Characterizing Flow in Oil Reservoir Rock Using Smooth Particle Hydrodynamics

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Abstract. In this paper, a 3D Smooth Particle Hydrodynamics (SPH) simulator for modeling grain scale fluid flow in porous rock is presented. The versatility of the SPH method has driven its use in increasingly complex areas of flow analysis, including flows related to porous rock for both groundwater and petroleum reservoir research. Previous approaches to such problems using SPH have involved the use of idealized pore geometries (cylinder/sphere packs etc.). In this paper we discuss the characterization of flow in models with geometries acquired from 3D X-ray microtomograph images of actual porous rock. One key advantage of SPH is realized when considering the complexity of multiple fluid phases (e.g., water and oil). By incorporating interfacial physics such as surface tension and wettability, it is possible to model the capillary behavior of multiple fluid phases with accuracy. Simulation results for permeability will be presented and compared to those from experimentation and other numerical methods showing good agreement and validating the method. By accurately reproducing the flow characteristics of actual porous rock samples, this work has made significant progress towards validating SPH for such applications.

INTRODUCTION

Complex gas/liquid/solid interactions are of interest in many areas of geoscience including enhanced oil recovery (EOR), groundwater contamination, carbon sequestration and hydrates mining. Such interactions have particular importance at the grain scale where phase interfacial physics such as capillary forces, can dictate much of the dynamics of a highly confined system. A significant amount of insight can be gained by accurately simulating multiphase fluid flow at such scales. However, this has been a challenging area for existing numerical methods to address.

Smooth Particle Hydrodynamics (SPH) is a meshfree Lagrangian particle method first proposed for astrophysical problems [1,2] and now widely applied to fluid mechanics problems [3,4,6,7] and continuum problems involving large deformation [7,8] or brittle fracture [9]. While SPH is a computationally

expensive numerical method, in many circumstances the expense can be justified by the versatility of the method and its ability to easily handle multi-physics phenomena.

We have developed a 3D, multiphase SPH simulator including surface tension effects such as contact angle and surface wettability. The simulator is programmed within a multi-core numerical framework which allows efficient, scalable parallel execution [10]. Several results from the simulator are provided in what follows.

SINGLE PHASE FLOW

While the ability to simulate a diverse range of complex phenomena with SPH represents a key advantage over alternate methods, the accuracy of such a method must be supported by verifying tests on more simple, single-phase benchmark problems. The performance of SPH in the reproduction of one-

dimensional flow characteristics have been well defined in the literature [10,11,12]. Additionally, two-dimensional flows past systems such as periodic arrays of cylinders [13,14] and more complex flow obstructions [14] have demonstrated good agreement with conventional numerical and analytical solutions to the same problems.

2D Single Phase Permeability Verification

Figure.1 illustrates SPH simulator results of permeability for single-phase flow through a 2D periodic array of cylinders. Results for SPH were within less than one percent of the Stokes solver benchmark [15].
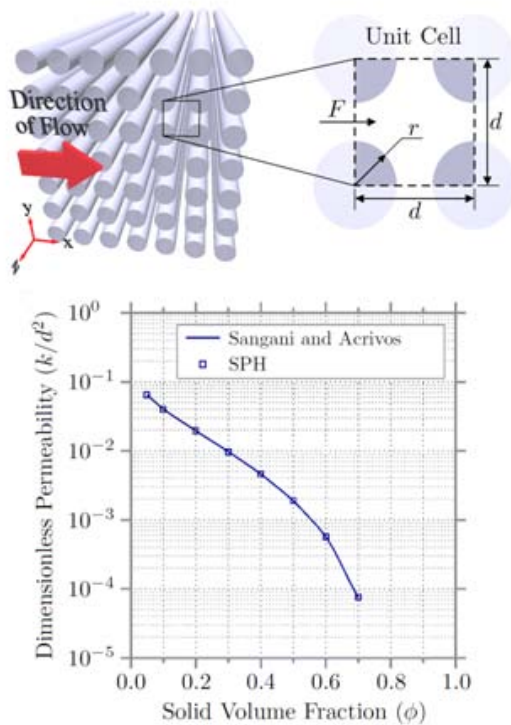

FIGURE.1. Permeability results from the SPH simulator for single-phase flow through a 2D periodic array of cylinders. Permeability is plotted against a range of solid volume fractions (1 - porosity) and compared with the widely accepted Stokes solver results of [15].

