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Pore network modeling of two-phase flow in a liquid-(disconnected) gas system

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Abstract

The appropriate description of two-phase flow in some systems requires a detailed analysis of the fundamental equations of flow and transport including momentum transfer between fluid phases. In the particular case of two-phase flow of oil and gas through porous media, when the gas phase is present as disconnected bubbles, there are inconsistencies in calculated flow properties derived by using the conventional Darcean description. In a two-phase system, the motion of one fluid phase may induce significant changes in the mobility of the second phase, as known from the generalized transport equations derived by Whitaker and Kalaydjian. The relevance of such coupling coefficients with respect to the conventional relative permeability term in two-phase Darcean flow is evaluated in this work for an oil-(disconnected) gas system. The study was performed using a new Pore Network Simulator specially designed for this case. Results considering both, Darcy's equation and generalized flow equations suggest that the four transport coefficients (effective permeabilities and coupling coefficients) are needed for a proper description of the macroscopic flow in a liquid-disconnected gas system.

Keywords: Two-phase flow; Porous media; Viscous coupling; Relative permeability; Pore network modeling; Bubbles

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1. Introduction

The understanding of fluid flow in porous media is of interest to many areas of science and engineering since it has a number of practical applications in well known areas such as hydrocarbon recovery and hydrology. In the last 50 years a lot of effort was dedicated to unravel the phenomenology associated to flow in porous media. Despite this attention there are still many open questions concerning the flow dynamics.

It is known that two-phase flow in porous media is very rich in problems of a complex nature such as the relations of properties at different length scales, the existence of a variety of flow patterns, and the difference

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between unsteady and transient response, etc [1]. Most previous studies concentrate on conditions where the flowing phases are connected throughout the flow domain. However, in some cases, one of the fluid phases may be disconnected, leading to a different flow dynamics which can not be described using the simple Darcy equation relating the flow rate and the pressure gradient acting on the phase.

One of the problems of interest to the oil industry is related to an unconventional behavior observed in some heavy oil reservoirs where recovery factors obtained with commercial simulators are found to be up to 50% smaller than the ones recorded in the field [2,3]. Several factors have been proposed as responsible for the "out of prediction" behavior observed in such formations, including the existence of an unusual variety of solution gas drive mechanism, which has been studied in the last few years. In the solution gas drive process the gas is released as the pressure decreases [4,5]. It is known that the nucleation and growth of gas bubbles in a supersaturated system decrease as the system reaches equilibrium; however, if for any reason (like in the presence of a very low diffusion coefficient) the system does not lose the supersaturation condition for a long period of time, the bubbly condition due to nucleation prevails. Also, it has been observed that under certain conditions (flow rates, oil viscosity, etc), the bubble breakup process might prevent the increase of bubble size and eventually the gas connection due to coalescence and growth [3,6]. In this case a two-phase distribution given by a disconnected gas phase (gas bubbles) inside of a connected liquid phase (heavy oil) is observed over periods of time large enough to consider that such a phase distribution is governing the flow dynamics.

In this work, we study a simple system consisting of two fluid phases' oil and gas, where the gas phase is disconnected. We developed a pore network simulator to study the dynamics of the fluid flow under these conditions and use it to study how this two-phase flow distribution may lead to the unusual macroscopic behavior.

In the conventional approach, the macroscopic modeling of flow associated with solution gas drive processes is normally performed using Darcy's equation. This approach assumes that the pressure gradient through each phase path is the only factor responsible for its motion, neglecting the reciprocal viscous drag among the fluids due to momentum exchange. The role of viscous coupling effects on the macroscopic flow has been discussed for many years. The conclusions reached vary from statements that the fluid–fluid coupling can be neglected at all to claims that the coupling is really relevant to the flow [7–11]. The relevance of viscous coupling varies from case to case and it is normally tied to properties such as fluid saturation, viscosities, etc [12]. The viscous coupling may play an important role in the flow process resulting from the fluid distribution assumed here (gas bubbles—oil), and any analysis in this direction can not be approached from the traditional Darcy's equation.

In Section 2, the generalized approach for two-phase fluid transport through porous media is discussed and the applicability of this formulation to the phase distribution considered here is presented. Since we are interested in finding the macroscopic formulation that describes this flow dynamics, we use a modeling technique that addresses the problem from the pore scale. Pore network modeling is a good tool to achieve such a goal.

In Section 3 an overview of different types of pore network models reported is given. It is followed by the description of the pore network simulator developed in this study.

Section 4 introduces the method used to estimate the four coupling coefficients involved in the generalized Darcy's equation. In Section 5, we present numerical results that support the relevance of the generalized equation for the description of the gas bubble-oil flow through porous media. The effect of gas saturation and bubble size on the transport coefficients is discussed. The need of considering both coupling and effective permeability terms for the entire range of saturations and gas bubble sizes studied here is demonstrated.

2. Macroscopic transport equations

2.1. Darcy's equation

Experimental results obtained under steady flow conditions showed that when two fluids flow simultaneously through a porous medium, each fluid establishes its own tortuous path, creating very stable flow channels [13]. Under this approach, it is assumed that a unique group of channels corresponds to a given