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Infra-Red measurements of an evaporating meniscus with imposed contact angle

Cosimo Buffone [a, b, *], Khellil Sefiane [a, b], John Christy [b]

[a] Tianjin Key Lab of Refrigeration Technology, Tianjin University of Commerce, Tianjin City 300134, PR China
[b] School of Engineering, The University of Edinburgh, Mayfield Road, Edinburgh, EH9 3JL, United Kingdom

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A B S T R A C T

In this paper temperature profiles in a meniscus formed by ethanol at the mouth of a capillary tube with the meniscus' shape dependent on the liquid supply rate are studied as evaporation occurs. An Infra-Red camera is used to measure the meniscus interfacial temperature and the results are compared for four tube sizes and three tube materials. This work follows on from work on evaporating sessile drops which has attracted much scientific attention in recent years. It is found that when the meniscus is still inside the tube, the interface temperature profile is similar to that of previous work (Buffone and Sefiane [19]). The interesting finding is that as the meniscus becomes flat at the tube mouth, the temperature profile of the interface evens out to the temperature of the contact line region. When the meniscus is eventually pushed out of the tube, the temperature of the meniscus interface becomes non-uniform again (depending on the contact angle). We demonstrate that this phenomenon is consistent for different tubes sizes and tube materials (with different wettabilities). We develop a simplified model for the meniscus inside the tube and the meniscus outside the tube which agrees qualitatively with the experimental findings.

1. Introduction

Evaporation and condensation have attracted significant attention for application in cooling technologies in the last few decades because of the high heat transfer rate and the uniformity of temperature achievable at the interface. In practical applications employing heat transfer with phase change, the high latent heat of vaporisation, relative to sensible heat, results in low working fluid mass flowrates which in turn means low mass of the apparatus; small temperature variations also lead to reduced thermal stresses and increased equipment life span.

One of the applications relying on evaporation and condensation is the heat pipe [1,2]. Inside a heat pipe, a fluid undergoes evaporation at one end due to heat being transferred into the heat pipe and condensation at the other end where heat is removed from the heat pipe. The liquid is driven by the capillary pressure generated inside a wick structure, which is the core part of a heat pipe. The wick structure is a porous material inside which the working liquid is drawn back to the evaporator. If the pores of the wick are too large they will not generate enough capillary pressure to overcome the pressure drop of the liquid flow within the heat pipe and therefore the heat pipe will not function, as dry-out will occur at the evaporator end of the heat pipe. If the pores are too small, on the other hand, although they will generate high capillary pressure, they also lead to a considerable liquid pressure drop and therefore again the heat pipe is unlikely to operate effectively. The evaporator is the most thermally loaded part of a heat pipe and generally receives lot more attention from researchers and designers alike. However, the condenser is the bottleneck for heat transfer [3,4] as heat transfer coefficients are lower for condensation than for evaporation and this typically results in the need for a much larger heat transfer surface area at the condenser.

The contact angle in the evaporator and condenser depends strongly on the wettability of the wick. The situation in a heat pipe wick can be idealised as a single heated pore, inside which a meniscus is formed and from which evaporation takes place. We devise here an experiment in which ethanol evaporates spontaneously to the open air from inside a capillary tube where the meniscus is located at the tube mouth. This experimental arrangement has been explored before by the present authors

* Corresponding author. Tianjin Key Lab of Refrigeration Technology, Tianjin University of Commerce, Tianjin City 300134, PR China.
E-mail address: cosimobuffone@gmail.com (C. Buffone).

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[5–9] as well as other researchers [10–15] where other aspects where investigated. However, in a heat pipe, the liquid evaporates in its own vapour, whereas in the present case ethanol evaporates in a mixture of air and its own vapour and the evaporation process is more vigorous. The fact that ethanol has a negligible partial pressure in air, means that it evaporates spontaneously inside the capillary tube and no heat need be supplied from outside. We have demonstrated [16] that the heat necessary for sustaining the evaporation at the meniscus interface is drawn from the external environment surrounding the tube.

Most of the investigations of an evaporating meniscus inside a capillary tube have been performed with the meniscus having a given contact angle. Buffone et al. [17] recently performed a study with a meniscus pinned at the tube mouth with three different meniscus shapes, namely: concave, flat, and convex. They demonstrated that the hydrodynamics in the liquid phase close to the meniscus is not changed as a function of the meniscus shape. However, they could not explain fully the preliminary InfraRed (IR) temperature measurements of the flat meniscus which should have led to inversion of the vortex motion within the liquid.

The present work performs a study of evaporation of ethanol inside different tube sizes and different tube materials with the meniscus approaching the tube mouth; once the meniscus is pinned at the tube mouth, the syringe pump causes the contact angle of the meniscus to change and eventually pushes the meniscus out of the tube, though it remains pinned to the end of the capillary. A reverse experiment is also performed where the syringe pump is stopped and the meniscus recedes inside the capillary tube because of the mass lost due to evaporation. Contactless IR temperature measurements are performed and temperature profiles are extracted along the vertical axis at the tube mouth.

