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

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Abstract

This study employs a stochastic foam number conservation model to numerically investigate inlet effects in foam fluid flow processes within homogeneous porous media. The stochastic foam number conservation model utilizes only two parameters: foam generation rate Kg and maximum foam number n∞, to characterize foam generation and development during unsteady displacement processes in porous media. The IMPES method is adopted to solve the governing equation system for foam two-phase flow in two-dimensional media. Based on analysis of parameters such as liquid phase pressure, liquid phase saturation, and bubble density distribution during the displacement process, inlet effects in foam displacement processes are investigated in detail. The results demonstrate that increasing the foam generation rate Kg attenuates inlet effects in the foam flow process; while increasing parameter n∞, although it can enhance displacement pressure difference, exerts minimal influence on the distribution patterns of various parameters within the inlet section of the porous medium.

Full Text

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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. This model robustly describes foam generation and development during unsteady displacement processes 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. The 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. While increasing n_∞ yields higher pressure drops 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

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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 enable simple and reliable analysis, simulation, and prediction of foam displacement characteristics in porous media. Some researchers have simulated foam rheological behavior using single-phase non-Newtonian fluid assumptions [7-9], but such approaches lack 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 two-phase flow assumption, foam number n_f is a crucial parameter. Among current foam number models, the most notable are the fractional flow model and the bubble population balance model. Rossen [10-14] proposed the fractional flow model, which does not precisely account for temporal variations in bubble number and is therefore primarily used to simulate steady-state foam seepage characteristics. Patzek and Kovscek et al. [15-18] developed bubble population balance models that, while based on dynamic equilibrium of bubble density, contain too many parameters for practical application. Consequently, current successful reservoir multiphase flow simulation software 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 motion in porous media. This model is based on three fundamental assumptions: (1) Foam, as a complex fluid, exhibits rheological characteristics described by the Herschel-Bulkley model; (2) Foam rheology is essentially determined by foam density (number of bubbles per unit volume of porous media); and (3) At the microscopic level, foam generation is treated as a random process following simple exponential growth kinetics. Compared with traditional population balance models, the stochastic bubble population balance model includes only two fundamental variables, making it easier to determine experimentally.

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 the phenomenon where certain variables exhibit significantly different distributions within a region near the entrance compared to other regions. In foam displacement processes, these variables include liquid-phase saturation, liquid-phase pressure, and foam density. The IMPES method is used to solve 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] shows the computational domain: a two-dimensional homogeneous porous medium of length L, width d, porosity ϕ, and permeability K. Fluid enters through 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. The gas and liquid velocities are denoted as u_g and u_w, respectively. Foam generates and develops within the medium, displacing the original liquid phase, and finally exits through the outlet boundary, where pressure is maintained constant at 0.1 MPa.

1.2 Governing Equations Based on Stochastic Bubble Population Balance Model

The governing equations for foam displacement in porous media are:

The auxiliary equations are:

where ρ_i, S_i, 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 the governing equation set (1) is the stochastic bubble population balance model, where foam generation rate K_g and maximum foam number n_∞ are two parameters related to foam generation and development that can be measured experimentally. The liquid phase is assumed incompressible during calculations, while the foam phase follows the ideal gas law. In the auxiliary equations, P_c represents capillary pressure, which is a function of liquid saturation S_w only:

where σ_{wg} denotes gas-liquid interfacial tension, γ is a fitting parameter, and λ is a constant.

The mobility λ_i of phase i is defined as:

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

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

The relative permeability k_{ri} is expressed as:

where S_{wc} denotes residual water saturation.

1.3 Numerical Solution Method

This study employs the IMPES method [23] to solve the governing equation set (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 level n is calculated implicitly from the previous time level' s pressure field P_w^{n-1}, saturation S_w^n, and foam density n^n. The capillary pressure P_c^n is obtained from equation (3), and foam pressure P_f^n can be determined as the sum of P_w^n and P_c^n.

(2) The saturation distribution S_w^{n+1} at time level $n+1$ can be obtained explicitly from P_w^n.

(3) The foam density distribution n^{n+1} at time level $n+1$ can also be obtained explicitly from S_f^{n+1}.

1.4 Parameters in Numerical Simulation

Parameters used in the numerical simulation are listed in Table 1 and Table 2.

