

*Full Length Research Paper*

## Enhancement or suppression of dehumidification process by surface treatments

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Received 8 August, 2014; Accepted 20 April, 2015.

In many engineering applications, either the suppression or the enhancement of dehumidification is desired. If so, the dehydration in air-conditioned space can be solved, less condensation water pollution can be achieved, or the dehumidification process can be more efficient. In this study, the effects of various surface treatments were explored to enhance or suppress the condensation. It was found that optical observation to the appearance of water droplets was the best solution. A USB microscope is able to discover a droplet as small as 13  $\mu\text{m}$  in diameter. When the first droplet was found, the corresponding surface temperature was considered as the dew-point temperature in the circumstance. A cold-plate platform, which is cooled by cool water from a refrigeration circulator, was designed and established. The surface temperature can be regulated by settings of the refrigeration circulator. Tests of step-wise temperature drops were performed. The original surface was made of aluminum alloy Al-5083. Spin-coated, blasted, anodized, Teflon-coated, and polymer-coated surfaces were prepared on the same substrates. The results show that the polymer-coated surface exhibited an effective dew-point of 2.95°C higher than the original surface. On the other hand, the Teflon-coated surface exhibited an effective dew-point of 1.025°C lower than the original surface. In this study, a platform and methodology were established and further surface treatments can be explored in the future.

**Key words:** Dehumidification, condensation, surface treatment, blasted, wettability

### INTRODUCTION

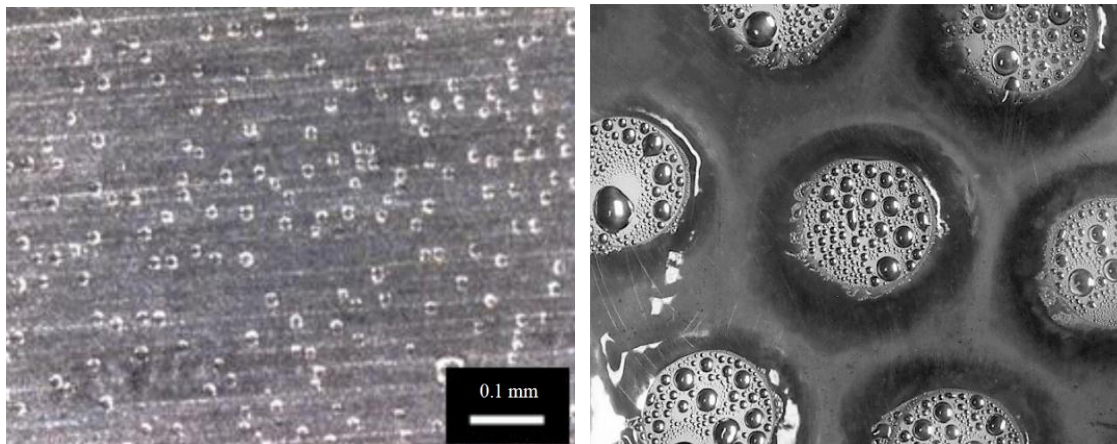
Condensation is a high-efficiency heat transfer process with phase change. The mechanism often occurs at surface of heat exchangers, such as evaporators or condensers. When superheated vapor encounters with a cool surface, the vapor releases a lot of heat to the

surface and changes itself to the liquid phase. The condensed liquid then can be found on the cool surface as droplets or a film.

The condensation process can be categorized into filmwise and dropwise condensation. Because of

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**Figure 1.** The droplets on cold surface during the dehumidification process (Leipertz and Fröba, 2008).

different surface energy, the surface wettability is different (Leipertz and Fröba, 2008; Rausch et al., 2010). A hydrophilic surface tends to wet surface, so the condensed liquid form a film easily. On the other hand, due to hydrophobic characteristics, non-wet surfaces tend to exhibit dropwise condensation. Liquid droplets gather to bigger ones and fall down, if possible. Since some of the heat exchanging surface is not covered with a liquid film, the heat transfer coefficient of dropwise condensation can be 10 times than that of filmwise condensation. The photos of the dropwise condensation and filmwise condensation are shown in Figure 1.

