Fundamental Analyses and Observations of Liquid Droplet on Aluminum Surface for Heat Exchangers

N. Charoensuk¹, C. Sae-kung², J. Charoensuk¹, S. Hirai³, A. Treetong⁴ and V. Lilavivat²*

¹ Department of Mechanical Engineering, King mongkut’s Institute of technology of lardkrabang, Lat Krabang, Khet Lat Krabang, Bangkok, Thailand
² National Metal and Materials Technology Center, National Science and Technology Development Agency 114 Thailand Science Park, Pathum Thani, Thailand
³ Department of Mechanical Engineering, Tokyo Institute of technology, Tokyo, Japan
⁴ National Nanotechnology Center, National Science and Technology Development Agency 111 Thailand Science Park, Phahonyothin Road, Khlong Nueng, Khlong Luang, Pathum Thani 12120 Thailand

E-mail: visarn.lil@mtec.or.th

Abstract. Aluminum is one of the most popular materials in the industry because of lightweight. Furthermore, the heat exchanger is using more aluminum rather than cumbersome and costly copper inside the system. Nowadays, all of the low-temperature heat exchanger fins are aluminum. However, when the heat exchanger is used for a long time the fin of the heat exchanger will accumulate contamination inside such as dust. The existence of contamination has strongly effect heat exchanger system performance. In this study, the physical of the water droplet with the different surface roughness (Ra) on the aluminum surfaces were studied. Hence, in this experiment, the liquid water droplet behaviors on the aluminum surfaces were observed by the contact angle. The interaction between liquid droplets and solid surface on the flat plate affect the contact angle of the water droplet. Liquid water droplet movements were analyzed by considering the change of the contact angle, were used to explain liquid droplet behaviors on the aluminum surface. Consequently, in this study, the liquid droplet behaviors on the aluminum surface can be used to improve the self-cleaning surface of the heat exchanger such as the air-conditioning system.

Keywords: aluminum surface, heat exchanger, contact angle, surface roughness

1. Introduction
The heat exchanger is a device used to transfer heat between solid and fluid. Generally, the heat exchanger system has fins to increase the surface area inside the system. Over time, when operating the heat exchanger, the fins collect the contamination such as dust that reduces the overall efficiency of the system [1]. Excess release dust from the fin hence to improve the solid surface as self-cleaning of the fin, liquid-solid interaction has been studied in this project.

The materials for heat exchanger before use copper with the fin and affected to high price for processing. Moreover, in this case, want to adopt the materials on the fin of the heat exchanger to aluminum. Likewise, the aluminum has a lightweight and approximately density 2.7g/ml and popular use with the
automotive industry. The significance of this study to improve the surface roughness of aluminum such as average surface roughness (Ra) [2] by laser scanning microscope. Moreover, the aluminum surface to test liquid droplets by the contact angle machine.

The contact angle machine of the droplet uses water drop on the aluminum surface. The movement of water droplets on a solid plane; this method was introduced by Thomas Young [3]. The contact angle is related to the surface tension of the angle between solid-liquid, and liquid-vapor. The equation1 that describes the angle of liquid droplets on a flat solid surface in where the vapor, liquid, and solid phase come into contact angle in Figure 1. Can describe this equation

\[
\cos \theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}
\]

In this equation \( \gamma_{SV}, \gamma_{SL}, \gamma_{LV} \) are the interfacial tensions [4] of the solid-gas, solid-liquid, and liquid-gas interfaces, and \( \theta \) is contact angle of liquid droplets. If the liquid wets on the surface called (hydrophilic surface), the value of the contact angle is \( 0 \) degree \( \leq \theta \leq 90 \) degree: on the other hand if the liquid does not wet the surface (hydrophobic surface), the value of the contact angle is \( 90 \) degree \( \leq \theta \leq 180 \) degree.

On the other hand, Wenzel’s [5] demonstrated the contact angle on a rough surface and modified from Young’s equation to describe this equation

\[
\cos \theta' = \frac{r(\gamma_{SV} - \gamma_{SL})}{\gamma_{LV}}
\]

Where \( r \) is the roughness factor and \( \theta' \) is apparent contact angle. In this equation, the value of \( r=1 \) is called smooth surface. On the other hand, \( r<1 \) the surface is very smooth and \( r>1 \) the surface is very roughness. The apparent contact angle will be changed with the roughness factor.

