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Quantification of the microstructure, effective hydraulic radius and effective transport properties changed by the coke deposition during the crude oil in-situ combustion

Qianghui Xu[a], Wei Long[b], Hang Jiang[c], Bin Ma[a], Cheng Zan[b,d], Desheng Ma[c], Lin Shi[a,*]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China
[b] iCore Digital Reservoir Group, Katy, TX 77450, United States
[c] State Key Laboratory of Enhanced Oil Recovery, Research Institute of Petroleum Exploration & Development, China National Petroleum Corporation, Beijing 100007, China
[d] Research Institute of Tsinghua University in Shenzhen, 518055, China

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A B S T R A C T

Coke deposition during crude oil in-situ combustion (ISC) is an important phenomenon that significantly impacts the pore topology and permeability. In this study, X-ray computed microtomography and a specific image processing procedure were used to reconstruct the micro-tomographic images of packed beds with coke deposition. From the reconstructed images, the microstructural parameters related to the transport were analyzed, such as the effective porosity, the constrictivity and the geodesic tortuosity. The Lattice Boltzmann method was used to simulate the species diffusion and fluid flow through the microstructures to quantify the mass diffusivity and permeability. The experimental work was performed to validate the digital microstructures and the simulated permeability. The effects of the coke deposition on the pore topology and the permeability were analyzed. The coke deposition pattern showed significant deposition in the pore throat. Analyses of the pore size distribution lead to a more reasonable geometric approach to measure the effective hydraulic radius for the better permeability prediction. Based on the effective transport properties and the microstructural parameters, a developed permeability relation was introduced by factorizing the permeability into two distinct contributions from the characteristic length and the microstructural effect. The permeability model describes the main influences of all the relevant geometric parameters on the permeability reduction by the coke deposition.

1. Introduction

In-situ combustion (ISC) is an important thermal enhanced oil recovery technique to exploit the unconventional crude oil [1]. Toe-Heel Air injection (THAI) is a developed modification of the conventional ISC technique by the integration of the horizontal well [2]. The in-situ reaction heat is released by the burning of the solid residue, so called coke at the combustion front. The significant open questions are raised including the effects of coke formation on the pore structure and the permeability [3]. During ISC, the effect of coke deposition on the oxygen transport further promoted the bypassing of the oxygen at the combustion front into the downstream low temperature zone. The bypassing oxygen impacts the combustion front stability and increases the difficulty in the regulating and controlling the combustion front. In terms of THAI process, however, the coke deposition inside the horizontal producing wells is considered to create a gas seal such that the coke prevents the air breakthrough into the producer and stabilizes the THAI process [4]. For engineering application, a quantitative relation between the permeability reduction rate and the coke deposition density is highly required in the reservoir simulation. For example, the STARS simulators by Computer Modelling Group Ltd. requires a reliable model to simulate the permeability variations with coke deposition [5]. Therefore, the permeability changes due to the coke deposition need to be characterized better to incorporate an accurate permeability model in the reservoir simulation to explore the effect of coke deposition on the fluid transport during ISC and THAI.

Xu et al. [3] presented an experimental study to physically simulate the coke formation and measure the post-deposition permeability. The

Abbreviations: ISC, in-situ combustion; THAI, Toe-Heel air injection; LBM, Lattice Boltzmann method; micro-CT, X-ray computed micro-tomography; MIP, mercury intrusion porosimetry; PSD, pore size distribution; cPSD, continuous pore size distribution; SEM, Scanning electron microscope; REV, representative elementary volume; DnQm, n-dimension, m-speed velocity space; ME, mean error

* Corresponding author.
E-mail address: rnxsl@mail.tsinghua.edu.cn (L. Shi).

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experimental uncertainty was introduced by the existence of the heterogeneous coke distribution at the core scale [3]. Furthermore, the limited experimental data due to the experimental complexity did not support an efficient model relating the permeability with the coke deposition over a wide range. Furthermore, the experimental data could not help establish a micro-macro relation to understand the quantitative dependence of the permeability on the microstructural parameters, such as the effective hydraulic radius, the constrictivity and the tortuosity.Advances in the X-ray computed micro-tomography technique (micro-CT) and well-established image processing techniques open a great possibility to create a three dimensional (3D) micro-tomographic image to present the real pore structure with sufficient spatial resolution [6–9]. The developed image analysis methodologies are introduced and support a new perspective to distinguish the microstructure effects originating from the pore channel variation [10] and from the tortuous pathways [11]. When the real microstructure is take as structural input, the pore-scale transport process can also be simulated and visualized based on the general application of numerical simulation techniques, such as Lattice Boltzmann method (LBM). Compared to traditional numerical methods for fluid dynamic problems, LBM emerges as an alternative powerful method and shows the great advantage in dealing with the complex geometry inside the porous medium [12,13]. The approximation of incompressible Naiver-Stokes equation is successful at low velocities where $O(u^3)$ term becomes negligible if $Ma^2 \ll 1$. Therefore, the LBM is greatly suitable for the pore-scale fluid dynamic problems in the reservoir underground conditions. These new approaches make it possible to acquire microstructural parameters [10,11] and effective transport properties [14] at the scale of representative elementary volume (RVE) in order to understand the influence of the coke deposition on the pore topology and the effective transport properties, such as the permeability.

