



## Contact line behavior for a highly wetting fluid under superheated conditions

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### ABSTRACT

The contact line behavior of a highly wetting, dielectric liquid (FC-72) droplet under superheated conditions is investigated. Relatively large macroscopic contact angles atypical of FC-72 droplets were observed under superheated conditions. The addition of a non-condensable dissolved gases in the system increased the contact angle at a given superheat. Numerical simulations of the transport phenomena near the microscopic three phase contact line were performed that show how the macroscopic contact angle is related to the superheat and thickness of the adsorbed film ahead of the contact line. The use of a macroscopic contact angle that is a function of superheat in established models for bubble departure diameter and the onset of nucleate boiling enhanced the ability of those models to describe the behavior of highly wetting fluids.

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### 1. Introduction

Relatively little experimental research is available regarding the behavior of three-phase contact lines under highly superheated conditions despite their importance in the modeling of a wide range of phenomena including drop evaporation, thin film stability, bubble nucleation, growth and departure during boiling, and the critical heat flux in pool and flow boiling. The role of the contact line is generally accounted for using a macroscopic contact angle obtained from measurements at ambient temperatures. This contact angle is usually lower than that at the saturation temperature but is still used in modeling of these phenomena. However, it has been observed by numerous researchers that the contact angle can increase significantly if the wall is superheated, even for perfectly wetting fluids. Much of that work has focused on partially wetting systems.

Chandra and Avedisian [1,2] observed significant increases in the contact angle of heptane droplets during their evaporation on a polished stainless steel surface under ambient conditions. The contact angle remained relatively constant (32–40°) in the subcooled regime (wall temperatures below  $T_{\text{sat}} = 98.4^\circ\text{C}$ ), however, sharp increases were observed in the superheated regime (Fig. 1). At very high superheats near the Leidenfrost temperature, the measurement of the contact angle was complicated by bubbles nucleating within the film and the disturbances they created in the contact line. The authors assumed a contact angle of 180° at 200 °C (Leidenfrost temperature) to obtain a complete variation throughout the nucleate and transition boiling regimes. While

some of the contact angle increase may be ascribed to the fact that these were droplet impingement experiments and hence the contact angles were advancing contact angles, the sharp increase in contact angle cannot be attributed solely to the droplet motion.

Anderson and Davis [3] performed a 2-D analysis of volatile liquid droplet evolution and showed that the contact angle of an evaporating droplet would be higher than that of a sessile droplet. The presence of evaporation had a dramatic effect on the equilibrium droplet profile and contact angle. They found that thermocapillary convection transports mass from the hot regions (near the contact line) to colder regions (near the top of the droplet) and this tended to contract the droplet, increasing the contact angle and delaying evaporation. Hocking [4] derived an expression for the macroscopic contact angle for an evaporating droplet. His conclusion that the contact angle was increased by evaporation was in qualitative agreement with the results of Anderson and Davis [3]. The increase in contact angle was attributed to a large evaporative loss near the edge and the inability of the fluid in contact with the plate to move and compensate for the loss. They considered only partially wetting drops where intermolecular interactions between the solid, liquid and vapor were neglected. Recently, Nikolayev [5] investigated an evaporating drop and discussed the dynamics of the contact line, but also chose not to include the influence of intermolecular forces since the drops were partially wetting. A major conclusion of this work was that both Navier slip and Marangoni forces were required to resolve the hydrodynamic singularity at the contact line when evaporation occurred.

Elbaum et al. [6] observed that a methanol droplet would completely wet a silicon substrate when the substrate temperature was lower than the saturation temperature, but form a droplet with a

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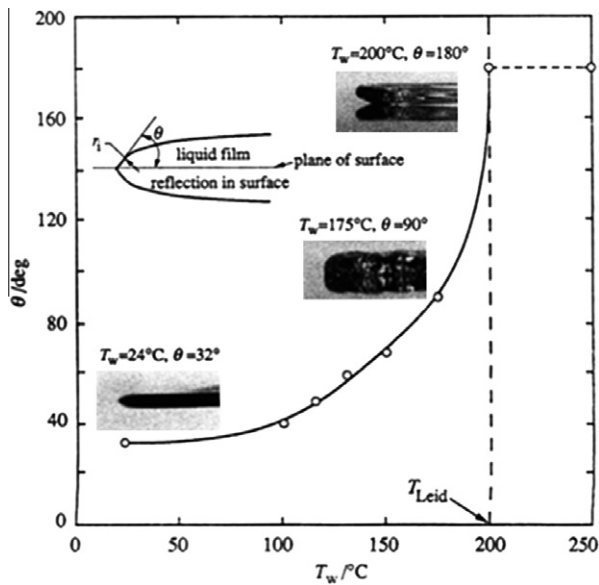


Fig. 1. Contact angle of heptane on a stainless steel surface [1].

non-zero contact angle when the substrate was superheated. A thermodynamic justification for the increase in contact angle with superheat was provided. However, Bonn and Meunier [7] later showed that the governing equations used by Elbaum et al. [6] are only valid on the macroscopic scale and do not account for interaction between solid/liquid and liquid/vapor interfaces in the drop. The flawed assumption wherein the wetting film was assumed to be in equilibrium with a drop at the same temperature under evaporating conditions was also questioned.

