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An experimental investigation of the heat transfer dynamics during drop impact onto a liquid layer

T G Gigola[1, 3], V V Cheverda[1, 2], A L Karchevsky[1, 4] and O A Kabov[1,3]

[1]Kutateladze Institute of Thermophysics SB RAS, Lavrentyev Avenue 1, Novosibirsk, 630090, Russia
[2]Novosibirsk State University, Pirogov Avenue 1, Novosibirsk, 630090, Russia
[3]Novosibirsk State Technical University, K. Marx Avenue 20, Novosibirsk, 630073, Russia
[4]Sobolev Institute of Mathematic SB RAS, Koptyug Avenue 4, Novosibirsk, 630090, Russia

E-mail: t.evans2010@yandex.kz

Abstract. In the present work an experimental investigation of a drop impact onto a liquid layer of certain thickness placed on a heated thin foil is presented. The heat transfer and dynamics of drop impact on liquid surface has been studied and visualised with using infrared thermography. The experimental data obtained by means of an infrared scanner, that is, the measured temperature distributions on the opposite side of the foil will be used for the next stage of the research. The primary task of the research is to determine the heat flux from the foil by solving Cauchy problem for the non-stationary heat transfer equation that describes the heat conductivity inside the foil.

1. Introduction

The study of a drop impact onto liquid films is motivated by a wide spread of this phenomenon in industrial applications and processes. Drop impact on a liquid layer can be faced in various ecological and engineering areas: spraying of fertilizers and pesticides in agriculture, coating of solid surfaces by liquid films, combustion engines with direct fuel injection, cryogenic cooling of human tissues in medicine, spray liquid cooling systems for electronics [1], thermal management of light emitting diodes (LEDs) [2] etc.

Nowadays in electronic industry the engineers try to increase the devices' performance that, in turn, causes the thermal power growth, which must be taken away from the equipment for its stable operation. In view of this fact the advance of cooling systems which are appropriate to the trends of permanent technology improvement, is one of the critical goals. The spray liquid cooling system is one of the most promising cooling systems. It represents a process when spray impacts onto a heating surface, as a result of a directional flow of drops a liquid film constitutes and partly or totally wets the solid target. This liquid film depending on the impacting drops velocities can break up and form the secondary drops. Thus, there is a need of deeper experimental, numerical, and theoretical research of the phenomena involved in drop impingement onto various surfaces and liquid layers, interaction and coalescence of the drops on a heated surface and their evaporation.

Important number of researches was carried out to understand the hydrodynamics and phenomena that occurs during the impact of single drop on dry surfaces, thin films, liquid layers of certain thickness and pools of different depths [3-5]. The certain aspects of this phenomenon were explored experimentally in details: impingement angle at which drop breaks up [6], temperature at which drop bounces [7, 8], secondary droplets received after the impact [9], heat transfer connected with a drop impact on a heated solid surface [10] and etc. In the work [11] the characteristic steps of drop interaction with a substrate at various temperatures are determined, that is impact, spreading, rollback, one liquid column splashing, microdrops detachment, formation, stabilization, breakup, boiling, and evaporation. The interaction of drops impacting onto a dry solid surface was considered in some experimental and theoretical works [12]. The coalescence of single impacting drop with another drop placed on a heated solid substrate was studied in [13]. The impact of a drop on a substrate was also simulated in many numerical works [14-16] and extended to multiple-drop impacts.

The main subject of the given work is the experimental study of the heat transfer dynamics of impacting drop at the surface of a heated solid substrate with a liquid layer of certain thickness by means of infrared thermography.

2. Experiment

Experiments are conducted by using the experimental setup presented schematically in figure 1. The experimental setup can be divided into the heating system, the drop generation, the illumination system, the observation system and the computer control unit.

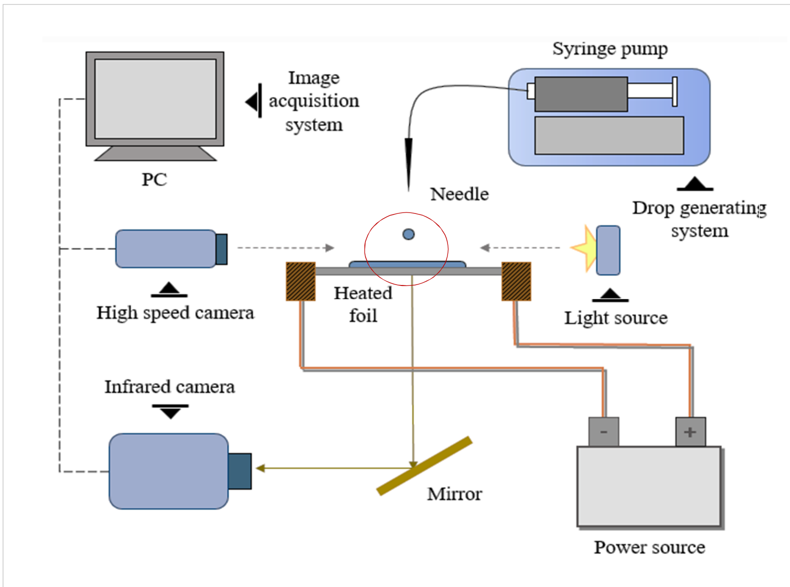

Figure 1. The scheme of the experimental setup used in the present study.

