Measurement of the interfacial temperature jump during steady-state evaporation of a droplet

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MEASUREMENT OF THE INTERFACIAL TEMPERATURE JUMP DURING STEADY-STATE EVAPORATION OF A DROPLET

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KEY WORDS

Evaporating droplets, interfacial temperature profile, heat and mass transfer at liquid-vapor interface

ABSTRACT

Introduction

Evaporation is an important phenomena that occurs in a wide range of natural and industrial processes. Although this phenomena has been a subject of research for many years, it is still not fully understood. Experimental results of the last few decades seem to contradict with each other, and with the theory which describes this process, e.g. the kinetic theory of gasses (KTG) and non-equilibrium thermodynamics (NET) [1, 2, 3, 4]. Temperature jumps of about 3.2-8.1^{o}C at the interface of a steady state evaporating water droplet at a pressure of about 245 Pa were measured [1, 2]. In order to determine whether this temperature jump exists and what influences this temperature jump, an experimental setup has been developed.

Experimental setup

The experimental setup (Figure 1) consists of an evaporating spherical droplet (diameter of 8 mm) placed on temperature controlled, stainless steel tube in a cylindrical stainless steel vacuum chamber (diameter of 150*mm* and length of 275*mm)*. One end of the cylinder is closed by a stainless steel plate, while the other end is closed by glass window for optical access. Purified, degassed, temperature controlled water of 4^{o}C (controlled by a build-in heat exchanger) was supplied to an evaporating geometry by a mass flow controlled syringe (VWR gas tight syringe 549-0536). The evaporating mass flow is prescribed by the syringe and controlled by a CCD camera (Teledyne Dalsa Genie), which measures the height of the droplet with a precision of 35μm per pixel. The appropriate mass flow was determined by adjusting the flow rate until the droplet height remains steady state. The pressure in the chamber was controlled by a rotary vane pump (vacuumbrand PC8 / RC6) which can reach a vacuum of 0.4 Pa . The pressure is measured by a pressure transducer at the side of the cylinder (Keller PAA 33x) with an accuracy of 10 Pa. The temperature profile at the interface of this droplet was measured by a K-type thermocouple made of two 25.4μm wires with an

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accuracy of about 0.4°C. The thermocouple is moved towards the interface by a micrometer spindle (Freinmeyer) mounted on top of the vacuum cylinder this spindle can move the thermocouple toward the interface with an accuracy of $2\mu m$.

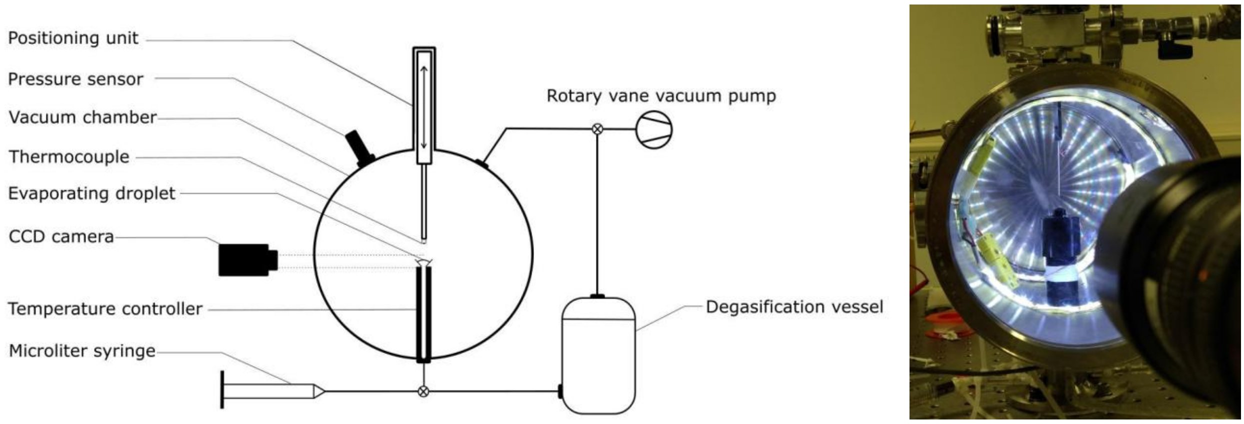

Figure 1. (Left) Schematic overview of the experimental set-up and (right) front view of the experimental setup with the glass window through which the camera can measure the height of the droplet.

Results and Discussion

Before and after the start of the experiments, the thermocouple was calibrated in a bath of boiling and ice water and the offset and a proportionality constant have been determined. The measured uncertainty was about 0.4°C and did not change over time.