In fact, the term of condensation is more suitable where the working fluid is a pure substance. When the working fluid is air with vapor, the usual atmospheric air, the term of dehumidification may be more proper. For condensation cases, the air inside the vapour is treated as the non-condensable gas. However, for dehumidification cases, the vapor in the air occupies a very small portion. When an evaporator is cooler than the corresponding dew point, dew or frost can be form on the surface. While people expect strong condensation inside a dehumidifier, the frost in a freezer is a degraded film for heat transfer. If the dehumidification process can be suppressed or enhanced, making the dew point lower or higher, the applications can be useful.

In literature, the effects of liquid surface tension (Rykaczewski et al., 2014), surface roughness (Zhao and Beysens, 1995), and wettability (Kewen and Abbas, 2000) on the condensation performance were often reported. Ion implantation could alter the surface free energy and affect the nucleation of condensed liquid (Bani Kananeh et al., 2006; Rausch et al., 2010). During dropwise condensation, droplets grew and formed bigger ones by combining with others nearby. The temperature

difference between the vapor and surface affected condensation rate. Suitable temperature difference could maintain a stable dropwise condensation (Rose, 2002).

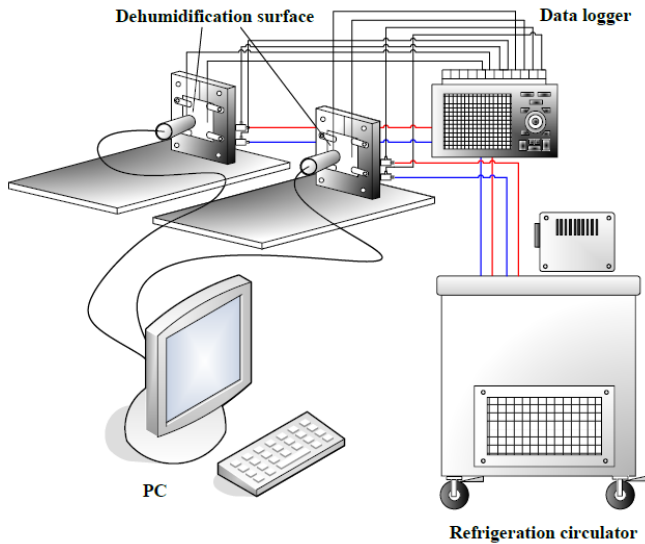
While most applications focused on the condensation of pure vapor, Thomas et al explored the dehumidification heat transfer of wet air (Thomas et al., 2012). They found that filmwise condensation seemed more efficient than dropwise one. Once the dew could be found on the surface, the heat transfer increased due to the phase change mechanism. The onset of dew depended on the relative humidity of the environment.

The temperature and relative humidity are two key parameters to indoor comfort (Fanger, 1973). In the past, the relative humidity drops when the air get cooled passing through the evaporator. If the dehumidification can be suppressed or enhanced, the indoor relative humidity can be kept in a good range easily. Also, the energy to overcome the latent heat cooling load can be decreased and saved. In this work, various surface treatments were explored to examine the effects of dehumidification suppression or enhancement.

Several sample surfaces were prepared. Each was made of aluminium alloy Al-5083 with different surface treatment. Some treatments make surfaces hydrophobic, and some produce hydrophilic ones. The original surface was cleaned by alcohol only to be the comparison baseline with others. Five treatments are introduced as follows.

1) A surface was spin-coated with SiO<sub>2</sub> aqueous solution. In the solution, the particle size is 10 to 30 nm in diameter, and 20 wt. % in concentration. The spin-coating was operated at 360 RPM. A soft baking at 60°C is performed thereafter.

2) A surface was blasted by SiO<sub>2</sub> beads at 110 psi. The



**Figure 2.** The apparatus used in this study to observe the dehumidification process.

size of  $\text{SiO}_2$  beads is 60~100  $\mu\text{m}$ . The treatment made the surface rougher and hydrophilic. The surface roughness increase from 100 nm to 9.57  $\mu\text{m}$ .

3) An anodized surface was prepared as the cathode during electrolyzation. Anodizing is an electrolytic passivation process used to increase the thickness of the natural oxide layer on the surface of metal parts. Then, a condensed oxidation surface was form for good erosion and wear protection.

