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Effect of vapor flow on the wetting behavior of unstable evaporating menisci in heated capillary tubes

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ABSTRACT

The wicking height of a heated, evaporating meniscus formed by surface-wetting liquid in a vertical capillary tube with dynamic flow has been investigated. Previous experimental results and analytical models for measuring/predicting wicking heights in capillaries are also reviewed. An analytical model is presented that accounts for both major and minor vapor pressure losses along the vertical capillary tube. It is shown that during thermo-mechanical instability, vapor/meniscus interaction can become more prevalent due to increased vapor generation/pressure near the meniscus free surface. A relatively simple procedure for estimating onset of meniscus instability is presented and, when used with the vapor Reynolds number, can estimate whether vapor pressure loss is significant. By comparing the current model with the available experimental data, it is shown that the wicking height of an unstable, evaporating meniscus of n-pentane in a vertical, glass capillary tube is better estimated by considering vapor flow pressure losses – providing a 40% improvement over previous models that neglect vapor flow. In addition to vapor flow pressure loss, the dynamic contact angle and thin film profile must also be calculated to ensure accurate prediction of wicking height. Although the proposed model shows improvement, it is prone to under-predicting the actual meniscus wicking height for stable, evaporating menisci at lower relative heat loads. The proposed model can be used for predicting wicking behavior of heated, vertically-aligned liquid columns in capillary structures – which is relevant to the design of miniature heat transfer equipment/media such as wicked heat pipes, micro-channels and sintered/porous surfaces.

Introduction

Background

The advantages of liquid–vapor phase change for transferring high heat fluxes and maintaining uniform operating temperatures are exploited in many heat rejection devices, such as mini and micro heat pipes and micro heat spreaders (Benson et al., 1998; Ming et al., 2009; Peterson, 1994; Peterson and Chang, 1998; Ranjan et al., 2011; Weibel and Garimella, 2012; Yang et al., 2009). For many phase-change heat transfer devices, capillary force is required to adequately, and passively, pump liquid from the condenser (heat sink region) to the evaporator (heat source region) in order to maintain a continuous and efficient heat rejection process. The wetting characteristics of the working fluid on the solid surface directly affect the capillary pumping ability and thus the maximum energy transport achievable.

Experimental investigations and theoretical analyses have been conducted to determine the fundamental wetting characteristics of thin liquid films on the outer surfaces of heated rods, horizontal surfaces of flat plates and the inner surfaces of heated tubes (Chan, 1994; Ma et al., 1998; Ma and Peterson, 1997; Peng and Peterson, 1992; Pratt and Hallinan, 1997; Wayner, 1994). The evaporating thin film profile within a heated conduit or channel at the capillary scale also depends on surface heat flux. Due to a pressure difference between the vapor and liquid at the phase-change interface, the confined evaporating liquid takes the form of a depressed, spherically-shaped meniscus with elongated, thin film regions in which heat transfer dominates and a 'dynamic' contact angle is defined. Ma and Peterson (Ma and Peterson, 1997) established a model for predicting the heat transfer and thin film profile occurring in triangular grooves and found that the (dynamic) contact angle increases with superheat.

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Pratt and Hallinan (1997) investigated, experimentally and analytically, thermocapillary stresses that affect the wetting characteristics of a heated, curved meniscus of n-pentane in a capillary tube as shown in Fig. 1. In Fig. 1, it may be seen that the wall-to-fluid heat transfer near the meniscus region, Q, is either sensible, $Q_{sensible}$, or latent, Q_{evap} – with latent heat transfer occurring predominantly near the thin film of the meniscus. They demonstrated that the liquid wicking height decreases as the heat input on the outer surface of the capillary tube increases and that the wicking height cannot be accurately predicted by a Laplace–Young equation. The reduction in wicking height was attributed to dynamic, liquid flow effects caused by interfacial thermocapillary stresses. These stresses, induced by temperature gradients in vicinity of the vapor–liquid interface, adversely affect the wetting/wicking ability of the evaporating liquid. The thermocapillary-based model was shown to predict wicking heights in close agreement with the experimental data.

Ma et al. (1998) developed a mathematical model for predicting the wicking height formed by a wetting liquid in a vertical, heated capillary tube based on a thin film evaporation model. It was found that the applied heat flux significantly affects the surface-to-liquid contact angle, as well as the thin film thickness variation/profile within the capillary tube. Effects such as surface tension variation, disjoining pressure and fluid flow in the evaporating thin film region were shown to impact the wicking ability of the liquid column. The contact angle variation, coupled with the dynamic flow frictional pressure loss occurring inside the tube, was shown to be the two major factors for decreasing the wicking height. Further, the temperature gradient existing in the evaporating thin film region was shown to be very small due to the dominance of phase-change heat transfer; with the majority of heat transfer occurring within or very near the meniscus interline region. The model presented by Ma et al. (1998) demonstrated that thermocapillary effects cannot sufficiently explain the discrepancy between analytically-predicted and experimentally-observed wicking heights during evaporating-meniscus heat transfer.