Lee et al. [8] measured the time evolution of a droplet of FC-72 as it evaporated on a superheated wall. The very small contact angles under subcooled conditions were observed to increase to between 34–45° as the wall superheat varied between 8–28 °C. Kandlikar and Steinke [9] studied water droplet evaporation on various surfaces. They attributed the observed increase in contact angle during evaporation to a vapor recoil force that pushed the interface into the liquid, and termed this “vapor cutback”. Kuznetsov et al. [10] observed that the width of a falling film of R11 in contact with its own vapor decreased with increasing superheat. This was accompanied by an increase in the contact angle from near zero at  $T_{sat}$  to 15° at a superheat of 0.8 °C. Gokhale et al. [11] measured the shape of the vapor–liquid interface in the vicinity of the contact line for a butanol drop under evaporating and condensing conditions. They showed that the contact angle was a function of the surface temperature, that the dependence of the velocity on the apparent contact angle obeyed Tanner’s law, and that the apparent contact angle was larger for a drop than for a meniscus of the same fluid under equilibrium conditions. Gokhale et al. [12] also investigated evaporation and condensation of surfactant laden water droplets. The dynamics of contact line motion was shown to be a function of surfactant adsorption and the contact angle was a function of contact line pinning for both evaporation and condensation. Ojha et al. [13] studied the contact line behavior during both droplet condensation and evaporation on smooth and rough surfaces. The contact angles during evaporation were always larger than during condensation, and were consistent with a decrease in the adsorbed film thickness that accompanied evaporation.

All of the above analytical, numerical, and experimental studies clearly indicate that the droplet contact angle can be a strong function of wall superheat. The mechanisms responsible for this in-

crease in contact angle are not always clear, however, nor are the effects of non-condensable gas environments and surface properties. Also, the change in contact angle is more pronounced for highly wetting fluids such as refrigerants and fluorinerts, so the use of a contact angle measured at subcooled conditions to model evaporative phenomena such as boiling and spray cooling could result in faulty interpretations of the contact line transport phenomena.

The objectives of this paper are to clarify the contact line transport mechanism for highly wetting dielectric fluids through experiments and corresponding numerical simulations. In particular, we are interested in why the apparent contact angle for a highly wetting fluid increases, how fast it increases as a function of superheat, the mechanisms that drive the increase, and whether the increase can occur in models that do not require the use of hydrodynamic slip to resolve the stress singularity at the contact line. Measurements using FC-72 on a copper substrate are described. The effects of surface oxidation and gas content are also explored. Numerical models of the heat and mass transport near the three-phase contact line are presented and the obtained contact angle values are compared with the experimental results to identify the underlying mechanism responsible for driving the increase in contact angle with superheat. Finally, the implications of these results on the theory and modeling of phase change phenomena of dielectric fluids are discussed.

## 2. Experiments

### 2.1. Experimental setup

A schematic of the test chamber used to measure the droplet contact angle is shown in Fig. 2. A copper cylinder (3.8 cm length and 3.8 cm diameter) was heated by a cartridge heater (Omega CSS-10120/120V, 20 W, 2.54 cm length  $\times$  0.64 cm diameter). Copper was chosen since its high thermal conductivity and large thermal mass could be used to provide a nominally isothermal surface for the impacting droplets. The heater temperature was controlled by a PID controller (Omega CN1166-DC1) and a K-type thermocouple placed 1.3 cm below the droplet impact surface. Another PID controller (Omega CNi16), a RTD, and six thin-film Kapton heaters attached to the side of the test chamber were used to control the bulk fluid temperature. The chamber was filled with nominally 0.25 l of distilled FC-72 ( $C_6F_{14}$ ). The working fluid was degassed to varying levels by repeatedly pulling vacuum on it, and the final dissolved gas concentration in the liquid was determined using the chamber temperature ( $T_{bulk}$ ) and pressure ( $P_{bulk}$ ), the thermophysical properties of working fluid, and Henry’s law. The reader is referred to Henry et al. [14] for the details of the degassing procedure and dissolved gas concentration calculation.

The relevant thermophysical properties of FC-72 at room temperature are summarized in Table 1. During an experiment, liquid was intermittently pumped to the pipette tip through which very small FC-72 droplets ( $\sim 3 \mu\text{l}$ ) were released onto the heater surface. The initial droplet temperature was not experimentally measured, it is expected to be at the chamber temperature ( $T_{bulk}$ ) as the feed line from the peristaltic pump to the pipette tip that is inside the chamber is very long and contains significant fluid volume to generate many more droplets than ever used at a given stretch during the experiments. The peristaltic pump speed, tube diameter and the pipette tip size were used to control the droplet frequency and volume. Images of the droplets as they evaporated were captured through a side view CCD camera at 30 Hz.

Three copper surface oxidation levels (none, light oxidation, and medium oxidation) were tested. The same copper block was used

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