For this simulation a new technique for enforcing no-slip boundary conditions for low Reynolds number flows was used [16]. This is one of the most numerically efficient and accurate SPH no-slip boundary methods available, details can be found in the Publications section.

3D Single Phase Permeability Verification

While the above two-dimensional flow verification is a reproduction of existing work published on SPH, verification of three-dimensional flow remains largely untreated within the published literature. Ordered sphere packs are an idealized three-dimensional porous media and modeling flow through such media has commonly been used as a standard test problem to verify the three-dimensional accuracy of a numerical method [15,17,18,19]. The simulation of such a system using SPH goes a long way towards verifying the method for all flow and validating its more advanced capabilities.

Figure 2 illustrates SPH simulator results for single-phase flow through a 3D ordered packing of spheres. Results are compared with the widely cited 3D Stokes solver results of [19] and again compare accurately with the benchmark (a deviation of less than 3% in the worst case).

Once again, no-slip boundaries have been enforced resulting in the high level of accuracy observed.
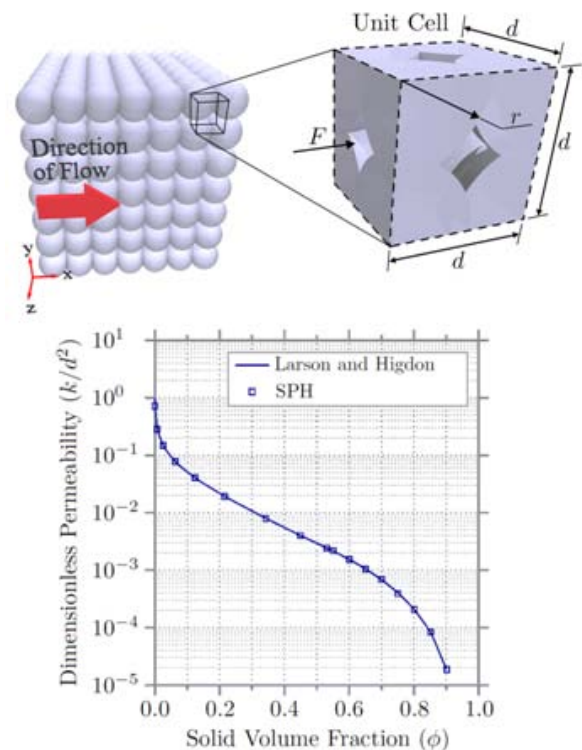

FIGURE 2. Permeability results from SPH simulator for single-phase flow through a 3D ordered packing of spheres. Permeability is again plotted against a reange of solid volume fraction (1-porosity) up to levels indicative of actual permeable reservoir rock (~10% porosity). Results are compared with the widely cited 3D Stokes solver results of [19].

MULTIPHASE FLOW

A key aspect of characterizing fluid flow in porous rock is the behavior of multiple immiscible fluid phases. The resulting multiphase flow behavior is dictated by properties such as permeability, viscosity, cohesion, and wettability of the individual phases and their relative behavior.

In the simulation of multiphase fluid flow, a challenge that emerges is the tracking of each species of the fluid and the interfaces between them. Every method that addresses multiphase flow must track each species and should minimally be able to preserve their mass. As such, one must either track "densities" at fixed nodes (e.g., Lattice Boltzmann), or track moving particles (e.g., SPH, Molecular Dynamics, Discrete Element Modeling).

However, the challenge of tracking interfaces through fixed grids is non-trivial and efforts to master it have been the subject of much research. The most successful fixed-grid approach has been "Level Sets with Particles" [20]. With these techniques, even in fairly "simple" test simulations such as Raleigh-Taylor instability the interfaces become extremely complex. The CPU time spent on resolving these surfaces dominates the solution. Figure 3 (b) illustrates the thousands of separate interfaces that evolve.