Others have focused on the dynamic wicking/capillary problem (i.e. imbibition); which includes the response of liquid, as well as the transient motion of its unstable meniscus region, during evaporation (Polansky and Kaya, 2015; Ramon and Oron, 2008; Washburn, 1921; Zhmud et al., 2000). In modeling the transient wicking problem, an oscillating/time-variant model for the vapor–liquid interface motion can be obtained for both isothermal and/or evaporating menisci (Polansky and Kaya, 2015). By idealizing the meniscus profile as horizontal (i.e. neglecting disjoining pressure and thin film regions), a force balance on the capillary rise provides a Lucas–Washburn equation of motion for the vapor–liquid interface height (Washburn, 1921). Effects of vapor flow during imbibition have been shown to be important for the isothermal case in which the liquid has low viscosity (Zhmud et al., 2000). The viscous drag of air, or vapor, within a capillary tube can dampen the amplitude of the liquid–air interface during imbibition.

Polansky et al. experimentally and analytically investigated the imbibition of various fluids, including n-pentane, in heated vertical capillaries of varying radii, including 0.25, 0.5 and 1.0 mm, while the power input was varied up to 10.6 W. The experiments demonstrated that the wicking behavior was influenced by the evaporation heat transfer and that their Washburn-based model could not accurately predict the dynamic wicking height of n-pentane for the smallest tube investigated during heated conditions (Polansky and Kaya, 2015). Ramon and Oron (2008) considered the effects of vapor recoil – a reaction force opposing capillary action due to significant acceleration of vapor at the evaporating vapor–liquid interface – on the dynamic wicking height of an evaporating liquid constrained in a heated, vertical capillary tube. It was demonstrated that the evaporating liquid stability can be related to local temperature discontinuities.

While many efforts have focused on the dynamic wicking height within a heated capillary tube, phenomena inside the curved meniscus region such as disjoining pressure, vapor pressure drop and dynamic contact angle are typically not considered. As shown herein, these higher-ordered phenomena can have significant effects on the steady-state wicking behavior of evaporating menisci.

Pratt and Hallinan's experiment

Pratt and Hallinan's experiment for observing the macroscopic wetting characteristics of a heated, evaporating meniscus within a capillary tube is shown schematically in Fig. 1 (Pratt and Hallinan, 1997). The setup included a glass capillary tube that was circumferentially heated via an electrical resistance heater – allowing for the meniscus to be heated from above. A portion of the capillary tube was submerged into a reservoir of liquid n-pentane allowing for the liquid to partially wick up the length of the tube from the bottom. The dimensions of the capillary tubes tested, along with other experimental parameters, are summarized in Table 1 where: L_f is the heater length, L is the capillary tube length, L_1 is the distance between the bottom of the heater and first thermocouple and L_2 is the distance between thermocouples T_t and T_b along the outside of the capillary tube.

The device was placed within an evacuated chamber to minimize convection with surroundings and fluid contamination.

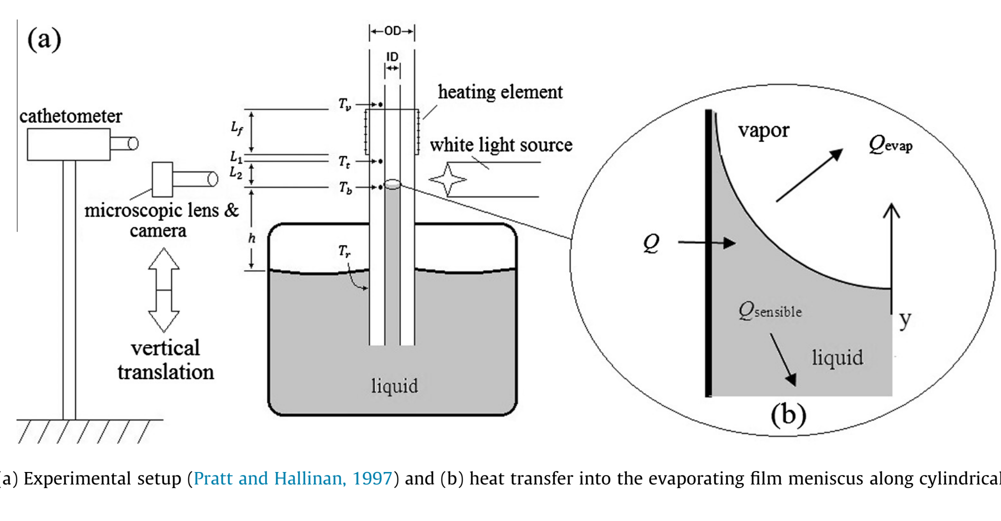

Fig. 1. (a) Experimental setup (Pratt and Hallinan, 1997) and (b) heat transfer into the evaporating film meniscus along cylindrical tube wall.