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A FLOW AND TRANSPORT MODEL FOR SIMULATION OF MICROBIAL ENHANCED OIL RECOVERY PROCESSES AT CORE SCALE AND LABORATORY CONDITIONS

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Abstract. A general 3D flow and transport model in porous media was derived applying an axiomatic continuum modeling approach, which was implemented using the finite element method to numerically simulate, analyze and interpret microbial enhanced oil recovery (MEOR) processes under laboratory conditions at core scale. From the methodological point of view the development stages (conceptual, mathematical, numerical and computational) of the model are shown. This model can be used as a research tool to investigate the effect on the flow behavior, and consequently the impact on the oil recovery, due to clogging/declogging phenomena by biomass production, and interfacial tension changes because of biosurfactant production. The model was validated and then applied to a case study. The experimental results were accurately predicted by the simulations. Due to its generality, the model can be easily extended and applied to other cases.

Key words. Axiomatic continuum modeling approach, microbial enhanced oil recovery, clogging/declogging, interfacial tension, wettability change, trapping number.

1. Introduction

The oil fields at the initial stage of operation produce using basically its natural energy, which is known as *primary recovery*. As the reservoir loses energy it requires the injection of gas or water in order to restore or maintain the pressure of the reservoir. This stage is called *secondary recovery*. When the secondary recovery methods become ineffective it is necessary to apply other more sophisticated methods such as steam injection, chemicals, microorganisms, etc. These are known as *tertiary or enhanced oil recovery* (EOR). Some important oil fields in Mexico are entering the third stage.

For the optimal design of enhanced oil recovery methods it is required to perform a variety of laboratory tests under controlled conditions to understand what are the fundamental recovery mechanisms for a given EOR method in a specific reservoir.The laboratory tests commonly have a number of drawbacks, which include among others, that they are very sophisticated, expensive and largely unrepresentative of the whole range of phenomena involved. A proper modeling of the laboratory tests would be decisive in the interpretation and understanding of recovery mechanisms and in obtaining the relevant parameters for the subsequent implementation of enhanced recovery processes at the well and the reservoir scale.

In this work, a very general 3D flow and transport model in porous media was obtained to numerically simulate, analyze and interpret microbial enhanced oil

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recovery (MEOR) processes under laboratory conditions at core scale, such as clogging/declogging and interfacial tension changes because of biosurfactant production. The model was validated with experimental data from [28] and then applied to a case study using a sandstone Berea core, while the oil and the microbial culture are from Agua Fría field, reported in the work of [7].

From the methodological point of view the development stages (conceptual, mathematical, numerical and computational) of the model are shown. In particular, for mathematical modeling was used the axiomatic continuum modeling approach, for numerical modeling a finite element method and COMSOL Multiphysics® Software for computational implementation.

In section 2, we present a review of the State of the Art leading to this work. In section 3, we present the core idea of this paper, which is to describe the systematic methodology used to define a conceptual model, then how to derive a mathematical model, then how to discretize this later numerically, and finally how to make computational implementations for validation and application to a case study. In section 4 a broad description of the axiomatic modeling of continuum systems is given, with the necessary details for the description of flow and transport of the MEOR model. In section **??** the validation of the flow model is described. In section 6, this work was compared with the experimental data and numerical simulations of other authors, to validate the clogging and declogging process. In section 7, this MEOR model was applied to our own experimental data. In section 8, the results of the case study are analyzed, and in section 9 the main contributions are summarized.

2. Review of the State of the Art

The modeling of the microorganisms behavior influencing the enhanced oil recovery through microorganisms (MEOR) and their activities in the reservoir, has attracted a strong interest from the beginning of the research about MEOR. Some models describe transport equations in one or at most two dimensions, describing the clogging process, without solving the flow equation, as in [16, 17] and [35]. Others, beside the transport equations and clogging process, do include a flow formulation, coupled with the transport equations, as in [32, 33] and [48]. Still others investigated the mechanisms of the change in wettability, besides the described process, as in [9, 10, 11, 12].

One of the problems for modeling, is obtaining the parameters for the equations, so experiments in laboratory conditions have been performed, as in [4]. The rate of growth or chemical reactions coming from, or acting on the microbial activity has also been investigated, as in [50], together with their action on recovery process, due, for example, because of the surfactant produced by the microorganisms. Others, concentrated on some or all parts of the growth and decaying process of the microorganisms, as in [18].

The problem of clogging and declogging has been addressed through transport equations as in [49] or [34]. Others, give more importance to the effects of surfactant produced by the microorganisms, as in [42]. Of course there are some models which include both clogging/declogging and surfactant, as in [37], although most of them are one-dimensional, with exceptions like [31], and this work, which are fully 3-D.

3. Modeling Methodology

A fundamental issue that is pursued by this paper is to illustrate how to develop a flow and transport models in porous media applying a general systematic modeling