Drop of required volume is produced using a programmable syringe pump Cole-Parmer EW-74905-54 with a constant pre-set flow rate. 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 onto a liquid layer, located on a heated solid substrate. Liquid layer with thickness on the order of 3 mm is used for the study of drop impingement onto a wetted surface and heat transfer dynamics during this experiment. The distance from the tip of the needle to the substrate is equal to about 10 mm. The rectangular constantan (CuNi) foil (90 × 35 mm^2) of the thickness of 25 μm and heat conductivity of 23 W/mK is used as the substrate. The horizontally placed foil is heated by Joule heating. The heating power Q is varied by using the DC power source TTi QPX 1200L, connected to the substrate by means of the brass electrode holders. The impacting drop and target liquid are from the same fluid, i.e., an ultrapurified water obtained in the Milli-Q system.

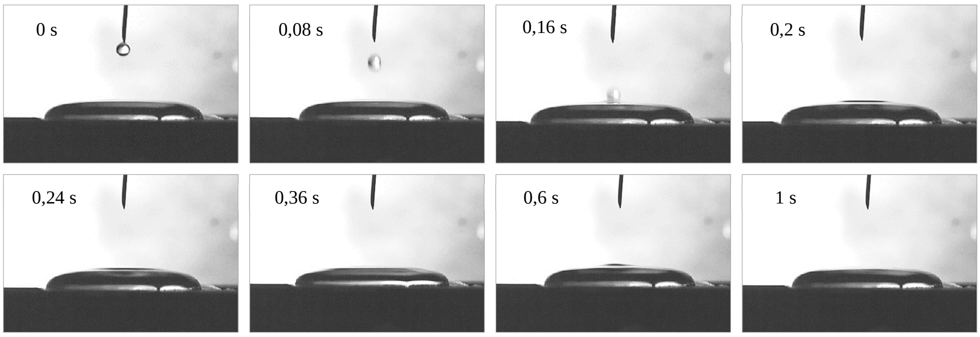

Figure 2. Typical time images of single water drop impacts onto a water surface.

Drop impingement is imaged by using a high-speed camera Fast Video 500M (1280 × 1024 pixels, 25 Hz). The full process is illuminated with the help of a light source to obtain a clear image. The typical time images of single water drop impacts onto a water surface in these experiments are given in figure 2. At the velocity of impact given in the experiments, the falling drop merges with the liquid without formation of any secondary drops. When the drop falls on the surface of the liquid, formation of a small crater of the liquid is observed.

The temperature distributions on the bottom side of the foil are determined by means of the infrared camera Titanium 570M. The thermographic study is carried out at the resolution of IR-camera in experiments equal to 640×513 pixels. The scanning frequency and temperature resolution is equal to 25 Hz and 0,1 K respectively. A metal mirror is fixed below the foil substrate. The infrared radiation from the bottom surface of the foil reflected from the mirror is registered by the infrared camera.

The wetting angle of water and foil is defined by the method of a sessile drop by means of Kruss DSA-100 and it is about 50°.

3. Results and discussion

Figure 3 presents IR-pictures which show the initially measured temperature distributions on the opposite side of the foil during the impact of the small water drop of 6,2 µl volume to the target water layer at the heat power generated on the foil surface P = 0,6 W.

