Measurement of Damköhler number on the X-Ray computed tomography basis in the process of heavy oil carbonate reservoir acidizing

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Abstract. Nowadays, cases of the joint use of thermal and chemical methods of enhanced oil recovery have become more frequent. In this regard, acid treatment has an important role, which allows increasing the productivity of wells with low-permeability carbonate reservoirs. At the experimental level, the presence of an optimal injection mode has been proven, that depends on the dimensionless of Damköhler number and leads to the formation of "wormholes" of dissolution with increasing reservoir permeability. In this work, a new optimized method for calculating the Damköhler number based on X-ray computed tomography data is proposed. A comparison of the calculation of values by the classical and the new technique for different wormholes is presented.

Keywords: EOR, acid treatment, carbonate acidization, wormhole, Damköhler number, microCT, X-ray computed tomography.

1. Introduction

In recent years, there have been cases of the integrated use of different enhanced oil recovery methods (EOR), including combining thermal and chemical types. In order to achieve high oil recovery efficiency, acidic treatment of the carbonate reservoir can be used in thermal EOR, which is the dominant practice in the industry to increase the productivity of wells in low-permeability. For example in work [1], to enhance oil recovery during the process of thermal-steam stimulation (TSS) in high-viscosity reservoirs, acid system was injected into low productivity production wells.

Despite many years of experience in the application and a large amount of research conducted aimed at improving and increasing the efficiency of the method, a significant part of the treatments does not give good results. The heterogeneity of carbonate rock formations significantly influences to the filtration characteristics. The success of acid treatment is
affected by the structure, length and branching of the filtration channels. In this regard, an important task is the formation of optimal channels of dissolution, leading to an increase in reservoir permeability. At the experimental level, the presence of an optimal injection mode has been proven. It depends on the dimensionless of Damköhler number and is associated with the formation of "wormholes" during the acid treatment [2]. The Damköhler number for channels of maximum efficiency has established in the interval 0.21-0.57 [3]. To determine the optimal characteristics, it is necessary to conduct experiments aimed at studying the pore space of the reservoir and its changes during the interaction of rock with acid.

X-ray computed tomography is the most convenient way to study the shape of the formed filtration channel. It allows getting maximum information about the real three-dimensional geometry of the "wormhole". However, all the advantages of this method are offset by the need to select the boundaries of the filtration channel and use approximate values of diameter and length for its calculation. The diameter of the wormhole can vary along its tracking, the wormhole itself can wriggle, making it difficult to determine its length. The situation is complicated by the formation of numerous branches from the main channel and the possible presence of several large connected channels. A new method of measurement the Damköhler number using the abilities of X-Ray computed tomography is proposed in this article.

2. Methodology

A correlation is established between the geometry of the filtering channels and the Damköhler number $N_{Da}$, which is defined as the ratio of the rate of flow of chemical interaction to the rate of acid supply, [3]. For the particular case of formation of the acid dissolution channel in the reservoir model, the dimensionless Damköhler number $N_{Da}$ is determined by the formula [4]:

$$N_{Da} = \frac{\pi dlk}{Q},$$

where $k$ is the total reaction rate constant, cm/min; $Q$ is the flow rate of fluid filtration, cm$^3$/min; $l$ is the length of the dissolution channel, cm; $d$ is the diameter of the dissolution channel, cm.

The ratio $\pi dl$ is the lateral surface area of the cylinder that is closest to the size of the filtration channel. However, the wormhole often has bends and additional branches; it is very difficult to approximate its shape with a cylinder, which can significantly distort the calculation of the Damköhler number $N_{Da}$.

Therefore, instead of the lateral surface area of the "wormhole" $\pi dl$ in formula (1), it is proposed to use an alternative parameter, which would simply be derived from the digital model. To characterize the area, it can be used not only the main filtration channel, but the entire network through which the acid has passed [5]. It can be easily segmented, as the largest associated object in the void-pore space of the sample. Thus, the new "Damköhler number" will look like:

$$N_{CT} = Sk / Q,$$
where \( k \) is the total reaction rate constant, cm/min; \( Q \) is the flow rate of fluid filtration, cm\(^3\)/min; \( S \) is the surface area of the dissolution filtration network, cm\(^2\).

To compare the results of the measurement of \( N_{Da} \) and \( N_{CT} \) on cylindrical carbonate samples with a diameter of 30 mm and a height of 30 mm, experiments with filtration of acidic compositions were performed. The flow rate for all samples was equal – 0,5 ml/min. After that, X-ray computed tomography was done for the obtained samples with wormholes. Further, the boundaries of the filtration channels were identified on the 3D rock models. The values of \( N_{Da} \) and \( N_{CT} \) were measured according to the method described in more detail in [5].

### 3. Results and Discussions

The tomography results in the form of 3D visualization of wormholes are presented in Figure 1. The morphology of the obtained wormholes shows difference of their possible shapes. The first wormhole has the widest channel with thick side branches. In the second sample, two main filtration channels were formed. The wormhole of the third sample has a tortuous shape with numerous tree-like side channels.

Based on the formulas (1) and (2) for the data of wormholes, the values of the standard Damkeller number \( N_{Da} \) and the new \( N_{CT} \) were calculated (table 1). As can be seen from the results, an increase in \( N_{Da} \) values corresponds to an increase in \( N_{CT} \), however, \( N_{CT} \) values increase to a greater extent. This is due to the fact that only the change in the diameter and length of the channel affects the \( N_{Da} \) parameter, whereas the \( N_{CT} \) takes into account not only the change in the area of the main channel, but also the area of all the resulting side branches.

| Parameter | 1 | 2* | 3 |
|-----------|---|----|---|
| \( N_{Da} \) | 0,26 | 1,94 | 2,54 |
| \( N_{CT} \) | 0,84 | 18,15 | 19,49 |

* in the sample 2 \( N_{Da} \) and \( N_{CT} \) were counted only for the biggest wormhole (the left one in Fig. 1)

### 4. Conclusions

Despite the similarity of formulas (1) and (2), they demonstrate different rate of dynamics when changing filtration parameters. Thus, the value of the classical Damköhler number will increase, but the new ratio will increase faster due to the increase in the network surface area according to a power law. Nevertheless, it is proposed to use a new dimensionless parameter, as more accurate for the current level of technology development. In the course of further experimental work, it is planned to compare the values of these parameters for easy orientation between them.
Figure 1. 3D visualization of wormholes, obtained for different acid compositions with flow rate 0.5 ml/min

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