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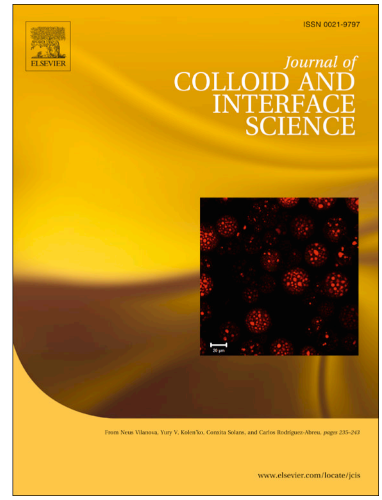

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Evaporation Effect on Two-Dimensional Wicking in Porous Media

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Abstract

We analyze the effect of evaporation on expanding capillary flow for losses normal to the plane of a two-dimensional porous medium using the potential flow theory formulation of the Lucas–Washburn method. Evaporation induces a finite steady state liquid flux on capillary flows into fan-shaped domains which is significantly greater than the flux into media of constant cross section. We introduce the evaporation-capillary number, a new dimensionless quantity, which governs the frontal motion when multiplied by the scaled time. This governing product divides the wicking behavior into simple regimes of capillary dominated flow and evaporative steady state, as well as the intermediate regime of evaporation influenced capillary driven motion. We also show flow dimensionality and evaporation reduce the propagation rate of the wet front relative to the Lucas–Washburn law.

1. Introduction

Evaporation in porous media has significant effects on the behavior of capillary-driven flows but is not presently well understood. Often, evaporation is considered from the perspectives of coupled multiple phases, heat transfer, and species diffusion, which are conjointly very difficult to model and test experimentally, particularly within a porous solid matrix [1, 2]. However, for certain systems these complex phenomena may be simplified to source and sink terms in the liquid-saturated portion of the medium [3, 4]. Capillary-driven flows define a broad and extensively investigated topic, which has a significant impact on numerous fields of study [5–7]. The wicking process in porous media is an important research area in medical and energy technologies [8–10], thin layer chromatography, and hydrophysical phenomena [11–14]. Phase changes in porous media such as evaporation and condensation affect the advancement of fluid in porous media for many different systems [4, 15]. Design of capillary-driven devices requires quantitative knowledge of the effects of evaporation on the absorption of liquids into unsaturated porous media. Capillary driven flows do not require an active input of energy and as such they are "free," which makes them attractive for a variety of engineering applications [16, 17]. A class of new microfluidic devices, for example, use capillarity to drive motion of the liquid through the unit, but they require a steady, finite flow rate for continuous and predictable wicking [18]. Evaporation allows the capillary media to be designed and adaptively tuned to the desired flow rate through the device.

Capillary driven flows in porous materials can be significantly controlled by designing their macroscopic shape. For example the flow rate in expanding porous media exhibits a very different time behavior from the simple $v \sim 1/\sqrt{t}$ dependence predicted by the Lucas and Washburn (LW) analysis [19, 20]. Several studies have considered expanding flows into two- (2D) and three-dimensional (3D) porous domains [10, 21–24].

In general, continuum two phase flows in porous media can be successfully analyzed using the continuity equation for unsaturated capillary flow commonly known as the Richards equation [25–29].

Recently, the phenomenology and potential effects of evaporation in connection with capillary flows have increasingly been analyzed. Lockington *et al.* [3] developed an approximate analytical solution for 1D capillary diffusion under evaporation. Fries *et al.* [4] compared the solution for saturated wicking with evaporation and gravity to experiments in a metallic weave. Barry *et al.* [30] used the Lockington capillary diffusion model to explain discrepancies in Fries' determination of the front position via absorbed mass. Villarrubia *et al.* [18] observed a steady-state flow of water due to evaporation into porous paper after an initial wicking behavior similar to the LW equation in a quasi-2D medium. Liu *et al.* [31] extended Fries' methods into 2D radial flow to study convergence between inner and outer wetting flows.

In this paper, we present analytical solutions to the flow behavior of a liquid wicking into an expanding two-dimensional porous system which is undergoing isotropic evaporation from the surface normal to the 2D porous medium. Hence, a particular focus of the our study is on the interplay between the evaporation effect and the shape of the porous material. We consider 2D domains where the evaporation from the surface normal to the plane of the medium dominates the overall mass loss. The evaporation losses across the side boundaries can be ignored; in most cases this loss is insignificant because of the vanishingly small contact area with the surroundings.

We show that the evaporation has an increasing effect on the liquid motion over time, wherein the flow transitions from purely capillary dominated flow, to a transitional flow

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