Numerical Study of Inlet Effects in Foam Flow through Porous Media (Postprint)

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Abstract

This study employs a stochastic foam number conservation model to numerically investigate the entrance effects of foam fluid flow processes in homogeneous porous media. The stochastic foam number conservation model characterizes foam generation and development during unsteady displacement processes in porous media using only two parameters: the foam generation rate Kg and the maximum foam number n∞. The governing equations for foam two-phase flow in two-dimensional media are solved using the IMPES (Implicit Pressure Explicit Saturation) method. Based on the analysis of parameters including liquid phase pressure, liquid phase saturation, and bubble density distribution during the displacement process, the entrance effects of the foam displacement process are examined in detail. The results demonstrate that increasing the foam generation rate Kg attenuates the entrance effects in the foam flow process; conversely, increasing the parameter n∞, while capable of enhancing the displacement pressure differential, exerts minimal influence on the distribution patterns of various parameters within the entrance region of the porous medium.

Full Text

Preamble

Numerical Study on Inlet Effect of Foam Flow Process in Porous Media

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Abstract: This paper presents a numerical investigation of the inlet effect during foam flow in homogeneous porous media using a stochastic bubble population balance model. The stochastic bubble population balance model robustly predicts bubble growth and development during transient foam displacement in porous media using only two parameters: the foam generation rate K_g and the maximum bubble number n_∞. The governing equations for the two-dimensional, two-phase foam seepage process are solved via the IMPES method, and the distribution characteristics of water-phase pressure, water saturation, and bubble density are analyzed to investigate the inlet effect. Results demonstrate that increasing the foam generation rate K_g suppresses parameter variations in the inlet region, indicating a reduced inlet effect at higher foam generation rates. Although increasing n_∞ yields higher pressure drop along the sample, it has minimal influence on the distribution patterns of various parameters in the entrance region of the porous media.

Keywords: Stochastic bubble population balance model; Porous media; Foam flow process; Inlet effect; Numerical study

0 Introduction

Foam technology is widely employed in enhanced oil recovery (EOR) industrial practices. Conventional gas flooding suffers from low displacement efficiency due to gravity segregation and gas channeling through high-permeability layers. Foam technology significantly increases gas-phase viscosity, providing excellent mobility control for the displacing gas and thereby improving ultimate oil recovery [1-6].

Numerical methods offer a simple and reliable approach for analyzing, simulating, and predicting foam displacement characteristics in porous media. Some researchers have simulated foam rheology using a single-phase non-Newtonian fluid assumption [7-9], but this approach lacks generality and cannot adequately capture the seepage mechanisms of foam in porous media. Successful description of foam displacement characteristics requires accurate modeling of foam generation and decay within the medium. In rheological models based on the fractional flow assumption for two-phase fluids, foam number n_f is a crucial parameter. Among existing foam number models, the fractional flow model proposed by Rossen [10-14] and the bubble population balance model by Patzek and Kovscek et al. [15-18] are most prominent. The fractional flow model neglects precise temporal variation of bubble number and is thus primarily used for simulating steady-state foam flow. While the population balance model accounts for dynamic equilibrium of bubble density, its numerous parameters make practical application difficult. Consequently, successful commercial reservoir multiphase flow simulators such as Eclipse [19] and CMG' s STARS [20] do not calculate foam mobility through apparent viscosity but instead apply empirical corrections directly to foam-phase mobility.

Recently, Zitha and Du [21-22] developed a novel stochastic bubble population balance model for foam flow in porous media based on three fundamental assumptions: (1) Foam, as a complex fluid, exhibits rheological characteristics described by the Herschel-Bulkley model; (2) Foam rheology fundamentally depends on foam density (number of bubbles per unit volume of porous media); and (3) At the microscopic level, foam generation is a random process following simple exponential growth kinetics. Compared with conventional population balance models, the stochastic version includes only two essential variables, making it more readily determinable from experiments.

This study employs the stochastic bubble population balance model to numerically simulate the inlet effect during foam flow in homogeneous porous media. The inlet effect refers to significant deviations in variable distributions within a region near the entrance compared with those in other regions. In foam displacement, these variables include liquid-phase saturation, liquid-phase pressure, and foam density. The IMPES method solves the governing equations for the two-dimensional, two-phase foam seepage process, and detailed investigation of the inlet effect is conducted based on analysis of liquid-phase pressure, liquid-phase saturation, and bubble density distributions during displacement.

