

The effect of surface roughness on dynamic behaviour of the successive multiple droplets impacting onto aluminium hot surfaces

M L Hakim^{1*}, T Wibowo^{1,3}, A Widyatama¹, D Deendarlianto^{1,2} and I Indarto¹

¹Department of Mechanical & Industrial Engineering, Faculty of Engineering
Universitas Gadjah Mada, Jalan Grafika No.2 Yogyakarta 55281, Indonesia

²Center for Energy Studies, Universitas Gadjah Mada, Sekip Blok K 1A, Kampus
UGM, Bulaksumur, Yogyakarta 55281, Indonesia

³Department of Mechanical Engineering, Sekolah Tinggi Teknologi Adisutjipto, Jl.
Janti Blok R. Lanud, Yogyakarta 55198, Indonesia

*luthfihakim93@gmail.com

Abstract. The effects of hot surface roughness on dynamic behaviour of multiple droplets impacting hot solid surfaces were investigated in this research. The test material is Aluminium 6061 with surface roughness variation of 0.08 μm , 0.18 μm and 0.52 μm . The surface temperatures were 100 °C, 120 °C and 140 °C. The droplet dynamics during the impact have been observed using high-speed video camera then the results were characterized by using image processing technique. It could be concluded that each temperature shows different thermodynamic impact regime. The results also reveal that at surface temperature lower than 140 °C, the increase of surface roughness leads the increase of spreading diameter. In contrast, the spreading factor decreases with the increasing of surface roughness at 140 °C due to incomplete wetting of droplet on the surface. Meanwhile, the maximum spreading factor is relatively independent to the change of surface roughness.

1. Introduction

The high demands of industry for products with enhanced material properties which is easy to manufacture and low cost are challenging processing techniques. Processing of aluminum alloys has gained considerable attention from the automobile and aerospace industries because it could improve the quality of material i.e. strength to weight ratio and corrosion resistance. Spray cooling is one of the method in metal processing frequently applied in aluminum and steel industries, electronic devices and emergency cooling application which has powerful heat management technique to control microstructural development [1]. Spray cooling involves the liquid drops i.e. water hitting to a hot metal surface. On the other hand, the limited knowledge of the heat transfer phenomena during spray cooling have aroused some researcher to examine the complete picture of the mechanism.

Deendarlianto have proposed a clear method to investigate the surface wettability effect on the phenomena of heat transfer and dynamics behavior of droplet. The single water droplet was dropped onto the aluminium heated surface [2]. They found that the increasing of static contact angle decreased the wetting limit temperature. The results also showed that the increasing of static contact angle increased the maximum spreading diameter for the temperature below the wetting limit.



The effects of surface roughness on the evaporation successive droplet dynamics on inclined heated stainless steel SUS 304 surface were also investigated by Deendarlianto [3]. The results show that quenching behavior was significantly influenced by varying the surface roughness. The increase of surface roughness results in faster quenching time, higher contact time of solid-droplet and higher spreading diameter of droplet

Kim have examined the effect of surface roughness on pool boiling heat transfer which using water as the fluid on aluminum surface. They concluded that boiling heat transfer increases with the increase of surface roughness (Ra) [4]. It is because of the improvement of aluminum surface wettability which deteriorates boiling heat transfer performance caused by nucleation cavities.

The research about heat transfer phenomena of droplet impacting hot surface on some thermodynamic regimes i.e. single phase, nucleate boiling and transition boiling is limited. Therefore, the investigation about the effect of surface roughness at dynamic behavior of multiple water droplets impinging aluminum heated surface will be revealed in present study.

2. Methodology

The illustration of the experimental apparatus and procedure used in the present study were described in previous paper by Wibowo [5] where the schematic diagram of the experiment is shown in Figure 1.

