Multiphase Flow in Complex Fracture Apertures Under a Wide Range of Flow Conditions

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The summary below is an update of our previous progress report of June, 2003. That previous progress report, which was submitted as a PDF document, is not recorded on the RIMS website but will appear on the EMSP website. Our recent results are in the following areas: 1. Single-component flow through a rough-walled fracture to validate our methods, we have simulated slow single-component fluid flow through a geometry taken from analogous laboratory experiments. The permeability of this fracture is studied as the direction of the driving force is changed. We find that the lattice-Boltzmann method agrees with the experimental data and with previous numerical efforts. Additionally, flow enhancement compared to the well-known cubic law is observed in certain directions, i.e., the direction in which channels are most strongly correlated. Conversely, flow inhibition is observed in the perpendicular direction. Fluid flow appears to follow the correlated channels. We are currently extending these studies to higher Reynolds numbers where classical approximations based on assumptions of slow creeping flow are no longer valid. 2. Capillary rise in simple and complex geometries Capillary rise is studied using the lattice-Boltzmann method. The geometries used are a circular tube, a rectangular tube, and a fracture between two rough walls. The capillary rise height and the shape of the interface is studied as a function of the size of the tube, the wetting tendency of the walls, the surface tension, and the magnitude of an applied body force. In performing this study we discovered a technical problem with the lattice-Boltzmann method: it exhibited lattice pinning. This pinning created two significant problems: the entrapment of small bubbles and a history dependence of the contact angle. We solved these problems by modifying our algorithm so that it now allows interfaces to move at a smaller velocity. The new method practically removes all effects of lattice pinning. For the case of rectangular tubes, we have shown that the shape of the interface follows theoretical predictions and that the pressure drop across the interface obeys Laplace's law. Consequently our improved method solves a significant problem encountered in lattice-Boltzmann simualtions of drainage and imbibition. We are presently pursuing analogous studies in more complex geometries. 3. Macroscopic laws for two-component fluid flow through rough fractures. Macroscopic two-phase flow through porous media is commonly approximated by a generalization of Darcy's law, wherein "relative permeability’s" represent the mobility of wetting and non-wetting fluids. We have recently begun studying the applicability of this approximation for two-phase flow through rough-walled fractures. We find that when the nonwetting fluid is unconnected it can become trapped in tight geometries. Once forcing exceeds a certain capillary threshold the non-wetting fluid starts to move again. This capillary threshold depends on the roughness of the fracture surface and the size of the fracture aperture. Further simulations are being performed to better specify these dependencies along with the relationship of relative permeability to fracture roughness. 4. Multiple relaxation-time lattice-Boltzmann method. We are exploring ways to use the lattice-Boltzmann method in a rectangular lattice with different spacing in one direction. This idea is motivated by the fact that self-affine fracture surfaces exhibit different scaling perpendicular to the plane of the fracture than they exhibit in the plane. Therefore, allowing different lattice spacing in the different directions should greatly increase the efficiency of our simulations. We also seek a practical way of solving a well-known problem that derives from using the "bounce-back" method to approximate no-slip boundary conditions. We are pursuing a new generalization of the "multiple relaxation time generalized lattice-Boltzmann method" and are in the process of implementing it. 5. Study of thermal fluctuations of fluid-fluid interfaces. We have included thermal fluctuations in our model. These fluctuations lead to a roughening of fluid-fluid interfaces. We have demonstrated that the roughening follows theoretical predictions. We are presently pursuing applications to the study of the formation and growth of capillary bridges in rough fractures.