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Lattice Boltzmann modeling of two-phase behavior under acoustic excitation: Capillarity–wettability interaction

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ABSTRACT

We report capillarity–wettability interaction of the trapped nonwetting phase. The displacement of immiscible nonwetting phase subject to oscillatory acoustic excitation in a sinusoidal channel is analyzed with the lattice Boltzmann method. The effect of the surface wettability, frequency and geometry of the channel on two-phase behavior is discussed. The effect of capillarity induced resonance on mobilization of trapped nonwetting phase blob is explored for a range of capillary number for uniform and mixed-wet surfaces. It is observed that transport of a nonwetting phase can be achieved by exciting with the frequencies near to the resonant frequency which is vital in mobilization of the trapped nonwetting phase in the application like recovery of oil and two-phase flows.

1. Introduction

In the recent past, vibrational and acoustic stimulation of oil reservoirs has been investigated for possible application in enhanced oil recovery [1–3]. Hilpert et al. [2] estimated the frequencies of pulsing pressure in an channel that increases the volume of the displaced nonwetting phase. Many studies have discussed how vibrations overcome capillary entrapment that keeps the fluids in place [4,5] which emphasized the enhancement in two-phase flow by vibrations under field and laboratory conditions. Hilpert [6] discussed the use of capillarity induced resonance to mobilize blobs by exciting them at their resonant frequency. Recently Randive and Dalal [7] have employed lattice Boltzmann (LB) modeling to simulate displacement of trapped blobs. However, the influence of different wettability scenarios like uniform, mixed-wet in conjunction with capillarity induced resonance on mobilization of the trapped blob is hardly explored. The work explores the displacement of blobs from a numerical point of view in this context.

The displacement of immiscible fluids is an active area of research and studied extensively by various investigators [8,9]. These systems show typical three-phase contact lines with menisci touching the solid surface. They considered the contact line dynamics as pinned and sliding. Pinned oscillation can be seen in defects like chemical heterogeneities and microscopic surface roughness which traps or pins the contact line. Thus the finite force for releasing the contact line is required. For the contact line sliding over the surface, the meniscus follows the induced flow without any change in shape. In most of the studies [10,11] regarding to the resonance of a meniscus in a capillary tube owing to imposed oscillatory flow; it has been concluded that the response of the meniscus is a function of geometrical and chemical properties of the surface, frequency and flow amplitude.

Many researchers work in the area of sound propagation in porous media saturated with multiple immiscible fluids and explored contact-line dynamics explicitly [12–16] but could not provide expressions for the resonances. The use of elastic waves to the subsurface [17,18] is known to make water flooding of oil reservoirs more efficient. Graham and Higdon [4] have stated that droplet deformation in response to an applied oscillatory force leads to dramatic increase in mean flow rate for flow in straight capillary tubes. Beresnev and Johnson [1] reviewed the use of elastic waves. Also, the recovery of non wetting phase blobs in porous media by imposing a flow on the surrounding wetting phase is difficult. This is primarily due to the large wetting phase velocities required and especially to longer blobs along which the pressure gradient in the wetting phase can impose a greater force [19–21]. This becomes the major barrier in the process of oil extraction from its natural reservoir or non aqueous phase liquid (NAPL) contamination from water-wet aquifers. Vapor extraction, cosolvent flushing, surfactant flushing, steam injection, in situ biodegradation. are the methods widely used for mobilization of trapped non wetting phase blobs.

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Nomenclature

f_i	probability density function
f_i^{eq}	equilibrium density function
g_{1w}	interactive force strength between non wetting phase and wall
g_{2w}	interactive force strength between wetting phase and wall
g_k	interactive strength between the component k and wall
$G_{k\bar{k}}$	interactive potential
n_w	number density of the wall
Q	collision integral
u	macroscopic velocity of particle
δW	force amplitude
δt	change in time
δx	mean displacement

Greek symbol

θ	contact angle
μ	dynamic viscosity
ν_k	kinematic viscosity of kth component
ρ_k	density of kth component
σ	surface tension
τ	relaxation parameter
Ψ_k	effective mass density function
Ω	collision operator

Abbreviations

blob	binary large object
Ca	capillary number
GDL	gas diffusion layer
LB	lattice Boltzmann
LBM	lattice Boltzmann model
NAPL	non aqueous phase liquid
S–C	Shan and Chen model

Iassonov and Beresnev [5] theoretically investigated the effect of low frequency sonic vibrations on the flow of non aqueous phase liquids through a porous medium. They reported that yield stress rheology of the pore-filling fluid and capillary trapping generates the similar behavior at the macroscopic level. This is very vital to understand the mobilization of reservoir fluids with acoustic stimulation technologies. They further establish the fact that vibrations can considerably decrease minimum pressure gradient required to mobilize entrapped fluid and increase the average flow rate. They argued that the vibrations are most effective in the zones of relatively low pressure gradients. They further stated that application of sound can increase the efficiency of oil recovery methods [1].

