Modelling two-phase flow in multi-mineral porous media using coupled level set-volume of fluid (CLSVOF) method

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Summary

A numerical scheme for modeling multiphase flow in multi-mineral, micro-scale porous media is presented. The numerical procedure is implemented for stable and reliable CFD-based modeling of multiphase flow in micro-scale media with complex interface motion and rough solid boundaries. The method enables multiple mineral materials, allowing for different wettabilities and contact angles on each mineral. To deal with interface motion and construct stable interfaces, the Volume of Fluid (VOF) method is coupled by level set approach. In particular, to capture interface, a modified VOF advection function is used and then to overcome inaccuracy of curvature calculation, the interface is reconstructed based on the level set method. The code validation shows that our method is stable, less sensitive to the capillary number and density ratio and mass is conserved very accurately. The developed scheme was used to study the effect of wettability heterogeneity on trapping and mobilization of the non-wetting-phase during two phase displacement scenarios.

Introduction

Micro-scale investigation of fluid flow in porous media is of the utmost importance in a wide range of applications such as enhanced oil recovery and carbon dioxide storage in underground aquifers. In this regard, Eulerian grid-based methods such as finite volume, finite difference or finite element are considered to be the desirable approach for solving the Navier–Stokes equations because of their supremacy in numerical adeptness and ability to simulate fluid flow in wide range of density and viscosity ratios. They allow to evaluate which flow instabilities are dominant and which flowing conditions lead to different levels of instabilities at the pore scale (Haines jumps, oil blob mobilization, phase bypassing and entrapment, and so forth). The achilles' heel of these methods is handling the motion of the interface and contact line. In this regard, there are myriad of methods proposed to track the interface, categorised into three main classes: (a) moving mesh, (b) surface tracking and (c) volume tracking methods. In volume tracking methods, the fluids in both sides of interface are marked and advected either by an indicator function, which may be a volume fraction or a level set (LS) function. In the LS method, the interface is captured by a level set function, which is zero on the interface, is positive in one side and is negative in the other side. The interface is thus characterized by the zero level sets. The main advantage of the LS method is that it handles merging and breaking of the interface automatically, the interface never has to be explicitly reconstructed, and since level set function is always smooth, the unit normal and curvature of the interface can be easily calculated. The famous drawbacks of the LS method are mass loss/gain, the volume enclosed by the zero level sets is not conserved, and also the method is too sensitive to the discretization scheme and the mesh size distribution.

In the VOF method, a volume fraction is defined at each cell which represents the ratio of the volume of one of the fluids in this cell, called fluid 1, to the total volume of the grid cell. Thus, volume fraction is unity in a cell that is filled completely by fluid 1, and is zero if the cell lies completely in the other fluid, called fluid 2. For cells that contain an interface which means both fluid 1 and fluid 2 are present in the cell, volume fraction is between zero and unity. So, using the volume fraction distribution at each time step, the interface position can be traced. However, logical solution of the advection equation is not guaranteed. Because the

advection equation is a discontinuous function, using standard numerical schemes such as an upwind finite difference method to solve the flow field can easily diffuse the interface, which should, however, remain sharp. Inaccurate interface construction is thus the main problem of VOF method. In comparison with LS method, a remarkable importance of the VOF method is that it can conserve mass very precisely. This encouraged researchers to couple both methods and compensate for the disadvantages of individual methods in tackling two-phase interface related problems. Coupled Level Set/Volume of Fluid (CLSVOF) method is one of the most aggressively researched combined methods, based on VOF, which LS is used to overcome curvature and normals miscalculation problems.

Method

In this paper, the VOF-based solver "interFoam", of OpenFOAM CFD package, was used as the basis for our numerical simulation and modified for stable micro-scale two-phase flow modeling. We applied the CLSVOF interface capturing algorithm to the solver "interFoam". The coupled scheme takes advantage of the strengths of each of the two methods. The main idea is to benefit from the advantage of each strategy, which is to minimize mass loss through the VOF method and to keep a fine description of the geometrical properties of the interface with the LS method. Both LS and volume fraction functions are evolved individually. LS function is used to calculate the unit normal and curvature of the interface by using the modified volume fraction function information. The volume fraction, together with the unit normal calculated from LS, is used to reconstruct a new interface. Thus, LS function can finally be reset to a signed distance function based on the reconstructed interface. Since volume function is tracked, mass and volume can be conserved very accurately. Also, because of continuous nature of LS, the calculation of the interface normal and curvature is rational, easy and accurate, in contrast to the VOF method, which requires unphysical smoothing of advection equation.

