Characteristics of Successive Droplets Impacting Hot Aluminum Surface around Nucleate Boiling regime

by Teguh Wibowo

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Abstract. The purpose of this experimental research is to comprehensively investigate the phenomena of successive droplets impacting the aluminum hot surface. It is understood that each region produces different behavior. Therefore, in-depth investigation is necessarily needed. This research will be useful to support the development of metal industry, especially in the spray cooling area. In the present work, Aluminum is used as the material. The surface temperature ranged from 110°C - 240°C, where the regime of onset boiling occurs. The droplet diameter was 2.8 mm. In addition to spreading ratio and apex height, the spreading velocity is also measured by using a specific image processing technique. This sequence algorithm works based on the binary recognition process where the object is marked as the white color, and the black color represents the background. It is supported with high-speed video camera data captured on 4000 fps. As a result, the obtained quantitative data successfully reveals the behavior of the successive droplets and can support the further heat transfer analysis study to achieve the most effective spray cooling condition in the aluminum hot surface.

INTRODUCTION

The droplet phenomena can be found in numerous industrial field such as coating manufacturing [1], ink-jet printing [2], and spray cooling [3]. Its strong relevance with a particular performance of those industrial systems causes the droplet to become a subject which has been studied for decades covering experimental and simulation works. In term of spray cooling, the main benefit of this method, compared with conventional forced convective cooling, is the high heat transfer rate leads.

Rein [4] studied the phenomena of liquid drop impact both on solid and liquid surfaces and successfully revealed the detailed mechanism occurred during the impact such as the instability on the region around lamella. In addition, Fujimoto et al. [5] focused on the droplet interaction on the inclined hot surface. The study considers the residence time as essential parameter to be analyzed and propose to predict the phenomena based on the experimental data. The heat transfer analysis conducted by Shen at al [6] concluded that various surface modification influences the contact angle between droplet and the solid surface and it is generally known that the contact angle represents one of essential parameter affecting the heat transfer process. Although those influential findings are thoroughly defined, there is still further study needed since the phenomenon of the droplet, especially on the multiple droplet, is very complicated.

In the last three decades, visualization study becomes the fundamental approach to understand the interfacial dynamics on the subject of multiphase flow and fluid dynamics such as the behavior of small bubble in the gas-liquid flow [7] and particle movement on the three-phase vertical flow [8]. The ability to conduct in-depth analysis

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without disrupting the flow is one of the most substantial advantages of this method. In the research area of droplet, many scholars rely [9] [10] [11] on this method to investigate the specific behavior. The recent development of high-speed camera and processing software allows novel finding on its physical characteristics can be revealed.

The present research aims to investigate the successive droplets phenomena impacting hot aluminum surface. This preliminary study is a part of comprehensive droplet behavior in various condition. In order to characterize the droplet dynamics, a high-speed camera is used. It is supported by the developed image processing technique. Next, the surface temperature is also varied to understand the effect of each region around the nucleate boiling. The study will provide new insight into the behavior of droplet and support the further development of the research.

RESEARCH METHODOLOGY

The experimental apparatus utilized in the present study is schematically depicted in Figure 1. The setup is specially designed to produce high-quality experiment data and has been used by previous researchers [10] [12] to characterize the droplet phenomena. In general, it consists of droplet generator, induction heater system, video camera, and illumination set.

To capture the droplet phenomena, a phantom miro m310 camera was utilized so each dynamics of the droplet can be recorded. It is supported with a macro lens which is able to capture the detailed image without producing blur. The camera offers flexibility in term of recording speed and image size. In the present work, the video image was set on 4000 fps and 1024 x 768. Next, a set of LED lamp was installed to obtain good lighting for image acquisition. Before the phenomenon the droplet was recorded, the calibration process was conducted to set the focus point and determine the conversion scale between the image in pixel and the real object in mm.

In the present experimental study, data about droplet impacting the polished aluminum surface is presented. The surface temperature is set between 110 – 240 °C. The temperature was carefully determined to obtain the data which represents every boiling regime. The desired condition was achieved by utilizing the induction heater. As shown in Figure 1, the tested material was monitored by 3 K-type thermocouples coupled with microcontroller.

