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The temperature jump at water – air interface during evaporation

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ABSTRACT

The temperature profiles are measured across a liquid–gas two-layers system at normal atmospheric conditions. A thin water layer is locally heated from the bottom substrate and it evaporates from the liquid–gas interface. A micro-thermocouple with sensor thickness of less than 4 μm has been specially manufactured for the accurate measurement of the temperature profiles. This micro-thermocouple is displaced with micro-steps near the interface, providing the detailed information on the temperature field. A temperature jump at the liquid–gas interface is clearly detected even for small evaporation rate. This jump is measured for heater temperature varying in the range 25–60 °C at normal atmospheric conditions. The temperature jump value is found to increase with increasing the temperature difference between heater and ambient gas, and, hence, with increasing of the evaporation rate. A specific evolution of the temperature profile with increasing of the heater temperature is obtained. Depending on the ambient condition, the temperature in the gas phase near the liquid–gas interface can be higher or lower than that of the liquid. The temperature profiles with negligible temperature jump at liquid–gas interface are observed for some operating conditions. The temperature jump depends not only on evaporation rate, but also on temperature gradients in liquid and gas phases near the interface. The experimental results are found to be qualitatively in agreement with the kinetic theory and quantitatively with classical energy balance on the interface. The reported detailed data on the phase transition phenomena for relatively high heat flux are presented for the first time in the literature. However, more precise measurements of the temperature profiles at the liquid–gas interface should be done further.

1. Introduction

A detailed description of molecular transport across a liquid–gas interface during evaporation/condensation process is important not only for understanding surface chemistry [1,2] but also for many industrial applications involving the microsystems and dispersed phase systems (bubbles and microbubbles) with phase transition [3,4]. An evaporation of a liquid is accompanied by heat exchange between two liquid and gas phases as well as by other coupled phenomena as e.g. thermocapillary convection. A liquid–gas interface is usually far from its thermodynamic equilibrium state, which can lead to the development of different instability mechanisms.

Two most important parameters, involved in the evaporation process according to the energy balance at a liquid–gas interface, are the mass and heat fluxes in both gas and liquid directions. A detailed information on the temperature profile across the liquid–gas layers is indispensable for determination of the heat flux by Fourier law. The investigation of the temperature profile across two different phases is an important issue for the thermal management of cooling systems, such as heat pipes, for the production of new materials as well as for design and manufacture of the microsystems with phase change. The correct definition of the boundary conditions is also an issue of fundamental importance which could be helpful for the better understanding of non-equilibrium phenomena, like for example, the Leidenfrost effect [5,6] and contact line dynamics [7,8]. Reliable and accurate measurements of the temperature and pressure near the liquid–gas interface and particularly in the Knudsen layer are a real

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challenge. As far as the authors are aware, no reliable and coherent data exist in the literature.

The existence of temperature and pressure jumps at the interface (in the Knudsen layer) during evaporation and condensation is known in the kinetic theory from the long time [9–11] as phase transitions occur under non-equilibrium conditions. Due to investigations of evaporation/condensation process, based on the kinetic theory, some progress was achieved in the determination of temperature and pressure jump coefficients using linearized and nonlinear Boltzmann kinetic equations, Refs. [12–15], which allows now to improve essentially the modeling of evaporation rates [16–19]. Recently, an approach for the describtion of the heat and mass transfer in two-layer liquid–vapor system, is proposed in [20]. This approach is based on the Navier–Stokes equations with temperature and pressure jumps conditions, derived from the kinetic equation. The obtained in [20] results are in a good agreement with the temperature and pressure profiles, calculated on the basis of the Boltzmann kinetic equation. However, the experimental data on the pressures and temperatures jumps at the interfaces are extremely rare, which limits the validation of the existing mathematical models.

The first attempts to measure the temperature jump across the liquid–vapor interface upon evaporation of the liquid in the closed system were performed by Shankar and Deshpande [21], where ten thermocouples with a wire diameter of 0.3 mm were arranged inside the chamber. Measurements were made with water, Freon 113, and mercury. The authors of Ref. [21] have not detected any temperature jump at the liquid–vapor interface for water and have also not provided any information about the evaporation rates.

