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# Study on microscopic flow characteristics of foam in porous media

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***ABSTRACT.*** *The flow behavior of foam in pores affects the sweep range and displacement efficiency, it plays an important role in enhancing oil recovery. The numerical simulation method of foam transport in capillary tubes is summarized. The flow behavior of foam in capillary model was simulated and analyzed by Level Set method combined with gas-liquid two-phase flow. The Jia Min effect produced by the migration of bubbles from large channels to small channels is analyzed. The results show that the migration of foam in porous media can be replaced by a model of capillary tubes with different diameters. It will provide beneficial enlightenment for field application of gas-liquid dispersion system in profile control and enhanced oil recovery.*

***KEYWORDS:*** *foam, porous medium, capillary, two phase flow, level Set method*

## 1. Introduction

When the oilfield is in the high water cut stage, it is urgent to solve the problems of low recovery and high water cut. The viscosity of foam is higher than that of the gas and liquid. The flow of foam in porous media is selective, large and not blocked, and has temporary plugging. It will not cause permanent pollution to the remaining oil layers. Therefore, foam profile control is the best choice. The research and control of foam flow behavior is related to the success or failure of foam flooding. Therefore, studying the motion rule of foam in porous media is of great significance for understanding its mechanism of profile control and improving the water injection efficiency of reservoirs with low water injection efficiency.

The mechanism of foam profile control is mainly focused on the flow behavior of foam in capillary pipes. A lot of numerical and experimental studies have been carried out at home and abroad. Raza et al. used Pyrex tube flow experiments to study the rheological properties of Foam Fluids in capillary tubes[1]. Patton et al.

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studied the rheology of foam through capillary viscometer experiments[2]. Zaruba et al. used high-speed photography to track the trajectory of a single bubble in the bubble stream[3]. Unverdi et al. used the front tracking method to simulate the flow behavior of a single bubble [4]. Tsui et al. coupled the VOF method and the Level Set method to numerically study rising bubbles[5].

## 2. Methodology

### *2.1 Basic content of foam migration in porous media*

During the migration of foam fluid in porous media, foam fluid has both continuous and discontinuous parts. The flow process of the continuous part is the Jamin effect caused by the deformation and stretching when the foam passes through the narrow throat, and the flow process of the discontinuous part is caused by the liquid film breaking and coalescence mechanism of the foam.

Due to the limitations of physical experiments and the complexity of the pores of porous media, it is impossible to capture the details of the migration of bubbles in porous media.And the complex channels of porous media can be simplified as the combination of simple channels, and the simple channels can be replaced by capillary model. Therefore, the flow of foam in porous media can be simulated by capillary combined model.

### *2.2 Basic content of computational model*

The process of the gas-liquid two-phase flow in the capillary is generally attributed to the gas-liquid two-phase unsteady laminar flow. The focus of this article is how to determine the location of the interface between gas and liquid phases.Because the grid quality of the level set method is stable and easy to control, and the calculation of the curvature of the gas-liquid two-phase flow interface is simple, at the same time, by using a fixed value to express the free surface, other methods can be avoided to cause different Free surface shape, so Level Set interface tracking technology is widely used in CFD research of this flow process[6].

In this paper, a mathematical model of foam transport in a single capillary tube is established. The Navier Stokes equation is used to describe the momentum transfer characteristics of the two phase fluid in the two phase flow in the pore scale. The Level Set algorithm is used to characterize the dynamic change of the gas water two phase interface at different times. The two simultaneous mathematical models are established. The assumptions are as follows:

(1) The gas-water two-phase flow in the pores is incompressible, and the flow state is laminar flow with low Reynolds number;

(2) The gravity of fluid is ignored;

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(3) Ignoring the thickness of the single capillary model, the fluid in the single capillary belongs to two-dimensional flow.

In the incompressible laminar two-phase flow with low Reynolds number, Φ of the Level Set equation is regarded as the volume fraction of the fluid in the gas-water two-phase flow. Therefore, the interface transport equation of two-phase fluid can be expressed as follows:

$$\frac{\partial\varphi}{\partial t}+u\nabla\varphi=\gamma\nabla\left(\varepsilon\nabla\varphi-\varphi\left(1-\varphi\right)\frac{\nabla\varphi}{\left|\nabla\varphi\right|}\right) \tag{1}$$

Where the Φ is the contour of gas-water two-phase interface; γ is the reinitialization parameter in the equation solution; t is the interaction time of two-phase; u is the velocity; and ε is the thickness of the interface, which is generally less than the minimum element of mesh generation in the calculation model.

With the help of Level Set function, the physical properties of fluid can be expressed by the following equation:

$$\begin{cases}\rho\left(\varphi\right)=\rho_g+\left(\rho_w-\rho_g\right)\varphi\\ \mu\left(\varphi\right)=\mu_g+\left(\mu_w-\mu_g\right)\varphi\end{cases} \tag{2}$$

Where $\rho_g$ and $\rho_w$ are the density of gas and water respectively; μg and μw are the viscosity of gas and water respectively. The smooth heavisde function is defined as:

$$H\left(\varphi\right)=\begin{cases}0, & \varphi<-\varepsilon\\ \frac{1}{2}+\frac{\varphi}{2\varepsilon}+\frac{1}{\pi}\sin\left(\frac{\pi\varphi}{\varepsilon}\right), & -\varepsilon<\varphi<\varepsilon\\ 1, & \varphi>\varepsilon\end{cases} \tag{3}$$

Where the Ɛ is half of the thickness of the interface and can be taken as a certain proportion of the mesh size. After this definition, the density and viscosity of the fluid can be smoothly transferred at the contact surface of the two phases without sudden change, which ensures the stable convergence of the calculation.