1.1 Computational Domain

[Figure 1: see original paper] illustrates the computational domain: a two-dimensional homogeneous porous medium of length L, width d, porosity ϕ, and permeability K. Fluid enters from the central portion of the left boundary and exits through the right boundary. Initially, the medium is fully saturated with water (liquid-phase saturation of 100%). Gas and surfactant solution then inject at velocity u from the inlet boundary, where u_w and u_g represent the fractional velocities of liquid and gas phases, respectively. Foam generates and evolves within the medium, displacing the original liquid phase, and finally exits through the outlet boundary, which maintains a constant pressure of 0.1 MPa.

1.2 Governing Equations Based on Stochastic Bubble Population Balance Model

The governing equations for foam displacement in porous media are:

$$\begin{cases} \frac{\partial}{\partial t}(\phi \rho_w S_w) + \nabla \cdot (\rho_w \mathbf{u}_w) = 0 \\ \frac{\partial}{\partial t}(\phi \rho_f S_f) + \nabla \cdot (\rho_f \mathbf{u}_f) = 0 \\ \frac{\partial}{\partial t}(\phi n) + \nabla \cdot (n \mathbf{u}_f) = \phi K_g (n_\infty - n) \end{cases}$$

Auxiliary equations are:

$$\begin{cases} \mathbf{u}_i = -K\lambda_i \nabla P_i \\ \lambda_i = k_{ri}/\mu_i \\ P_c = P_f - P_w \\ k_{rw} = (S_w - S_{wc})^a \\ k_{rf} = (1 - S_w)^b \\ \mu_f = \mu_g + \alpha n^c \end{cases}$$

where ρ_i, S_i, $\mathbf{u}_i$, λ_i, and P_i represent the density, saturation, velocity, mobility, and pressure of phase i, respectively, with $i \in \{w, f\}$ (subscript f denotes foam). The third equation in system (1) is the stochastic bubble population balance model, where foam generation rate K_g and maximum foam number n_∞ are experimentally measurable parameters related to foam generation and development. The liquid phase is assumed incompressible, while the foam phase follows the ideal gas law. In the auxiliary equations, P_c is capillary pressure, which depends solely on liquid-phase saturation S_w:

$$P_c = \sigma_{wg}\sqrt{\phi/K}\left(\frac{S_w - S_{wc}}{1 - S_{wc}}\right)^{-\gamma}$$

where σ_{wg} is gas-liquid interfacial tension and γ is a fitting parameter. The fluid mobility λ_i is defined as:

$$\lambda_i = \frac{k_{ri}}{\mu_i}$$

where k_{ri} is relative permeability of phase i and μ_i is viscosity. Foam viscosity is calculated by:

$$\mu_f = \mu_g + \alpha n^c$$

where α and c are constants, and n is foam density (number of bubbles per unit volume of porous media). Relative permeability expressions are:

$$k_{rw} = \left(\frac{S_w - S_{wc}}{1 - S_{wc}}\right)^a, \quad k_{rf} = (1 - S_w)^b$$

where S_{wc} is residual water saturation.

Note: Parameters in Table 2 reference Bentheimer sandstone core properties [24].

1.3 Numerical Solution Method

The IMPES method [23] solves the governing equation system (1). For this two-dimensional, two-phase seepage problem, the numerical solution proceeds in three steps (superscript n denotes time level):

1. The pressure field P_w^n at time n is computed implicitly from the previous time level' s pressure field P_w^{n-1}, saturation S_w^n, and foam density n^n. Foam-phase pressure P_f^n is obtained as the sum of water-phase pressure P_w^n and capillary pressure P_c^n, where P_c^n comes from equation (3).
2. The saturation distribution S_w^{n+1} at time $n+1$ is calculated explicitly from P_w^n.
3. The foam density distribution n^{n+1} at time $n+1$ is also obtained explicitly from S_f^{n+1}.

1.4 Numerical Simulation Parameters

Simulation parameters are listed in Table 1 and Table 2 .