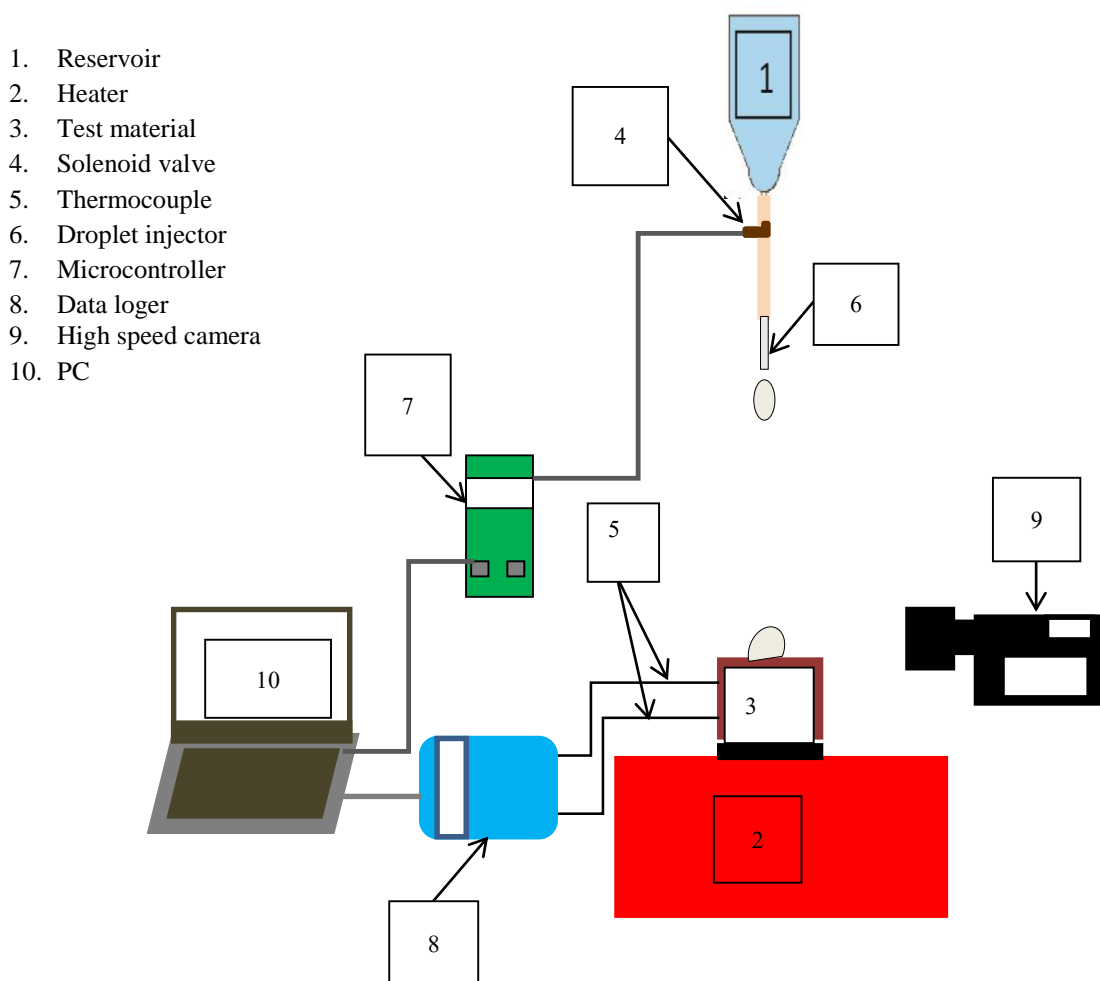


Figure 1. Experimental set up.

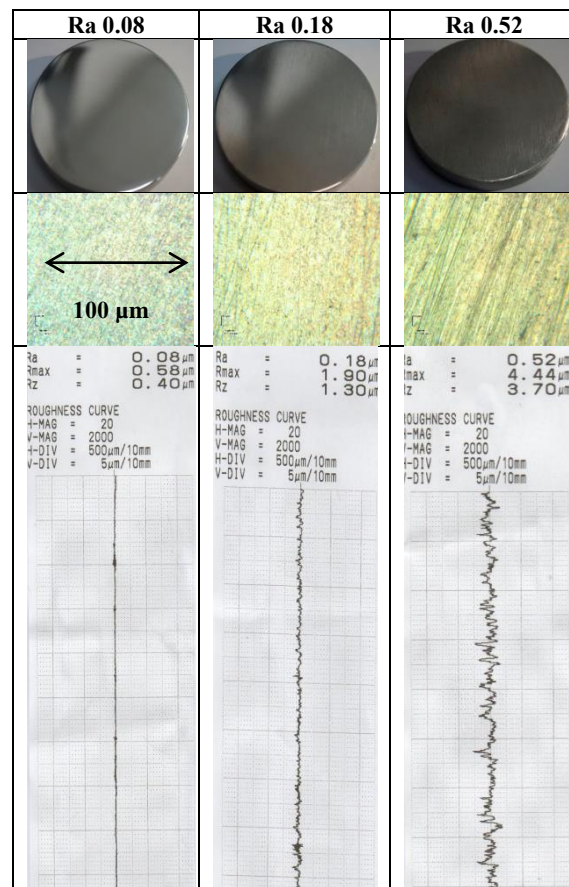


Figure 2. The microscope images and surface roughness test results of specimen surfaces (Aluminum A6061).