Palan et al. [22] applied the vibrio-acoustics method to withdraw water for the better fuel cell performance. They compared different approaches so as to optimize the minimum energy required for the formation of droplet for the given input excitation frequency and amplitude. Buick et al. [23] generated the sound wave using the sinusoidal source and compared with inviscid shock wave concept with the solution of Bergers equation. Frisch et al. [24] stated that lattice gas automata (LGA) includes the sound wave propagation in the small perturbation limit. Margolus et al. [25] studied theoretical and numerical method for sound wave technique. Chen et al. [26] proposed a model in which they simulated a linear sound wave without treating it as a small perturbation. A simple capillary physics mechanism was used by Li et al. [27] to study the vibration induced mobilization of trapped nonwetting organic phases in porous media.

Experimental studies on mobilization of blobs have been done by petroleum engineers due to its relevance to oil recovery. Gardescu [28] performed experiments to ascertain the pressure required to mobilize an isolated bubble of gas entrapped in a pore constriction. He used Laplace‘s law of capillary pressure for an explicit determination of the pressure needed to overcome the capillary entrapment. Taber [29] conducted several experiments to correlate the volume of mobilized oil phase with a parameter ratio $\frac{\Delta p}{L\sigma}$, where σ is the interfacial tension and ΔP is the pressure drop across the length of the porous core sample (L). Several field observations and laboratory experiments [30] has illustrated that capillary induced resonance can significantly enhance the recovery of nonwetting fluids from porous media. Continuous research/industrial efforts were made in the 1980s to duplicate earthquake effects by use of vibrators above a targeted zone. However, these attempts did not succeed due to lack of commercial viability. Roberts et al. [3] experimented on cylindrical sand packs saturated with water and offered laboratory evidence of seismic stimulation. Further, Li et al. [27] conducted experiments on flooding of water across a glass plate applied with and without vibrations in the direction of flood. Thereafter, Occidental of Elk Hills (Oxy) has employed in situ seismic stimulation to increase oil recovery in declining reservoirs [31]. Oxys seismic-stimulation project at the declining Elk Hills Field near Bakersfield, California (USA) have reported an improved oil recovery and increased flow. This turned out to be the first departure from variants on conventional stimulation methods like thermal, polymer, chemical and microbial to be introduced commercially since the 1970s.

Many researchers used lattice Boltzmann Shan and Chen model [32–34] to explore the dynamics of the contact line. This is mainly due to the interaction-potential based approach. Also, it is easy to apply the boundary conditions in complex porous structures and versatile in terms of handling fluid phases with different densities, viscosities and wettabilities. Zhang and Kwok [35] studied the wetting and movement of a three-phase contact line confined between two super hydrophobic surface using a mean field free energy lattice Boltzmann model. Two regimes were found for the velocity of the fluid flow as a function of surface roughness. This is related directly to the balance between driving force and flow resistance. Briant et al. [36] have simulated contact line motion in both liquid–gas systems and binary fluids using LB method.

Hilpert et al. [37] modelled to understand the dynamics of the trapping forces and blob mobilization. He analyzed the behavior of the three-phase contact lines which could remain pinned to the heterogeneities of the solid surface or slide if sound waves are applied. Hilpert et al. [2] hypothesize that the trapped oil blobs in porous media also show meniscus resonances like that of liquid column trapped in a capillary tube. They further stated that pinned contact lines can be observed not only for oscillatory flows but also for oscillatory vibrations of the solid surface. It is well known that pinned contact lines exist in natural porous media due to their surface roughness and chemical heterogeneities. Hence, it is more likely to lead to nonexistence of sliding contact lines. For such systems the three-phase contact line is not observed. Hilpert [6] discussed the phenomenon of resonance of the blob due to capillary induced resonant frequency for pinned configuration. However, the effect of surface wettability in conjunction with acoustic excitation has been largely overlooked.