Journal of Colloid and Interface Science 455 (2015) 1–5

Contents lists available at ScienceDirect

Journal of Colloid and Interface Science

www.elsevier.com/locate/jcis

Burst behavior at a capillary tip: Effect of low and high surface tension

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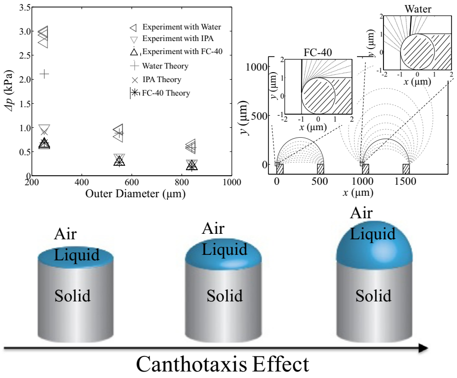
GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 April 2015
Accepted 18 May 2015
Available online 27 May 2015

Keywords:
Canthotaxis effect
Liquid pinning
Superomniphobic surfaces
Phase separation
Low surface tension liquids

ABSTRACT

Liquid retention in micron and millimeter scale devices is important for maintaining stable interfaces in various processes including bimolecular separation, phase change heat transfer, and water desalination. There have been several studies of re-entrant geometries, and very few studies on retaining low surface tension liquids such as fluorocarbon-based dielectric liquids. Here, we study retention of a liquid with very low contact angles using borosilicate glass capillary tips. We analyzed capillary tips with outer diameters ranging from 250 to 840 μm and measured Laplace pressures up to 2.9 kPa. Experimental results agree well with a numerical model that predicts burst pressure (the maximum Laplace pressure for liquid retention), which is a function of the outer diameter (D) and capillary exit edge radius of curvature (r).

1. Introduction

Passive stop valves (i.e. structures with no moving parts) have been used in microfluidics for restricting flow in microchannels via sudden expansions of a microchannel [1–4]. Rapid expansion of a microchannel produces a nozzle-like structure which can serve as a barrier for advancing liquid, requiring a decrease in radius of curvature and corresponding increase in pressure for a meniscus to enter into the expansion [5]. Strongly wetting liquids require larger expansion angles to exhibit adequate burst pressures [5–7]. Capillary stop valves have been shown to restrict the advance of aqueous liquids containing surfactants by varying the expansion angle along the capillary exit edge [1,8,9]. However, these studies demonstrated only pinning for liquids with finite equilibrium contact angles.

Highly wetting liquids, including dielectric liquids, have low surface energies and infinitesimal contact angles (∼0°) for all substrates of interest [10]. This makes it challenging to produce the convex menisci necessary to produce positive Laplace

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http://dx.doi.org/10.1016/j.jcis.2015.05.033
0021-9797/

Nomenclature

Ca	capillary number
D	capillary outer diameter (m)
d	capillary inner diameter (m)
N	number of tracking points
P	pressure (Pa)
R	radius of curvature of meniscus (m)
r	radius of curvature of capillary edge (m)
U	liquid front velocity (m/s)

Greek symbols

β	meniscus center-point angle (°)
γ	surface tension (N/m)
φ	angular location of triple line (°)
μ	dynamic viscosity (kg/m s)
θ	equilibrium contact angle (°)

Subscripts

NW	non-wetting
W	wetting

pressures. However, proper surface geometry can allow for liquid menisci to transition from concave to convex in shape, and so can be tailored to pin wetting liquids. For wetting liquids along a sharp-edged interface, any change in surface area and therefore total surface energy is balanced by an amount of work against the Laplace pressure, which can prevent the meniscus from further expansion [4,8,9]. The liquid can attain a range of stability angles along the rounded edge of a tube and exhibit positive pressures (i.e. $p_W > p_{NW}$), as will be discussed in further detail below [11]. Pinning of low surface tension liquids has been fairly extensively studied for microfabricated liquid repelling surfaces and related applications [12–15]. However, most of these studies illustrated liquid pinning on top of micropatterned structures and acting only on the hydrostatic pressure of the liquid [16,17], and not liquid retention or burst pressure in a nozzle-like structure.

