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Interfacial jumps and pressure bursts during fluid displacement in interacting irregular capillaries

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ABSTRACT

The macroscopically regular motion of fluid displacement fronts in porous media often results from numerous pore scale interfacial jumps and associated pressure fluctuations. Such rapid pore scale dynamics defy postulated slow viscous energy dissipation and may shape phase entrapment and subsequent macroscopic transport properties. Certain displacement characteristics are predictable from percolation theory; however, insights into rapid interfacial dynamics require mechanistic models for hydraulically interacting pores such as found along fluid displacement fronts. A model for hydraulically coupled sinusoidal capillaries was used to analyze stick-jump interfacial motions with a significant inertial component absent in Darcy-based description of fluid front displacement. High-speed camera provided measurements of rapid interfacial dynamics in sintered glass beads cell during drainage. Interfacial velocities exceeding 50 times mean front velocity were observed in good agreement with model predictions for a pair of sinusoidal capillaries. In addition to characteristic pinning–jumping behavior, interfacial dynamics were sensitive to initial positions within pores at the onset of a jump. Even for a pair of sinusoidal capillaries, minute variations in pore geometry and boundary conditions yield rich behavior of motions, highlighting challenges and potential new insights offered by consideration of pore scale mechanisms in macroscopic description of fluid displacement fronts in porous media.

1. Introduction

Fluid displacement processes in porous media are of interest for a wide range of applications from wetting and drying of soils, to building materials, food and paper products, and oil reservoir management. Detailed observations reveal that the macroscopically continuous and seemingly smooth motion of fluid displacement fronts results from numerous interfacial pore scale jumps. Such fast jumps have been known for more than 80 years as ‘‘*Haines jumps*’’ [1] or rheon [2] and are often dismissed as nothing more than curiosity. These jumps result from local (pore scale) competition between capillary, viscous and gravitational forces, affecting displacement regimes and shaping fluid front morphology (stable displacement, capillary and viscous fingering) [3]. Experimental studies and numerical simulations have established various scaling laws linking front morphology with dominating forces under a range of porous media, fluids and boundary conditions [3–5].

Most studies of dynamic capillary phenomena associated with pore scale fluid invasion have typically ignored inertia and focused primarily on balancing viscous, capillary and gravitational forces [6]. For certain conditions, additional insights were gained by consideration of inertial forces during capillary rise [7,8] as elegantly demonstrated by Quere et al. [9–11] concerning the importance of inertial forces at the onset of interfacial displacement. Realistic account of pore shapes has been studied [12,13] by linking geometrical parameters such as capillary shape with boundary conditions to deduce flow characteristics in a single irregular capillary. One of the early studies on pressure fluctuations during front displacement through glass beads was presented by Crawford et al. [14]. Nevertheless, with the notable exception of Måløy and coworkers [15–17], very few attempts have been made to develop a quantitative description of flow details and fluid interactions between neighboring pores along displacement fronts. Måløy and coworkers [15–17] have analyzed distributions of pressure bursts associated with interfacial pore scale jumps in a simple porous media (monolayer of glass beads). These studies provided new insights on key features characterizing distributions of jump volumes and waiting times deduced from invasion percolation arguments.

Considering the ubiquity of interfacial jumps and their rich dynamic interactions with associated pressure fluctuations and phase entrapment, the consequences of these pore scale processes on macroscopic fluid front behavior, on energy dissipation mechanisms and on phase entrapment remain largely unexplored [18,19]. Quantification of these processes offers new insights on

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phase distributions resulting from passage of fluid fronts that greatly shape subsequent macroscopic transport properties such as gaseous diffusion and hydraulic conductivity of partially saturated porous media [18]. Resolving these processes may shed new light on other long-standing questions such as mechanisms associated with hysteresis [19–21] and the onset of apparent dynamic capillary pressure [22].

The goal of this study was to characterize pore scale dynamics associated with fluid front displacement focusing on interfacial jumps and interactions among hydraulically connected neighboring pores along the front. For the mechanistic modeling of these interactions, we considered the simplest case of a pair of interacting capillaries with irregular cross-section to facilitate systematic yet tractable treatment of interfacial motions and capillary pressure dynamics. In the next section, we present a theoretical framework using force and mass balance between two hydraulically connected irregular capillaries subjected to macroscopic (steady) fluid withdrawal at prescribed rates. The numerical results were supported by experimentally observed interfacial jumps and oscillations in regular sintered glass beads micro-model captured with a high-speed camera and with pressure sensors as described in Section 3. In Section 4, we compare experimental and modeling results, which support application of the model for systematic studies of effects of boundary conditions (flow rate), geometrical dimensions and liquid properties on dynamic behavior of menisci. We then show how physical properties influence displacement patterns and affect characteristics of interfacial oscillations. We summarize and draw conclusions on pore scale interfacial dynamics in the last section.

