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The Effects of the Material Conductivity on the Dynamics Behavior of the Multiple Droplets Impacting onto Hot Surface

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Abstract. The effect of material conductivity on the dynamics behavior and the heat transfer phenomena of multiple water droplets impacting onto heated solid surfaces has been studied experimentally. The droplet diameter and Weber number were 2.8 mm 46.2 respectively. The test materials were Stainless Steel, Aluminum, and Cooper. The test temperatures ranged from 110°C - 140°C. The droplet dynamics during the impacting on the hot surfaces were investigated by using a high-speed video camera. To gather the quantitative information, a new developed image processing technique was developed. It is able to track the bubble movement, the contact time and spreading ratio can be determined. As a result, it is noticed that at 110°C, droplet impacting on aluminum showed the highest spreading ratio among the materials. The spreading ratio of droplet impacting on copper is the lowest. At 140°C, it is found that for all materials, the small bubble has started to appear around the first droplet and the contacting solid surface. Meanwhile on stainless steel, although the spreading ratio is low, the solid-liquid contact time is the highest among the test materials. Finally, it is generally concluded that the presence of second droplet improves the wettability, so the effectiveness of cooling process is significantly better.

INTRODUCTION

Spray droplets on hot surface have many industrial applications such as heat treatment from electronic equipment, desalination, petroleum refining, chemical combustion, gas turbine, diesel engine, spray painting, nuclear reactors, medicine and metallurgical processes [1]. Application of spray cooling thus promotes the ability to greatly reduce production cost and develop accurate and efficient heat transfer process for the making of high quality metal product which will ultimately determine the profitability of the final product [2].

The physics of a single droplet impact on heated walls can be used to predict the global heat transfer characteristics of an entire spray [3]. The heat transfer from a specific hot surface to droplet which is important for some industrial field may be influenced by many parameters, such as droplet size, contact angle, impact velocity, impact angle, liquid temperature, initial substrate surface temperature, surface roughness, and thermophysical properties, as well as surfactant and gravity effects [4]. In addition, it is also well known that one of the essential characteristics related to heat transfer is the wettability on a particular surface. As the contact area is wider, the heat transfer from the hot surface to impacting droplet also increases [5]

The hot surface is rapidly cooled with the spray cooling and film boiling regimes, the cooling rate changes with surface roughness, droplet size and velocity, and on the thermal properties of the hot surface. Also, the solid-liquid contact in high temperature region during first collision of droplet is considerably influenced by the surface condition. the effect of the hot surface thermal properties and the droplet size on the behavior of the droplet on the

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hot surface. shows that the contact time depends on the hot surface material. The maximum droplet spread diameter is higher as the higher the thermal properties of the hot metal [6].

Even though the application of multiple droplets is very essential, the research related to it is very limited. Many studies which have been conducted only focuses on the interaction of single droplet although in fact, the droplets often impact a hot surface in the form of successive multiple droplets. The present work investigates the behavior of successive multiple droplet, represented by the presence of leading droplet and trailing droplet, on a hot surface so the condition is considerably close to the industrial application Furthermore, the effect on different materials on the behavior of droplets is also covered in this works. The difference of thermal conductivity of each material influence the heat transfer process during the spray cooling and to the best of our knowledge there is no clear information offered related on it. Therefore, this study involving the presence of multiple droplet as well as different type of material is essentially needed in order to obtain in depth understanding and develop a new and accurate physic model on the relevant phenomena.

METHODOLOGY

The experiment conducted in Fluid Mechanics Laboratory of the Department of Mechanical and Industrial Engineering, Universitas Gadjah Mada can be divided into two main steps, data gathering and data analysis. To produce a comprehensive study, both qualitative and quantitative method are utilized. Here, an experimental apparatus is set to support the visualization study shown in Figure 1. In general, the apparatus consists of droplet generator, hot surface, and illumination system, a high-speed video camera, and personal computer.

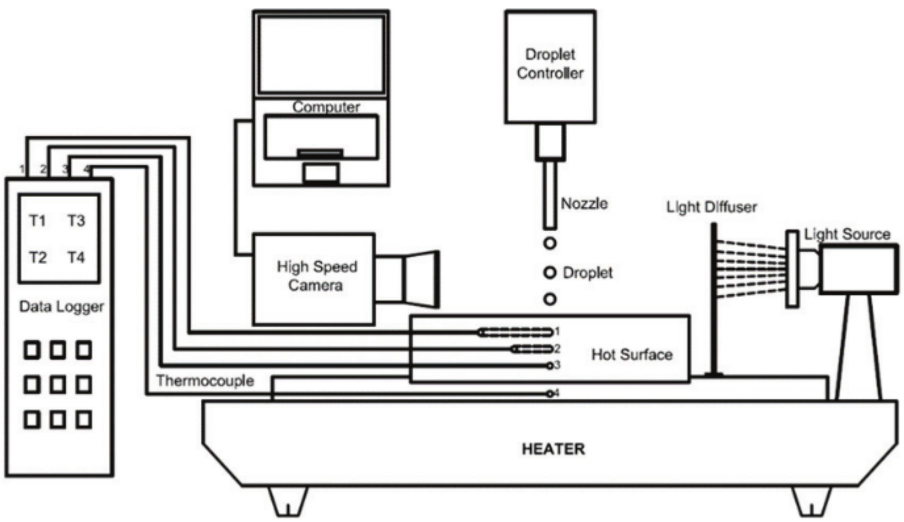

FIGURE 1. The schematic drawing of experimental apparatus.

