DRAINAGE AND IMBIBITION CAPILLARY PRESSURE CURVES OF CARBONATE RESERVOIR ROCKS BY DIGITAL ROCK PHYSICS

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ABSTRACT

In this paper, we present digital rock physics (DRP) methodology and results for the determination of capillary pressure-saturation relation in carbonate reservoir rocks. We simulate the porous plate laboratory special core analysis procedures and compute drainage and imbibition capillary pressure curves using a three-dimensional 19 velocity (D3Q19) immiscible lattice Boltzmann (ILB) model with two relaxation times (TRT). We also use graphics processing unit (GPU) and the compute unified device architecture of NVIDIA to accelerate our simulation. NMR and MICP experimental curves have been predicted by DRP and served as a basis for multiphase flow simulations. The Pc simulation results are compared with experimental laboratory measurements and show reasonable match.

INTRODUCTION

The properties of multiphase flows in reservoir rocks, such as capillary pressure (Pc) and relative permeability, are necessary input parameters to numerical reservoir simulators to reliably predict multiphase fluid displacements and to design and optimize hydrocarbon recovery processes. Traditionally, multiphase properties have been determined by special core analysis (SCAL) measurements in physical laboratories. The measurements can be difficult and time consuming to perform, especially under reservoir conditions with live reservoir fluids, and with uncertainty about established wettability conditions. Capillary pressure curves are measured in the laboratory using different experimental methods, mainly by porous plate (PP) and centrifuge methods. The Pc curves, including primary drainage and imbibition, may take up to two years to measure using the PP method. DRP is a new technology that can offer quick and accurate routine and SCAL by combining 3D high-resolution CT-imaging and pore-scale numerical modeling. Driven by the rapid advances in 3D pore-scale imaging and computing, DRP is showing promise in providing effective and efficient SCAL data that can be used in predicting rock properties and reservoir performance.

In a previous paper [1], we reported a comparative study of DRP and laboratory SCAL measurements on carbonate rocks. The measurements consisted of relative permeability and primary drainage Pc curves from two rock types. In this paper, we describe our DRP methodology in details for computing the Pc curves and report comparison of DRP results and laboratory measurements for primary drainage and primary imbibition curves on other rock type samples.

CORE MATERIALS AND DRP METHODOLOGY

The Reservoir Rock Samples

In this paper, we report results of drainage and imbibition Pc curves by DRP for one core plug representing tight reservoir rock type (“RRT”), i.e. sample #33 from RRT#6, according to a current ADCO RRT definition[2]. The image of microstructure of the rock sample was obtained utilizing X-Ray Computed Tomography (CT) with voxel resolution of 64 nano-meters and then was processed (segmented) to identify pores and various minerals present in the sample. Fluid flow simulations were run directly on the segmented microstructure image of size 500^3 voxels (about 30 millions pores). This is a micritic carbonate sample that was described in reference [1]. Sample #33 has Helium porosity of 24.3% and permeability of 0.82 mD. DRP gave porosity of 23.7% and permeability of 1.3 mD for this sample.

To compare the DRP results of sample #33 with laboratory data, we use the corresponding MICP curve from the plug end, and we also use measured centrifuge data from a sister plug #10V.

Pore and Throat Size Distributions

The pore and throat size distributions are important geometric and topological parameters of the pore structure and have strong influence on the pore-scale fluid flow behavior. The pore size distribution (PSD) can be derived from nuclear magnetic resonance (NMR) measurement, while the pore throat size distribution (TSD) can be derived from mercury injection capillary pressure (MICP) measurement. In DRP, we can compute the distribution of surface to volume ratio of a digital rock by pore space partitioning. The MICP curve of a digital rock, and hence the pore throat size distribution curve can be derived by a pore-morphology-based displacement approach. Our approach, however, is different from the one originally proposed by Hazlett[3] and Hilpert[4]. Capturing geometric and topological characters of the sample pore structure builds the basis for our multiphase flow simulations.

Immiscible Lattice-Boltzmann Method

Generally, LBMs for multiphase flow can be classified into five categories: Rothman-Keller, Shan-Chen, free energy, mean-field, and models based on index functions. All of those models have their positive and negative properties and which model to employ is dependent on the system under investigation. In the Rothman-Keller (R-K) model[5], the interfacial width is small and surface tension and contact angle are controlled by independent parameters, therefore the values of the surface tension and static contact angle can be adjusted separately. Since we are dealing with completely immiscible fluid flow in the complex geometry of porous media, we adopt the improved R-K model. The R-K model includes three key steps to impose interfacial dynamics of immiscible fluid flow: (i) compute color-gradient (interface curvature), (ii) apply perturbation operator (interface force), and (iii) phase-separation (recoloring operator). The R-K model has been improved significantly in all the three aspects since the pioneering work of Rothman and Keller[5]. We employ the following isotropic color gradient [6,7],