Cassie-Baxter [6] show an equation describe the contact angle at a heterogeneous surface with solid and air. If the contact angle of liquid droplets is more than 90 deg and the surface has a high roughness. The surface in Cassie-Baxter case has air trapped in the depression of the solid surface. Furthermore, the surface area has a wetted surface area fraction \( f \) with a water contact angle \( \theta \). In a situation, a drop of liquid surrounded by air has got a contact angle of 180 deg can describe this equation.

\[
\cos \theta'_{CB} = -1 + f (\cos \theta + 1)
\]

Where \( f \) is the solid surface fraction, \( \cos \theta'_{CB} \) is contact angle of Cassie-Baxter.

Figure 1. Schematic of liquid droplets on solid surfaces [3]

Figure 1. show the schematic of liquid droplets on solid surfaces related to Young’s equation and the angle between the liquid-vapor and solid-liquid interfaces of a solid-liquid-vapor system. The behavior of the water droplets was measured on the foundation of the contact angle. In this work, the various surface roughness of aluminum with different surface roughness to examine the impacts of water droplet contact angle with a different surface roughness on the aluminum.

2
2. Experiment Procedure

2.1 The Process of preparing the aluminum surfaces
The aluminum metal plate was cut into the sample size of 25 mm by 25 mm, as shown in Figure 2. Then, the aluminum sample was prepared surface used to polished different sandpaper number for varying different surface roughness by the polish machine (STRUER polish machine ROTOPOL-25) in Figure 3. In this experiment, the process to prepare different surface roughness.

![Figure 2. the aluminum surface sample in the preparing process.](image)

![Figure 3. polish the aluminum surface by the polish machine (STRUER polish machine ROTOPOL-25).](image)

2.2 The measurement of surface roughness
After polish, in order to observe the effect of surface roughness to the contact angle of water droplets with different surface roughness [7]. The aluminum surface roughness was measured by a laser scanning microscope (Shimadzu lext OLS4500). Further study, the surface layer profile of aluminum surface was observed by AFM(AFM-Setkospa400) with different surface roughness.

2.3 The measurement of the contact angle
The prepared sample surface by polishing, the 5 µL of the liquid water dispense is placed on top surfaces by the contact angle machine. Then, the value of contact angles between surfaces was showed on the screen monitor of contact angle machine to compare the different value of contact angle on different surface roughness of aluminum surfaces to study wettability on the aluminum surfaces as shown in Figure 4.
Figure 4. the contact angle water droplets on the aluminum surfaces

2.4 Sliding droplet on aluminum surfaces

The preparing sample aluminum surface to measure sliding droplet on the surface by dropped volume of water droplet 40 µL on the aluminum surfaces. Then, the tilt base was adjusted increase angle from 0 degree to 30 degree until water droplet is begun sliding [8] on the surface to study the begin sliding droplet on different surface roughness of aluminum surfaces as shown in figure 5.

Figure 5. the water droplet is begun sliding on the aluminum surfaces

3. Result and Discussion

This experiment was set up to understand the behavior of liquid water droplet on the aluminum surface with a different surface roughness that affects droplet movement on the surface.

3.1 The surface roughness

The aluminum surface profile was observed by laser scanning microscope and AFM as shown in Figure 5. Moreover, Figure 6. Figure 5(A) shows the optical images the roughest surface at Ra=350 nm and Figure 5(B) shows the smoothest surface at Ra =11.3 nm. However, the optical images only review 2D information of the surface layer. For this reason, the AFM was used to investigate the 3D profile of surface for further study as shown in Figure 6. Figure 6 (D) shows a 3D picture of a very smooth surface compare to Figure 6 (A) looking rougher.
Figure 6. Optical images of aluminum surface with different surface roughness from (A) $Ra=350\text{nm}$, (B) $Ra=183.3\text{nm}$, (C) $Ra=219.8\text{nm}$, (D) $Ra=122.7\text{nm}$ and (E) $Ra=11.3\text{nm}$.