The droplet generator is built three main parts: reservoir, valve, and injection needle. The reservoir is used to store the working fluid. Next, the valve is utilized to set the amount of liquid which determines the characteristic of the droplet. The injection needle works as the droplet generator. This set up is designed to produce various condition of the droplet, including its frequency and diameter. In the present work, the diameter and frequency of droplet are 3,12 mm and 8,5 droplet per second, respectively.

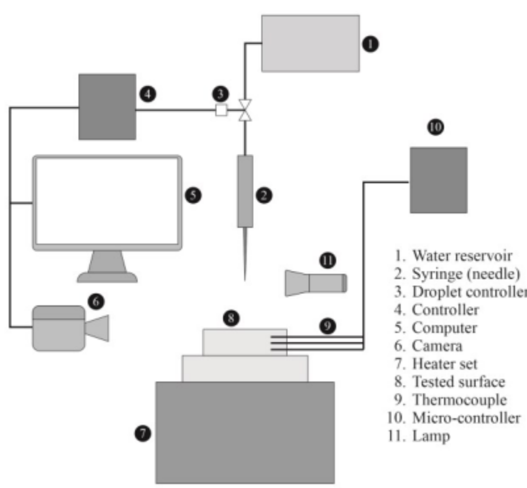

FIGURE 1. Experimental apparatus

To characterize the droplet behavior, image processing technique is applied to the raw image. After the video data is captured by high speed video camera, the raw video file is transferred to the computer. Next, it is converted to a series of images which will be processed in the MATLAB. Mitrakusuma et al. [13] and Wibowo et al. [12] has implemented the sequence algorithm to produce quantitative data from image. The present work adopted the previous approach and modified several steps due to the difference in experiment condition. The output of this method is several essential parameters to support further analysis. Figure 2 shows the physical parameters measured in this study. The spreading diameter of droplet, d, is obtained by finding the maximum and minimum pixel in bottom row. While the subtraction of the highest and lowest value of the object is used to determine the height of droplet, h. Those values are then normalized by the initial diameter of droplet.

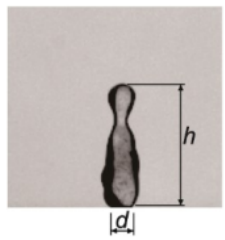

FIGURE 2. The measured parameter of droplet

RESULT AND DISCUSSION

The present investigation is designed to support the previous study [12] [14]. Hakim et al. [14] reveal that at 100° C, the first droplet hits the hot surface and stays in the initial impact position. Next, this study provides new insight into the detailed phenomena of droplet on the slightly higher surface temperature, 130° C, which is depicted in Figure 3. It is found that as soon as the droplet experiences the maximum spreading condition, around 5 ms, the nucleate boiling occurs on the droplet body. The color the droplet body becomes darker which indicates the presence of tiny bubbly inside the body. In another case in which the temperature is lower, or even there is no heat generated from the surface, the droplet would recede to the minimum contact area because of the surface tension of the droplet overcome the inertia impact force. However, this phenomenon is not observed in Figure 3. The internal flow turbulence, caused by the convection process, on the droplet leads the irregular change of droplet interface as shown in Figure 3 (e) and (f).

This phenomenon is followed by the initiation of the secondary droplet (Figure 3 (g)) causing the significant decreases of droplet volume. Previous studies [15] [16] have noticed the importance of this event on the heat transfer performance. In detail, Chavez et al. [17] explained the secondary droplet mechanism and several aspects which affect its occurrence. During this period, a part of droplet outer area does not make contact with the hot surface due to the rapid vaporization on the area around the surface. The second droplet is then released from the droplet generator and it completely hits the first droplet at around 109 ms. The presence of second droplet could revive the cooling performance of the droplet.

The Figure 3 represents the phenomenon of nucleate boiling regime which is characterized by the occurrence of bubble nucleation process. The bubble is generated in form of both ring of bubble and single central bubble inside the droplet and it grows and break up rapidly depending on the various factors such as wall temperature, liquid properties, and surface roughness. As the wall temperature increases, the boiling regime changes into the transition boiling and the film boiling. The film boiling regime is found in surface temperature of tested material is well above the Leidenfrost temperature. Although there is no bold line between the regime of transition boiling and film boiling, the presence of very thin layer under the droplet is believed as one of the strongest evidences of film boiling. The example of behaviour of the droplet on this regime is shown in Figure 4.