The droplet generator consists of two main parts, the water tank, as a water storage, and droplet injector. This generator is specifically designed so that some of droplet parameter can be adjusted based on experimental need. In this study, the droplet diameter and the distance of droplet injector from hot surface are 2.8 mm and 60 mm, respectively. In addition, the droplet generator is also set in high frequency so the interaction of two successive droplet can be observed. To ensure the all of the phenomena is clearly captured, a high-speed video camera is set on 4000 fps and very low shutter speed. An illumination system, which consists of a set of LED lamp, is also installed in particular position to obtain a uniform lighting and optimal visualization.

In the present experiment, three different specimens are used, namely the aluminum, stainless steel, and copper to investigate the effect of different properties on droplet behavior. The properties of those materials are shown in Table 1. In addition, all of the material are polished. The hot surface is also monitored by three thermocouples so the temperature can be determined precisely. To achieve the desired temperature of the hot surface, and induction heater which is very easy to adjust is used. Another advantage of this heater is the ability to increase the temperature fast.

The temperature of the hot surface is set in 110°C and 140°C. As described by Nukiyama, it is classified into natural convection and nucleate boiling region (105°C-140°C). On this area, the heat flux tends to significantly increase and affect the heat transfer between the droplet and hot surfaces.

Each experiment condition is recorded and the file is transferred to a personal computer. The multiple figures of multiple droplet is obtained by extracting the video into sequence frame. To support the visual observation, image processing procedures is also used to produce several quantitative data. This technique changes the raw image into binary image so the object tracking method can be used to determine the bubble boundary. Also, several functions, such as median filter, is used to enhance the quality of raw image before it is converted into binary image. Figure 2 depicts the final results of image processing techniques applied to present works. It is noticed that the bubble boundary can be clearly defined. Moreover, several parameters which can be determined is the properties bubble impacting the hot surface. The red line and the green line represent the height and the spreading diameter, respectively. Those parameters will be used to analyze the behavior of impacting droplet by comparing them to the initial diameter (do) and arranging them in time series diagram.

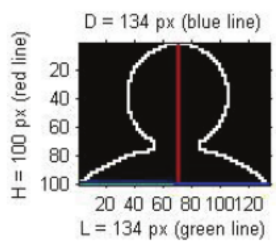

FIGURE 2. The Example of image processing result

TABLE 1. The properties of material used in the present work [7]

Material Properties	Stainless Steel AISI 304	Aluminum Alloy 2024	Pure Copper
Conductivity, K (W/m.K)	14.9	177	401
Density, ρ (kg/cm^3)	7900	2770	8933
Specific heat, C_p (J/kg.K)	477	875	385

RESULT AND DISCUSSIONS

The result of experiment which has been conducted is used to reveals the behavior of successive droplet on different specimens. Each material has different characteristics affecting the dynamics of droplet as shown in Figure 3.

According to Fujimoto [8], the time evolution of droplet shape depends on the surface temperature as well as the spacing between two droplets. Figure 4 shows the behavior of successive droplet, which is represented by spreading ratio (d/do) and apex diameter (h/do), impacting hot surface on 110° C. In general, it is noticed that bouncing phenomena don't occur in all of materials. In Aluminum, the maximum spreading ratio of leading droplet is 3.2 which occurs in 6.25 ms (Figure 4). After the maximum spreading is reached, the droplet starts to recoil and fluctuate for a while. At around 100 ms, the trailing droplet impacts the leading droplet so the spreading ratio reaches 3.6 which is bigger than the previous spreading ratio. Furthermore, those phenomena also occur when the droplet impacts stainless steel and copper. Since the droplet on all of hot surfaces shows the same behavior, the study is focused on the comparison of maximum spreading ratio each material. Close observation to the figure reveals that droplet impacting the hot aluminum surface has the highest spreading ratio among other. Moreover, the spreading ratio indicates contact area between hot surface on specific time which is very essential to determine the amount of heat transfer