The extended solver was validated against 2D and 3D benchmarks with and without solid boundaries. Using the proposed scheme, all pore-scale phenomena such as Haines jumps and phase entrapment could be captured accurately considering VOF function distribution. Figure below is an example of volume fraction propagation after first drainage and secondary imbibition scenarios.
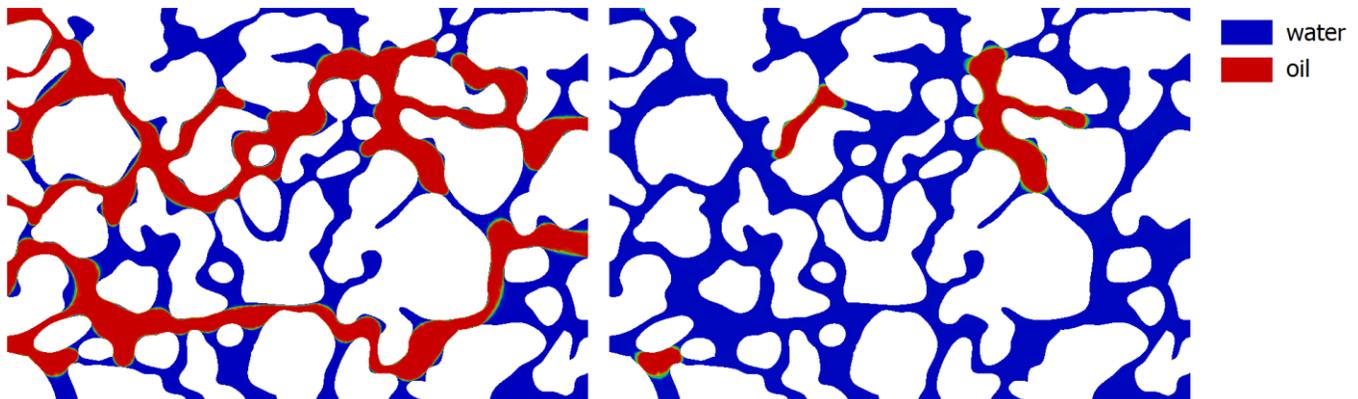

Figure 1 Phase distribution after first drainage (left), secondary imbibition (right)

Examples

Considering the impact of pore-scale mineralogy on reactive transport in porous media, it is a key aspect in pore scale simulations. The continuum and pore-scale equations involve different physics which are governed by the Navier-Stokes and pore-scale advective-diffusion-reaction equations. Here, the effect of complexity of mineralogy and thus heterogeneous wettability, on trapping and mobilization of the non-wetting-phase was considered. In particular, a 2D synthetic micro-scale porous medium with three different minerals was used. Different wettability, through different contact angle, was considered for each mineral.

