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An experimental and numerical study of capillary rise with evaporation

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ABSTRACT

An experimental and numerical study of spontaneous imbibition into capillary tubes subject to phase change is presented. A mathematical model is developed to predict the motion of a meniscus while undergoing phase change. The model addresses slip at the wall, viscous effects of the vapour in the capillary tube and transient evaporation. A set of experiments were performed for three fluids (acetone, n-pentane and iso-octane), three capillary tube diameters (0.5, 1.0, and 2.0 mm) and five heating conditions (0, 0.7, 2.7, 6.0 and 10.6 W). The experimental results demonstrated that the meniscus rise was altered by varying degrees of evaporation. A comparison of the experimental data and the mathematical model yielded a good correlation for the 1 mm capillaries, and deviated for both the 0.5 mm and 2 mm cases. It was found that an asymptotic transient mass function was unable to improve the fit to experiment.

1. Introduction

Capillary action is found to occur naturally in hydrology, anatomy and plant physiology; with industrial applications spanning textiles, biosensors, oil recovery, civil engineering and space based technologies. The static and dynamic aspects of capillary forces are of particular importance in space, as surface tension forces dominate small scale fluid flows given the reduced gravitational effects on the flow. Thus, the engineering applications of capillaries in space are common to liquid fuelled rocket motors and heat pipe based thermal control systems. In general, the utilisation of capillary structures for enhancing heat transfer presents a unique challenge. Historically the statics of a meniscus have been well studied, while the dynamics of its rise have been a more recent point of investigation. The early works of Lucas [1], Washburn [2], Bell and Cameron [3] and Bosanquet [4] founded much of the theoretical framework for capillary dynamics. Such works continue to be the basis from which more comprehensive mathematical models are being devised.

Subsequent works have sought to address the problem of capillary rise dynamics using theory, numerical solutions and experimentation. Some studies have included effects such as: dynamic contact angle [5–13], surfactants [14,15], gas/vapour displacement [14,16], slip [2,17,18], phase change [5,19,20], vena-contracta/jet [13,21–24] and tube inclination [25]. Others have sought to capture the various regimes of capillary rise thereby leading to criteria predicting oscillatory behaviour [24,26,27]. Fries and Dreyer [28] investigated the timing of competing forces during capillary rise, followed by their systematic analysis of non-dimensional governing equations describing imbibition [29]. While the majority of studies have focused on cylindrical capillaries and Newtonian fluids; Levine et al. [18] expanded the study to that of channel based imbibition, while Kornev and Neimark [30] extended to viscoelastic fluids.

Complementing the theoretical and numerical studies of capillary rise dynamics, some experimentation has shed light on the true physics and dynamics. Siebold et al. [6] experimentally confirmed that the meniscus changes curvature during the dynamic portion of the rise. This changing interface shape was also confirmed by Lorenceau et al. [21], where the interface was observed to produce a liquid finger during the initial stages of capillary rise.

Other factors postulated and experimentally captured include the viscous pressure drop associated with the displacement of the gas/vapour occupying the capillary. The effects of vapour displacement pressure drop were confirmed experimentally by Zhmud et at. [14], and shown to have considerable impact on the dynamics of capillary rise. Furthermore, slip at the solid–liquid

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Nomenclature

FM	factor of merit [N/m s]
$f(t)$	arbitrary temporal function [−]
g	gravitational acceleration [m/s^2]
h	avg. meniscus height [m]
h_{fg}	latent heat of vaporisation [J/kg]
j	mass flux [kg/m^2 s]
k	linearised mass flux coeff. [kg/m^2 s K]
L	capillary tube length [m]
M_W	molar mass [kg/mol]
P_{VIS}	viscous pressure drop [Pa]
P_{VR}	vapour recoil pressure [Pa]
r	radial coordinate [m]
R	capillary tube radius [m]
R_g	universal gas const. [J/mol K]
t	time [s]
T	temperature [K]
ΔT	superheat [K]
u	average fluid velocity [m/s]

Greek Symbols

α	accommodation coefficient [−]
β	slip length [m]
γ	slip coefficient [m^2]
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
τ	relaxation constant [s]

Superscripts

$'$	derivative with respect to time

Subscripts

eq	equilibrium
F	final
l	liquid
v	vapour

interface as reviewed by Neto et al. [31], can be extended to capillary flows. The potential for slip at the solid–liquid interface in capillaries was put forward by Washburn [2] and experimental studies by Pit et al. [32] support the potential for slip.

