Condensation performance of superhydrophobic aluminium surface material used for cooled ceiling panels under highly humid indoor conditions

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Abstract. The application of radiant cooling systems is very limited in hot and humid areas due to condensation. Research on superhydrophobic surface (SHS) materials has shown the potential of restricting the size of condensate drops on these materials, which provides possibilities for preventing dripping and thereby alleviating condensation risks for cooled ceiling panels, but there are few studies on the anti-condensation performance of these materials under the scale and conditions of building applications. An experimental study of condensation on superhydrophobic materials under indoor conditions is presented in this article. Two material samples with a size of 2.5 cm, including a superhydrophobic aluminum sheet and a pure aluminum sheet, were affixed on a cooled ceiling panel to perform the experiment under the following condition: temperature is 25°C ± 0.5°C, relative humidity is 80% ± 5%, and air dew point is 21.4°C. The panel was cooled by chilled water of 6°C for eight hours. The measured temperature on sample surfaces was about 13.5°C during the experiment. After eight-hour condensation, the diameter of drops on the superhydrophobic aluminum sheet was less than 150 µm, while the max drop on the pure aluminum sheet was near 4 mm. The results suggested that the size of condensate drops on superhydrophobic surface materials can be largely restricted during a long-time indoor operation below the dew point, which shows their potential for constructing condensation-free radiant cooling panels.

1. Introduction

Radiant cooling is an alternative to air-conditioning technology. Its features of fan energy reduction, potential of combining natural cooling sources, and raised chilled water temperature lead to great energy saving [1]. Radiant cooling system also has merits of quiet operation, high thermal comfort level, and integration with building design [2], but its application is very limited due to condensation issues, especially in hot and humid areas. To avoid condensation, indoor humidity and chilled water temperature...
must be carefully controlled [2]. Mumma [3-5] introduced dedicated outdoor air systems (DOAs) integrated with ceiling radiant cooling panels. Niu and Zhang [6, 7] combined desiccant dehumidification systems with radiant cooling systems to realize temperature and humidity independent control. Despite the necessary air dehumidification, the temperature of cooling surfaces should be strictly controlled at a safety margin of 1–2 K upper the indoor air dew point to tolerate the humidity variation [8, 9]. These strategies, however, either made cooling systems too complex, or limited the cooling capacity of radiant cooling systems by using high temperature chilled water. Furthermore, dehumidification systems could not handle sudden rises of indoor humidity, say, opening of windows. In addition to humidity control, novel radiant cooling panels covered with membrane transparent to infrared radiation [10] and novel radiant panels with cooled liquid desiccant dehumidification membrane [11-13] has been proposed.

Current condensation control methods of radiant cooling systems are inherently restricted to the wettability of radiant cooling surfaces. Cooled ceiling panels are usually made of white-painted galvanized steel sheets or aluminum sheets. Film condensation occurs on these hydrophilic surfaces, and droplets with scale of millimeters will be formed and drip down to occupied spaces due to gravity. Superhydrophobic surface (SHS) is characterized as that the contact angle of the surface is higher than 150° and the contact angle hysteresis (CAH) is ultra low (usually lower than 5°)[14]. Intensive research interest has been shed on the hydrophobic surfaces like anti-fogging [15] and anti-icing [16]. As for water condensation on SHS, Cheng and Rodak [17] found that some area of superhydrophobic lotus leaves lost the water repellency when water drops were condensed onto the surface. Chen et.al [18] observed the growth, merge, and disappearance of condensate drops on the superhydrophobic silicon substrate. Boreyko and Chen [19] found that the detachment of condensate drops from the superhydrophobic surface was mainly caused by the coalescence of scalable drops. The observed critical diameter of jumping-induced detached droplets was of order of 10 µm. The jumping motion was explained to be powered by the excess surface energy released during the coalescence of drops. Chen et.al [20] found that condensate drops grew and detached from the superhydrophobic surface periodically and the surface coverage of drops maintained around 25% during a one-hour condensation test in ambient environments. The average diameter of detached drops was about 50 µm.