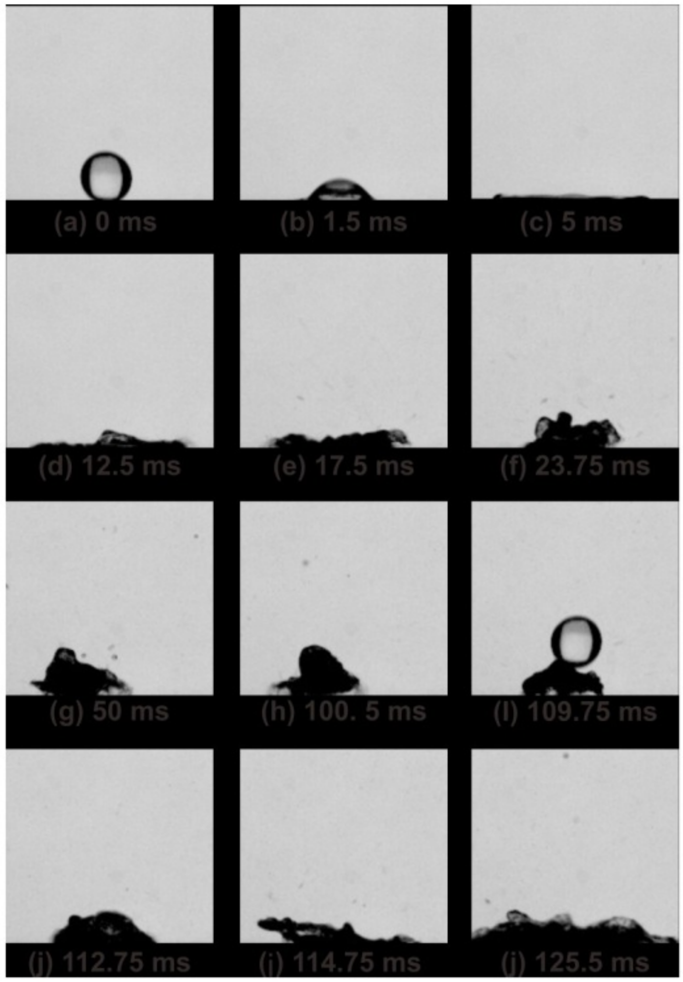

FIGURE 3. The sequence images of droplet dynamic on the surface temperature of 130° C

As the droplet hits the hot surface, the change of impact force to the radial direction causes the droplet spreads. While at the previous case (Figure 3) the maximal spreading condition produces a very thin layer (Figure 3 (c)), the observation on Figure 4 (c) reveals that the droplet interface becomes wavy on its spreading condition. It is believed that the heat transfer rate in this surface temperature affects the different characteristic between them. Then, the droplet pulled back the spreading body to form a vertical liquid jet after the receding process. As noted by Roisman et al. [18], the receding velocity and liquid properties determine the high of this vertical jet.

The droplet then bounces and leaves the hot surface. The study conducted by Liang et al. [19] explains that the rebound phenomenon of the droplet in general, is categorized into three types: reflection rebound, explosive rebound, and explosive detachment. Close observation of the figure reveals that the phenomenon occurs in the present study fits well with the characteristics of reflection rebound, which occurs on the high surface temperature and low Weber number. The droplet will rebound without the presence of any small secondary droplet. Its ability to overcome the gravity is resulted by the vapor pressure on the thin layer resulted by the fast liquid boiling. The second droplet, as shown in Figure 4 (l), hits the first droplet on the air. The collision between first and second droplet on the air lead the momentum direction change from vertical to the radial is not too dominant. As a result, the spreading phenomenon does not occur smoothly.