In literatures, great attempts have been performed to derive a general formula to relate the permeability with the microstructure parameters [15–18]. Recently, the development of imaging and numerical approaches motivates the discussion of this basic topic in the porous medium field [18–20]. A well-known relation is the semi-empirical Kozeny-Carman (K-C) equation for the idealized porous medium packed with spherical grains. The general form of the Kozeny-Carman equation highlights how the permeability depends on the pore structure. There is a consensus that the K-C equation is valid to the porous medium as an assembly of the uniform and spherical grains, but shows non-plausible deviation in the porous medium with irregular-shaped cementing material, such as clay [21], colloid [22]. Therefore, the present investigation will provide the opportunity to explore the quantitative micro-macro relationship between the permeability and the detailed microstructural parameters of the model porous media with and without coke deposition.The M-factor was introduced to take into account relevant microstructural effects on the permeability of porous medium [18,20,23]. Berg [23] presented a theoretical derivation to relate the M-factor to the effective porosity, the tortuosity and the constrictivity in the following expression $M = \frac{\varepsilon\beta}{\tau^2}$. According to the theoretical study [23], the permeability is believed to be reduced by the less effective pore space given by a smaller effective porosity ε, longer flow paths given with a higher tortuosity τ, more variations in pore channels described by a lower constrictivity β. In the Berg's study [23], all the geometric properties were averaging over the streamline values with the transport property-dependent characteristic. However, the microstructural parameters determined by the image techniques are defined in terms of geometric approaches. The different definitions of microstructure parameters lead to different relationships with different exponents of these microstructural parameters [18,20]. With respect to the application, these geometric approaches are straightforward, well-established and high efficient. Gaiselmann et al. [18] proposed an empirical expression for the M-factor as the following equation $M = a\frac{\varepsilon^b\beta^c}{\tau^e}$. The fitting of the preface factor and three exponents are required based on the abundant data [18]. Such empirical expression is confirmed to have the most satisfied predictive capacity with the detailed comparisons to the Archie's law, the tortuosity equation and the constrictivity equation [18].

Due to the fluid viscosity, it is also important to consider the effect of the friction at the solid-wall interface on the permeability. The dynamic characteristic length is accounted in the porous medium by the effective hydraulic radius [17,23]. Johnson et al. [24] introduced a dynamic length, Λ, defined by weighting with the electric field. The estimation method of the Λ was somewhat complicated, and the Λ could not be experimentally measured [25]. Later, Katz and Thompson [17] described a rigorous definition of d_c as a critical pore diameter based on the percolation theory. The attractive advantage of d_c was the length could be directly measured from mercury injection experiments. The inflection point in the mercury intrusion curve was regard as the value of d_c [17]. Furthermore, Schwartz et al. [25] tried to measure d_c for digitized microstructures by an intrusion simulation with spherical particles in various sizes. The work limitation was the geometric approach was difficult to capture the pore size distribution feature of the heterogeneous materials [25], including several distinct pore sizes for the viscous transport. The simulation of the mercury intrusion porosimetry (MIP), proposed by Münch and Holzer [10], has been highly acceptable to better assess the MIP-pore size distribution (PSD) from the 3D image data, especially for the heterogeneous systems as indicted by "breakthrough-distribution-like" MIP spectra. An interesting work by Holzer et al. [20] employed the MIP-PSD spectra to measure the effective hydraulic radii. The validity of the effective hydraulic radius determination method in the Holzer et al.'s work [20] should be confirmed by larger number of samples. In addition, the basic question is raised whether it is reasonable to describe the effective hydraulic radius in the same way for both the packed beds with and without coke deposition.

The purpose of this study is to describe the influence of the coke deposition on the pore topology and the effective transport properties. A micro-macro model was developed to predict the permeability based on the relevant geometric parameters. In terms of the engineering application of ISC or THAI processes in sandstone reservoirs, the study also provided an empirical relation correlating the permeability reduction rate with the coke concentration. Therefore, the present study was started from the reconstructions of micro-tomographic images by micro-CT for the model porous media with 500 nm pixel size. The detailed image processing procedure was presented with the validity confirmation by experimental coke volume fractions. From the reconstructed images, the microstructural parameters related to the transport were analyzed, such as the effective porosity, geodesic tortuosity and geometric constrictivity. An in-house developed LB simulator was employed to simulate the species diffusion and viscous fluid flow through the prior-deposition and post-deposition packed beds and compute the corresponding mass diffusivity and permeability. The study also presented a detail validation of the simulated permeability based on the idealized porous medium and laboratory experimental data. The effects of the coke deposition on the pore topology and the permeability were analyzed. From pore size distribution analyses, a more reasonable geometric approach was proposed to measure the effective hydraulic radius for better permeability description in terms of the generality and accuracy. As inspired by the general K-C relation, a modified permeability model was introduced by combining the two distinct contributions from the characteristic length and the microstructural effect reflected by the M-factor. Based on the developed permeability model, main effects were analyzed to quantitatively understand the influence of all the relevant geometric parameters on the permeability reduction with the coke deposition.

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