Relaxing the Capillary Equilibrium Constraint for Automated Contact Angle Measurement of X-ray Micro-Tomography Images in Porous Media

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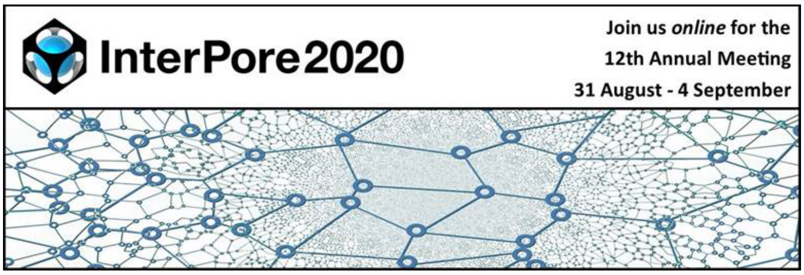

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Relaxing the Capillary Equilibrium Constraint for Automated Contact Angle Measurement of Time-Resolved X-ray Micro-Tomography Images in Porous Media

Content

The advances in pore-scale imaging in the past decade have enabled routine imaging of multiphase flow in porous media. This has allowed in-depth studies of governing multiphase flow mechanisms at the pore-scale. However, most of these studies are performed on static images of fluid/fluid interfaces in porous media due to ease of access to smaller X-ray flux sources available in lab-based systems. More recently, high-quality time-resolved data acquired by high flux X-ray synchrotron imaging [1,2] has enabled the micro-scale study of non-equilibrium fluid invasion events that are more directly relevant to fluid dynamics [3]. The present work focuses on improving dynamic contact angle measurements by relaxing the capillary equilibrium constraint (constant fluid/fluid interface curvature) required by existing automated contact angle measurement methods [4,5] to infer the actual location of the three-phase contact line.

We present a method for automated contact angle measurements along three-phase (solid/wetting/nonwetting phase) contact lines that can output separate contact lines for each specific ganglia. The method extracts the contact surfaces between phases from segmented images by employing the Delaunay refinement method [6] for surface mesh generation. The method by default respects the boundaries and does not split them with triangle facets, and thus preventing the method from moving the contact lines during surface generation from voxels. This allowed us to relax the constraint of constant curvature of the fluid/fluid interface (at capillary equilibrium) that is required by other available methods to infer the actual location of the three-phase contact line [4,5]. This can potentially allow more accurate measurement of dynamic contact angle measurements or experiments where the time scale is likely too short to establish full capillary equilibrium [7,8]. Depending on the parameters of the methods (facet size, facet distance and cell size), minimal smoothing could be introduced into the method while maintaining the integrity of observed features (general guidelines are advised based on image resolution of the size of features of interest). Moreover, extra Gaussian smoothing of the solid or fluid/fluid interface or the contact line is not required for this method. The three-phase contact line is defined as the set of vertices common to the surface of all phases. At these vertices, the normal vectors of the solid surface ($\vec{a}$) and the fluid/fluid interface ($\vec{b}$) are calculated. The contact angle (the angle between tangent planes to the solid surface and fluid/fluid interfaces) in each vertex is then calculated from equation 1:

$$\theta = cos^{-1} \frac{\vec{a}.\vec{b}}{|\vec{a}||\vec{b}|} \quad (1)$$

The algorithm is then validated using synthetic images of an idealized geometry (sphere of non-wetting phase) that is intersected at known angles with a solid plane [9]. Furthermore, we employ the method to provide dynamic contact angle distribution for each separate contact lines of selected ganglia in time-resolved synchrotron data [8] and verify the measurements by manual contact angle measurements.

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