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Research/Technical Note

Modeling an Ascending Nitrogen Gas Bubble in a Medium Crude Oil by Lattice Boltzmann Method

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Abstract: The study and modeling of oil biphasic systems, liquid-liquid and liquid-gas, focus mainly on the details of the modifications and application of the numerical methods itself. The correspondence between theoretical and experimental results and the information needed to apply a certain numerical method, usually remain in the background. On the other hand, in the particular case of the prediction of minimum miscibility pressure, extremely important parameter in oil exploration, references that show qualitative and numerical data associated with the characterization of the systems are scarce. The above reasons motivated the realization of this work. We used the Lattice Boltzmann Equation method to model a two-dimensional system of the displacement of a nitrogen gas bubble through a medium crude oil, under different pressure conditions keeping the temperature constant. According to experimental data, the bubble is not miscible by the crude, under a pressure range of 5000 psi to 6500 psi; nevertheless, the bubble is miscible in the range of 7000 psi to 7500 psi. Throughout simulations performed under similar conditions, we showed that it can be inferred the critical pressure range of miscibility of a medium crude oil.

Keywords: LBE Method, Minimum Miscibility, Pressure, Gas Bubble

1. Introduction

The Lattice Boltzmann Equation (LBE) method is based on representation of particles collections as a unity. Considering that the behavior of the macroscopic fluid arises from the collective behavior of many microscopic particles, at the same time it allows to build simplified kinetic models which contain the essence of the microscopic processes; thus enabling the average macroscopic properties obey macroscopic equations associated. Particles collections properties are represented statistically by a distribution function, as shown in the central figure of Figure 1 [1, 2].

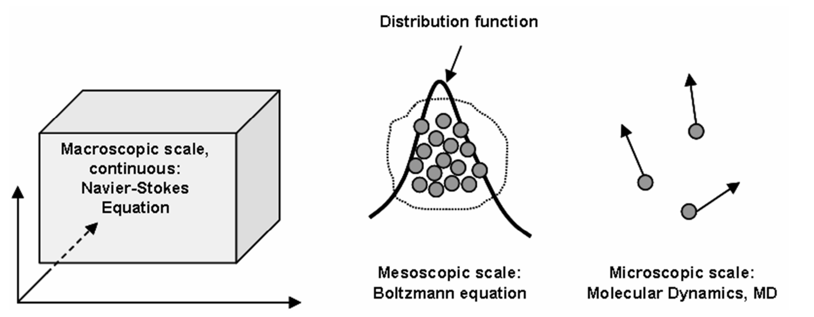

Figure 1. Schematic representation of several simulation techniques for fluids at different scales.

The LBE method treats the fluid as a set of coarse-grained fictitious particles, represented by distribution functions, confined to a network where through two processes, the diffusion across network connections and process of collision to the network nodes, the dynamics of the system is performed [1, 2].

During evolution of the system, some of these particles collide, interact with others and spread, moving along specific network addresses to neighboring nodes. The number of addresses and connections between nodes depends on the arrangement of the network. The method applies the discretization of space, time and speed to describe fluid evolution [1, 2].

In the LBE method, a large number of small particles moving with random motions represent gases and fluids. The exchange of momentum and energy is achieved through particle streaming and particle collision. This process can be modeled by the Boltzmann transport equation, defined as [3, 4]:

$$\frac{\partial f}{\partial t} + \bar{v}.\nabla f = \Omega \quad (1)$$

where f is the particle distribution function, $\bar{v}$ is the particle velocity, and Ω is the collision operator.