A heat source or heater is placed directly under the test material. K-type thermocouples which have an uncertainty of 0.75% were used as temperature sensors. The multiple droplets were injected from reservoir to aluminum hot surface through a droplet injector which is controlled by an automatic valve and located 70 mm above hot surface as done by previous research [6]. The droplet diameter was 3.1 mm with the frequency of 7 drops/second. The surface temperature was varied from 100 °C up to 140 °C. The test material is Aluminum 6061 with surface roughness variation of 0.08 μm , 0.18 μm and 0.52 μm (Figure 2).

A high speed video camera which is set at 4000 frame per second and 1024x768 of resolution were utilized to investigate the droplet behavior during impact phenomena on the aluminum hot surface. Furthermore, an image processing technique was applied to analyze the video images by converting them become binary images (Figure 3). The outcomes are the droplet spreading diameters thus the spreading ratio could be obtained by dividing droplet spreading diameter with initial droplet diameter. Next, the results is pictured in a time series diagram which compares every surface roughness.



Figure 3. Example of image processing result.

3. Results and discussions

Surface roughness plays a very important role in transferring the heat from metallic surfaces to the other materials or fluids during boiling. Predicting or correlating the boiling heat transfer data with micro surface geometry and finding the effective method in enhancing heat removal are challenging some researchers. Three aluminum surfaces were prepared in order to investigate the effects of surface roughness on boiling heat transfer at aluminum surfaces which dynamic behaviors could be seen in Figs. 4-6 which belong to surface temperature of 100 °C, 120 °C and 140 °C, respectively.

Fig. 4 shows effect of surface roughness on droplet dynamics impacting aluminum hot surface at 100 °C. It was observed that there is no presence of nucleate in droplet impact mechanism at 100 °C. The behavior of the impacting droplet is almost similar for all surface roughness. On the other hand, surface roughness highly influences the spreading maximum period where $Ra = 0.52 \mu\text{m}$ was the fastest time required to reach the maximum spreading. In this case the heat transfer occurs by single-phase convection.


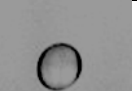
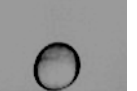
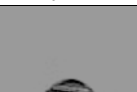
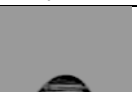
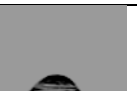
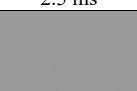
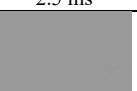
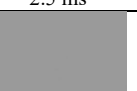
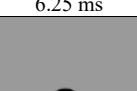
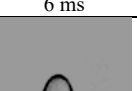
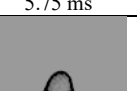
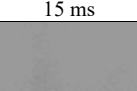
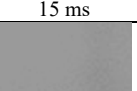
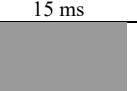
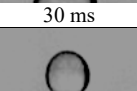
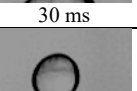
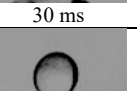
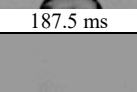


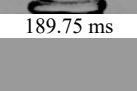
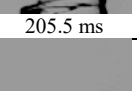
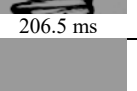
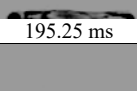
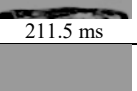
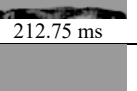
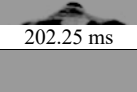
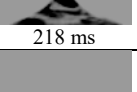
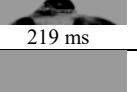
Aluminium Surface			
Phenomena	Ra 0.08	Ra 0.18	Ra 0.52
1 st impact	 0 ms	 0 ms	 0 ms
Spreading	 2.5 ms	 2.5 ms	 2.5 ms
Max Spreading	 6.25 ms	 6 ms	 5.75 ms
Recoil	 15 ms	 15 ms	 15 ms
Single Phase	 30 ms	 30 ms	 30 ms
2 nd impact	 187.5 ms	 203 ms	 204 ms
Spreading	 189.75 ms	 205.5 ms	 206.5 ms
Max Spreading	 195.25 ms	 211.5 ms	 212.75 ms
Recoil	 202.25 ms	 218 ms	 219 ms
Single Phase	 217.75 ms	 233 ms	 234 ms

Figure 4. The surface roughness effect on droplet dynamics impacting aluminum hot surface at 100 °C.