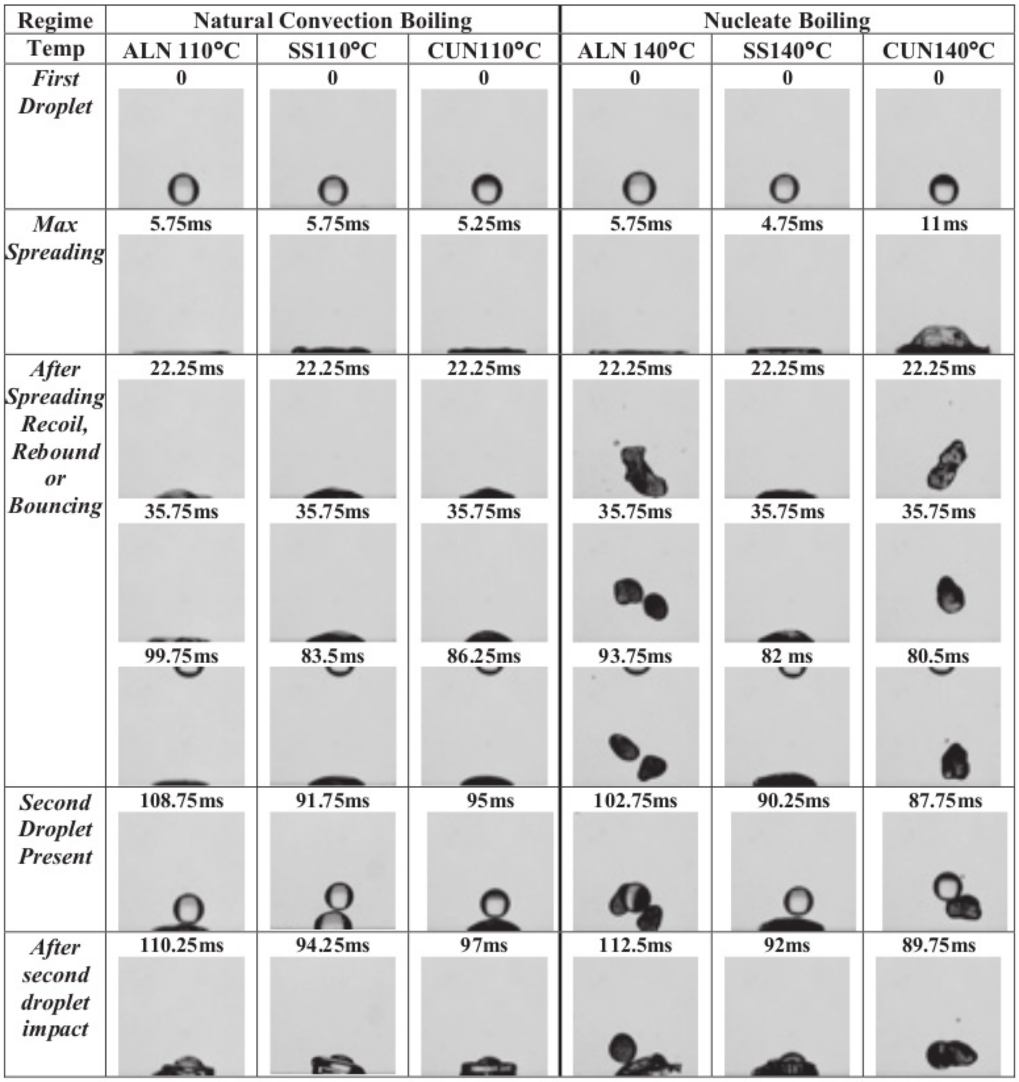

FIGURE 3. The visualization of the dynamics of successive droplets on hot surfaces (110°C and 140°C)

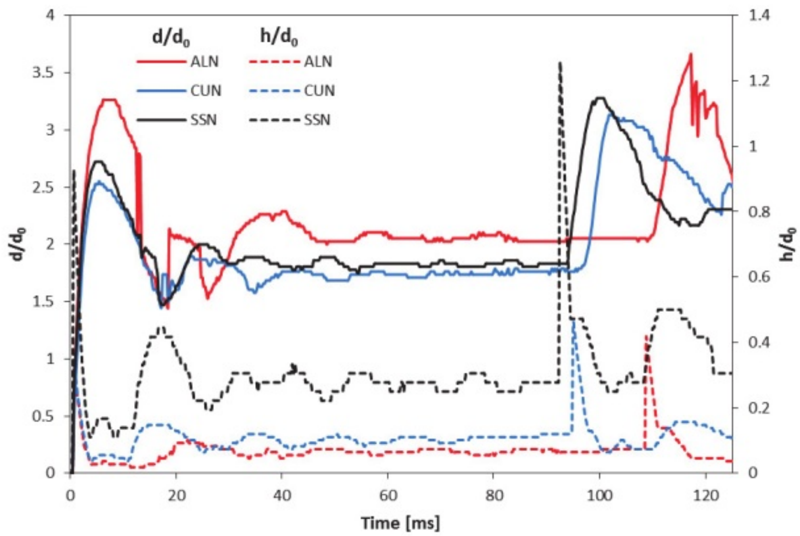

FIGURE 4. Time evolution of dimensionless spreading ratio (d/d_0), and apex height, (h/d_0) at temperature 110°C.