4) A sample was spin-coated with a 500-nm polymer film was on the surface. Spin coating is a procedure used to deposit uniform thin films to flat substrates.

5) A PTFE (Polytetrafluoroethylene) coated surface was also tested. PTFE is produced by free-radical polymerization of tetrafluoroethylene. The Teflon coating is known for its durability, low friction, and good chemical stability.

## EXPERIMENTAL METHODS

An apparatus was established to produce various cool surfaces by changing the samples on a water jacket. The apparatus consisted of three parts: cooling system, optical observation system, and measurement system. The cooling system was used to provide low, stable, and uniform surface temperature to perform experiments. The system includes:

- 1) A refrigeration water circulator of 24 L in capacity was used. The temperature range of output water was -10 to 100°C. The maximum flow rate was 400 L/h.
- 2) A flow meter (YMA-33-SSA, Dwyer, USA) was utilized to control and display the flow rate in the range of 10 to 110 ml/min.

3) A water jacket made of aluminium alloy, and 150 mm in height, 150 mm in length, and 20 mm in width was the holder for samples. Three passes were designed inside for the purpose of better heat transfer and more uniform temperature distribution.

4) PU (Polyurethane) form was used to fill the 10 mm gap between the water jacket and the outer plastic holder for the insulation purpose. The thermal conductivity of the PU form is around 0.02 W/mK.

The optical observation system was a USB microscope (AM7013MZT4, Dino-Lite, Taiwan) being used to observe the appearance of condensed droplet. The microscope used a 500 Mega-pixel CCD, and a maximum magnification of 480 times can be achieved. Droplets greater than 8 pixels in diameter were distinguishable. The corresponding minimum size of the observation system was around 13  $\mu\text{m}$ .

The measurement system consists of the following:

1) A contact angle measurement platform used a CCD and a 2-D precision moving table to take photos for droplets placed on the original surface (Al-5083) and the treated surfaces. After running image processing software, the contact angle can be derived. The average of contact angle was calculated from the six data acquired in the measurement.

2) A data logger (GL-800, Graphtec, Japan) with the minimum resolution of 0.1°C, and the highest sampling frequency of 10 samples per second was used.

3) Three T-type ( $\pm 0.5^\circ\text{C}$ , -40 to 125°C) thermocouples were used to measure the surface temperatures at two different locations on the surface, and the environment temperature. Two PT-100 RTDs were set at the inlet and the outlet of the water jacket.

Two sets of apparatus were established and located side by side to ensure the consistent and close environment conditions. One set was for treated surface, and the other was placed with the original surface for comparison. To minimize the environment variation, two samples were tested simultaneously.

Thermocouple wires were used to measure sample surface temperatures and environment temperature. The environment temperature was also recorded for subsequent calculation of convective heat transfer coefficients. Two RTDs were used to measure the temperatures of the inlet and the outlet of the water jacket. The flow rate of the chilled water circulation was set at 50 ml/min. The flow rate was so low to ensure that the temperature difference between the inlet and outlet of the water jacket was greater than the intrinsic error. Data logger was used to continuously record all temperature variations during the whole process.

To lower the surface temperature, the temperature regulator of the circulator was set 2°C lower each time. Photo taking and temperatures acquired to calculate the surface heat transfer were not performed until equilibrium of temperature oscillation less than 0.1°C achieved. Eventually, based on the recorded temperature and RH data, the surface heat flux, convective heat transfer coefficient can be plotted versus surface subcooling temperature. The schematic of the experimental apparatus is show in Figure 2.

## RESULTS AND DISCUSSION

Results are mainly shown as plot of heat flux ( $\text{W/m}^2$ ) versus surface superheat. The theoretical dew points are