From Fig. 5 it is shown that after impacting the solid surfaces, the droplets spread until reaching the maximum diameter and afterwards shrink. Even though there is no linear correlation between surface roughness and spreading maximum period as previous temperature, the effect of the geometry could be taken into consideration. The small vapor bubbles formed at droplet surface interface at temperatures slightly exceeding the saturation temperature indicated that the liquid heat transfer developed in nucleate boiling regime [7].

The increasing of temperature leads to regime alteration where nucleate boiling regime changes into transition regime. In transition regime, vapor bubbles are generated by heat transfer from the wall developed and break the liquid lamella forming some secondary drops as observed in Fig. 6. This regime is characterized as the transition-boiling regime [8] which is an intermediate regime between nucleate and film boiling.

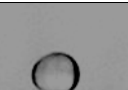
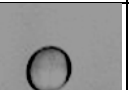
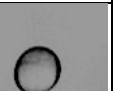














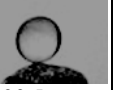






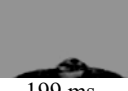
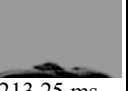

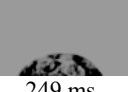
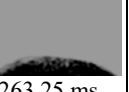

Aluminium Surface			
Phenomena	Ra 0.08	Ra 0.18	Ra 0.52
1 st impact			
	0 ms	0 ms	0 ms
Spreading			
	2.5 ms	2.5 ms	2.5 ms
Max Spreading			
	6 ms	6.25 ms	5.75 ms
Recoil			
	15 ms	15 ms	15 ms
Bubble Boiling			
	125 ms	125 ms	125 ms
2 nd impact			
	181.75 ms	196 ms	199.5 ms
Spreading			
	184 ms	198.25 ms	201.75 ms
Max Spreading			
	190.5 ms	205.25 ms	208.25 ms
Recoil			
	199 ms	213.25 ms	216.75 ms
Bubble Boiling			
	249 ms	263.25 ms	266.75 ms

Figure 5. The surface roughness effect on droplet dynamics impacting aluminum hot surface at 120°C.

Two physical parameters are employed in order to characterize droplet dynamics which impacts the aluminum hot surfaces. Those are droplet wetting diameter d and the droplet height above the surface. By dividing these quantities by initial droplet diameter d_0 we obtain 'spreading factor' (d/d_0) and 'dimensionless height (h/d_0)' [9].

In favor of examining the effect of surface roughness on spreading factor, the wetted diameter was measured by using image processing techniques. The evolution of spreading factor as a function of time is presented in Fig. 7. There are oscillations with the same pattern found for all variations of surface roughness at 100 °C as a result of unbalanced force or energy inside the droplet produced by pressure differential between inside and outside the droplet and/or momentum [10]. Close investigation of the figure reveals that the effect of surface roughness on the spreading factor become stronger within $t = 100 \text{ ms} - 180 \text{ ms}$. The higher the surface roughness, the higher the spreading factor. Contact angle increases with the increase of surface roughness [11] thus provides low damping coefficient [12] causing larger droplet spreading diameter.




























Aluminium surface			
Phenomena	Ra 0.08	Ra 0.18	Ra 0.52
1 st impact			
	0 ms	0 ms	0 ms
Spreading			
	2.5 ms	2.5 ms	2.5 ms
Max Spreading			
	6 ms	6.25 ms	6 ms
Recoil			
	15 ms	15 ms	15 ms
Secondary Droplet			
	168.5 ms	168.5 ms	168.5 ms
2 nd impact			
	193.5 ms	197.5 ms	0 ms
Spreading			
	197.75 ms	200 ms	201 ms
Max Spreading			
	203.75 ms	207.5 ms	208.25 ms
Recoil			
	225.75 ms	208.5 ms	233.25 ms

Figure 6. The surface roughness effect on droplet dynamics impacting aluminum heated surface at 140°C.

Figure 8 shows the transformation of spreading factor (d/d_0) on different surface roughness as the parameter at 120 °C. Spreading factor is significantly affected by the surface roughness at $t > 20$ ms where spreading factor increases with the increase of surface roughness. The spreading diameter for rough surface is higher than the smooth one on account of large number of cavities on bubble nucleation which enhances the wettability [4]. The evidence is shown in Fig. 5 at $t = 125$ ms of $Ra = 0.52 \mu\text{m}$.