Figure 2 Synthetic 2D porous media including three minerals

Zones with green and yellow colors are oil wet and gray color shows water wet grains. In the first scenario we set a drainage case which oil displaces water. As it is shown in the following graphs, activity and sweep efficiency in oil wet sections is much higher than water wet sections.
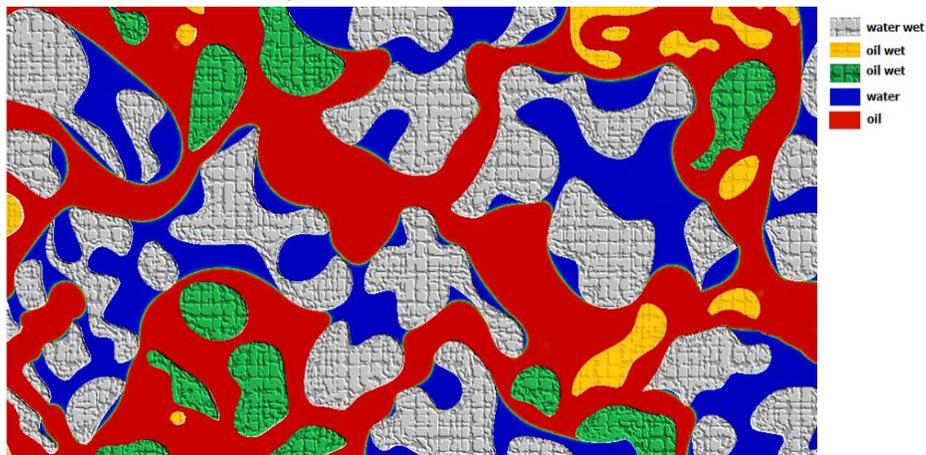

Figure 3 Saturation profile after oil break through (drainage), oil sweeps oil wet sections
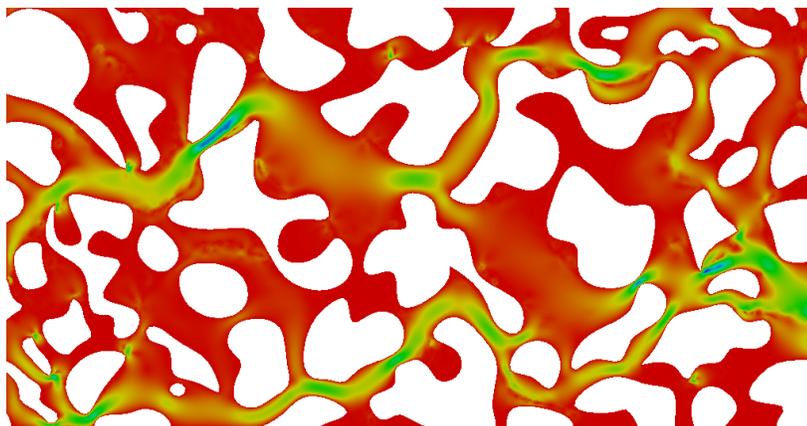

Figure 4 Velocity profile after oil break through (drainage), velocity in oil wet sections is higher than water wet zones

In the second scenario, secondary imbibition was simulated on the previously drained medium. Both scenarios were applied on a similar model this time with a single contact angle.
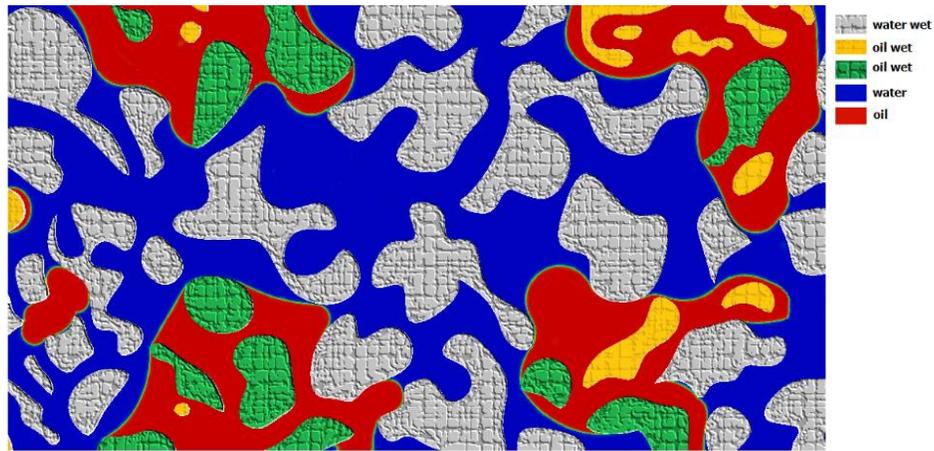
Figure 5 Saturation profile (secondary Imbibition), oil remains trapped in oil wet sections

As it is expected, the oil recovery in the mixed wettability system is lower than the similar case with homogenous wettability assumption. The velocity magnitude in both cases is in order of 0.00001 m/s and viscosity ratio is 5.