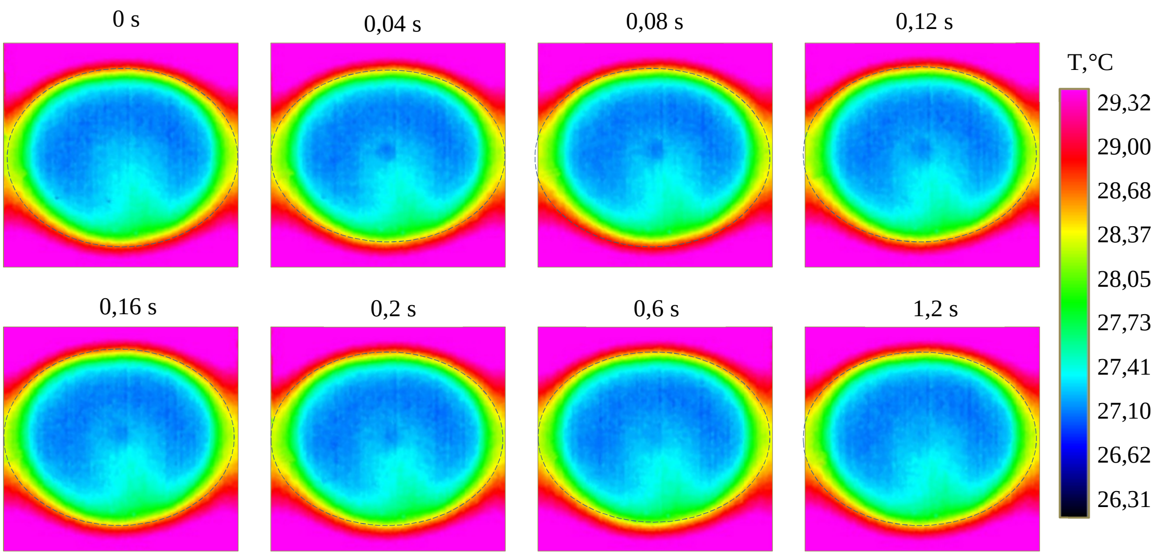

Figure 3. The IR-pictures from the bottom side of the foil during the drop impact for successive time moments (dashed line – position of the contact line).

The experimental data amply demonstrate that when the drop comes in contact with a heated water layer located on the heated foil surface an insignificant cooling of the surface under the drop take place. As shown in figures 2 and 3 the temperature under the drop initially decreases due to cooling by the drop impingement and then the temperature increases again due to mixing of the liquid and the drop. It can be also seen that the graph has two symmetric gentle minimums. Such a temperature distribution on the substrate is explained by more intense evaporation at the edges of the liquid layer and especially in the region of the "gas - liquid - solid" contact line [17]. The temperature increases in the central part of the foil due to the fact that the liquid layer has a sufficient length and there is no effect of the contact lines anymore.

The obtained data of the IR-thermography will be used to determine the heat fluxes on the surface of the foil with the liquid layer. It is mathematically reduced to solving the problem of thermal conductivity with data on the time like boundary. In the heated thin foil technique used in the study the numerical problems of the heat flux determination are incorrect and require special methods of solving. In this research the method considered in [18] and applied to experimental data processing in [19] will be used.

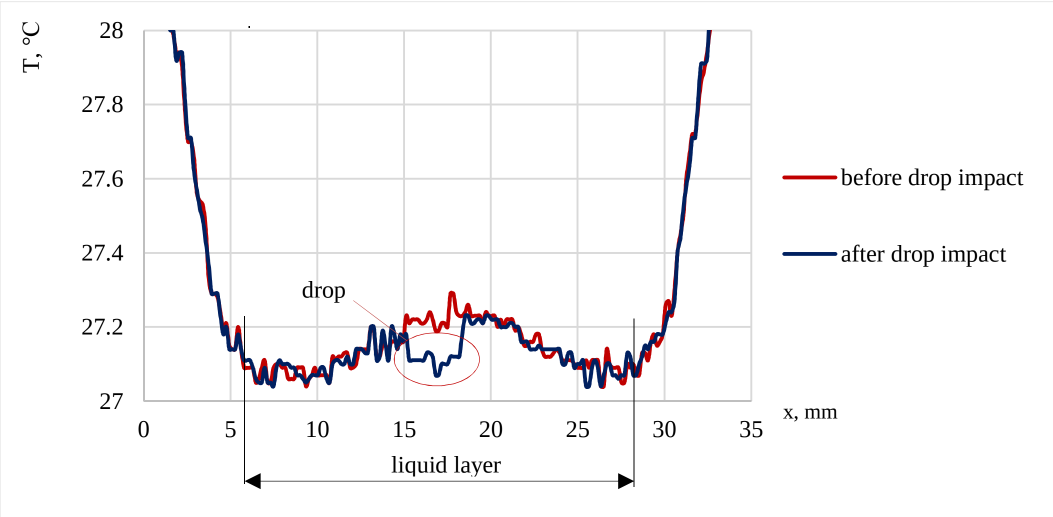

Figure 4. The plot of the temperature distribution on the foil surface from the opposite side along the line passing through the central cross section of the foil before and after the 6,2 µl volume drop impingement.

4. Conclusions

The impacts of single water drop onto a plane water layer has been visualized using an infrared camera to provide experimental information on the heat transfer dynamics during the coalescence. It is thought that the present results reflect a part of the complex drop impact process for the future spray cooling systems. The further numerical research is necessary for a better understanding of the heat transfer process.

Acknowledgments

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