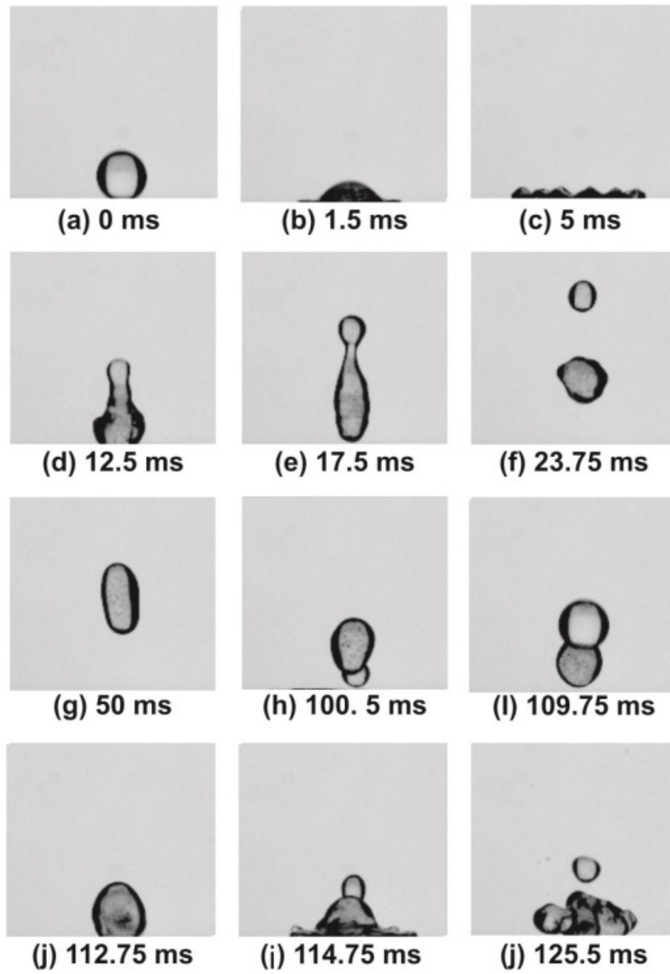

FIGURE 4. The sequence images of droplet dynamic on the surface temperature of 230° C

Present visualization study successfully reveals the dynamics behavior of the droplet on the various surface temperature. Next, further investigation of the droplet utilizes the quantitative data obtained by own developed image processing technique. Figure 5 illustrates the example of image processing results. The red line represents the edge detection applied in the present work. It is overlapped with the raw image to validate the result. The figure reveals that the red line successfully detects the outer area of the droplet. Hence, the accurate measurement of physical parameter of the droplet can be conducted.

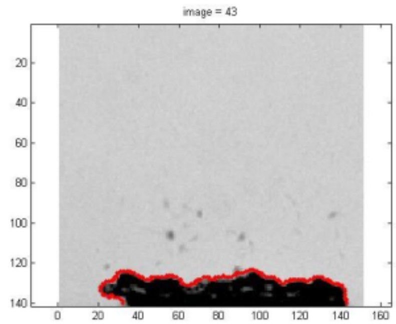

FIGURE 5. The result of image processing technique overlapped with the raw image

Figure 6 dan 7 shows the example of the change of the droplet physical parameter. Here, the surface temperature of 130° C is chosen as example. In detail the behavior of spreading ratio is depicted in Figure 6 while the evolution of dimensionless height is illustrated in Figure 7. Figure 6 illustrated that after the impact of the first droplet, the spreading ratio rapidly increases to its highest position, around 3.0. It is followed by the continuous spreading-receding phenomena until the second droplet comes and boost the value of spreading ratio. On the contrary, the phenomenon of dimensionless height broadly produces the opposite trend in comparison to that of spreading ratio. The sudden change on the 110 ms shows the first contact of second droplet with the first droplet.

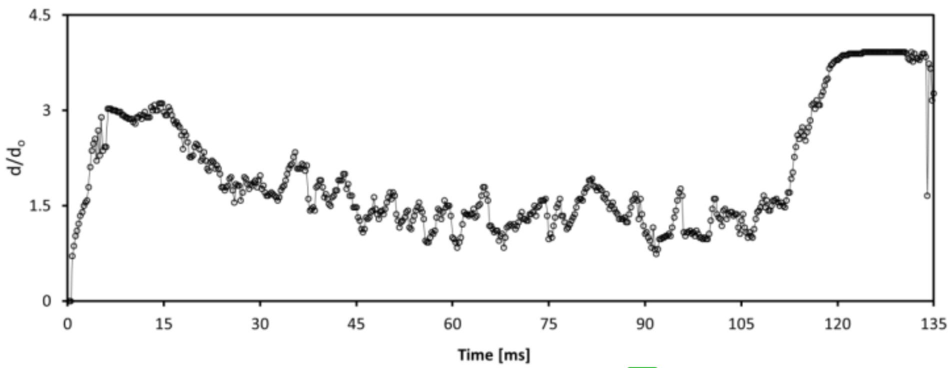

FIGURE 6. The behavior of droplet spreading ratio on the surface temperature of 130° C

