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Experimental research of the tracer characteristic curves for fracture-cave structures in a carbonate oil and gas reservoir

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ABSTRACT

Due to the complexity of the connection between fractures and caves in a carbonate oil and gas reservoir, it is still difficult to recognize their production characteristics, which, in turn, significantly restricts the exploitation of such reservoirs as the Tahe oilfield, China. Therefore, in this work, five typical fracture-cave structures in the Tahe oilfield were modeled to investigate their tracer characteristic curves and to understand the differences in production. The experimental results indicate that the characteristic curves of the models are highly consistent with the curves obtained from the oilfield. For the signal fracture-cave connection, a "single-peak" behavior was observed on the tracer concentration curve; meanwhile, for the parallel fracture-cave structure, the tracer concentration curve shows a "double-peak" feature. For all models, a smaller internal space of the fracture or cave (especially for the fracture) corresponds to a s breakthrough time of the tracer (KBr), a higher peak value, and a faster mass concentration increase in the first stage after the breakthrough of the tracer. As the space increases, the dimensionless cumulative mass curves approach the line $y = x$, and the caves are closer to the line $y = x$ than the fracture. The bottom water dilution, tracer injection rate, injection and production model impose significant effects on tracer curves. These results are highly useful in identifying the real fracture-cave structures in the reservoirs and may at least provide a reference for analysis.

1. Introduction

The carbonate reservoir of the Tahe oilfield is the largest and also the first marine Paleozoic fracture-cave carbonate reservoir in China. The oil production of this oilfield has continued to increase since it was developed in 1997. In 2013, the annual oil production reached 6 million tons, which makes it the most productive fracture-cave carbonate reservoir in China. This carbonate reservoir was formed through the combination of multiphase tectonic movement and paleokarst, which is very different from the Middle-East fractured carbonate reservoirs and the typical Chinese eastern fractured carbonate reservoirs. The storage spaces are composed of tectonic fractures formed by structural deformation, vugs, caves, and fractures, which were generated by karstification. The large caves are considered the main storage spaces, while fractures serve not only the main reservoir storage space but also as the main flow channels. Fractures and caves usually occur in different forms, size and distributions, making the reservoir extremely heterogeneous. In addition, the deep burial depth (5000 m) also makes it more difficult to identify and characterize the fracture-cave connectivity features (Li and Fan, 2011). In other words, it is notably hard to understand the mechanism and propose an efficient development strategy for the oilfield. The primary reasons causing the difficulty in identifying the fracture-cave connectivity features are as follows: (1) due to the burial depth and the drilling cost, a large well spacing is usually applied, which leads to insufficient logging data and difficulty delineating the formation heterogeneity; (2) the low resolution of the current seismic data of the deep formation creates numerous uncertainties in geometry characterization. Therefore, conventional exploration methods such as logging, seismicity, and well drilling exploration are ineffective in characterizing the connectivity features (Li, 2012; Kang et al., 2012).

In previous reports, well test analysis, reservoir numerical simulation, geochemistry assessment, and dynamical retrieval have been used to study the dynamic connectivity of the reservoir. Ni et al. (2013) summarized six possible combinations of well and fracture-cave structures and thus established a geological model of

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reservoirs. Based on the findings, the best combination for production was also proposed. However, analysis of the interconnectivity within fracture-cave systems has not been well addressed. Luo et al. (2013) developed a cave system analysis approach via seismic reprocessing which improved the seismic image of a karst reservoir. However, it was found that their results were not in agreement with production data. Juliusson and Horne (2013) suggested a hybrid method combining historical matching and tracer testing. This method is better than pure historical matching due to the uncertainties of the fracture system. Wang et al. (2014) built a 3-D model to simulate waterflooding and investigated the factors that might affect oil recovery, assuming a connection structure of fracture-cave. However, in these researchers' work, all caves were uniformly distributed, which is too ideal to reflect the real situation. Usually, well surveillance was implemented to investigate the connectivity of fracture-cave units, including 1) single-well transient testing; 2) inter-well transient testing; 3) abnormal well performance analysis; 4) analysis of the fluid property difference; 5) CRM combining producer BHP and rate; and 6) tracer testing (Wang et al., 2003; Ding, 2009; Yi et al., 2011; Kang et al., 2012; Yousef et al., 2006; Sayarpour et al., 2009a, b; Kaviani et al., 2012; Zhang et al., 2015). However, it is easy to understand that the first three methods are not appropriate for a fracture-cave reservoir because these methods are based on the percolation theory. Methods 4) and 5) always require data with high accuracy that is almost impossible to acquire in the field. All of the methods mentioned above can only be used to analyze the connectivity between wells and the degree of the connectivity. Nevertheless, the methods are not able to identify the fracture-cave structures connecting different wells, not even the tracer tests that have been extensively carried out in the Tahe oilfield. From 2006 to 2013, a total of 53 pilot tracer tests have been carried out in the Tahe oilfield. These tests are helpful in recognizing the connectivity of the wells. However, for exploitation of the oilfield, we are more concerned about the characteristics of the tracer curve among different types of fracture-cave structures or the feature of the fracture-cave structures in the characteristics curve.