The LBE method idea is to reduce the number of particle by confining them to the nodes of a lattice. For a two dimensional model, like the well-known square lattice scheme D2Q9, which was chosen in this work, a particle is restricted to stream in a possible of 9 directions, including the one staying at rest, involves 9 velocity vectors, $\bar{e_i}$. For each particle on the lattice we associate a discrete probability distribution function, $f_i(\bar{x},\bar{e_i},t)$, which describes the probability of streaming in one particular direction [3, 4]. Connections of the distribution function with macroscopic quantities as the density and velocity are defined as follows:

$$\rho(\bar{x},t) = \sum_{i=0}^{0} f_i(\bar{x},t) \quad (2)$$

$$\bar{v}(\bar{x},t) = \frac{1}{\rho}\sum_{i=0}^{0} cf_i\bar{e_i} \quad (3)$$

The method is mainly based on two processes, the streaming (the term on the left), and collision (the term on the right) processes, which are given by:

$$(\bar{x}, c\bar{e_i}\Delta t, t+\Delta t) - f_i(\bar{x},t) = \frac{1}{\tau}\left[f_i(\bar{x},t) - f_i^{eq}(\bar{x},t)\right] \quad (4)$$

where τ is considered as the relaxation time toward local equilibrium [3, 4].

Different computational methods are used successfully to model and study liquid systems with gas bubbles, among them one of the most applied is the Lattice Boltzmann method. In this sense, Agarwal et al [5] presented an algorithm for the simulation of a single bubble rising in a stagnant liquid using BGK approximation of Lattice Boltzmann method and Lagrangian particle tracking approach to model the dispersed gas bubble phase. Anderl et al [6] made an improvement to the free surface Lattice Boltzmann method for the simulation of bubbly flows including rupture and breakup of bubbles. Yang and collaborates [7] investigated the bubble dynamics from a systematic and multiscale perspective, probing the behavior of a single bubble, a bubble pair, and a bubble swarm with a Multiple-Relaxation-Time, using this method.

Huber et al [8] successfully applied the Lattice Boltzmann method for free surface flows, to model Ostwald ripening and bubble deformation under simple shear flow conditions. Tao Sun and Weizhong Li [9] proposed a three-dimensional hybrid Lattice Boltzmann model to simulate nucleate boiling. On the other hand, E. Khamehchi et al [10] studied two important properties of crude oil, bubble point pressure (Pb) and formation volume factor (Bob) using genetic programming.

Following this line of research, our work used a general purpose mesoscopic simulation package, the Lattice Boltzmann Equation (LBE), to model a two dimensional system of the displacement of a nitrogen gas bubble through a medium crude oil, under three different pressure (P) conditions while keeping the temperature (T) constant, in order to estimate the minimum miscibility pressure (MMP).

When an oil reservoir cannot be enough productive due to factors such as low bottom-hole pressure, high viscosity of oil, invasion of connate water, between others, an option to raise oil production is to displace a fluid miscible with the crude to reduce oil entrapment by capillary forces, and let increase the volume of oil in surface [11].

In this sense, miscible gas injection processes have become widely used technique for the enhanced oil recovery (EOR) or improved oil recovery (IOR). In miscible gas flooding, the goal is to miscible displaces the trapped oil fractions with the help of gaseous solvent, such as natural gas, enriched natural gas, carbon dioxide, flue gas, methane, nitrogen, among others or a hydrocarbons fluid [12, 13].

To increase the displacement efficiency and improve the oil recovery, the knowledge of minimum miscibility pressure (MMP) is essential. At MMP, the interfacial tension across the interface between the concurrent streams (injected gas or hydrocarbon fluid in contact with the reservoir fluid) approaches zero, which results in potential transfer of molecules across the interface leading to mutual miscibility and homogeneous fluid formation [12].

Miscibility is a term commonly used to refer to the liquids property to mix in all proportions in order to form a homogeneous solution. The MMP is the lowest pressure for which a gas can develop miscibility through a multi-contact process with a given reservoir oil at reservoir temperature. The reservoir to which the process is applied should be operated at or above MMP to develop multi-contact miscibility. Reservoir pressures below MMP result in immiscible displacements and as result in lower oil recoveries [14].

