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Coupled wetting meniscus model for the mechanism of spontaneous capillary action

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A B S T R A C T

Capillarity plays a significant role in many natural and artificial processes, but the mechanism responsible for its dynamics is not completely understood. In this study, we consider capillary flow characteristics and propose a coupled wetting meniscus model for the mechanism of spontaneous capillary action. In this model, capillary action is considered as the dynamic coupling of two interfacial forces, i.e., the wall wetting force at the contact line and the meniscus restoring force on the free interface. The wetting force promotes the motion of the contact line directed toward an equilibrium contact angle, whereas the meniscus restoring force promotes a reduction in the interface curvature, which is more consistent with a 90° contact angle. The competing interaction between these two forces is coupled together via the evolution of the interface shape. The model is then incorporated into a finite volume method for a two-fluid flow with an interface. Capillary flow experiments were performed, including vertical and horizontal flows. Phenomena analysis and data comparisons were conducted to verify the proposed model. According to the results of our study, the model can explain the capillary flow process well and it can be also used to accurately guide capillary flow calculations.

1. Introduction

Capillary action plays a significant role in many natural and artificial processes, such as plant metabolism, agronomic irrigation, oil recovery, textile printing, and microfluidic analysis. Capillary action is attributed to the competing effects of cohesion at the interface and adhesion to the solid wall, which can influence the hydrodynamic characteristics near the wall and considerably change the configuration of the interface of the disturbed liquid. Thus, understanding the mechanism of capillary action is very important.

Since the pioneering studies by Lucas [1] and Washburn [2], the dynamics of capillary-driven flows have been studied for about 100 years [3,4]. Various models may be employed to describe capillary flow on the macroscale, which can be categorized into two classes according to their description of the interface, i.e., the Lucas–Washburn-based spherical interface

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class [5–10] and the interface evolution-based class. According to capillary force modeling, the latter class mainly comprises the Laplace pressure boundary model [11–17], the continuum surface force volume force model [18–23], the Shikhurzaev surface tension gradient model [24–26], and the Cahn–Hilliard–van der Waals (CHW) diffuse interface model [27,28]. In addition to these macroscale hydrodynamic models, microscale approaches have also been employed to model capillary flow, such models as based on the lattice Boltzmann method [29–32] and molecular dynamics [33–35]. These models are based on microscale particle interactions and they belong to a different conceptual framework compared with that considered in this study.

Capillary action involves the meniscus restoring effect (cohesion) and the wall wetting effect (adhesion). In general, the restoring effect is always represented by the Laplace force and the wetting effect is characterized by an empirical contact angle boundary condition in an explicit numerical scheme, or by an artificial wall wetting condition in an implicit scheme (such as the liquid–solid surface tension gradient in the Shikhurzaev model or the wall free energy in the CHW model). Existing models can describe the capillary flow process but the underlying physical mechanism responsible for capillary action is still not very clear. First, although conventional capillary theories model the capillary flow process [1,9,12,14,18,33,36,37], they do not clearly explain why the capillary flow can start and continue without an external driving force. Second, the dynamic contact angle is a result of the evolution of the interface, and thus it should be calculated directly from the capillary flow solution. However, current models cannot achieve this because most specify an empirical contact angle function as a boundary condition during the calculation [1,9,11–14,18,20]. By contrast, Malgarinos et al. [38] tried to impose the boundary condition as a wetting force instead of a contact angle but this only holds for a circular contact line, and it cannot clearly explain why the wetting force is necessary in capillary action and how the wetting force acts. Third, the restoring effect and wetting effect act together on the meniscus, and they influence each other. However, the wetting effect has been considered little in macroscale simulations of capillary-driven flows [2,11–14]. In particular, the relationship between the two effects has not been reported in previous studies [18,20,26,28,38]. Thus, due to these problems, the existing capillary models are incomplete and a new physical model is still needed that considers the underlying interaction mechanism.

To address these problems related to capillary action, we propose a novel model called the coupled wetting meniscus model in this study. According to this model, the capillary force is reformulated and incorporated into a finite volume method (FVM) to perform numerical calculations. Different capillary flow experiments were also conducted using this model. Finally, the proposed model was verified by phenomena analysis and experimental comparisons.

The remainder of this paper is organized as follows. Section 2 describes the coupled wetting meniscus model and the numerical calculation method. Section 3 explains the experimental method. In Section 4, we present the results and discussion. Finally, we summarize our conclusions in Section 5.

2. Theory and calculation

2.1. Coupled wetting meniscus model

Capillarity is a spontaneous and self-sustaining process, so there must be an underlying driver of capillary action. As discussed above, two effects are involved with capillary action, i.e., the meniscus restoring effect and wall wetting effect. The so-called restoring effect arises from the difference in pressure (described by Laplace's formula) across the meniscus and the so-called wetting force is due to the action of the interface tension at the triple-phase contact line [39,40]. During a capillary process, the contact angle at the contact line varies considerably from its initial value relative to that at equilibrium with the contact line movement, where the change in the angle is the dynamic contact angle [38]. The wetting force depends on the dynamic contact angle. According to Young's formula, the wetting force at the contact line (per length) is:

$$\sigma_w = \sigma(\cos\theta_{eq} - \cos\theta_{ad}), \tag{1}$$

where σ is the liquid–gas interface tension, θ_{eq} and θ_{ad} are the equilibrium and dynamic contact angles, respectively.

According to Laplace's formula, the meniscus restoring force on the free interface (per area) is:

$$p_r = \sigma\kappa, \tag{2}$$

where κ is the curvature.

The wetting force promotes contact line motion, thereby driving the dynamic contact angle toward the equilibrium contact angle. The meniscus restoring force promotes interface motion to achieve a flat interface. Obviously, neither of these forces can produce a long-lasting capillary flow when it acts separately.

In order to study the mechanism responsible for spontaneous capillary action, we consider a capillary rise in a parallel plate channel, as shown in Fig. 1. We consider an initially flat meniscus and a 90° contact angle, which occurs when the end of the empty capillary is first inserted vertically into the bulk liquid (Fig. 1(a)). In this case, the wetting force will drive the liquid up along the wall, where the contact angle decreases toward its equilibrium value, thereby creating an interface curvature, as shown in Fig. 1(b). The increased curvature makes the meniscus restoring force move the liquid further into the capillary to reduce the curvature, as shown in Fig. 1(c), which then increases the contact angle away from its equilibrium value and this again activates the wetting force, as shown in Fig. 1(d). The cycle then repeats itself and the liquid enters the capillary. The actions of these forces are described sequentially for convenience, but they act simultaneously in reality.