Colloids and Surfaces A: Physicochem. Eng. Aspects 481 (2015) 384–392

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

# The effect of wall thickness and material on Marangoni driven convection in capillaries

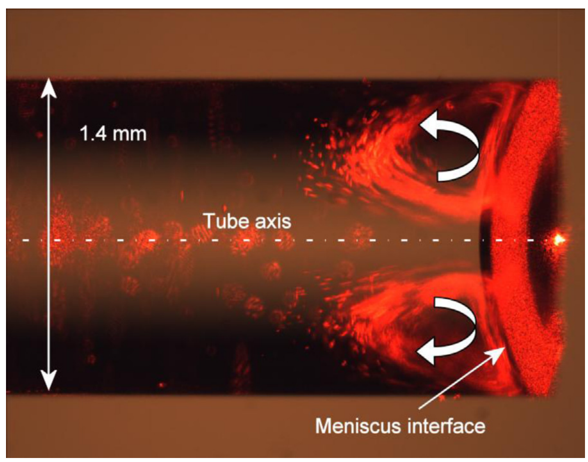
Cosimo Buffone[a,*], Khellil Sefiane[b], Christophe Minetti[a]

[a] Microgravity Research Centre, Université libre de Bruxelles, Avenue F. Roosevelt 50, 1050 Bruxelles, Belgium
[b] Institute for Materials and Processes, School of Engineering, The University of Edinburgh, EH9 3JL Edinburgh, United Kingdom

## HIGHLIGHTS

- The measured evaporation rate from capillary tubes is influenced more by the thermal conductivity of the tubes than the wall thickness.
- The infrared camera interfacial temperature measurements at the meniscus pinned at the tube mouth and also along the wall of the tube close to the tube mouth allowed to perform a heat and mass transfer balance.
- The heat and mass transfer analysis allowed the evaluation of the difference between the wall and meniscus interface temperatures and the evaporation rate, respectively, and comparing these results with the measured ones. The deviation found is maximum 65% for difference between measured and evaluated temperature difference and 6.7% for the evaporation rate.
- The results are qualitatively assessed in the light of those obtained for evaporating sessile drops and the trends found are similar.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 23 March 2015
Received in revised form 15 May 2015
Accepted 16 May 2015
Available online 12 June 2015

*Keywords:*
Marangoni convection
Evaporation

## ABSTRACT

We present results of an experimental investigation of Marangoni convection for an evaporating meniscus in open air pinned at the mouth of a capillary tube. Four different liquids have been studied: ethanol, methanol, acetone and, for the first time, also FC-72. This experimental configuration has been studied before by the present authors and others. However, it is the first time that the effect of the capillary tube thickness and material is experimentally investigated. In particular, the study considered the same internal diameter for all the tubes (1 mm) and three borosilicate external diameters (1.4, 2, and 3 mm) as well as one polycarbonate (1.25 mm) and one sapphire (3 mm). These three tube materials were chosen for their very different thermal properties and their optical transparency. The evaporation rate is measured

* Corresponding author. Fax: +32 2650 3126.
*E-mail address:* cbuffone@ulb.ac.be (C. Buffone).

http://dx.doi.org/10.1016/j.colsurfa.2015.05.050

Meniscus interface
Infrared temperature measurements

by tracking the second meniscus receding inside the capillary tube while the first one is pinned at the tube mouth. It was found that the evaporation rate is influenced more by the thermal conductivity of the tubes than the wall thickness. An infrared camera has also been employed to measure the interfacial temperature at the meniscus pinned at the tube mouth and also along the wall of the tube close to the tube mouth. In addition, a heat transfer analysis has been performed at the tube mouth along with a mass transfer analysis which allowed the evaluation of the temperature of the meniscus interface and the evaporation rate, respectively, and comparing these results with the measured ones. The deviation found is maximum 65% between measured and calculated temperature differences between wall and meniscus and 6.7% for the evaporation rate. The results are qualitatively assessed in the light of those obtained for evaporating sessile drops and the trends found are similar.