With SPH, the problem of complex interface tracking becomes easier [21,22]. Each particle represents a fixed number of Moles of a species and mass is conserved explicitly. There is no problem of mass creation or destruction. In any volume we also know precisely the fraction of species present, and surface tension (Helmholtz Energy) calculations can be applied.
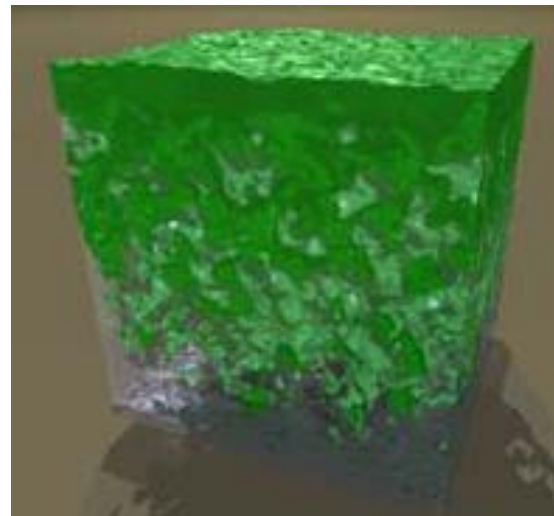
Rayleigh-Taylor Instability

The Rayleigh-Taylor instability is a well known experimentally observed multiphase fluid phenomenon which is commonly used to demonstrate the ability of a simulation code to handle several fluid phases. The Rayleigh-Taylor instability results between two layers of fluid when the upper layer has a higher density, forcing it to flow to the bottom of the container due to gravity. The shape of the fluid interfaces as the heavier fluid displaces the lighter is what is referred to as the Rayleigh-Taylor instability.

Figure 3 illustrates two timesteps from a 3D SPH simulation of Rayleigh-Taylor instability. This result demonstrates the ability of the developed numerical algorithms to handle complex multiphase surfaces, i.e. air-water-oil-wall. Surface tension effects are important for the formation of fluid droplets and their subsequent return to the fluid mass.
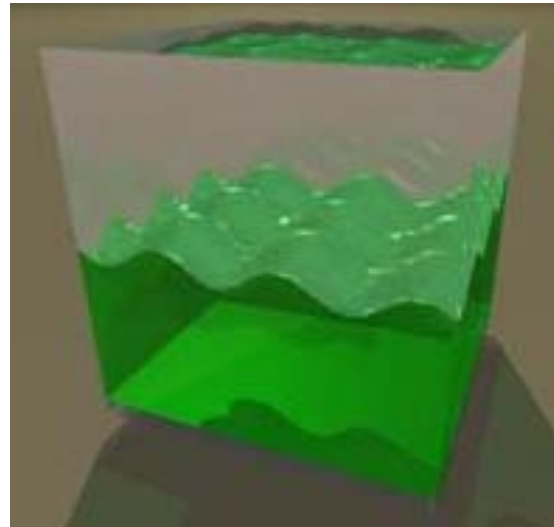
(a) Early timestep in simulation with dense fluid above and lower density fluid below

(b) Late timestep simulation illustrating the complex inter-fingering of the two immiscible fluids. With SPH, this timestep took the same amount of time to compute as the early timestep

FIGURE 3. SPH simulation of Rayleigh-Taylor Instability

IMBIBITION

Imbibition is an important phenomenon for multiphase flow in porous rock. Imbibition involves the displacement of one immiscible fluid phase by another. In an oil reservoir this can occur naturally during hydrocarbon migration when low density oil displaces higher density water due to gravity forces. Imbibition also occurs during oil production: the oil well reduces the pressure in the overlying oil saturated rock causing the water in the underlying aquifer to displace the oil. In another oilfield development

scenario, when there is insufficient pressure support to allow the oil to flow out of the reservoir into the oil well, another well might be drilled to inject water into the reservoir in order to displace the remaining oil and drive it to the producing well.

Often, oil remains "bound" to the porous rock, reducing the oil that can be recovered by pressure support or injection. In these cases it may be beneficial to inject specialized fluids that reduce the wettability of the oil allowing more of it to be displaced.

Figure 4 illustrates imbibition through a random packing of spheres with different diameters. In Figure 4 (b) the injecting fluid is non-wetting, while in Figure 4 (c) the injecting fluid is wetting. It is visually clear that more fluid is being displaced when the injecting fluid is wetting.
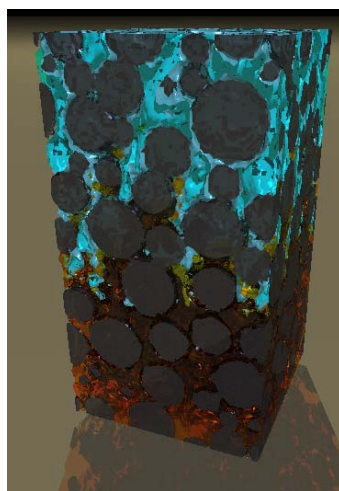
(a) 3D view of imbibition

(b) Non-wetting imbibition   (c) Wetting imbibition

FIGURE 4. Multiphase immiscible flow simulation in random pack of spheres. (a) 3D view of ntermediate time frame (b) Imbibition from top by non-wetting phase

displaces relatively little of wetting phase, while in (c) when the invading fluid is wetting, more of the saturating phase is displaced and replaced.