At or above the MMP, miscibility can develop through a vaporizing process, a condensing process, or depending on the reservoir characteristics, a combination of the two processes. In the vaporization process, intermediate molecular weight hydrocarbons from the crude oil are transferred to the leading edge of the gas front, enabling it to become miscible with the reservoir crude. In the condensing process, the injected gas is enriched with light hydrocarbons.

The reservoir oil, left behind the gas front, is enriched by net transfer of the light hydrocarbons from the gas phase into the oil. Enrichment of the reservoir oil proceeds until it becomes miscible with the injected rich gas. In all cases, the MMP determination is essential and in the present day, there are a number of experimental techniques for the determination of MMP like slim tube, vanishing interfacial tension (VIT) and rising bubble apparatus (RBA) [12].

2. Rising Bubble Experiment

The design of the rising bubble model was based on experimental data, obtained from RBA technique implementation by the IOR Gas Injection Laboratory [15].

The RBA consists of a cell gage containing a flat glass tube where oil samples are placed and an injection needle where gas is injected in to the flat glass tube. To simulate reservoir conditions, the glass tube is pressurized using deionized water, and heating plates surrounding the cell are used to regulate temperature. Visual observation of the injected gas bubble behavior is captured by a camera as it rises and moves upward along the oil column. By observing the shape and dissolution behavior of the bubble, the MMP can be determined [16]. A schematic diagram of the RBA experiment is shown in Figure 2.

The RBA determines the MMP by adopting a multi-contact miscibility approach. Injected fluid is observed as it moves and rises through an oil column at a set pressure and temperature. If a gas bubble rises through the oil column while maintaining its near-spherical shape, then the pressure is still below MMP. Otherwise, if the injected bubble disperses more rapidly or dissolves instantaneously, the pressure is above the MMP. In the case of the trailing edge of the bubble, noticeably dissolves while the leading edge maintains its spherical shape until it dissolves near the top of the apparatus, the displacement pressure is at or just above the MMP [16].

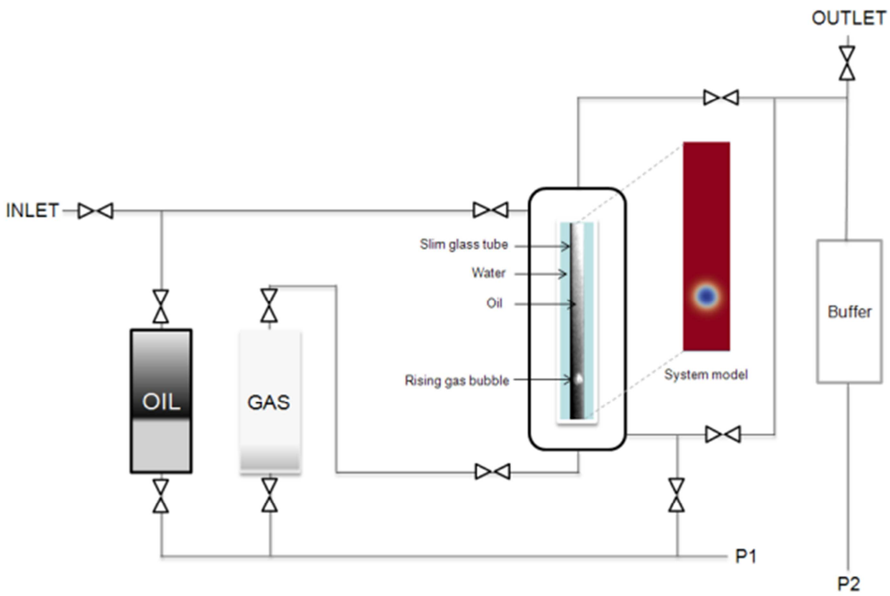

Figure 2. *Schematic diagram of the RBA experiment. P1 is the injection pump and P2 is the receiving pump.*

The criterion used for modeling a rising gas bubble through a medium crude oil from RBA experimental data is due to this technique provides a reliable estimation of the MMP because the gas loses its interfacial tension and forms a single phase after traveling a short distance through the oil. Moreover, the travel distance represents the multiple contact areas between the oil and gas, which takes place in this studio through a vaporizing process.