The Navier Stokes equations can be used to describe the mass and momentum transfer characteristics of incompressible fluids. Because of the capillary force, the surface tension is very important in the model. In a fixed Eulerian coordinate system, the continuity equation and momentum equation of two-phase medium flow with incompressible surface tension and neglecting gravity term can be described by the following equations :

(1) Continuity equation:

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$$\nabla \cdot u = 0 \tag{4}$$

Where $u$ is the velocity of the fluid, m/s.

(2) Momentum equation:

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla \cdot \left\{ -pI + \mu \left[ \nabla u + (\nabla u)^T \right] \right\} + F \tag{5}$$

Where ρ is density, kg/m$^3$; μ is dynamic viscosity, Pa/s; P is pressure, Pa; I is unit matrix; F is gas-liquid interfacial tension, N/m.

(3) Surface tension equation:

$$F = \nabla \cdot \left( I - nn^T \right) \sigma \delta \tag{6}$$

Where σ is the surface tension coefficient; δ is the dyke function, which is zero in the region outside the two-phase interface; n is the interface normal vector, which can be expressed as:

$$n = \frac{\nabla \varphi}{|\nabla \varphi|} \tag{7}$$

The combined capillary pipe model derives from the physical fact that the foam flows from the small channel to the large channel and then flows through the large channel into the small channel. The two-dimensional model is shown in Figure 1.

The left side of the model is velocity inlet, the volume fraction of gas phase is set to 0.5, the right side is pressure outlet, and the other walls adopt no-slip boundary conditions.The viscosity model is laminar flow model. The mesh is divided into trianglesthe(Fig.2). The calculation model is unsteady simulation, and the solution method is PARDISO method.

*Figure. 1 Combination tube model*

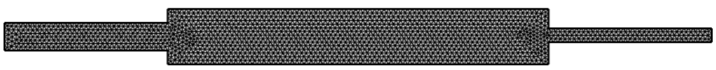

*Figure. 2 Mesh generation of combined pipe model*

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## 3. Results and discussion

Kong et al. studied the micro plugging characteristics of foam through glass bead filling foam flooding experiment, and observed the deformation and plugging phenomenon of foam[7]. As shown in Fig. 3, the foam A with the same size as the throat is stuck at the pore throat and produces resistance. Foam A starts to get stuck in the throat inlet. The subsequent fluid forces foam A to deform, stretch and extend gradually, and finally flow through the throat.

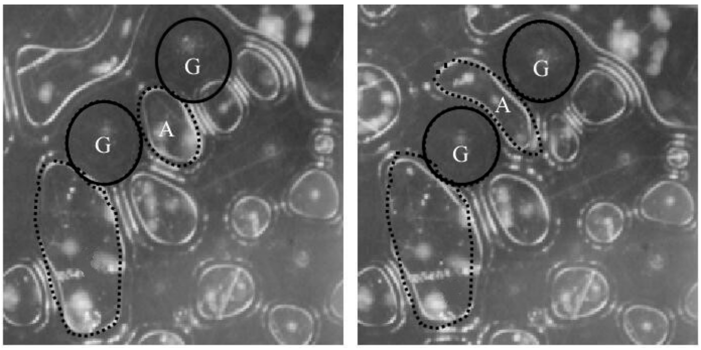


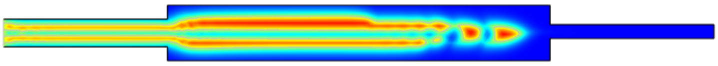

*Figure. 3 Process of bigger foam through narrow porous media channel*

The simulation results of foam migration in a composite pipe are shown in Figure 4. In the initial stage of gas-liquid mixture flow, the bubbles are arranged in the larger pipeline on the left side. With the further fluidization of the foam fluid, the foam enters the big pipe, the foam begins to expand and gradually occupy the pipe. After the further development of the flow, the leading edge of the liquid film begins to enter the small pipe on the right side, and the front edge of the liquid film is deformed, and then due to the action of capillary force and the scour of liquid flow, the liquid membrane began to break up the big bubbles, and produced small bubbles at the leading edge of the flow. Finally, this process occurred continuously, and a large bubble became small bubbles in the small pipe. This process is in line with figure 3.

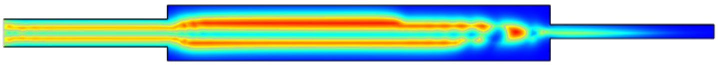
(a) t = 0.001ms

(b) t = 0.003ms

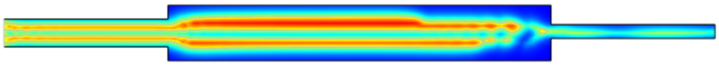
(c) t = 0.005ms



(d) t = 0.012ms



(e) t = 0.013ms



(f) t = 0.014ms

*Figure. 4 Migration of foam in combination tube model (fraction of gas volume)*

## 4. Conclusion

The Level Set method can effectively simulate the physical process of foam flow in capillary tubes, reproduce the fluid flow phenomena in complex porous media, expand the scheme of indoor laboratory simulation. In this study, a combined pipe model was used to simulate the flow of foam in porous media. The characteristics of foam flow in porous media are analyzed, and have important theoretical significance for improving the effect of foam flooding by gas-liquid dispersion system.

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