To examine the stability of the solver in 3D cases, the following medium was used to simulate two phase displacement scenarios. In comparison with "interFoam", the CLSVOF has less numerical problems, less runtime, and the pressure and velocity profiles are less fluctuating and thus the post processing of the results are more reliable.
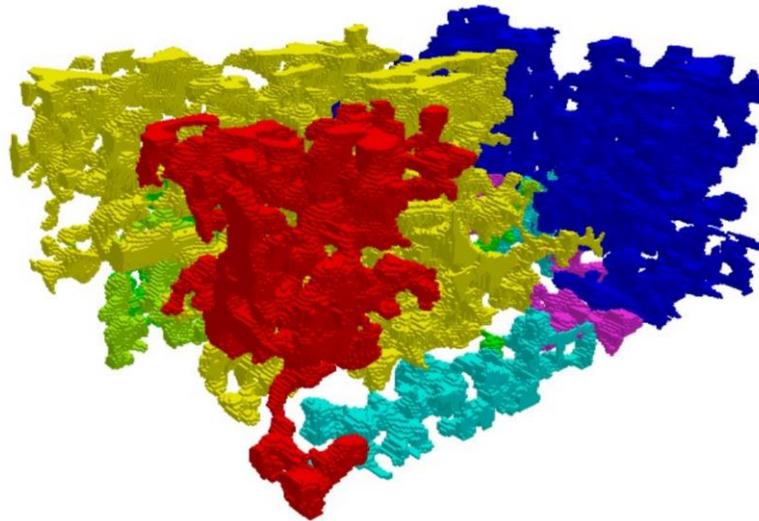

Figure 6 The 3D medium with complex mineralogy used in this study

Conclusions

- A modified CLSVOF-based solver was developed and validated against 2D and 3D benchmarks.
- The magnitude of curvature miscalculations and numerical problems are much lower in compare with VOF-based solvers.
- The pressure and velocity profiles are less fluctuating duo to using LS function.
- The CSLVOF numerical scheme is less sensitive to the capillary number and density ratio.
- Uncertainty is raised in pore scale simulations if the micro scale heterogeneity in minerals is ignored.

References

[1] Bourlioux, A., 1995. A coupled level-set volume-of-fluid method for tracking material interfaces. In: Proceedings 6th Annual Int. Symp. on Comp. Fluid Dynamics, Lake Tahoe, USA.

[2] J. Lopez, J. Herna´ndez, P. Go´mez, F. Faura, 2004. A volume of fluid method based on multidimensional advection and spline interface reconstruction, J. Comput. Phys. 195 (2004) 718–742.

[3] J.E. Pilliod, E.G. Puckett, 2004. Second-order accurate volume-of-fluid algorithms for tracking material interfaces, J. Comput. Phys. 199 (2) (2004) 465–502.

[4] Sussman, M., Fatemi, E., Smereka, P., Osher, S., 1998. An improved level set method for incompressible two-phase. Comput. Fluids 27,663–680.

[5] Sussman, M., Smereka, P., Osher, S., 1994. A level set approach for computing solutions to incompressible two-phase flow. J. Comput.Phys. 114, 146–159.

[7] Tanguy, S., Berlemont, A., 2005. Application of a level set method for simulation of droplet collisions. Int. J. Multiphase Flow 31, 1015– 1035.

[8] Unverdi, S.O., Tryggvason, G., 1992. A front-tracking method for viscous, incompressible multi-fluid flows. J. Comput. Phys. 100, 25–37.

[9] Wang, Z., Yang, J., Koo, B., Stern, F, 2009. A coupled level set and volume-of-fluid method for sharp interface simulation of plunging breaking waves. Int. J. Multiph. Flow 35, 227–246

[10] Yang, X., James, A.J., Lowengrub, J., Zheng, X., Cristini, V., 2006. An adaptive coupled level-set/volume-of-fluid interface capturing method for unstructured triangular grids. J. Comput. Phys. 217, 364–394