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Onset of Marangoni convection in low viscosity silicon oil inside a heated capillary tube

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ABSTRACT

In the present experimental investigation the onset of Marangoni convection inside a heated capillary tube filled with low viscosity silicon oil is presented and discussed. The 1 cSt viscosity silicon oil used evaporates spontaneously at ambient temperature. The evaporation of silicon oil inside the 1 mm internal diameter tube is not uniform, being larger near the meniscus triple line region than in the centre; this creates gradients of temperatures (which have been measured by InfraRed thermography) and therefore of surface tension. For the unheated tubes this gradient of surface tension is found to be not big enough to set a convection motion (Marangoni convection) which was reported by one of the present authors in previous studies using alcohols. With increasing power supplied to the tube by an electric heater, the Marangoni convection sets in and strengthens at increasing powers till the pinned meniscus detaches from the tube mouth and recedes inside the capillary.

1. Introduction

Phase change (evaporation, condensation and boiling) is key to many industrial applications such as condensers, heat pipes [1], and combustion. The last decade has seen miniaturization of components such as cars condenser because of the higher performances found at small scale [2]. At small scale (typically below few millimetres) surface tension plays an important role and it is believed to enhance the heat and mass transfer because of the thinning of the micro-region where most of the phase change takes place [3]. Surface tension is important to many other industrial applications such a glass manufacture [4], crystal growth [5], and welding [6].

An overview of different research advancements on the subject, with particular attention to the potential technological applications of Marangoni convection and instabilities, including solidification and crystal growth, bubbles and drops dynamics, heat and mass transfer, multiphase flows processes, can be found in Ref. [7].

One of the present authors has reported in numerous publications the self-induced evaporation of volatile liquids inside capillary tubes [8–11]. The thermocapillary convection observed was characterised by the use of μ-Particle Image Velocimetry. Evaporation rates were also measured as well as the tracer particle spinning frequency. It was found that small tube sizes strongly enhance the evaporation flux and the tracers spinning frequency (which is a measure of vorticity) [8]. The competition between surface tension and gravity forces observed [9], produces an important distortion of the Marangoni toroidal vortex which has important potential implications in crystal growth. In Buffone et al. [10] the authors report instabilities in a horizontally oriented 600 μm tube filled with ethanol; instabilities were found in the Marangoni vortex, in the meniscus position at the tube mouth and in the meniscus temperature. InfraRed temperature measurements were performed in Buffone and Sefiane [11], for different capillary tube sizes and different alcohols; it was concluded that small tube sizes and more volatile liquids create larger temperature deeps at the meniscus micro-region where most of the evaporation takes place.

Dhavaleswarapu et al. [12] reproduced the results of Buffone and Sefiane [8] and Buffone et al. [9] by analysing 5 different tube sizes ranging from 75 to 1,575 μm using μ-Particle Image Velocimetry. They found that the evaporation rate and flux scale parabolically and hyperbolically respectively instead of linearly as in Buffone and Sefiane [8]; the vorticity scales hyperbolically with the

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tube diameter in contrast with the linear relationship of Buffone et al. [9]. Chamarthy et al. [13] reported μ-Particle Image Velocimetry measurements of horizontally oriented capillary tubes with ethanol as working fluid. They found distortion of the flow field which they attributed to the action of gravity; interestingly they reported that there is no distortion of the flow pattern for capillary sizes of 75 μm. This is a very interesting finding with important repercussions in industrial and lab applications such as crystal growth.

InfraRed temperature measurements have been recently conducted to map the temperature distribution on the liquid of a heated sessile water droplet [14]. The authors found a non-uniform temperature distribution along the droplet surface with lower temperatures at the contact line compared to the droplet top. The evaporation mechanism in sessile drops is similar to the meniscus interface inside a tube investigated in the present work.

Transient Marangoni convection in pendant evaporating drops of different liquids have been investigated both numerically and experimentally, using a *laser sheet* illumination system and a video camera for tracer particles visualization and infrared temperature measurements in Refs. [15,16]. More recently, infrared visualization of thermal motion inside evaporating sessile drops of ethanol, methanol and FC-72 onto a heated surface has been investigated [17].

It is well known in literature dealing with Marangoni flows that a surface tension gradient exceeding a threshold value corresponding to a critical Marangoni number lead to an onset of convective flow, of the type of the Benard–Marangoni instability that was originally observed on a thin liquid layer. Such variations of the surface tension can arise naturally due to the dependence of the surface tension on the temperature field and on the concentration of dissolved species in binary or multicomponent liquid mixtures. For single-component evaporative systems, the onset of Marangoni convection is generally driven by temperature gradients. In this case thermal energy is removed from the liquid resulting in local change in the temperature and thus also in the surface tension.