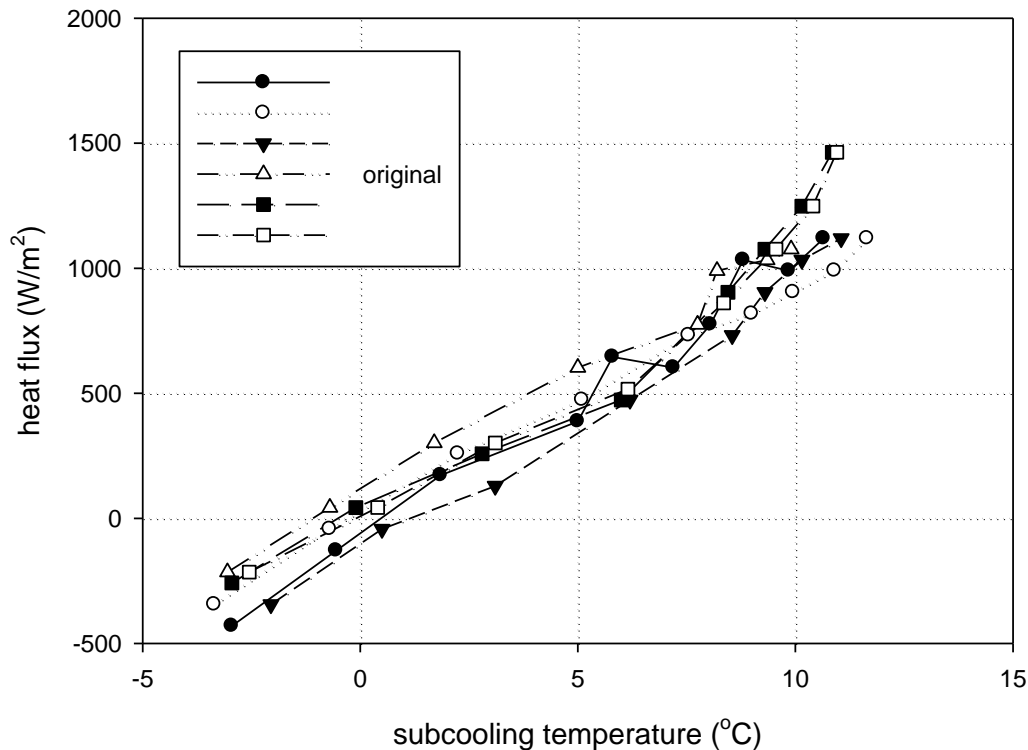


Figure 3. Test results of original surface.

also marked as vertical lines. It is expected the lines turn up when the surface dewing occurs.

First, results of original surface are plotted in Figure 3. Although the environment conditions were not exactly identical, the overall trends seemed consistent. This also implies the stability of the apparatus. The results of the five treated surfaces compared with the original one are shown in Figure 4.