An experimental study of static meniscus height as a function of capillary radius, length and subject to evaporation was performed by Kuz'mich and Novikova [33]. In this experimental study, the meniscus static height was studied with only a qualitative mention as to the dynamic aspect of the meniscus motion. The oscillatory motion noted by Kuz'mich and Novikova [33] was dependent upon the capillary radius and attributed to changes in the wetting angle. The evaporation from the capillary tubes was driven by changes in ambient vapour pressure, not heating.

The study of capillary rise dynamics subject to phase change has received some attention theoretically [5,19,20], and to our knowledge none experimentally. The problem of meniscus motion and phase change is a unique one lending well to flow dynamics akin to those found in capillary pumped loops and loop heat pipes. The main objective of this work is to expand upon the theoretical framework and compare our mathematical model, to experimentally measured rise dynamics subject to evaporation. In this paper, we will outline the basis of our mathematical model, the experimental setup and methods, and data extraction techniques outlined thereafter. Then, the experimental results will be given. Finally, the experimental and numerical results will be compared and analysed.

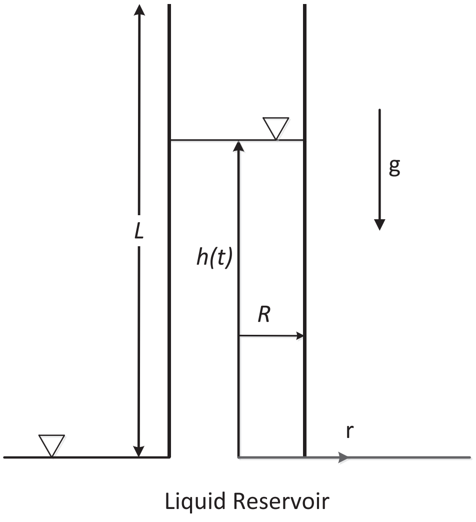

Fig. 1. Solution domain.

2. Mathematical model

The system consists of a capillary tube of radius R and length L, oriented in the vertical such that gravity is consistent with the axis of the capillary tube as shown in Fig. 1, with a large liquid reservoir positioned below the entrance of the capillary. The atmospheric environment is assumed to be that of a saturated single species of uniform temperature.

When the capillary tube makes contact with the liquid reservoir interface, the liquid begins to wet the wall thereby facilitating spontaneous imbibition. During spontaneous imbibition, surface tension draws liquid from the reservoir into the capillary tube. To simplify the problem, the liquid–vapour interface is taken to be flat and at an average height h, invariant in r, for an incompressible Newtonian fluid. Therefore, the dynamics of the liquid–vapour interface can be described by the equation of motion as:

$$\rho \frac{d}{dt}(hu) = \frac{2\sigma}{R} - \rho g h + P_{VIS} + P_{VR} \tag{1}$$

This is the Lucas–Washburn equation as modified by Ramon and Oron [19]. The momentum of the liquid phase is balanced by capillarity, hydrostatics, viscous drag and vapour recoil. The capillary pressure is assumed to have a time invariant contact angle consistent with that of an ideal wetting fluid.

As the liquid enters the capillary and progresses upward; the viscous drag results in a pressure drop. While the problem addresses the transients of the meniscus motion, it is assumed that the flow achieves a fully developed profile sufficiently quickly and maintains this profile throughout the solution time.

The viscous pressure drop in the capillary can be affected if the fluid is able to exhibit a degree of slip at the wall interface. A slip condition for capillary flow was proposed by Washburn [2], where