A series of works by Ward and co-workers [22–26] was devoted to investigations of the temperature discontinuity at the liquid–vapor interface for the water–vapor system using a micro-thermocouple type-K with 25.4 μm wire and about 50 μm bead diameters, respectively. The experiments were performed under reduced pressure conditions (compared to atmospheric pressure), so that the temperature can be measured across a thicker, compared to that at atmospheric pressure, Knudsen layer. Its thickness was estimated to be comparable to the thermocouple bead diameter. The maximal measured evaporation rate was 0.044 μl/s with evaporation flux 0.5386 g/m^{2}s. In experiments of Ref. [22] it was found that the temperature of the vapor was larger than that of the water near the interface (−14.5 °C), with the maximum of measured temperature jump of 7.8 °C for the pressure 194.7 Pa. In Ref. [23] the measured temperature discontinuities for two hydrocarbons, octane and methylcyclohexane, were found following the same tendency as that obtained previously for water: the temperature of vapor was larger than that of liquid at interface. The measurements were performed at reduced pressure conditions, in a range of 318.6–2950.4 Pa using the same experimental setup. The statistical rate theory was suggested in [23] for physical interpretation of the experimental results and for the prediction of the evaporation flux. Steady-state evaporation and condensation experiments were reported in [24]. At the interface, independently of the direction of the phase transition, evaporation or condensation, a temperature discontinuity has been found. In experiments of Ref. [24] the interfacial vapor temperature was also higher than that in the liquid. The possible effect of the thermocapillary flow, induced by water evaporation, was discussed in [25]. It was suggested that this effect plays an important role in the energy transport near the interface of evaporating water. In experiments [22–25] the measured evaporation rates were quite small, with the maximal evaporation flux of 4.242 g/m^{2}s in [25]. The liquid–vapor interfacial temperatures were below 20 °C for all experimental conditions with evaporation at reduced pressure.

The experimental setup of Badam et al. [27] contained an external vapor side heat source, whereby the influence of vapor side heat flux on the evaporation process was investigated. The authors of Ref. [27] studied also the steady-state evaporation under low-pressure conditions using thermocouple with bead diameter less than 50 μm. It was found that the temperature jump across the liquid–vapor interface was as high as 15.68 °C, and the vapor phase temperature was always higher than that of the liquid phase. The evaporation rate was slow under the experimental conditions of Ref. [27].

Furukawa, Murakami and Iida [28] investigated the evaporation of He II caused by the thermal pulse leading to stepwise heating of a liquid–vapor interface. The evaporation phenomena are visualized by a laser holographic interferometer, and the pressure and temperature measurements are provided using a pressure transducer and a superconductive temperature sensor, respectively. The authors of Ref. [28] conclude that the temperature amplitude of the reflected thermal pulse is smaller than that of the impinging one due to evaporation. The authors of Ref. [28] used He II because its heat transfer efficiency is very high. Another class of substances with large thermal conductivity is metals. Evaporation and condensation of the liquid mercury has been studied by Rose and co-workers [29,30]. Interface temperature discontinuities up to around 70 °C have been observed at low vapor pressure and high condensation rate.

The authors of Ref. [31] measured the temperature profile with a 50 μm diameter type-T thermocouple across the layers of air and silicone oil. A thin planar liquid layer, subjected to horizontal temperature gradient evaporated freely to air open in atmosphere. The measurements were carried out under ambient temperature of 20 °C, atmospheric pressure and humidity of 40–50%. Temperature discontinuities have been found at the interface. These discontinuities increased with increasing of the imposed horizontal temperature difference.

The provided short review shows that the liquid–gas interface phenomena is far to be completely understood. Almost all previous experiments were carried out at a pressure below atmospheric pressure, so only slow evaporation rates, but relatively high temperature jumps at the interfaces were measured. In order to clarify the mechanism of evaporation a new coherent and carefully targeted experimental study is required. Two aspects of these delicate measurements have to be underlined. The first one is a choice of a temperature measurement tool; the second choice concerns the nature of a evaporation liquid. We provide below the comments on these two points.

For delicate and precise measurement as a measure of a temperature difference at interface liquid–vapor (temperature jump) it is important to have small and precise measurement apparatus. One of the contact methods for the temperature measurement is the use of the thermocouples. When one uses the thermocouples for the temperature measurement the following constraints have to be take into account: the material of the thermocouple and its isolation, the response time, the conduction and radiation effects, the placement of the thermocouple, its junction and mounting system [32–34]. The size of thermocouple is also important for accurate measurement, especially in Knudsen layer, which thickness is of the order of a few molecular free path (the molecular mean free path in air at atmospheric conditions is 0.07 μm). Two examples of using a micro-thermocouple with the thickness of the sensor element of about 5–6 μm can be found in [35], where the measurements of the temperature in viscous layer of turbulent fluid flow were fulfilled and in [36], where the micro-thermocouple is used for thermal investigation of vortex flow. Recently, the new implementation of micro-thermocouple for the temperature profile measurements in two-layer system is reported in Ref. [37].

Water and air is one of the most vital coexisting pair *in vivo*, so it is extremely important to obtain the complete information about phenomenon of evaporation appearing at its interface. However,