3. Theoretical and Experimental Data Model

As mentioned before, the research goal was MMP estimate through a two-dimensional model of a nitrogen gas bubble rising through a medium crude oil column. In this case of study, nitrogen gas was selected because it has been positioned as an economical alternative injection gas for gas based enhanced oil recovery (EOR) processes.

Although the carbon dioxide is known as a very effective agent to displace oil from the reservoir by achieving miscibility through multiple contacts with oil via vaporization and swelling, there are major drawbacks to CO_2 flooding including but not limited to availability and high cost, asphaltene precipitation, corrosion in the well and surface facilities and environmental constraints. Such that, the limitations on cost and availability of CO_2 has made nitrogen a potential candidate for EOR processes, especially for deep and high pressure reservoirs of light and volatile oil where miscible displacement could be achieved [13].

On account of this was made a theoretical model in two dimensions, of a cell of 12 mm long (discretized in 30 divisions measure from zero to 120) by 4 mm wide (discretized in 10 divisions measured from zero to 40) inside which the nitrogen gas bubble design with an area of 6.50 mm^2 was added, the edges of the cell are located parallel to x-axis at position zero and 40 of y-axis. The nodes outside bubble region were allocated, density and relaxation times values characteristic of the type of medium crude oil from the Venezuela Furrial field, described in Table 1.

Two types of regions were modeled; one describing the nitrogen gas bubble and other representing the crude oil and cell that contains it as to be shown in Figure 2. The system, for a medium crude oil specific gravity of 0.829, was modeled by setting a speed sound of 1300 m/s.

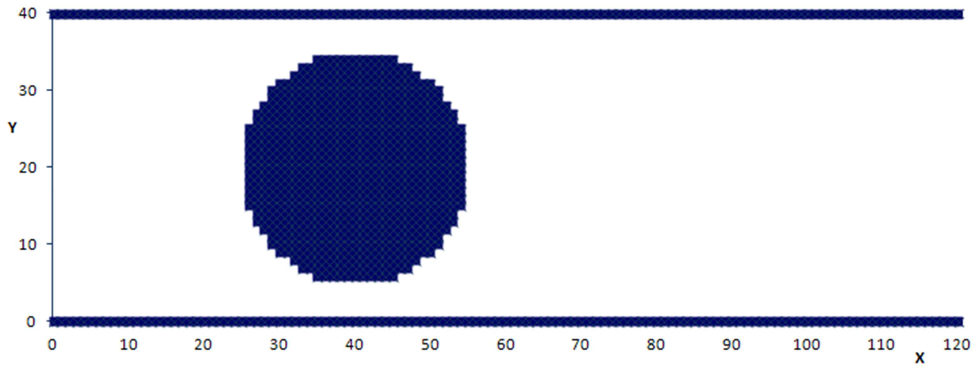

Figure 3. *Two dimensional model of ascending nitrogen gas bubble system.*

In order to describe mesophase interactions, was chosen the method of Lishchuk continuum-based interactions [17] and to model the collision type, it was used the BGK with Guo forcing [18]. In the Lishchuk model for single phases and multiple components, the force acting between components *a* and *b* (F_{ab}) is expressed as:

$$\overline{F}_{ab} = \frac{1}{2} g_{ab} K_{ab} \nabla \rho_{ab}^{N} \quad (5)$$

$$\rho_{ab} = \frac{\rho^a - \rho^b}{\rho^a + \rho^b} \quad (6)$$

Where, g_{ab} is non-zero interaction parameters between the fluid species, K_{ab} is the local curvature from the interface model, which can be determined from spatial gradients of the phase index. The experimental parameters, geometric properties and simulation conditions are displayed in Table 1 and Table 2.