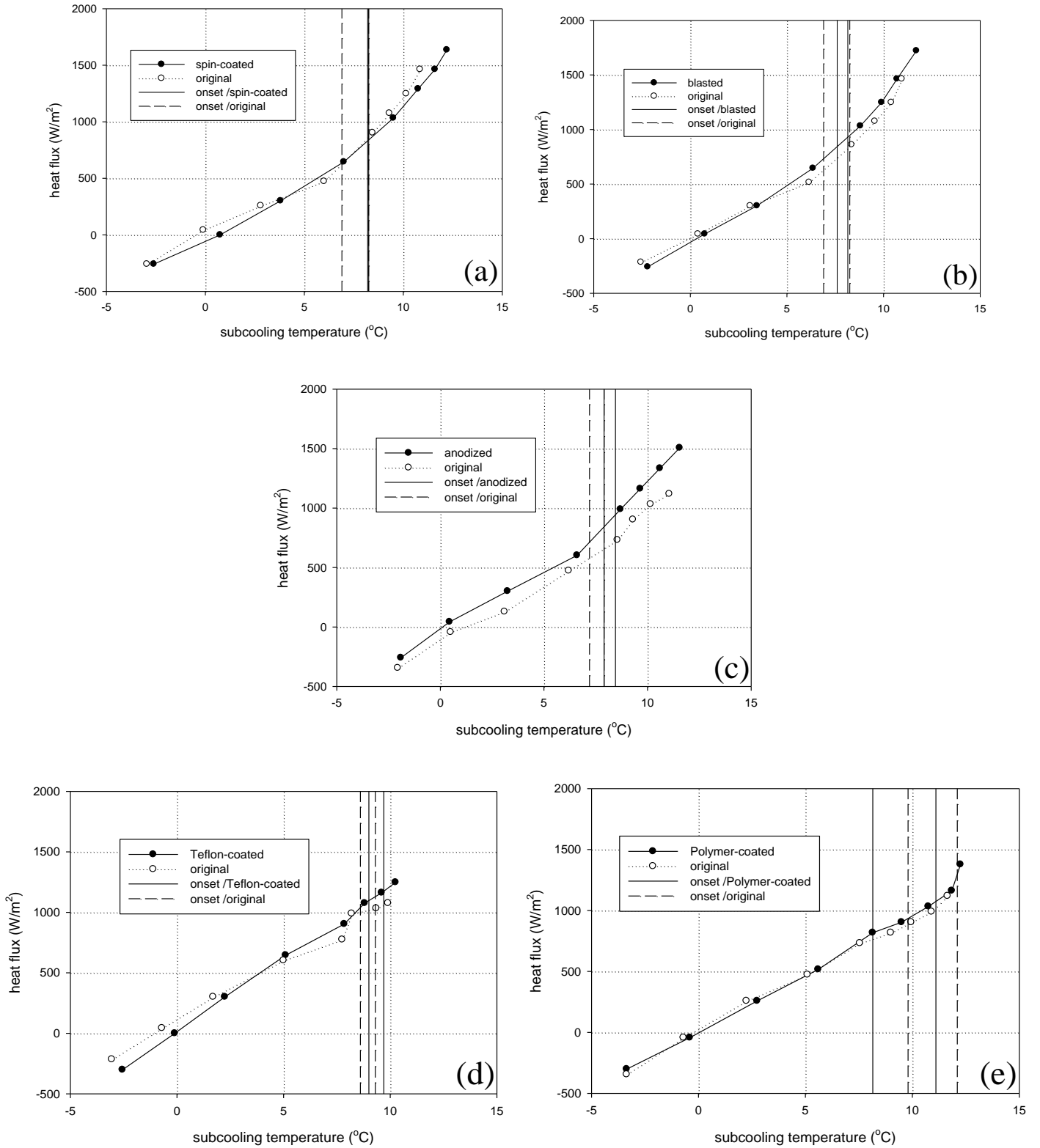
Images from contact angle measurements for the six surfaces (one original and five treated) tested in this work can be found in Figure 5. It can be found that the spin-coated, blasted, and anodized surfaces are more hydrophilic, while the original, Teflon-coated, and polymer-coated surfaces are somehow hydrophobic.

The contact angles and the test results of the six surfaces are listed in Table 1. According to the Table 1, the Teflon-coated surface needs more subcooling of 1.025°C to achieve dewing. On the other hand, the polymer-coated one requires 2.95°C subcooling less than the original surface. However, the advancing or receding dewing does not monotonically depend on hydrophobic or hydrophilic. The spin-coated surface is quite

hydrophilic, but the tested subcooling is almost identical to the original surface. It seems like that the advancing or receding dewing does not depend on the wettability only. Further researches would be necessary to understand the physics behind.

## Conclusions

In this study, an apparatus for evaluating the effects of various surface treatments on the dehumidifying heat transfer was established. Five surface treatments, SiO<sub>2</sub> aqueous solution spin-coated, blasted by 110 psi SiO<sub>2</sub> beads, coated with a 500 nm layer of polymer, Teflon coated, and anodized, were tested and explored. Results were shown as plots of surface heat flux versus the surface subcooling. According to repeated experiments, the apparatus seemed stable and was able to produce trustworthy results. It was found that the polymer-coated surface raised the effective dew-point by 2.95°C, and the Teflon-coated surface lowered the effective dew-point by 1.025°C. However, the advancing or receding dewing



**Figure 4.** Results for the five surface treatments comparing to the original surface. (a) spin-coated (b) blasted (c) anodized (d) Teflon-coated (e) Polymer-coated.

