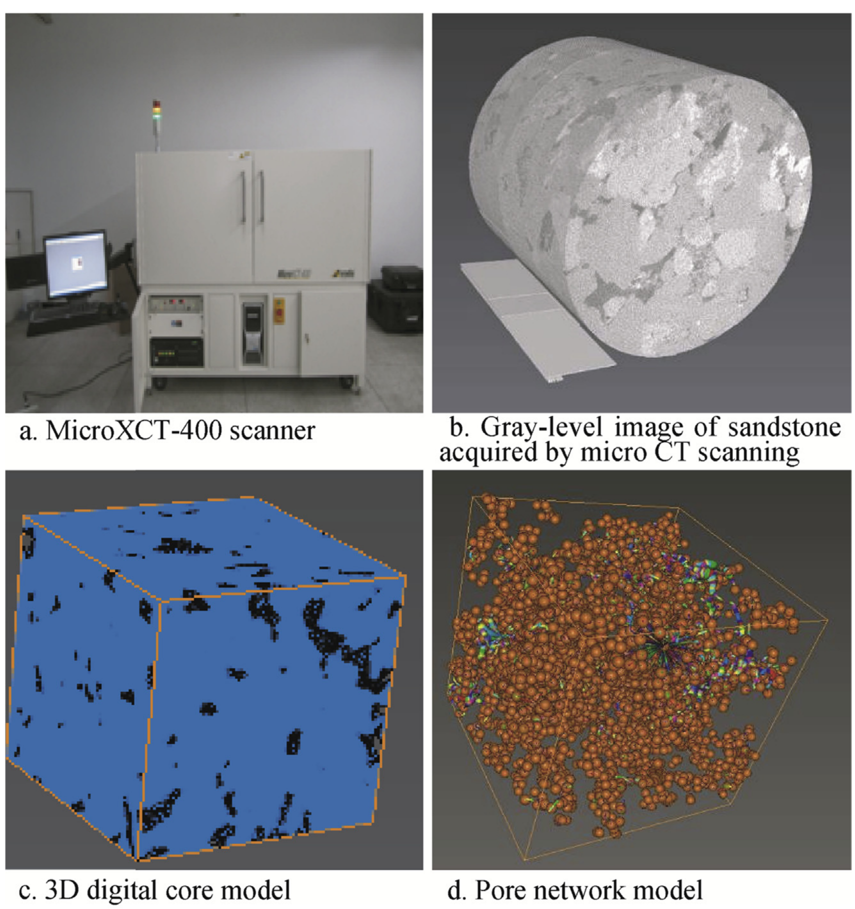

Fig. 1. Lab equipment and results.