$$\mathbf{f}(\mathbf{r},t)=\tfrac{1}{2}\sum_i \omega_i \mathbf{c}_i \frac{\rho_R(\mathbf{r}+\mathbf{c}_i)-\rho_B(\mathbf{r}+\mathbf{c}_i)}{\rho_R(\mathbf{r}+\mathbf{c}_i)+\rho_B(\mathbf{r}+\mathbf{c}_i)},$$

and the following perturbation term [8] to impose interfacial tension:

$$\tfrac{9}{2}\sigma\omega_i\left|\mathbf{f}(\mathbf{r},t)\right|\left[\frac{\left(\mathbf{f}(\mathbf{r},t)\cdot\mathbf{c}_i\right)^2}{\left|\mathbf{f}(\mathbf{r},t)\right|^2}-\left|\mathbf{c}_i\right|^2+\frac{2}{3}\right],$$

where σ is the surface tension. We also use formulaic segregation method instead of the numerical segregation to eliminate lattice pinning[8-10]. All those improvements and the TRT collision operation [11] lead to smaller unphysical spurious interfacial currents, higher accuracy, and optimal stability of our ILB model.

Efficient Implementation on GPU

Ginzburg[12] reformulated the R-K model and used as independent variables of the model only one kind of population to reduce the ILB memory requirement by almost a factor of two for CPU implementation. To massive-thread parallel implementation on GPU using this reformulation, one has to use atomic operation. We reformulated the R-K model to efficiently implement on GPU. We still use two kinds of populations, but do not require additional device memory for the macroscopic properties of the flow such as densities and velocities. We also use sparse data structures and indirect device memory access. Unlike the sparse data structure in [13], we only allocate device memory for pore nodes to reduce the device memory requirement and also reduce the amount of data reading and writing. For multi-GPU implementation, we use the message passing interface (MPI). We achieved very high computational performance on single GPU (one-order of magnitude faster than on high-end Inter multicore CPU) and also high parallel efficiency for multi-GPU because of using communication hiding.

Boundary Condition and Wettability

To mimic the PP experiment, we employ the pressure boundary condition for the injected phase and bounce-back for the displaced phase at inlet and outlet. Advanced impermeable boundary conditions have been developed for the boundaries parallel to the flow direction to reduce the end- and wall-effects.

Wettability is a critical factor controlling multiphase flow and phase trapping in reservoir rocks. DRP allows us to model the aging effects in the reservoir and to alter the wettability of the pore walls based on pore shape and fluid contact history of pore wall. For the LBM, the input parameters for wettability are the static contact angles – the contact angle dynamic effects do not have to be known a priori. The in-situ contact angles (dynamic contact angles) are consequence of the fluid dynamics and local pore geometry. In our simulation, we assume uniform wetting conditions for primary drainage. At the beginning of imbibition, we estimate the aging effects and then assign pore walls with different contact angles (i.e. wettabilities), water- or oil-wet contact angle [14].

RESULTS AND DISCUSSION

The input parameters of fluid properties and wettability for our DRP simulations are listed in Table 1. Figure 1 shows laboratory NMR-derived PSD and DRP PSD curves for sample #33 from RRT#6. We did not convert NMR T_2 to length unit due to the lack of surface relaxation parameter from the laboratory data. The NMR and DRP curves have been aligned by peak position. Laboratory- and DRP-derived TSD curves are presented in figure 2 for the same sample. The DRP curve is limited in the small pore throat size range due to image resolution. The comparison between numerical results and laboratory data in figure 1 and figure 2 shows that the geometric and topological characters (including connectivity and accessibility of pore structures) of the sample have been properly captured by DRP.

Figure 3 and figure 4 present DRP and laboratory results for primary drainage and primary imbibition Pc curves, respectively. The DRP curves simulated porous plate experimental setup. The DRP results are compared with MICP Pc curve from sample #33 and centrifuge data from a sister plug #10V. The centrifuge laboratory data provided spontaneous imbibition from Amott cell, and hence no data points are measured in the positive imbibition Pc.

For the primary drainage Pc curves shown in Figure 3, there is a reasonable match with the DRP curves from the mercury-derived and the centrifuge Pc curves. The residual water saturation (Swr) at the end of primary drainage is about 14% from the DRP curve and around 10% from the centrifuge laboratory curve. The MICP curve even gave lower Swr. The differences in Swr values could be due to several reasons including heterogeneity, sample size and image resolution.

For the spontaneous imbibition curves presented in figure 4, it is noted that DRP gave a lower Sw at the x-axis crossing point (Pc = 0) than the laboratory experiment, which may indicate that the DRP simulated more oil-wet behavior. This may be due to the input parameter of contact angle. This is also consistent with the fact that DRP showed forced imbibition with more negative pressure than the laboratory data. Another reason for the mismatch could be due to the centrifuge setup that involves Amott cells for the spontaneous imbibition process. Nevertheless, the residual oil saturation (Sor) value from DRP is in close agreement with the laboratory measurement.