The behavior of successive droplet impacting hot surface on 140° C is depicted in Figure 5. As of temperature explained on methodology section, it represents the nucleate boiling region. The phenomena shown in the figure is slightly different with Figure 4 because the bouncing phenomena of leading droplet on aluminum and copper surface have often occurred before the trailing droplet arrived. Furthermore, in this condition, the presence of tiny gas bubble inside the droplet can be clearly observed.

On Aluminum surface, the dynamics behavior of leading droplet on early phase is relatively same with previous case. After the droplet impacts the hot surface, the spreading ratio increase to the maximum value, 3.14 at around 10 ms, due to the impact force. Next, the leading droplet starts to recoil and it is detached from hot surfaces several times. Around 100 ms, the trailing droplet impacts the leading droplet so the wettability of droplet can improve since the spreading ratio has increased into 3.4. In addition, similar sequence phenomena are also found when the droplet impact the copper hot surface. However, it is noticed that the dynamics of leading droplet to reach the maximum spreading ratio is the fastest among the test materials.

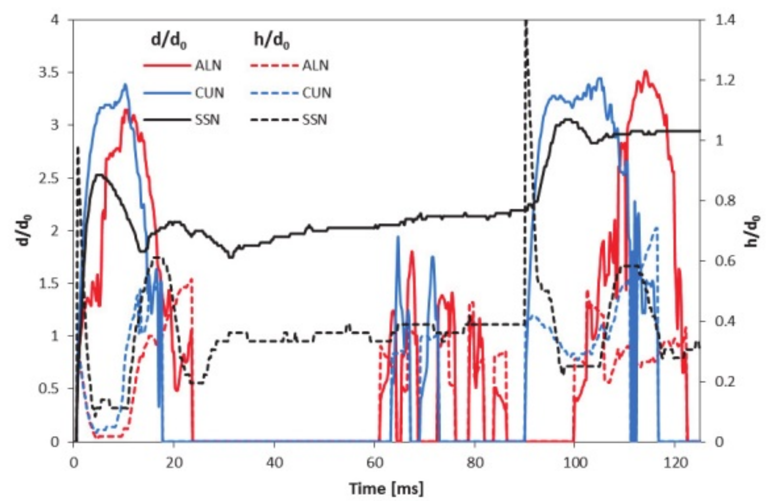

FIGURE 5. Time evolution of dimensionless spreading ratio (d/d_0), and apex height, (h/d_0) at temperature 140°C

On stainless steel surface, having the lowest material conductivity, the bouncing of leading droplet doesn't occur. After the leading droplet impact the stainless steel surface, it spread into the maximum spreading ratio (2.5) followed with recoil process. While leading droplet sticks on the stainless steel surface, it is also observed that a number of tiny gas bubble has grown inside the leading droplet until the trailing droplet arrive and increase the spreading ratio again. The presence of tiny gas bubble inside the droplet on this surface is not as much as inside the droplet on the aluminum and copper surface. It is because stainless steel has the lowest value of thermal conductivity so the heat transfer process is considerably low compared to the other test material. Briefly, in this case, the thermal conductivity affects the cooling process of material although in-depth investigation is also needed.

Apex height (h/d0) represents the surface energy of the droplet and it is the opposite of spreading ratio. When the spreading ratio reach the maximum value, the apex height tends to reach the lowest value. In addition, the apex height also can be used to determine the leading and trailing droplet coalescence as shown in Figure 4 and 5. The apex height suddenly increases as the trailing droplet impact the leading droplet on hot surfaces. However, the sudden increase doesn't occur in the dynamic behavior of droplet on aluminum and copper surface (140° C). It is because, as shown in Figure 5, the coalescence of leading and trailing droplet occurs when the leading droplet bounce on the air.

CONCLUSIONS

This study focused on the investigation of the effect of the material the dynamics behavior of multiple droplet. Based on the experiment and data analysis, it is noticed that at 110°C, droplet impacting on aluminum showed the highest spreading ratio among the materials. The spreading ratio of droplet impacting on copper is the lowest. At 140°C, it is found that for all materials, the small bubble has started to appear around the first droplet and the contacting solid surface. Meanwhile on stainless steel, although the spreading ratio is low, the solid-liquid contact time is the highest among the test materials. In addition, it is found that as the thermal conductivity increases, the number of tiny gas bubble also increase so the heat transfer is faster. Finally, it is generally concluded that the presence of second droplet improves the wettability, so the effectiveness of cooling process is significantly better.

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