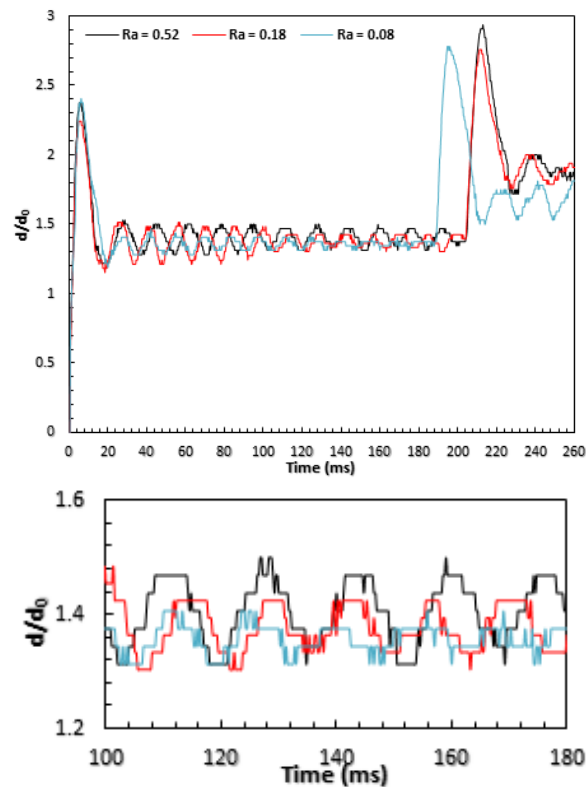


Figure 7. Time transformation of spreading factor (d/d_0) during the impact of multiple droplets on aluminum heated surface at 100 °C.

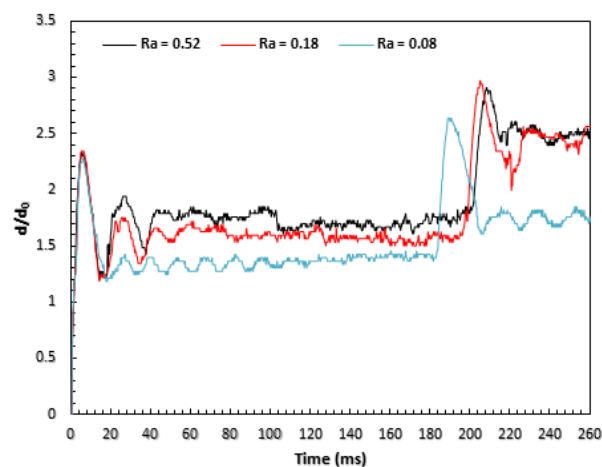


Figure 8. Time transformation of spreading factor (d/d_0) during the impact of multiple droplets on aluminum heated surface at 120 °C.

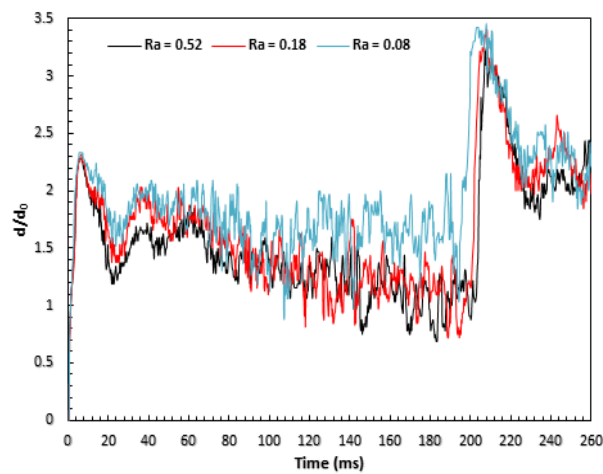


Figure 9. Time transformation of spreading factor (d/d_0) during the impact of multiple droplets on aluminum heated surface at 140 °C.

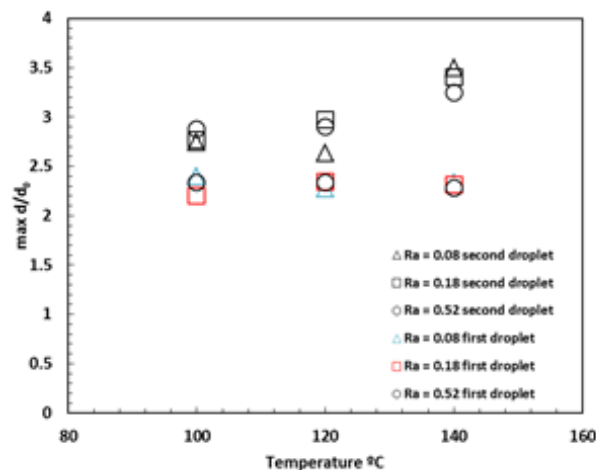


Figure 10. The comparison of maximum spreading ratio of first and second droplet.