Before the start of the experiment, water was placed in the degasification channel and degassed for about one hour. Also the vacuum chamber was degassed for one hour at a pressure <10 Pa. Meanwhile the cooling device and pump were turned on to cool the evaporating liquid. After this hour, the thermocouple above the interface (at a fixed position) and the pressure was set at 780 *Pa*. Due to the occurrence of bubbles inside the syringe and the channel between the syringe and the droplet geometry, it was not possible to do an experiment lower than 780 *Pa*. The measurements started when both measured temperature and measured pressure in the vacuum chamber were at steady state.

The vapor and liquid temperatures were measured between 4mm above the interface and 1.5mm underneath it. The measured temperature profile is shown in Figure 2. Due to evaporation the liquid temperature near the interface is lower than the bulk liquid temperature T_{bl}.

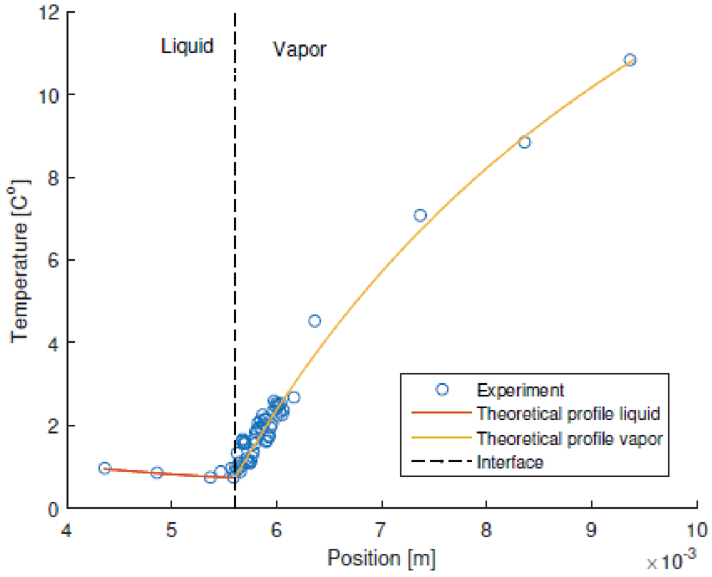

Figure 2. Theoretical (solid line) and measured (circles) temperature profile at the liquid-vapor interface of an evaporating droplet. The vapor pressure is set at 780 *Pa*. The position of the liquid-vapor interface is indicated by the vertical dashed line.

The measured temperature profile has been analyzed by the same model that has been used for the experiment conducted by Fang et al. [2]. The liquid temperature T_l is described by:

$$T_l(r) = T_{cl} + (T_{bl} - T_{cl}) \exp\left(\frac{r - r_i}{r_l\, a_l\, r}\right) \tag{1}$$

With $T_{cl} = \frac{Q_i}{j_i\, c_l} + T_0$ $\;and\;$ $a_l = \frac{\kappa_l}{j_i r_i^2 c_l}$.

For the vapor temperature T_v holds:

$$T_v(r) = T_{cv} + (T_{bv} - T_{cv}) \exp\left(\frac{r - r_v}{r_v\, a_v\, r}\right) \tag{2}$$

With $T_{cv} = \frac{Q_i}{j_i\; c_p} + T_0 - \frac{\Delta h_0}{c_p}$ $\;and\;$ $a_v = \frac{\kappa_v}{j_i\; r_i^2\; c_p}$.

Where r_i is the interface location, Q_i is the mass flux at the interface, j_i the mass flux at the interface, *h* the enthalpy, c_p the specific heat, κ the thermal conductivity and T_{bv} and T_{bl} the bulk temperature of the vapor and liquid. The subscripts *v* and *l* indicate the liquid and vapor phase respectively.

The calculated temperature profile seems to approximate the measurement profile well (Figure 2). However, the calculated evaporative mass flux of $j_i = 6 \cdot 10^{-5}\; kg\,/m^2\, s$ seems to be lower than would be expected from the experiments by Fang et al. [2], who measured a mass flux of $j_i = 2.5 \cdot 10^{-4}\; kg\,/m^2\, s$ for an evaporating spherical conditions. The difference between this value and the mass flow calculated model can partly be explained by the lower pressure of the experiment by Fang et al. (493 *Pa*) compared to our experiment that was performed at 780 *Pa*, and the fact that the liquid temperature entering the evaporation chamber was 15 °C in the experiments by Fang et al, while we controlled it to be $4^{\circ}C$.

Conclusions and Future Research

An experimental setup has been developed to measure the temperature profile at the liquid-vapor interface of an evaporating droplet. At 780 *Pa* the measured temperature profile shows good agreement with other experiments and models from literature . However the evaporative mass flow is lower than expected from the experiments by Fang et al. [2].

In order to investigate the evaporation phenomena further and to determine the relation between temperature jump and external pressure, the setup will be further modified in order to go to lower pressures (order 200-600 Pa) without bubble formation.

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