Heat transfer at a single drop impingement on liquid–vapor–solid triple contact line

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Abstract. In the current study an experimental investigation of heat transfer at a single drop impingement on liquid–vapor–solid contact line of a liquid layer located on a heated substrate has been performed. The heated thin foil technique is used for experimentation. The interaction dynamics of a drop with a contact line is considered with the help of high-speed visualization and infrared thermography. The obtained experimental data will be processed by solving inversed Cauchy problem for the non-stationary heat transfer equation. The effects of the drop impingement height on the heat flux in the region of the contact line will be determined in the further steps of research.

1. Introduction

The three-phase contact line is defined as the region where the solid, liquid and the gas phases intersect. Due to the interaction among these phases, the nature of this region is unlike the rest of the drop, rivulet or film surface and deserves a thoughtful investigation. A detailed review of theoretical and experimental studies of the configurations including liquid-gas interfaces in contact with heated solid substrates which can be dry or covered with micro- or nanoscale films is presented in [1].

The triple contact line region is a sharp border between the bulk liquid and the ambient gas as might appear at first sight, but in fact larger view reveals a more comprehensive picture. In work [2] the contact line region was divided into four regions - the adsorbed film region, the transition region, the meniscus region and the micro convection region. The studies [3, 4] have presented that the local evaporative flux reaches a maximum value in the transition region, which is also called microregion. The transition region experiences large heat fluxes because the resistance to heat transfer in the liquid is very low due to its small thickness. It is difficult to make observation in this region since the liquid layer thickness is varied from a few micrometres to tens of nanometres. However, the full understanding of the heat and mass transfer phenomena in the region of the contact line is of great significance for optimizing the various industrial processes especially for the evaporative cooling [5-7].
The miniaturization of microelectronic equipment and the growing power dissipation require extensive investigations on high performance cooling systems. One of the possibilities when such systems are based on evaporative cooling processes in spray cooling devices [8, 9]. Spray cooling can remove high heat fluxes with low working liquid consumption and comparative good temperature uniformity [10]. The creation of a new hybrid evaporative cooling system with using the film and drop flows for the systems with the high heat release is also one of the tasks of particular urgency today. In the spray cooling systems, the heated wall is only partially covered with a macroscopic liquid layer and the flow pattern is described by the presence of three phase contact lines characterized by extremely high heat fluxes. Drop impingement onto the liquid film can provide significant agitation, increasing the amount of heat transfer [11]. Thus, there is a direct interest in experimental study on influence of the drop falling on the contact line on the dynamics of liquid layer and the heat transfer.

To clarify the complex heat transfer mechanisms on the spray-covered hot surface, a large number studies considered the different aspects of the spray cooling involving spray nozzle-to-surface distance, inclination angle [12], structured surface [13], local drop characteristics [14], cooling liquid with additives [15, 16], cooling non-uniformity and temperature fluctuations [17] and so on. The current study is aimed at the investigation of the heat transfer during a single drop impingement on the three-phase contact line “gas-liquid-solid” of the target liquid layer located on the heated surface by using the heated thin foil technique and high-speed infrared thermography. In previous studies the temperature distributions during the spray coolant impinged a thin stainless-steel foil heater were obtained by applying thermo-chromic liquid crystals on the lower heater surface [18].

2. Experimental method

The heated thin foil method is used to determine the heat flux density based on the surface temperature measurements using infrared thermography. It was described in details in [19] and used in several previous studies [20-23]. The authors showed the local increase in the heat flux in the contact line area. In work [24] it was shown how heated-thin-foil technique can be applied for measurements in non-stationary transfer processes.

The experimental setup includes two main components: the heat transfer section and the imaging system. These are demonstrated in the schematic figure 1.

![Figure 1. Schematic of the experimental setup.](image)

The heat transfer section consists of a 25 µm thick constantan foil which is clamped at both ends by two brass electrode holders, that are electrically connected to the DC power source TTi QPX 1200L.
The underside of the foil is used for direct temperature measurement by an infrared camera. This side is coated with a layer of the black graphite paint of an emissivity factor close to 1 to more accurate temperature measurement. A metal mirror is assembled below the foil. The infrared radiation from the bottom surface of the foil reflected from the mirror is recorded by the infrared camera.

The imaging system consists of a high-speed camera and a thermal imaging camera Titanium 570 M. The thermal camera is set to record an image that is $640 \times 512$ pixels with the scanning frequency of 25 Hz and temperature resolution of 0.1 K. A side view camera (Fast Video 500M, $1280 \times 1024$ pixels, 25 Hz) is utilized to record the process of the drop impact. Both cameras are controlled by a computer.

The working fluid is super-purified water from Milli-Q system. The limiting wetting angle of water and foil is measured by the sessile drop method described in [25] and is equal to $60 \pm 10^\circ$. Experiments are conducted in ambient surroundings and atmospheric pressure. The initial drop volume is set at 6.2 µl. The volume is achieved using Cole-Parmer EW-74905-54 programmable syringe pump. The drop is generated at the needle tip and grows until its weigh exceeds the surface tension force. After the drop separates from the needle it falls on the liquid layer contact line. Liquid layer with thickness on the order of 3 mm is created on the foil before heating. The drop impingement height, i.e. the distance from the tip of the needle to the liquid layer, is equal to about 1.5 cm in the present experimental series.

3. Results

The interaction dynamics of the drop with the contact line is visualized with the help of infrared thermography. Figure 2 shows the temperature distributions of the foil underside at drop impingement on the contact line of the liquid layer depending on the time. When a cold drop falls on the contact line of a warm liquid layer, it is seen how, within 3 s, the cold trace from the drop is completely distributed over the liquid layer.

![Figure 2](image)

Figure 2. The temperature distribution over time during the 6.2 µm drop impingement on the contact line at $P = 0.6$ W (heat power generated on the foil).
Figure 3 illustrates the temperature distributions for the first-time moments along the vertical line drawn in the figure 2, which passes through the central section of the drop and the liquid layer. Reducing of the temperature of the foil surface under the fallen drop is clearly visible in the plot. Further the temperature increases due to the coalescence of the drop with the bulk liquid and mixing of the water.

In our view, the relatively fast mixing of the drop and the liquid layer occurs due to the thermocapillary effect [26]. As seen from figure 2 the temperature of the drop surface is lower than the temperature of the liquid layer. It is known that the surface tension of liquids decreases with increasing the temperature [26]. Therefore, the surface tension in the drop region is higher than in the liquid layer region. A tangential force (1) proportional to \( \nabla T \) appears on the liquid surface, which seeks to move the liquid from an area with a higher temperature to an area with a lower temperature.

\[
\tau_{sur} = \nabla \sigma = \frac{\partial \sigma}{\partial T} \nabla T.
\]

**Figure 3.** The graph of the temperature distributions along the line passing through the central section of the drop and the liquid layer before drop impingement and for the first-time moments after impingement.

**4. Conclusions**

The impact of single drop on the liquid layer contact line is visualized with the help of the infrared camera to give experimental information on the heat transfer during the interaction of the drop with the contact line. It is expected in the near future that the data on temperature distribution will be processed by solving inversed Cauchy problem for the non-stationary heat transfer equation to obtain the heat flux density values. The effects of the drop impingement height and the drop falling position concerning the contact line on the heat flux in the region of the contact line will be determined in the further stages of research. The optimal distance for the maximum average heat flux will be determined.

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