The transformation of spreading factor as a function of time is demonstrated in Fig. 9. It could be seen that spreading factor decreases with the increasing of surface roughness. The increasing of surface roughness causes the heat transfer increases [4] due to fast vapor produced near the contact line. The peripheral part of the lamella levitates in that vapor layer made the solid surface was not completely wetted. This is supported by visual examination in Fig. 6 at $t = 168.5$ ms of $Ra = 0.52$ μm .

Figure 10 illustrates the comparison of maximum spreading ratio at various temperatures with surface roughness as parameter. The result reveals that the maximum spreading factors are unresponsive to the surface roughness changing. Although the aluminum surfaces have different surface roughness, the maximum spreading factor of the rough surface is almost the same with the smooth surface, hence, it can be summarized that the surface roughness does not affect the maximum spreading factor. This conclusion confirms to that of Deendarlianto [3] who investigated the spreading ratio maximum of water droplet which impacted onto inclined heated surface with different surface roughness and reported that the ratio is not influenced by the surface roughness. Lee et al. [13] also performed the experimental study of drop impact on smooth and rough surface where the conclusion leads to the small influence of surface roughness on the spreading.

4. Conclusions

An experimental study has been performed in order to investigate the effects of surface roughness on the dynamic behavior of multiple successive droplets which impact the aluminum heated surfaces. The results are summarized as follows:

- a. The same oscillation pattern found for all variations of surface roughness at 100 °C. However, the effect of surface roughness on the spreading factor become stronger within $t = 100 \text{ ms} - 180 \text{ ms}$ where the spreading diameter increases with the increase of surface roughness.
- b. Spreading factor is significantly affected by the surface roughness at $t > 20 \text{ ms}$ for temperature of 120 °C. The increasing of surface roughness leads to the increasing of spreading diameter.
- c. Due to incomplete wetting of droplet on the surface, the spreading factor decreases with the increasing of surface roughness at 140 °C.
- d. The maximum spreading factor is unresponsive to the surface roughness alteration.

References

- [1] J D Bernardin, and I Mudawar 2002 *Trans. ASME* **124**(864)
- [2] Deendarlianto, Y Takata, S Hidaka, Indarto, A Widyaparaga, S Kamal, Purnomo, and M Kohno 2014 *International Journal of Heat and Mass Transfer* **71**: 691–705
- [3] Deendarlianto, Y Takata, S Hidaka, Indarto, A Widyaparaga, S Kamal, Purnomo, and M Kohno 2016 *International Journal of Heat and Mass Transfer* **101**: 1217 – 1226
- [4] J Kim, S Jun, J Lee, J Godinez, and S M You 2017 *Journal of Heat Transfer* **139**: 1–9
- [5] T Wibowo, A Widyatama, S Kamal, Indarto, Deendarlianto 2018 *MATEC Web of Conferences* **154**
- [6] A Riswanda, I Pranoto, Deendarlianto, Indarto, and T Wibowo 2018 *MATEC Web of Conf.*, **154**: 01114
- [7] I V Roisman, J Breitenbach, and C Tropea, *J. Fluid Mech.*, **842**: 87-101
- [8] G E Cossali, M Marengo, and M Santini 2005 *Experimental Thermal and Fluid Science* **29**: 937–946
- [9] S Chandra, and C T Avedisian 1991 *Proc. Math. Phys. Sci.* **432**: 13–41
- [10] W H Mitrakusuma, S Kamal, Indarto, M D Susila, Hermawan, and Deendarlianto 2017 *Heat and Mass Transfer Journal*, **53**: 1–13
- [11] A S Moita, and A I N Moreira 2007 *Int. J. Heat Fluid Flow* **28**(4): 735–752
- [12] S Lin, B Zhao, S Zou, J Guo, Z Wei, L Chen 2018 *Journal of Colloid and Interface Science* **516**: 86–97
- [13] J B Lee, N Laan, K G de Bruin, G Skantzaris, N Shahidzadeh, D Derome, J Carmeliet, and D Bonn 2015 *J. Fluid Mech.*, **786**: 1-11