Table 1 Numerical simulation parameters

Parameter	Value
Length L (m)	
Width d (m)	
Time step Δt (s)	
Grid number in X direction N	
Grid number in Y direction M	
Time t (s)	
$u_{g,in}$ (m/s)	
$u_{w,in}$ (m/s)	
$v_{g,in}$ (m/s)	
$v_{w,in}$ (m/s)	
$P_{w,0}$ (Pa)	

Table 2 Fluid and rock characteristics parameters

Parameter	Value
μ_g (Pa • s)	18.1×10^{-6}
μ_w (Pa • s)	8.6×10^{-7}
K (m²)	2.0×10^{-12}
σ_{wg} (N/m)	1004.0×10^{-6}
	30×10^{-3}

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

2.1.1 Two-Dimensional Parameter Distribution Contours

[Figure 2: see original paper] and [Figure 3: see original paper] present two-dimensional contour maps of liquid-phase saturation, liquid-phase pressure, and foam density distributions at the same moment ($T = 500$s) after displacement completion for different K_g values while keeping $n_\infty = 200$ constant. The results show that in the inlet region of the porous medium, liquid-phase saturation values in the central region are greater than those on the sides, liquid-phase pressure in the center is significantly higher than on the sides, and foam density is minimum at the inlet but gradually increases along the flow path toward the maximum foam number. The distinct differences in parameter distributions within the inlet section demonstrate a pronounced inlet effect during foam displacement in porous media. Comparing [Figure 2: see original paper] and [Figure 3: see original paper] reveals that the variation ranges of liquid-phase saturation and foam density in the inlet region are significantly larger in [Figure 2: see original paper] than in [Figure 3: see original paper], indicating that larger K_g values correspond to smaller inlet effects. This occurs because K_g determines the foam generation rate; larger K_g means faster foam generation that can reach fully developed conditions within a smaller region, thereby reducing the inlet effect of the displacement process.

2.1.2 Parameter Distribution Characteristics Along the Flow Path

[Figure 4: see original paper] and [Figure 5: see original paper] show the distributions of liquid-phase saturation, liquid-phase pressure, and foam density along the medium length direction during dynamic displacement for different K_g values. The along-path parameters are obtained by averaging across the same cross-section. The figures clearly show that foam breakthrough at the medium outlet occurs at 200s for both K_g values. Both cases exhibit obvious inlet effects, with larger liquid-phase saturation values and smaller liquid-phase pressure drops in the inlet region after foam breakthrough, along with significant changes in foam number. Comparing [Figure 4: see original paper] and [Figure 5: see original paper] shows that the inlet effect is more pronounced in [Figure 4: see original paper], indicating that larger K_g values produce smaller parameter variation ranges in the porous medium inlet region—that is, a smaller inlet effect—consistent with the two-dimensional contour analysis results.

2.2.1 Two-Dimensional Parameter Distribution Contours

[Figure 6: see original paper] presents two-dimensional contour maps of liquid-phase saturation, liquid-phase pressure, and foam density distributions at displacement completion ($T = 500$s) for $n_\infty = 500$. The results show that in the porous medium inlet region, liquid-phase saturation in the central portion of the sample is greater than on the sides, liquid-phase pressure is also greater on the sides, and foam density is minimum at the inlet. Variations in all three parameters decrease significantly in the latter portion of the sample, again demonstrating a clear inlet effect. Compared with the results for $n_\infty = 200$ in [Figure 2: see original paper], although [Figure 6: see original paper] with larger n_∞ shows smaller liquid-phase saturation, larger displacement pressure differential, and greater foam number, the spatial distribution patterns of the displacement parameters are essentially the same in both figures, indicating that n_∞ has little influence on the inlet effect of foam displacement in porous media.

2.2.2 Parameter Distribution Characteristics Along the Flow Path

[Figure 7: see original paper] shows the distributions of liquid-phase saturation, liquid-phase pressure, and foam density along the medium length direction for $n_\infty = 500$. The figure reveals decreasing liquid-phase saturation in the front portion of the porous medium, smaller pressure drop magnitudes in the inlet region compared to the rear portion, and more significant foam density changes in the inlet section, all indicating a pronounced inlet effect. Further comparison with the results for $n_\infty = 200$ in [Figure 4: see original paper] shows that although the absolute parameter values differ between the two cases, the along-path distribution patterns are essentially consistent, demonstrating that n_∞ values do not significantly affect the inlet effect of foam displacement in porous media.

Conclusions

This study employs the stochastic bubble population balance model to conduct numerical simulation and analysis of the inlet effect during foam flow in two-dimensional homogeneous porous media, yielding the following conclusions:

(1) After foam injection at the center into porous media, foam generates and gradually develops within the medium, with the displacement process exhibiting a significant inlet effect.

(2) As the foam generation rate parameter K_g increases, the parameter variation range in the porous medium inlet region decreases—that is, the inlet effect diminishes.

(3) Although different maximum foam density parameter n_∞ values affect the absolute values of displacement parameters, the along-path distribution patterns remain essentially consistent, indicating that n_∞ has minimal influence on the inlet effect of foam displacement processes.

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Note: Figure translations are in progress. See original paper for figures.