Study of the heat transfer dynamics when a drop of liquid falls on a heated surface

T G Ponomarenko¹,² and V V Cheverda¹,²

¹Kutateladze Institute of Thermophysics SB RAS, Lavrentyev Avenue 1, Novosibirsk, 630090, Russia
²Novosibirsk State University, Pirogov Avenue 1, Novosibirsk, 630090, Russia
E-mail: t.evans2010@yandex.kz

Abstract. The work is devoted to an experimental study of the heat transfer when a water drop falls on a heated horizontal surface, which is a thin constantan foil coated with a fluoropolymer film. Using infrared thermography data, the temperature distributions on the opposite side of the foil from the drop are obtained. The graphs of the temperature distribution along the line passing through the center of the foil with the drop is plotted. The data obtained will be used to calculate the heat flux density in the region of the dynamic contact line of the drop.

1. Introduction

The movement of the liquid drops on a solid surface is widely spread in nature and is also used in the many industries. It is observed in the technology of coating solid surfaces with the liquid films, at spraying fertilizers and in the liquid cooling systems of electronic equipment. Because of the development of the energy-efficient technologies the requirements for the liquid cooling systems are increasing. They should meet the following conditions: removal of a high heat flux and minimization of the coolant liquid consumption. Thus, currently used cooling systems are not sufficiently effective. The spray cooling system is one of the most promising due to heat transfer in the contact line (with high heat transfer coefficient). It also corresponds to the tendencies of the rapid development and the improvement of technology.

The drop is the simplest and most convenient object for studying the processes of wetting, spreading and the properties of the three-phase contact line “gas - liquid - solid”. The study of the liquid drops (spraying, evaporation, dynamics, wetting, etc.) is given considerable attention in the scientific literature [1-3]. The heat transfer in an evaporating drop on a horizontal heated surface is investigated in [4,5]. In the work [4] the calculation of the heat flux density on the surface with the drop was performed by solving the stationary Cauchy problem for an elliptic equation with using the temperature field measured by an infrared scanner. The method described in [6] was applied for the calculation. The heat flux was determined as a result of the processing of infrared thermography data in the Matlab software environment in [5]. The research results showed that the maximum heat flux density is observed in the region of the three-phase wetting contact line of the drop, that is higher than the average heat flux density from the entire surface in several times.

At present, there is still a lack of complete understanding of the above-mentioned phenomena and the properties of the liquid drops in spite of the great attention to the study of the drop flow. It is also not clear about evaporation and heat transfer in a drop contact line. This fact holds back the development of the mathematical models of spreading and evaporating of the liquid drops on the solid surfaces, as...
well as the practical work to create the effective and compact spray cooling systems and other new applications in the energy, medicine, chemical, pharmaceutical and food industries. The method of heat flux calculations in thin foil by solving the stationary Cauchy problem is promising solution to understand physical process (evaporation, heat transfer coefficient) in a static/dynamic liquid drop.

2. Experimental setup
An experimental setup is designed to research the hydrodynamics, the change of the drop shape when it falls on a solid surface, the heat transfer processes in a three-phase contact line. The scheme of the experimental setup and the photo of the working experimental stand are presented in Figure 1.

![Figure 1](image-url)

**Figure 1.** a – scheme of the experimental setup; b – photo of the experimental stand:
1 – power source, 2 – high-speed camera, 3 – IR-camera, 4 – brass electrodes with a constantan foil stretched between them, 5 – syringe with water, 6 – light source, 7 – syringe pump.

The main part of the experimental setup is a 25 µm thick foil, 80x35 mm in size, connected through brass electrodes to a TTi QPX 1200L electrical power supply, which is used for heating the foil. The foil material is a constantan with a thermal conductivity of 23 W/(K⋅m). The wetting contact angle is measured by Kruss DSA-100 and about 50°.

A Cole-Parmer EW-74905-54 syringe pump and a syringe with water are used to inject a drop from height about 10 mm to the foil. The diameter of the syringe needle is 8 mm. The water used in the experiments is super-purified, obtained with the help of the Milli-Q system. However, in the future it is planned to do the same experiments with using the other liquids. The observations and the measurements of the surface temperature of the foil are carried out using a Titanium 570M infrared camera with the help of a metal mirror. A high-speed FastVideo 500M camera is used to observe the drop from side view. A light source is installed to receive a clearer image. The heat fluxes released on the foil during the experiments are not very high, so the natural convection does not disturb the temperature distribution on the foil.

3. Results
The IR-pictures from the bottom side of the foil (without a drop) and the photos of the drop during impact on the foil for different time moment are obtained. Figure 2 shows the experimental data for three cases with the different heat power on the foil surface. The curves of the temperature distribution along the line passing through the middle of the foil with drop are plotted in the software of the Titanium 570M IR-camera for each certain time moment.
Figure 2. Photos, thermal images and graphs of the temperature distribution of water drop (12.2 µl):

a – $P=0.41$ W, $q_{av}=73.21$ W/m$^2$;
b – $P=0.92$ W, $q_{av}=163.29$ W/m$^2$;
c – $P=1.64$ W, $q_{av}=292.86$ W/m$^2$. 
As shown in the graphs that the temperature of the foil surface under the drop initially decreases due to cooling by the drop, and then increases again due to heating and further evaporation of the liquid. The drop diameter increases due to spreading of the drop on the foil.

Figure 3 shows the diameter of the drop for different moments of time. For the first period when drop is impact – diameter of the drop is increasing after that evaporation take place and drop diameter is decreasing.

![Graph showing drop diameter vs. time](image)

**Figure 3.** Diameter of the drop on the foil versus time: 1 – $P=0.41$ W, $q_{av}=73.21$ W/m$^2$; 2 – $P=0.92$ W, $q_{av}=163.29$ W/m$^2$; 3 – $P=1.64$ W, $q_{av}=292.86$ W/m$^2$.

The obtained data of infrared thermography will be used now to calculate the heat flux density near the dynamic contact line of the drop when it falls on the heated surface.

To assess the intensity of the heat transfer near the contact line it is need to use a numerical method, such as solving Cauchy problem for the non-stationary heat transfer equation in the thin constantan foil. This method is used because the direct measurement of the heat flux density in this area cannot be performed because of the small cross size of the contact line region. The constant heat flux and the temperature distribution for the bottom side of the foil for different moment of time are chosen as boundary conditions.

**Conclusions**

The experimental investigation is carried out for first time to study the heat transfer in a contact line of drop of water when it falls on a heated horizontal surface. The topicality of this work is based on the necessity to develop a spray cooling system for modern electronics, as well as for equipment from other industries. The experimental data obtained by infrared and high-speed cameras, namely, the recorded falling of the drop on the heated surface and the measured temperature field on the opposite side from the drop will be used for the next stages of the study.

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