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Prediction of coupled menisci shapes by Young–Laplace equation and the resultant variability in capillary retention

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Abstract

This paper shows how 2 coupled Young–Laplace equations can be solved to predict the shapes of two coupled menisci formed in a capillary system. Experiments are performed, which demonstrate that the equilibrium volume of liquid retained in a vertical capillary, can be variable, even when all the properties of the system are invariant. This variability in liquid retention also leads to different equilibrium shapes of the top and bottom menisci. A coupled form of the Young–Laplace equation is solved to predict the two coupled menisci shapes. The curvature of the top meniscus is fitted to the experimentally recorded meniscus shape. The coupled Young–Laplace equation solution is used to predict the shape of the bottom meniscus. The shape of the bottom meniscus thus obtained, is shown to match the experimentally recorded bottom meniscus shape reasonably well. This observed coupling of the menisci has a significant impact on some porosimetric techniques which are based on liquid extrusion and explains why the volume of liquid that can be retained in a capillary can vary, under invariant conditions. Retention of liquids in capillaries is of interest in several applications like fabric wash.

Keywords: Liquid retention; Capillary retention; Capillary rise; Capillary meniscus; Meniscus shapes; Young–Laplace equation

1. Introduction

Liquid rise in capillaries, of circular cross-sections, is one of the most common demonstrations of the existence of surface forces and has been studied in great detail in the past. More recently several authors have studied liquid rise in capillary systems, where the cross-section deviates from the circular. These include polygonal sections [1], star shaped [2], elliptic [2], eye shaped [3] and diamond shaped [4] cross-sections. Rise in capillaries shaped by the void between circles arranged in triangles and squares have also been studied [5]. The capillary rise in these systems is of interest since they can be used to predict water uptake by porous materials. Liquid rise also indicates the curvature pressure created by the meniscus, formed in such capillaries, which can be used to infer characteristics of porous materials and media. Liquid retention in capillaries is also of interest in applications of surface science such as fabric wash. The retention of liquid pellets in capillary systems and a qualitative discussion of the pressures required to eject these have been reported by Carroll [6]. The objective of the single capillary studies reported in this paper is to better understand and explain liquid retention in capillary systems and to obtain more accurate methods for porous media characterization.

Experiments performed in this work demonstrate that the equilibrium volume of liquid retained in a vertical capillary can vary significantly, even when all the properties of the system are invariant. This variability in liquid retention also leads to different equilibrium shapes of the top and bottom menisci. While the Young–Laplace equation has been extensively used to predict meniscus shapes [7,8], its use to predict "coupled menisci shapes" in a capillary, is demonstrated for the first time in this paper. The two coupled menisci shapes are predicted by using two coupled Young–Laplace equations, in the following manner. The curvature of the top meniscus is obtained by "fitting" the experimentally recorded meniscus shape. The coupled Young–Laplace equation solution is used to predict the shape of the bottom meniscus. The shape of the bottom meniscus thus obtained, is shown to match the experimentally recorded bottom meniscus shape reasonably well. This observed coupling

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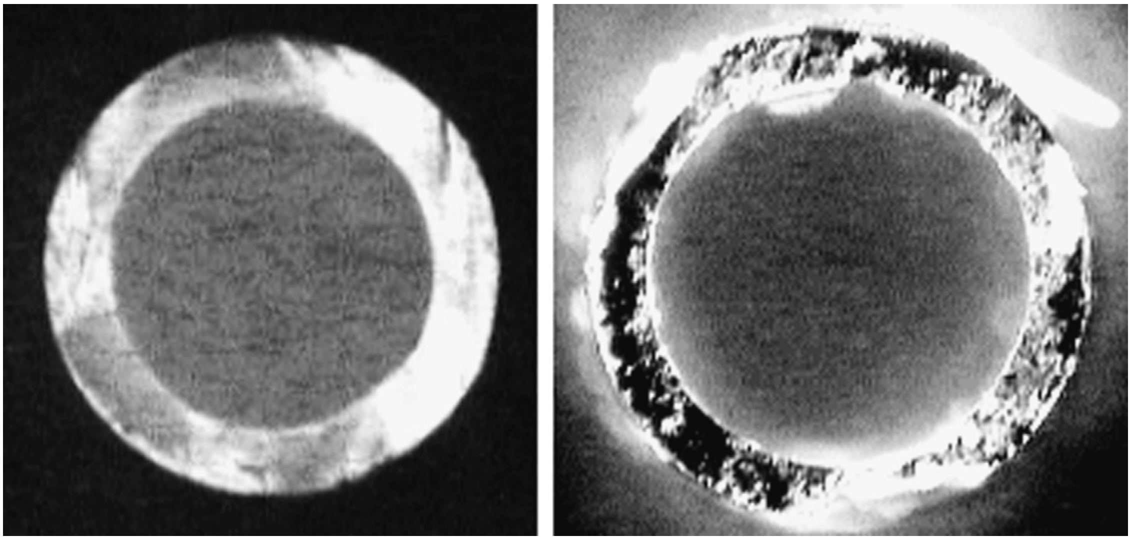