In this paper, we propose a new way to study the fracture-cave structures among different wells. Five typical fracture-cave structures were sculptured with marble and used for physical simulation experiments. Two tracer characteristic curves (mass concentration curves and dimensionless accumulative mass curves) of the five models were obtained through the tracer injection method. Afterward, the characteristics curves were compared with the field curves obtained by tracer tests in order to identify the fracture-cave structures. Meanwhile, the factors that affect the behavior of the characteristic curves were analyzed. The obtained characteristic curves could provide guidance for tracer tests carried out in the field to facilitate recognition of the real fracture-cave structure. This information is very important to the understanding of the oil recovery mechanism and to the creation of an efficient development strategy for gas and oil reservoirs.

2. Experimental section

2.1. Preparation of the fracture-cave models

The fracture-cave images were obtained from two typical wells with seismic recognition technologies. These technologies are reliable methods and have been extensively used in oilfields to investigate the connectivity of fractures and caves. These images were later converged into two simple images based on the basic shape, size and connectivity. These images were used to sculpture the physical models from marble. The physical models and the experimental conditions were designed according to the similarity principle (Li et al., 2012). During model sculpturing and tracer testing, five similarity principles were considered as follows:

1 *Material*

Considering the actual wettability of reservoir rocks, the white marble (contents more than 90% $CaCO_3$) was used to sculpture the models.

2 *Connection*

Models are developed from the structure connections of wells TK7–637H and TK421 that were detected by seismic recognition technologies (Figs. 1 and 2). The orientation of the fracture-cave is consistent with the results in the seismic curvature map.

3 *Model size*

The dimension of the model must be similar to the real structure (Li et al., 2012). The geometric similarity coefficient (k_1) can be calculated as given in Eq. (1).

$$k_l = \frac{l_m}{l_p} \tag{1}$$

Two models were sculptured according to the actual well distances of TK7–637H and TK421 using similar dimensionless numeral scale of 1:1000. The well spacing is between 300 and 977 m as shown in Figs. 1 and 2. The size of two models was 90*60*1.5 cm; the detailed dimension of the model is shown in Fig. 4.

4 *Time*

The relationship between the monitoring time in the experiment and the oilfield is expressed in Eq. (2).

$$k_t = \frac{t_m}{t_p} = \frac{l_p}{l_m} \tag{2}$$

The total injection duration is 140–200 days over the process of the tracer tests in the pilot test. The sampling was carried out every day. Therefore, according to the similar dimensionless numeral scale of 1:1000, the overall sample collection period is 3.6 h, and the sampling interval is 1.44 min.

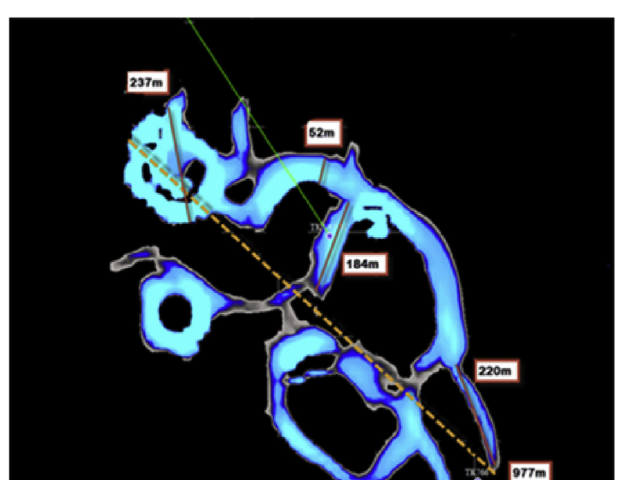

Fig. 1. Karst pipeline map of TK7-637H after curvature etching.