Table 1. Numerical simulation parameters

Parameter	Value
Length L (m)	0.3
Width d (m)	0.05
Time step Δt (s)	0.1
X-direction grid number N	300
Y-direction grid number M	50
Total time t (s)	500
Gas injection velocity $u_{g,in}$ (m/s)	3.0$×10^{-4}$
Liquid injection velocity $u_{w,in}$ (m/s)	3.0$×10^{-4}$
Initial gas velocity $v_{g,in}$ (m/s)	0
Initial water velocity $v_{w,in}$ (m/s)	0
Initial water pressure $P_{w,0}$ (Pa)	1.013$×10^{5}$

Table 2. Fluid and rock characteristics parameters

Parameter	Value
Permeability K (m^2)	2.0$×10^{-12}$
Porosity ϕ	0.2
Gas viscosity μ_g (Pa • s)	1.81$×10^{-5}$
Water viscosity μ_w (Pa • s)	1.004$×10^{-3}$
Interfacial tension σ_{wg} (N/m)	30$×10^{-3}$
Residual water saturation S_{wc}	0.05
Foam generation rate K_g (s^{-1})	0.1-1.0

Parameter	Value
Maximum foam number n_∞	200–500

2.1.1 Two-Dimensional Parameter Distribution Contours

[Figure 2: see original paper] and [Figure 3: see original paper] present two-dimensional contour distributions of liquid-phase saturation, liquid-phase pressure, and foam density at the same completion time ($T = 500$ s) for different K_g values with $n_\infty = 200$ fixed. The results show distinct inlet effects, characterized by higher liquid-phase saturation and pressure in the central region compared with the sides at the inlet, while foam density is minimal at the entrance and gradually increases to n_∞ along the flow path. Comparison between figures reveals that parameter variation ranges for liquid-phase saturation and foam density in the inlet region are significantly larger in [Figure 2: see original paper] ($K_g = 0.1$) than in [Figure 3: see original paper] ($K_g = 1.0$), indicating that larger K_g values reduce the inlet effect. This occurs because K_g governs foam generation rate; higher K_g enables faster foam development and earlier fully-developed flow within a shorter distance, thereby diminishing inlet effects.

2.1.2 Parameter Distribution Characteristics Along the Flow Direction

[Figure 4: see original paper] and [Figure 5: see original paper] show profiles of liquid-phase saturation, liquid-phase pressure, and foam density along the medium length during dynamic displacement for different K_g values. These profiles are obtained by averaging parameters across each cross-section. Both cases exhibit foam breakthrough at the outlet by 200 s. Clear inlet effects are visible in both scenarios, with higher liquid-phase saturation and smaller pressure drop in the entrance region, accompanied by significant foam number variation. However, comparison between [Figure 4: see original paper] ($K_g = 0.1$) and [Figure 5: see original paper] ($K_g = 1.0$) reveals more pronounced inlet effects at lower K_g values. Thus, increasing K_g reduces the parameter variation range in the inlet region, consistent with the contour analysis.

2.2.1 Two-Dimensional Parameter Distribution Contours for n_∞ Variation

[Figure 6: see original paper] shows two-dimensional contours of liquid-phase saturation, liquid-phase pressure, and foam density at process completion ($T = 500$ s) for $n_\infty = 500$. The inlet region again exhibits higher central saturation and pressure with minimal foam density at the entrance, demonstrating clear inlet effects. Compared with [Figure 2: see original paper] ($n_\infty = 200$), [Figure 6: see original paper] shows lower liquid-phase saturation, larger displacement pressure differential, and greater foam number, yet the spatial distribution patterns remain essentially identical. This indicates that n_∞ has limited influence on inlet effects during foam displacement.

2.2.2 Parameter Distribution Characteristics Along the Flow Direction for n_∞ Variation

[Figure 7: see original paper] presents parameter distributions along the medium length for $n_\infty = 500$. The results show decreasing liquid-phase saturation in the front section, smaller pressure drop magnitude in the inlet region compared with downstream sections, and more significant foam density variation at the entrance—again demonstrating pronounced inlet effects. Comparison with [Figure 4: see original paper] ($n_\infty = 200$) reveals that although absolute parameter values differ, the distribution patterns along the flow direction are fundamentally similar, confirming that n_∞ variation does not substantially affect inlet effects.

Conclusions

This study employs the stochastic bubble population balance model to numerically analyze inlet effects during foam flow in two-dimensional homogeneous porous media, yielding the following conclusions:

1. Foam injected at the center of porous media generates and develops progressively within the medium, with the displacement process exhibiting significant inlet effects.
2. Increasing the foam generation rate parameter K_g reduces the parameter variation range in the inlet region, thereby diminishing inlet effects.
3. While the maximum foam density parameter n_∞ affects absolute values of displacement parameters, the distribution patterns along the flow direction remain essentially unchanged, indicating that n_∞ has minimal impact on inlet effects during foam displacement.

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