2. Theoretical framework

Natural porous media are comprised of complex pore spaces characterized by pore size distribution, porosity and connectivity that collectively determine capillary–saturation relations and permeability. Even for the geometrically simplest porous media (e.g., resulting from cubic packing of spheres), pores are invariably irregular and flow pathways are tortuous. The characteristics of displacement fluid fronts induced by macroscopic pressure gradients or by volume withdrawal at system boundaries depend on pore characteristics, fluid properties and boundary conditions [3,23]. The focus on improving basic understanding by systematic quantification of key parameters affecting pore scale dynamics compelled us to consider a simple and idealized pore structure comprised of two hydraulically coupled sinusoidal capillaries with circular cross-sections. Fig. 1 depicts a sketch of pore structure with radius $r(z)$ is assumed to be a simple trigonometric function of height z:

$$r(z) = \frac{r_p + r_t}{2} - \frac{r_p - r_t}{2} \cos\left(\frac{2\pi z}{H}\right) \tag{1}$$

with radius of pore body r_p, throat radius r_t and vertical distance between constrictions H. In the following, we distinguish between the two capillaries using Roman numerals I and II as indices.

The force balance for the fluid in the coupled capillaries considering capillary, viscous, gravitational and inertial forces and mass balance is described by a coupled nonlinear second-order differential equation for momentum (2) and mass (3) balance:

$$-\frac{2\sigma}{r_I(h_I)} \cos(\theta_d(\dot{h}_I) + \alpha(h_I))_I + \frac{8\eta}{r_{sI}^2} h_I \dot{h}_I + \rho g h_I + \rho(h_I \ddot{h}_I + \dot{h}_I^2)$$
$$= -\frac{2\sigma}{r_{II}(h_{II})} \cos(\theta_d(\dot{h}_{II}) + \alpha(h_{II}))_{II} + \frac{8\mu}{r_{sII}^2} h_{II} \dot{h}_{II} + \rho g h_{II} + \rho(h_{II} \ddot{h}_{II} + \dot{h}_{II}^2) \tag{2}$$

$$Q = \pi r_I(h_I)^2 \dot{h}_I + \pi r_{II}(h_{II})^2 \dot{h}_{II} \tag{3}$$

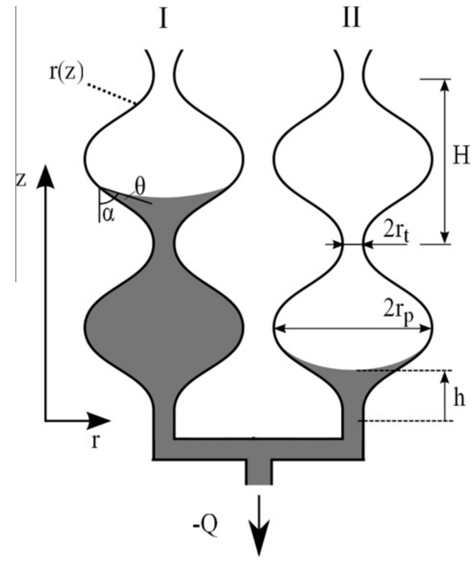

Fig. 1. Definition sketch of two hydraulically connected sinusoidal capillaries with pore throat radius r_t and pore body radius r_p. The distance between two throats (constrictions) H defines pore length. The inclination of the wall is given by α, and the contact angle is indicated by θ. Height of the interface is marked with h. Liquid is withdrawn with constant flow Q.

with surface tension σ, dynamic contact angle θ_d, local slope angle α, dynamic viscosity η, liquid density ρ, acceleration due to gravity g, height of interface (above a reference level) h and its first and second time derivative $\dot{h}$ and $\ddot{h}$, respectively. Eq. (2) describes force balance between capillary I and II (Fig. 1) expressed in units of pressure. Eq. (3) represents the mass or volume balance with liquid added or removed at a volumetric rate of Q. The four terms in Eq. (2) corresponding to capillary, viscous, gravitational and inertial force per area are related to the wetting phase elaborated next. We consider air as the non-wetting phase with negligible effects on loss mechanisms and own pressure (for other fluids with significant viscosity, the role of the non-wetting phase must be considered explicitly).

2.1. Capillary pressure

The capillary pressure p_c between the non-wetting and wetting fluid is given by the Young–Laplace equation for circular cross-section of radius r as

$$p_c = \frac{2\sigma}{r} \cos\theta_s \tag{4}$$

with static contact angle θ_s. Competing velocity dependent viscous and capillary forces require consideration of the dynamic contact angle θ_d. Numerous expressions describing the relation between dynamic contact angle, characteristic interface velocity, dynamic viscosity and surface tension have been suggested in literature, often expressed using the dimensionless capillary number Ca

$$Ca = \frac{\eta v}{\sigma} \tag{5}$$

Eq. (5) represents the local ratio of viscous to capillary forces. One proposed expression is

$$\theta_d^3 - \theta_s^3 = ACa \tag{6}$$

where the value of the coefficient A is 94 for θ in radians [24]. A was also established analytically by Voinov [25] and was found to be determined by the ratio of characteristic lengths affecting contact