Fig. 1. Cross-sectional views of the capillaries used in this study, for estimating the internal radius.

of the menisci has a significant impact on some porosimetric techniques which are based on liquid extrusion. The results also explain the significant variability in capillary retention of water by porous materials.

2. Experimental

The capillaries used in this study were made of borosilicate glass. Prior to their use the capillaries were soaked in highly alkaline aqueous phase. They were subsequently removed and washed repeatedly with de-ionized water. The radii of the capillaries were estimated in the following manner. Photographs of the capillary ends were taken at high magnification. From these photographs, the ratio of the inner diameter to the outer diameter was estimated in each case. The outer diameter of the capillary was measured using a digital vernier. Based on these measurements and ratio estimate, the inner diameters were estimated as 444 and 163 μm, for the two capillaries used in this study. Photographs of the capillary end, based on which the ratio of the inner to outer diameter was estimated, are shown in Fig. 1.

One end of one such capillary was dipped in a wetting fluid (de-ionized water). The fluid rises in the capillary to an equilibrium height, h_e. For the 444 μm capillary this rise was 3.3 cm. The capillary was then withdrawn from the liquid pool very slowly, in a reversible manner, such that the system was always near equilibrium. This capillary was then held in air, where the length of the liquid column was measured to be 3.3 cm. Photographs of the top meniscus and the bottom meniscus are shown in Fig. 2. The same capillary was then dipped into the water till a significant portion of the capillary was submerged. It was then quickly retracted from the fluid, such that the liquid retained in the capillary could not drain down to its equilibrium rise height, h_e, and the height $h > h_e$. After the excess external fluid drained off, the height of the liquid retained in the capillary was measured to be 5.2 cm. This capillary system, with the liquid column inside, was invariant with time, which showed that it was at equilibrium. Photographs of the top meniscus and the bottom meniscus are shown in Fig. 3. Next some of the water was removed from the capillary, till the residual liquid height was less than 3.3 cm. The height of the liquid column was measured to be 1.5 cm. Fig. 4 shows photographs of the top and the bottom menisci for this capillary system.

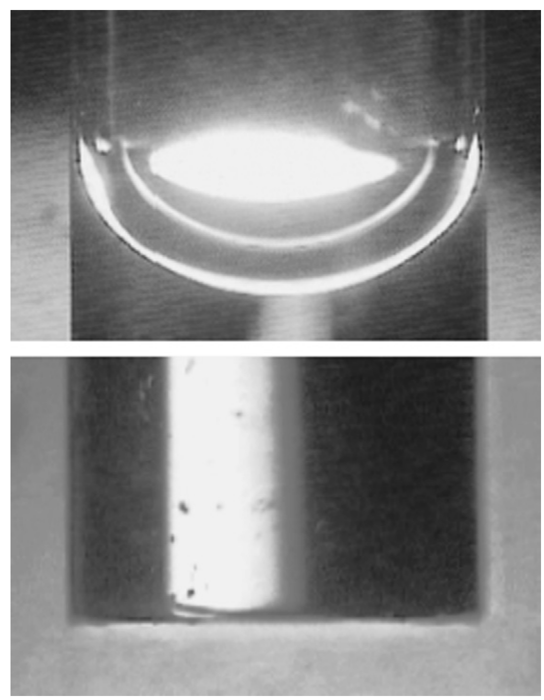

Fig. 2. Shapes of the top and bottom menisci of water in a capillary of radius = 444 μm, when the liquid column height (3.3 cm) = equilibrium rise.

Quantitative estimation of the menisci shapes based on Young–Laplace equation, for these hydrostatic heads, is discussed in later sections. Qualitatively it can be seen that when the rise is to the equilibrium rise height, i.e. $h_e = h$, the bottom meniscus is flat, which results in no curvature pressure. When the liquid column is larger than the equilibrium rise, i.e. $h > h_e$, the bottom curvature takes a shape which assists in sup-