Onset of Marangoni convection in evaporating sessile or pending drops has received attention in literature [18–20]. Despite numerous studies about Marangoni flows, there are very few of them conducted for the meniscus in microscale channels or tubes, which is a topic of interest in various heat transfer and microfluidic applications. For instance in Ref. [21] a numerical study is conducted on a flat meniscus considering an evaporative heat flux, with the initial meniscus temperature uniform. In this case the temperature gradients induced by the liquid evaporation may exceed a threshold value and thermocapillary convection is establishing. Knowledge of the critical surface tension difference provides guidance for design of a microfluidic device [21]. In a similar paper [22], the authors study the same problem and investigate the onset of the convective instability when the channel size or the temperature gradient are beyond certain values. The threshold Marangoni number for the instability turns out to be dependent also on the Biot number.

In the present work low viscosity silicon oil (which evaporates at ambient temperature) has been used inside a borosilicate tube of 1 mm ID positioned horizontally. The tube is heated by an electric heater made of a wire wrapped around the tube. The threshold temperature difference at the meniscus interface is induced by heating the system with the electric heater and only when the power settings become large enough the on-set of Marangoni convection is established. The convection pattern has been monitored by measuring the tracer particles spinning frequency (a measure of vorticity); InfraRed temperature measurements have also been performed along the meniscus interface at the tube mouth.

2. Experimental apparatus

The tube is a 1 mm ID (1.32 mm OD) made of borosilicate glass and is 100 mm long. The tube is positioned horizontally on a three-dimensional microstage with a 5 μm accuracy. The silicon oil made by Sigma–Aldrich has a viscosity of 1 cSt and it is therefore slightly volatile. The physical properties of the silicon oil used are reported in Table 1. The emissivity of the silicone oil has been set to 0.9, according to previous literature studies [16]. A number of tests were carried out in Savino and Fico [16] showing that the silicon oils employed are not transparent at the thermocamera wavelength, and therefore the observed temperature is the surface temperature with very little contribution of the liquid immediately beneath the surface. The tube was filled with silicon oil positioning one meniscus at the tube mouth (pinned meniscus) and leaving the second meniscus receding inside the tube while mass is being lost at the pinned meniscus. A small electric wire has been wrapped (7 turns not uniformly separated) around the tube to produce a heater. The heater is positioned at 5 mm from the tube mouth and is 3 mm in length. An electric power supply with fine tuning knobs has been used to deliver small power increments to the heater.

Two kinds of experiments have been performed in the present study. In the first experiment nylon tracer particles of average size 15 μm have been used to seed the silicon oil near the tube mouth. Fig. 1 is a photograph of the experimental set-up showing a microscope, a CCD camera of 752 × 480 pixels, and a computer with specialised "home-made" software used to track the particles and determine their spinning frequency as a function of the applied power. A power supply has been used to power the electric heater shown in the inset of Fig. 1.

The gravitational forces arising from the mismatch between tracers and fluid density are evaluated with the following formula (coming from Stokes's drag law) [23]:

$$U_{zP} - U_z = d_P^2 \frac{\rho_P - \rho}{18\mu} g$$

where, U_{zP} and U_z are the particle and fluid vertical velocity components respectively, d_P is the particle diameter, ρ_P (1000 kg/m3) and ρ (820 kg/m3) are the particles and fluid density respectively, μ (0.00082 Pa s) is the fluid dynamic viscosity and g is the gravitational acceleration. The aforementioned formula for the present case leads to:

$$U_{zP} - U_z \cong 4.8\ 10^{-4}\ \mathrm{m\ s^{-1}}$$

whereas the average particles velocity measured along the meniscus ($(U_{zP} \cong 5\ 10^{-4}\ \mathrm{m\ s^{-1}})$) for the highest heater power setting of 1.08 W is slightly higher. Therefore, we cannot strictly assume that the particles are neutrally buoyant. Smaller or less heavy particles would generate more accurate results.

In the second experiment InfraRed (IR) thermography has been employed to measure the temperature distribution on diametrical

Table 1
Thermophysical properties of 1 cSt silicone oil at 25 °C.

Density (kg/m^3)	Surface tension (mN/m)	Surface tension derivative (mN/m/K)	Specific heat (J/kg/K)	Thermal conductivity (W/m/K)	Dynamic viscosity (Pa s)	Thermal expansion coefficient (1/K)
820	16.9	0.06	2000	0.1	0.82 10^{-3}	1.3 10^{-3}