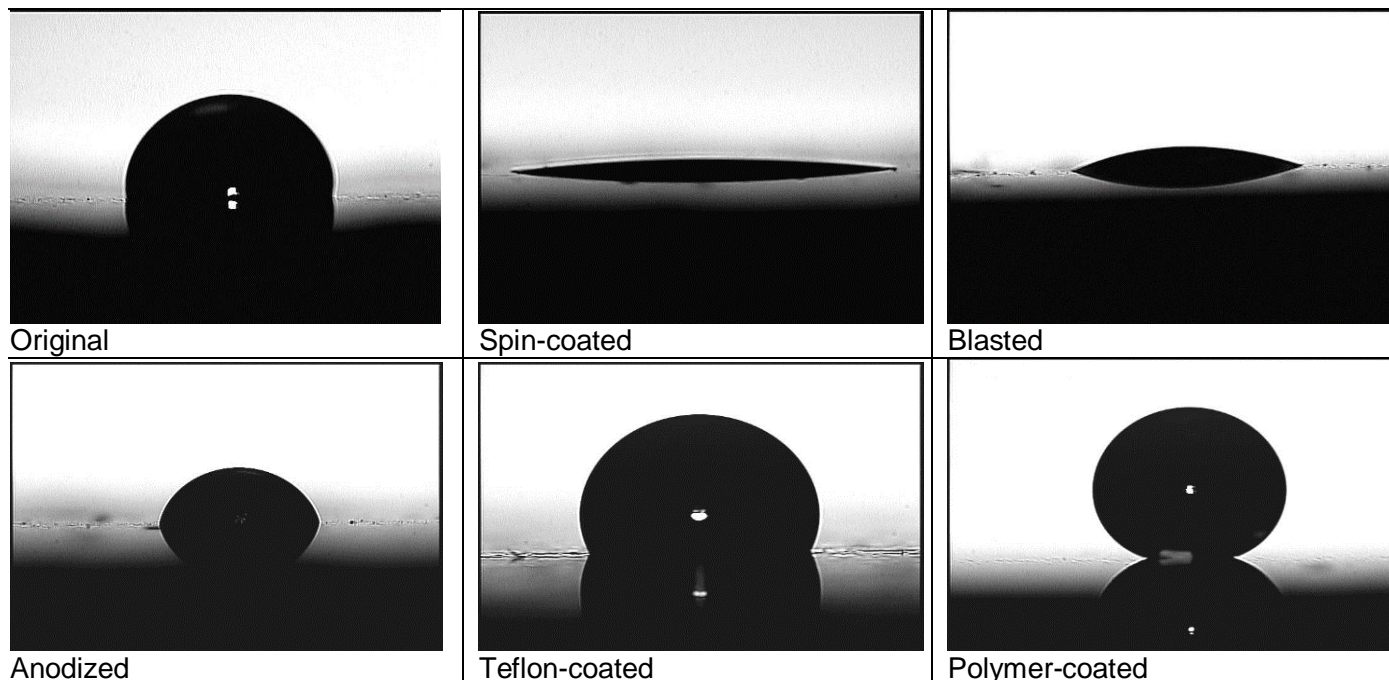


Figure 5. Images from contact angle measurements.

Table 1. Experimental results of the six tested surfaces.

Parameters	Original	Spin-coated	Blasted	Anodized	Teflon-coated	Polymer-coated
Contact angle ( $^{\circ}$ )	103.4	8.2	22.3	62.2	114.6	152.3
Contact angle standard deviations ( $^{\circ}$ )	2.9	1.3	1.8	7.3	2.2	4.5
$T_{amb} - T_{dew,obs}$ ( $^{\circ}$ )	9.09	8.25	8.15	8.45	9.925	8.15
$T_{amb} - T_{dew,theo}$ ( $^{\circ}$ )	8.28	8.2	7.6	7.9	8.9	11.1
Advancing or receding temperature ( $^{\circ}$ )	0.81	0.05	0.55	0.55	1.025	-2.95

does not depend on the wettability only. Further researches are required to discover the whole mechanism.

#### Conflict of Interest

The authors have not declared any conflict of interest.

#### ACKNOWLEDGMENT

The support from National Science Council of Taiwan under grant number 100-2221-E-002-150-MY3 is acknowledged.

#### NOMENCLATURE

$T_{amb}$ : ambient temperature ( $^{\circ}$ )  
 $T_{dew,obs}$ : observed dew point ( $^{\circ}$ )  
 $T_{dew,theo}$ : theoretical dew point ( $^{\circ}$ )

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