Table 1. *Experimental data used for model design rising bubble.*

Experimental data	
Crude oil origen	Furrial
Crude oil type	Medium crude oil
° API	25
Specific gravity	0.829
System temperature	150°C
Speed sound	1300 m/s
Immiscibility pressure range	5000 psi to 6500 psi
Miscibility pressure range	7000 psi to 7500 psi

4. Discussion and Results

According to the experimental data of the Reservoir Studies Management Laboratory Gas Injection IOR and Vakili-Nezhaad et al [7], the bubble gas did not change its shape and size when it released in the column of medium crude oil at a constant T of 150°C, within P range of 5000 psi to 6500 psi, indicating that the bubble is not miscible by the medium under these T and P conditions.

Figure 4, shows the result of bubble model evaluated at a T of 150°C and P of 5480 psi, which during its displacement through the oil column shown an important size decrease, exhibit an approximate area of 2.96 mm^2, which is 54% lower than the starting area of 6.50 mm^2.

Table 2. *Simulation parameters to perform the dynamics of the rising bubble system.*

System properties	
Space_dimension	2
Discrete_speed	9
Number_of_fluid	2
Number_of_solute	0
Grid_number_x	100
Grid_number_y	40
Grid_number_z	1
Simulation parameters	
Total_step	500000
Equilibration_step	10000
Save_span	500
Output format	VTK
Collision and propagation models	
Interaction_type	Lishchuk
Collision_type	BGKGuo

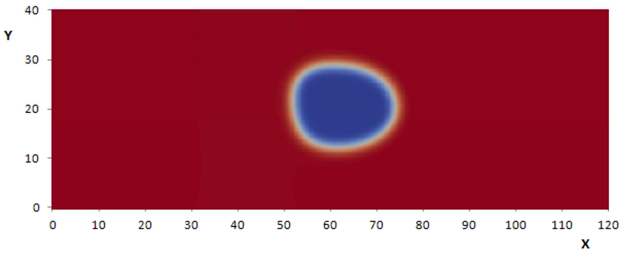

Figure 4. *Resulting system from the dynamics performed, by releasing a bubble of nitrogen gas (center), in a column of medium crude oil of 25 °API, at a constant temperature of 150°C and pressure of 5480 psi.*

By increasing the system pressure until 5832 psi, keeping T constant at 150°C, the bubble modified its shape, acquiring a more spherical shape and presented an area reduction of 2.26 mm^2 of about 24% compared to the previous area and 65% compared to the initial area. This behavior is consistent with the experimental result, carried out at a constant T of 150°C and a constant P of 5950 psi, on the IOR Gas Injection Laboratory.

In this case, the bubble got an elongated shape, and it showed a perceptible reduction in its size, with an approximate area of 1.96mm^2, very close to the area obtained theoretically, as illustrated in the Figure 5 and 6, wherein are displayed the dynamic snapshots, observed in the theoretically and experimental system. In both instances, pressure conditions were established located in the range of immiscibility. On the other hand, both results show that the bubble has started to be absorbed by the medium.

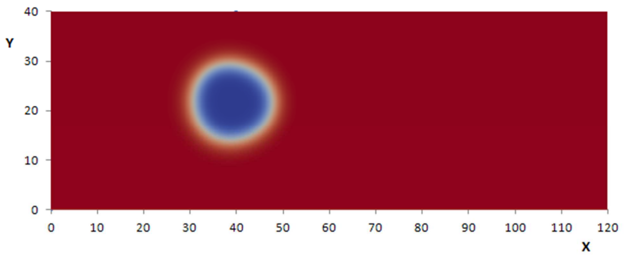

Figure 5. *Image of the performed dynamics by releasing a bubble of nitrogen gas (center at left end), into medium crude oil column of 25 °API at pressure value of 5832 psi.*