By taking into account uncertainties of interfacial tension and wettability, the DRP results agree well, in general, with those obtained in the laboratory. The obtained results show that pore-scale modeling on digital rock samples by the LBM allows for accurate detailed two-phase interfacial fluid mechanics for a priori calculations of multi-phase flow and residual saturations.

SUMMARY AND CONCLUSIONS

A DRP computational methodology has been presented on the prediction of capillary pressure behavior in carbonate reservoir rocks. NMR and MICP curves have been derived from DRP simulations and predicted very well the experimental data. Comparison between the results of capillary pressure obtained by DRP simulation and those obtained by laboratory SCAL tests shows practical ability of DRP based on LBM to predict two-phase flow properties of reservoir rock efficiently and in a shorter time than the current SCAL experiments.

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Table 1: Input parameters for the pore-scale two-phase fluid flow simulations

	Water	Oil
Density (kg/m^3)	1078	783
Viscosity (Pa s)	0.485x10^{-3}	1.102x10^{3}
IFT$_{OW}$ (N/m)	0.03	
Static contact angles	Primary drainage: 30^0	
	Imbibition: 30^0 (water wet solid) 135^0 (oil wet solid)	

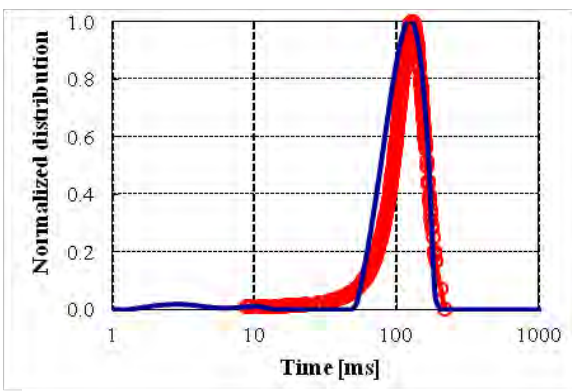

Figure 1: Comparison of pore size distribution from laboratory NMR measurement (in solid blue) with DRP results (in circle red) for sample #33

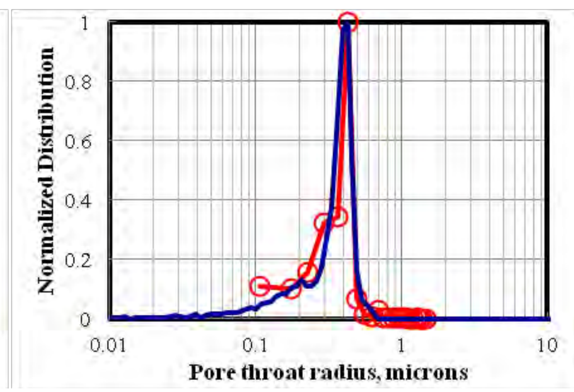

Figure 2: Comparison of pore throat radius from laboratory MICP measurement (in solid blue) with DRP results (in circle red) for sample #33

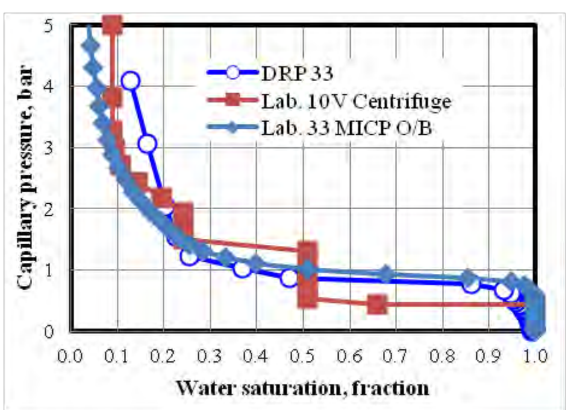

Figure 3: Drainage capillary pressure data resulting from laboratory test (MICP & Centrifuge) and DRP for RRT#6.

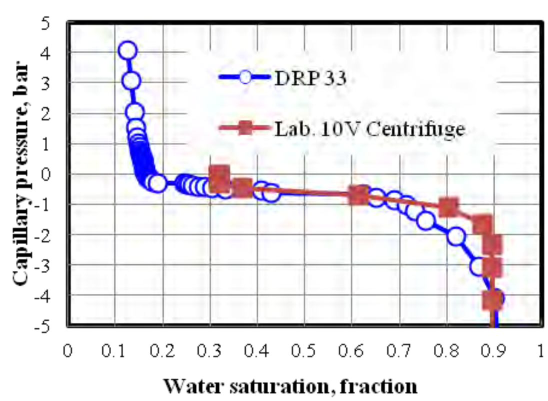

Figure 4: Imbibition capillary pressure data resulting from laboratory test and DRP for RRT#6