SIMULATION OF POROUS ROCKS

Oil companies and academic researchers are very interested in determining the macroscopic physical, chemical and transport properties of porous rock. Understanding these properties is crucial to the optimal development of an oilfield. Traditionally, small rock samples "core plugs" are obtained from wells drilled into the oil reservoir, on which a wide array of laboratory measurements are applied.

In the past decade it has become increasingly popular to also acquire high resolution Micro-CT (μ-CT) images of these rock samples [23]. These images are typically obtained on samples 5mm in diameter and are imaged at resolutions of 2.8μm per voxel to produce images composed of 2048^3 voxels. The promise of these images is that they can be used to directly compute the macroscopic properties, thereby augmenting and in some cases bypassing the need for complex and expensive laboratory based measurements.
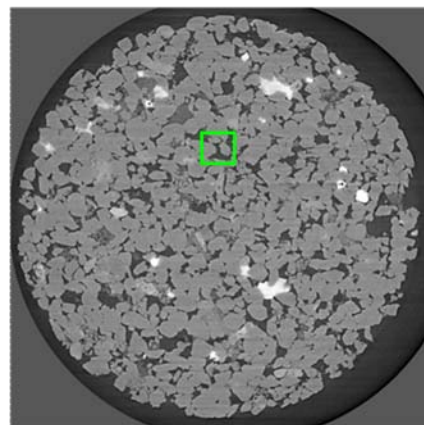
(a) 5mm diameter μ-CT image slice
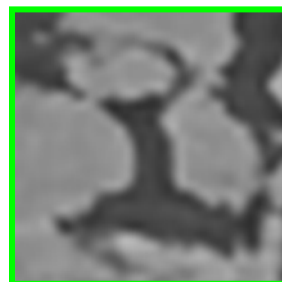
(b) 200μm sub-volume μ-CT image.
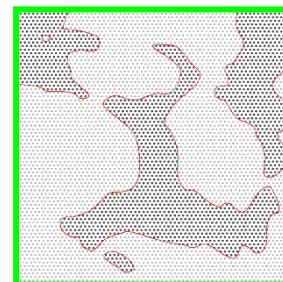
(c) SPH model of sub-volume with one particle per voxel

FIGURE 5 μ-CT image of Berea sandstone

Figure 5 illustrates an example of the type of data being acquired by μ-CT imaging. Our work suggests that SPH particle dimensions of the same order as the voxel dimensions are sufficient for representing the geometries and simulating the transport properties. Figure 6 illustrates a sub-volume of the rock sample modeled with SPH.
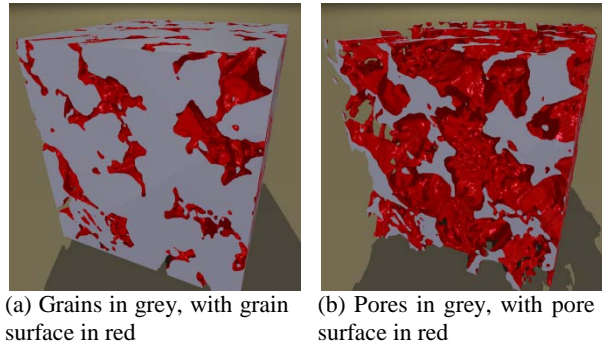

(a) Grains in grey, with grain surface in red

(b) Pores in grey, with pore surface in red

FIGURE 6. 300^3 voxel model of Berea sandstone

We are currently testing our simulator on single phase permeability computations on models generated from these μ-CT images. Results consistent with laboratory measurements have been obtained on samples with 400^3 voxels. For samples of 23.25% porosity Berea Sandstone, permeability results of approximately 800 md have been achieved, comparing well with the porosity-permeability relationship determined experimentally [24].

CONCLUSIONS

Multiphase fluid flow in complex porous media is influenced by pore network geometry, fluid viscosity, cohesion, and wettability. We have demonstrated the suitability of the SPH simulator to model these phenomena.

ACKNOWLEDGMENTS

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