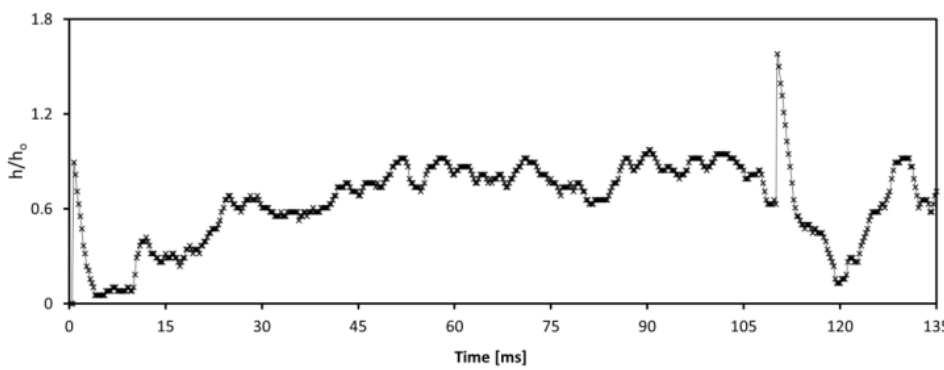

FIGURE 7. The behavior of dimensionless height ratio on the surface temperature of 130° C

Numerous researchers, such as Bernadin et al. [20] and Chandra et al. [21] has suggested that the boiling regime directly affects the heat transfer performance between liquid and hot solid surface. Furthermore, since the boiling regime is influenced by surface temperature, it is also important to understand the behavior of the droplet on various surface temperature. Figure 8 shows the comparison of droplet behavior, in term of spreading ratio, on three different surface temperature. The figure explains that at the low temperature, classified as nucleate boiling regime, the droplet thoroughly contacts with the hot surface. Whereas the higher surface temperature produces bouncing phenomena which can disturb the heat transfer process. One of methods to eliminate bouncing effects has been proposed by giving the surface coating treatment with a electrospun nanofiber mat as concluded by Weickgenannt et al. [22].