We here study retention of low surface tension liquids along the edge of the exit of a glass capillary, representative of a re-entrant geometry. The model we present shows that the minimum radius of curvature of a meniscus for a liquid with an infinitesimal contact angle coincides with an angle of 180° with the outer capillary edge (c.f. Fig. 1). We compare the numerical model predictions to pressure measurements and visualizations of menisci for a variety of liquids and capillary diameters. Experimental studies demonstrate that wetting liquids (e.g. alcohols, dielectric liquids) can be 'pinned' along sharp-edged geometry that yields convex meniscus curvatures and measureable burst pressures. To our knowledge, this paper presents the first study using capillary tips for retaining fluorocarbon-based dielectric liquids based on re-entrant surface geometry.

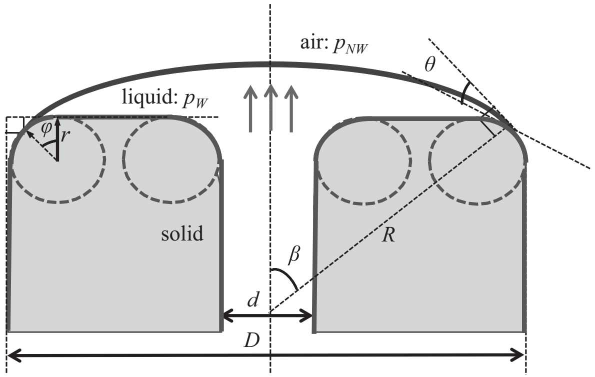

Fig. 1. Schematic of capillary model for a tip defined by outer diameter, D, and angle β defined as the angle between the centerline and the tangent edge to the meniscus radius of curvature, R. The three-dimensional pore geometry is defined by revolving the cross-section about its centerline. The model only considers capillary flow (i.e. $Ca \leqslant 10^{-5}$) and neglects gravitational, inertial, and viscous forces.

2. Materials and methods

2.1. Bursting pressure apparatus

Burst pressure experiments were performed on commercially available borosilicate glass capillaries (Vitrocomm). The glass capillaries had inner diameter, d, ranging from 150 to 600 μm and outer diameter, D, that ranged from 250 to 840 μm. The objective of the experiments was to measure maximum liquid retention (burst) pressure and study the conditions before and after bursting through glass capillary tips. Pressure measurements were accompanied by simultaneous visualizations of the menisci using an optical microscope (Nikon Eclipse 80i) with a Plan Fluorite objective and numerical aperture (NA) of 0.15. The bursting events were visualized in the region of the glass capillary tip and recorded using a CCD camera (Thorlabs DCC1545M), see Supplementary material (Appendix B). The setup included a programmable syringe pump (Harvard PHD 2000) which pumped liquid through stainless steel tubing (IDEX) with inner diameter 62.5 μm, connected in series with a pressure transducer (Omega PX419) with 0–5 psig range, see Supplementary material (Appendix B). The flow rates used in all experiments resulted in capillary numbers of $Ca \leqslant 10^{-5}$, where

$$Ca = \frac{\mu U}{\gamma}, \qquad (1)$$

μ is the dynamic viscosity, U is the liquid front velocity, and γ is the liquid–vapor surface tension. The liquids used for these studies were deionized (DI) water, Fluorinert (FC-40) (Sigma–Aldrich, St. Louis, MO, USA, CAS Number: 51142-49-5), and Isopropyl alcohol (IPA) (Sigma–Aldrich, St. Louis, MO, USA, CAS Number: 67-63-0), see Supplementary material (Appendix C) for thermophysical properties for each liquid.

3. Theory and model results

To study bursting events through capillary tips, we developed a theoretical model to demonstrate the mechanism for pinning liquids along the rounded outer edge of a capillary. Fig. 1 is a schematic of the capillary model in cross section. The primary geometric parameters for the model are capillary outer diameter (D) and edge radius of curvature (r). The location of the contact line of the solid–liquid–vapor interface is given by the angular coordinate φ defined with respect to the exit edge curvature, r (c.f. Fig. 1). The three-dimensional capillary geometry is defined by the revolution of the cross-section about its centerline. The model only considers capillary dominated flow (i.e. $Ca \leqslant 10^{-5}$) and neglects any inertial, viscous, or gravitational forces. Therefore, the meniscus forms a spherical cap. The model and the following derivation were modified from a previous study on pinning liquids at the interfaces of microposts [6,7].