Figure 7. AFM images of aluminum surface with different surface roughness from (A) $Ra=350\text{nm}$, (B) $Ra=183.3\text{nm}$, (C) $Ra=219.8\text{nm}$, (D) $Ra=122.7\text{nm}$ and (E) $Ra=11.3\text{nm}$. 
3.2 Wettability on the aluminum surface

According to the experiment, the static contact angle of a 5μl liquid water droplets on the aluminum surface with different surface roughness as shown in Figure 7. The static contact angle of the water droplet on the aluminum surface with different surface roughness is shown in Table 1. This table shows the contact angle of water droplets relationship with an average surface roughness (Ra). The result has shown that the value of the contact angle between 62.51 - 90.64 degrees. Furthermore, the result of the contact angle on the aluminum surface is the relationship with a different surface roughness (Ra) shown below Figure 8. This figure shows that surface roughness affected the static contact angle. The result has shown that when the aluminum surfaces are rough the contact angle slight increase. These results are disparity from Wenzel’s equation which the static contact angle decrease as surfaces roughness is rougher. Also, the Cassie-Baxter’s equation cannot explain these conditions as well.

![Figure 8](image)

Figure 8. Water droplet on the aluminum surface with a different value of surface roughness (Ra)

| Ra(nm)  | CA(Degree) |
|---------|------------|
| 350     | 80.8       |
| 219.8   | 79.5       |
| 183.33  | 74.4       |
| 122.7   | 72.6       |
| 11.3    | 62.5       |
3.3 Sliding droplet on aluminum surfaces

In this part, the aluminum surfaces were measured by water repellent with different surface roughness. The tilt base angle of the water droplet on the aluminum surface with different surface roughness has shown the value of contact angle between 15.08-21.48 degrees from Table 2. Furthermore, the tilt base angle with the different surface roughness has shown the figure10. Furthermore, figure11 show tendency of graph relationship between tilt base angle (TB) and average surface roughness (Ra). Consequently, figure 12 shows the tendency of graph contact angle hysteresis and tilt base angle with different surface roughness (Ra). Furthermore, the surface roughness increasing affected to contact angle hysteresis begin sliding in a lower angle. Because the aluminum surface is Ra=11.3nm smoother than Ra= 350nm affected to surface between water and solid surface has low friction force, resulting in sliding angle of water droplet is low. The water droplet is begun sliding low tilt base angle. These results are similar Wenzel’s equation because the water droplet is spreading and wetting on the aluminum surfaces but the result the data from the experiment is a difference from the theory is shown, when the surface roughness is increasing the contact angle is lower angle. The Cassie-Baxter’s equation is also cannot explain for this result because the water droplet is not non-wetting or contact angle not more than 90 degrees hence the Cassie-Baxter’s equation is cannot explain this result also.
Figure 10. Water droplet sliding on the aluminum surface different with surface roughness (Ra)

Table 2. The relationship between average surface roughness (Ra) and the tilt base angle (TB) of a water droplet.

| Ra(nm)  | TB(Degree) |
|---------|------------|
| 350     | 15.1       |
| 219.8   | 19.1       |
| 183.33  | 20.6       |
| 122.7   | 21.5       |
| 11.3    | 15.5       |

Figure 11. Relationship between tilt base angle (TB) and average surface roughness (Ra)
In this study, the liquid water droplet drop behaviors on the aluminum surface with different surface roughness were determined. The value of the average surface roughness of the aluminum surface sample is 11.3-350 nm. The result has shown that surface rough affect the static droplet contact angle. The value of the contact angle is decreasing when the value of Ra is decreasing, or the aluminum surface is smoother. The wettability is related to surface roughness.

In this part, the sliding droplet on the aluminum surface with different surface roughness and adjust tilt base angle from 0 to 30 degree were determined. The value of the tilt base angle begins sliding on surface roughness of aluminum surface between 15.08-21.48 degree. The result has shown that the
surface is rough affected to begin the sliding of the water droplet. The value of the tilt base angle is decreasing when the value of Ra is increasing or the aluminum surface is smoother.

Moreover, the surface roughness also affects droplet distortion and movement. Consequently, with the static droplet contact angle information and water droplets repellent investigate, the new equation model for the liquid water droplet on the aluminum surface can be defined. Also, this equation can be used to calculate drag force or repellent force to remove droplets on the aluminum surface and improve the self-cleaning surface of the heat exchanger

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