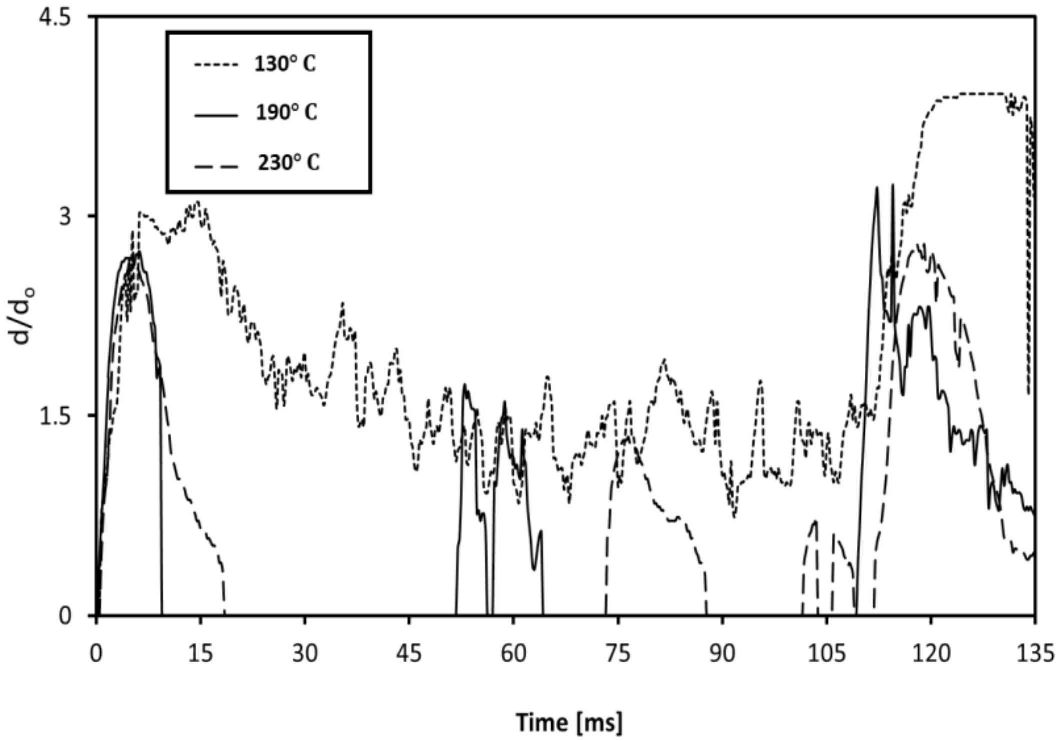

FIGURE 8. The comparison of spreading ratio characteristic on the various surface temperature

Deendarlianto et al. [23] comprehensively investigated the dynamic of droplet impinging inclined hot surface on various condition. In addition to revealing the effect of surface roughness on the characteristics of micrometric droplet, three regions of the droplet condition were introduced. It is classified based on spreading ratio and dimensionless height. Similar approach is used in the present work and the mapping result is shown in Figure 9. The region II, which is characterized by the high value of spreading ratio, attract the attention of many scholars due to its direct influence to heat transfer wetting area. Next, Region I shows the region between initial droplet impact event to the maximum spreading ratio point. It is apparent that Region I_a is smaller than Region I_b since on the Region I_b, the moment of second droplet, causing the radial spreading, experience moment disturbance due to the internal flow of the first droplet.

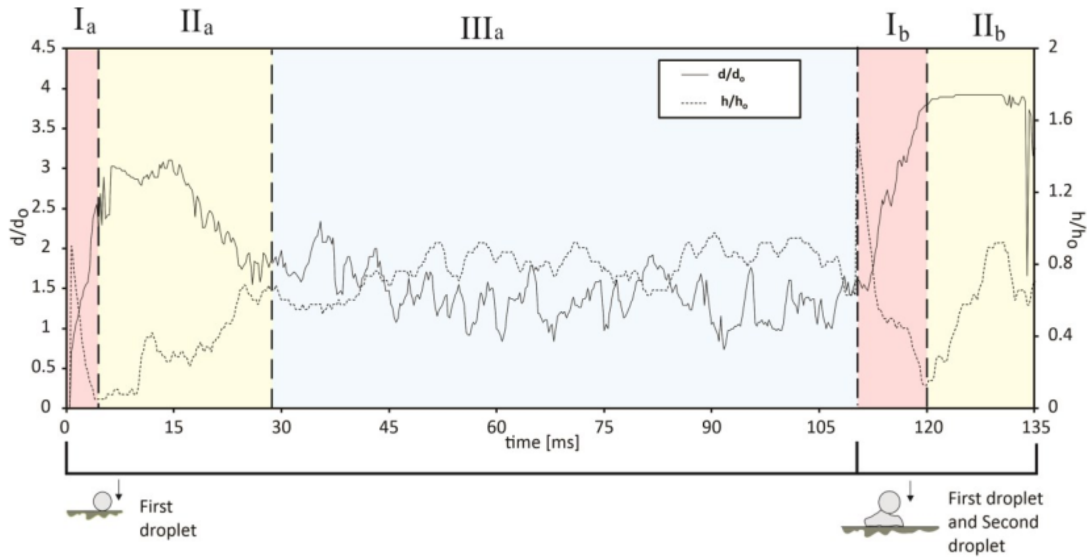

FIGURE 9. Three regions of droplet impacting hot surface (130° C)

CONCLUSION

In the present work, the dynamic behavior of successive droplets impinging aluminum hot surface is comprehensively investigated by visualization method and image processing technique. The different behavior between the phenomena on the low and high surface temperature is revealed. In addition, this work also introduces three regimes occurs during the impact phenomena. Finally, the high resolution data produced in this work can support further research regarding the heat transfer characteristics or model development.

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