2. Experimental facility and procedure

Capillary tubes, connected to a syringe pump and orientated with their axis horizontal, have liquid injected at a constant flow rate. The meniscus advances inside the tube till it reaches the tube mouth. There the meniscus pins itself to the tube mouth and from there onwards the contact angle changes as depicted in Fig. 1. Once the meniscus protrudes outside the tube, the syringe pump is stopped and because of continuous evaporation from the meniscus, the meniscus retracts back inside the tube. Fig. 1 shows the variation in meniscus shape during the pumping phase for one run: in a.1 and a.2 the meniscus advances to the tube mouth, becoming pinned at the tube mouth in a.3: the contact angle (indicated in a.3) decreases to 0° (by a.5) for the meniscus inside the tube and then becomes more than 0° when the meniscus protrudes outside the tube (a.6 to a.8).

Ethanol was chosen as the working fluid and we used it as received from the manufacturer (Fisher Scientific, with 99,99% purity). The tubes used in this study are made of borosilicate glass, stainless steel and Teflon. We investigated these three different tube materials to see what effect the wettability has on the shape of the meniscus. The sizes of the tube used are reported in Table 1 below. The tubes were also used as received, after being rinsed in ethanol and dried in air.

We used an IR camera to measure the meniscus interfacial temperature. The IR experimental setup is depicted in Fig. 2, where the main components are labelled. The infrared camera was directed at the curved meniscus interface at the tube mouth in the axial direction.

The IR camera used in this study is an FLIR ThermaCAM SC3000 that has a thermal sensitivity of 20 mK at 30 °C, an accuracy of 1% or 1 °C for temperatures up to 150 °C. The GaAs, Quantum Well Infrared Photon FPA detector has a spectral range of 8–9 μm centred in one of the two atmospheric "windows" with a resolution of 320 × 240 pixels and is Stirling cooled to 70 K. The field of view at minimum focus distance (26 mm) is 10 × 7.5 mm. A continuous electronic zoom (1–4 times) is also provided. The IR camera is calibrated annually by FLIR Systems and the error found during the last calibration is within the accuracy stated above. The system can acquire images in at high speed up to 150 Hz, with the ability to reduce the picture size so that each frame contains more than one image. The images grabbed are transferred to a dedicated PC with installed ThermaCAM research software (by FLIR System). The image spatial resolution of the present camera is 31.25 μm for a focal distance of 26 mm.

Ethanol, as used in this study, is semi-transparent to IR at the camera wavelengths of 8–9 μm. The emissivity of ethanol depends on the liquid thickness as clearly shown also by Brutin et al. [18] for drops. Therefore, the IR measurements of the present investigation give a good indication of the temperature distribution of the liquid close to the meniscus interface but not necessarily of the interface itself. In addition, given the limited depth of field (100 μm) of the IR camera this leads to measurement within a planer slice of the curved meniscus as described in Buffone and Sefiane [19]. We have chosen a value of the emissivity for ethanol of 0.9 in the software of the IR camera used.

3. Results and discussion

Fig. 3 presents eight IR frames of the borosilicate capillary tube with internal diameter (ID) 1.6 mm where the meniscus shape (concave, flat or convex) is also indicated. In the first frame of Fig. 3, (b1-1), we indicate with dashed circles the tube wall and, with a line in the bottom left corner, a 1 mm scale. From the IR frames of Fig. 3 it is worth noticing that when the meniscus becomes flat, liquid starts wetting the rim of the tube, as can be seen on the bottom left corner of third frame (b.2–1). In the subsequent three frames the liquid continues wetting the tube rim till eventually the rim is completely wetted and finally the meniscus starts pushing out of the tube as shown on the seventh frame (b.3–1). The typical temperature profile of the meniscus interface along the line A-A drawn on frame (b.1-1) is reported in Fig. 4. Here we have drawn two grey rectangles to indicate where the tube walls are and a dashed-dotted circle in the middle of the meniscus to indicate the region for which the meniscus is out of the depth of field of the IR camera and therefore where the temperature readings are unreliable. The temperature profile along this vertical line across the meniscus is not symmetrical, possibly because of the effect of gravity on the Marangoni convection, as explained in detail in Buffone and Sefiane [19]. The meniscus temperature dips at the inside surface of the tube, as reported in previous works [19,20]. We have chosen to extract temperature profiles along the vertical section of the meniscus interface because of the lack of symmetry due to gravity. In all subsequent temperature profiles the tube walls will not be indicated for clarity of presentation.

Fig. 5 reports the evolution of the meniscus temperature profile along the same vertical line as A-A of Fig. 3, with the meniscus changing shape from concave, to flat and eventually to convex. In Fig. 5 the tube is again borosilicate glass but has an internal diameter of 1 mm. The sequence of frames of Fig. 5 has been extracted from an IR movie in which the meniscus moves first from inside the tube to outside, pushed by the syringe pump and then the syringe pump is turned off and the meniscus retreats inside the tube; therefore in this sequence there are two instances in which the meniscus become flat (c.3 and c.6). As can be seen in frames (c.1) and (c.2), with the concave meniscus inside the tube, the temperature profile is similar to those reported in previous works by the present authors [19,20]. Frame (c.3) shows the case of the