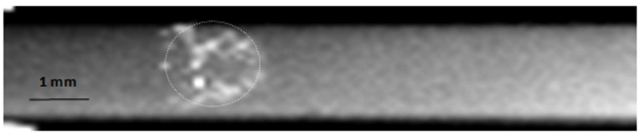

Figure 6. *Image of the dynamic observed in an experimental system of a nitrogen gas bubble (center, left end), releasing into a column filled of medium crude oil of 25 °API at a constant temperature of 150°C, and pressure of 5950 psi (Reservoir Studies Management Laboratory Gas Injection IOR, 2016).*

The result obtained under miscible condition is shown in the Figure 7, which displays the change in shape and size experimented by the gas bubble, when the P value increased to 7170 psi to reach the critical pressure range of miscibility. The bubble got a meaningful surface reduction, presenting an area of 0.92 mm^2, about 59% compared to the previous area and 86% compared to the starting area.

This result whatever agrees with the IOR Gas Injection Laboratory experimental result, as it is shown in the snapshot of the dynamics, displayed in Figure 8, with a critical P value of 7000 psi, and a similar area change and area reduction about 0.66 mm^2, around 66% compared to previous area.

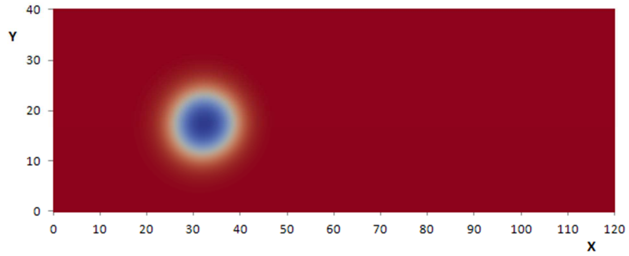

Figure 7. *Image of the performed dynamics by releasing a bubble of nitrogen gas (center at left end), into medium crude oil column of 25 °API at a pressure of 7170 psi.*

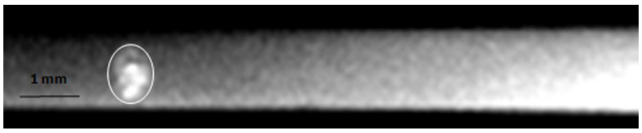

Figure 8. *Image of the dynamic observed in an experimental system of a nitrogen gas bubble (center, left end), releasing into a column filled of medium oil of 25 °API at a constant temperature of 150°C and P value of 7000 psi (Reservoir Studies Management Laboratory Gas Injection IOR, 2016).*

As can be appreciated, when comparing the theoretical and experimental results, performed under similar conditions, through the implementation of the LBE method, it was able to reproduce the dynamic behavior of a rising bubble experiment and estimated the critical pressure range of miscibility. In this particular case, the transit of nitrogen gas bubble into a column filled of medium crude oil of 25 °API, at a constant T of 150°C, so that the system pressure was increased until reaching the miscible critical pressure range.

5. Conclusion

A representative system of a rising gas bubble experiment, implemented by the IOR Laboratory of PDVSA Intevep, was modeled using a general purpose mesoscopic simulation package, which simulate lattice-gas systems using the Lattice Boltzmann Equation (LBE).

The results showed that it was possible to reproduce the dynamic behavior of a nitrogen gas bubble passing through a column filled of medium crude oil, under miscibility and immiscibility pressure conditions, keeping the temperature constant.

In the simulations carried out, under immiscible conditions at a pressure of 5480 psi, the bubble kept its shape and it was completely visible throughout its displacement by the oil phase. This was consistent with the experimental pressure range of 5000 to 6500 psi, under which there is no miscibility.

By increasing the pressure to 5832 psi, the bubble began to undergo changes in its shape and size, which agree with experimental result. Both results shown that the bubble start to be absorbed by the medium, when de pressure value approaches to the critical immiscibility pressure value.

For a pressure of 7170 psi, which is within the experimental range of miscibility pressure, the nitrogen gas bubble experimented a meaningful surface reduction and significant changes in its shape, which was consistent with the experimental changes observed

The results obtained showed that it can be inferred the critical pressure range of miscibility into a medium crude oil, using the LBE technique, with a very low computational cost, using two dimensional systems.

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