## 1. Introduction

Marangoni convection has been studied for many decades [1–2]. It has important industrial applications such as drying of paints, ink-jet printing, combustion, oil extraction, crystal growth, heat pipes, just to mention a few. Temperature differences along a thin liquid film have long been reported to generate vigorous convection which was first attributed to the role of surface tension by Pearson [1], while the Marangoni number was first introduced in 1960 by Scriven and Sternling [2]. Both temperature difference along or across the thin liquid layer were imposed. Much more recently a different experiment has been studied [3–7] where a meniscus interface is formed inside a capillary tube and a liquid evaporates spontaneously in open air because of its low partial pressure. These studies concluded that the evaporation is not uniform [4] being much more intense at the meniscus wedge than in the centre, and this causes small but noticeable temperature differences which were first reported in Buffone and Sefiane [4]. The temperature difference along the meniscus interface generates a gradient of surface tension, that given the small tube size involved, is found to be strong enough to set a vigorous convection (termed Marangoni convection) in the liquid phase of the meniscus that brings warm liquid from the centre to colder regions at the meniscus wedge. This convection is also believed to reduce the temperature difference between the centre and the wedge and therefore the strength of the convection itself. A main difference between this phenomenon and conventional Marangoni convection is that this is self-driven by the evaporation process.

Marangoni convection has become very important to many industrial applications; among these are: drying of paints, ink-jet printing, welding [8], glass manufacturing [9], crystal growth [10], and the recently intensively researched evaporation of drops [11–15]. In all these cases, there is an interface where a temperature difference is either self-established as in the present study or imposed or a combination of the two. The majority of the studies dedicated to Marangoni convection are carried out on a pure liquid and they are referred to as thermal Marangoni convection. Rare are the studies of thermo-solutal Marangoni convection [16] where at the interface there are temperature and concentration gradients, this latter sometimes being quite important.

In all the studies of this particular configuration by the present authors [3–5] and subsequent investigations [6,7], the effect of the tube wall thickness and its material have not been looked at. However, studies investigating substrate thickness and material have been performed for evaporating drops [17–19] which has attracted more attention in recent times. The experimental study of Ristenpart et al. [18] demonstrated that the relative thermal properties of the substrate as well as those the liquid can affect the direction of flow within evaporating droplets. Xu and Luo [19] revealed, that there is Marangoni flow in evaporating water droplets, with a stagnation point at the droplet surface, where the surface flow and the surface temperature gradient change their directions.

In the evaporation of drops, for instance, it is found that the substrate material plays a pivotal role in the heat and mass transfer at the drop interface and can dictate if evaporative cooling or conduction through the drop is the mechanism by which the temperature difference between the drop apex and the contact line is established in one direction or the opposite [19,20].

In the present work the authors perform, for the first time for this experimental configuration, a study of the effect of capillary tube thickness and material on heat and mass transfer from a curved meniscus interface pinned at the tube mouth. The tube internal diameter is kept the same (1 mm) between all tests as this is found to dramatically affect the evaporation rate and the consequent Marangoni convection. Three tubes of borosilicate glass have been used with external diameter of 1.4, 2, and 3 mm, as well as a polycarbonate (external diameter 1.25 mm) and a sapphire (external diameter 3 mm) tube. These three tube materials have been chosen because they are transparent and therefore the evaporation rate can be measured, and because they have quite different thermal conductivity, namely: 0.2, 1.14, and 33 W/(m K) for polycarbonate, borosilicate and sapphire tubes, respectively.

In one experiment the evaporation rate is measured by following the second meniscus inside the tube while the first meniscus is pinned at the tube mouth. In a second, separate experiment the temperature of the interface for the meniscus pinned at the tube mouth and of the external surface of the capillary tubes close to the tube mouth, is measured by the use of an infrared camera.

A heat and mass transfer analysis has also been performed to back-up the experimental findings. A 65% maximum difference between measured and calculated temperature difference between wall and meniscus and the evaporation rate differs by 6.7% from the calculated value.

## 2. Experimental facilities

Two experimental facilities have been employed in the present study. The experimental facility employed for flow characterization and evaporation rate measurement is reported in the photograph of Fig. 1. It comprises a microscope, a complementary metal-oxide semiconductor (CMOS) camera, the test cell with the capillary tube and a PC with specialised software for image acquisition and processing. The working liquids are: ethanol, methanol, acetone and, for the first time for this type of experiment, FC-72. The capillary tubes have an Internal Diameter (ID) of 1 mm and are of three materials: borosilicate glass with Outside Diameter (OD) of 1.4, 2, and 3 mm with length of 100 mm; polycarbonate with OD of 1.25 mm with length of 200 mm; and sapphire with OD of 3 mm with length of 50 mm. The capillary tubes and the liquid are used as