The concern for condensation can be largely mitigated if the condensate on radiant cooling panels is imperceptible to people. The size of condensate drops on some SHS materials has been found to have an order of tens to hundreds of micrometers [19-21], which is comparable or even smaller than people’s sensory threshold. However, the time scale and condensation conditions of these research is not suitable for building applications. Tang et.al [22] studied the size of condensate drops on a superhydrophobic copper sheet which was cooled 11.7°C below air dew point for 24 hours. The apparent CA and the CAH of the superhydrophobic copper sheet were 161.6° and 50.2° respectively. The results showed that the diameter of the most coalescence-induced detached drops in the observation area of the superhydrophobic copper sheet was smaller than 600 µm, but continuous growth of anchored drops with diameter finally reaching 1000 µm could be observed on the superhydrophobic copper sheet, which is possibly due to the large CAH of the material.

An experimental study of condensate on a superhydrophobic aluminum sheet with large CA and ultra low CAH was presented in this paper. The experiment was performed in a climate chamber with controlled indoor temperature of 25°C ± 0.5°C and relative humidity of 80% ± 5%. The size of droplets was analyzed through the image of condensate captured per minute during the experiment. The experimental methods and results will be introduced in the following sections.

2. Methods

2.1. Material fabrication

The superhydrophobic aluminum sheet was prepared through the following fabrication procedures. Pure aluminum (purity: 99.99%) with 0.2mm thickness were used as substrate. The aluminum foil was cleaned by sonication in acetone for 5 min, followed by an equal-time sonication in Isopropyl alcohol
(IPA) and deionized (DI) water successively. The sample was immersed in 80°C 0.05M NaOH solution to form microstructures by chemical etching method. Then, after heating in water bath at 90°C for an hour, the fluorination treatment in 0.5%wt 1H,1H,2H,2H Perfluorodecyltriethoxysilane (FAS)/hexane solution was conducted after 30min drying at 80°C. The topographies of the superhydrophobic surface were analyzed with scanning electron microscopy (SEM, JEOL-6390). The contact angle and contact angle hysteresis was measured using 5μl water droplets on Station Contact angle meter (Biolin Theta).

2.2. Experimental setup
The condensation experiment was performed in a climate chamber (length 4m, width 2.7m, height 2.9m) equipped with a primary air unit (PAU). The flow rate and temperature of supply air can be controlled through the PAU. An electric radiation heater and a humidifier was placed in the chamber to control the indoor temperature and humidity. A hydronic cooled ceiling panel (SAS International) with a size of 1.2 m x 0.6 m was mounted in the chamber. A water chiller was used to supply chilled water to the cooled ceiling panel. The pure aluminum sheet and the superhydrophobic aluminum sheet was affixed on the panel using silicone thermal grease (ShinEtsu X23-7868-2D). The schematic drawing of the experimental setup is shown in figure 1(a), and the image of the chamber and the attached aluminum sheets is shown in figure 1(b) and figure 1(c).

To obtain the temperature of the aluminum sheets during the experiment, T-type thermal couples (KAIPUSEN SA1TTT30SLE) were attached on the blank samples and the panel surface beside the testing samples. The temperature of supply chilled water, return chilled water, and panel surface was measured through three-wire RTDs. An infrared camera (FLIR T1040) was used to get the temperature distribution of the panel surface. Two temperature and humidity transmitters (HOBBO) were used to measure indoor temperature and humidity in the upper zone (ceiling area) and lower zone of the chamber respectively. The temperature and humidity of supply air and return air was measured by duct-mounted temperature and humidity transmitters (VAISALA HMD65). The image of the condensate on the superhydrophobic aluminum sheet was captured per minute by a digital camera (UCMOS05100KPA) with a zoom lens (FT-OPTO FB065). The image of condensate on the pure aluminum sheet was also captured per minute using a digital camera (Supereyes). Both the two digital cameras were mounted on an aluminum extrusion frame placed in the chamber.

![Figure 1](image_url)

**Figure 1.** The schematic drawing and image of experiment setup.

2.3. Experimental conditions
The experiment was performed under the following condition. The temperature in the zone near the panel was controlled at 25°C ± 0.5°C, and the relative humidity was controlled at 80% ± 5%. The condition is to simulate highly humid environment. The PAU was not launched during the experiment.
The cooled ceiling panel was cooled by chilled water of 6°C. The water flow rate was 20 L/min to ensure the temperature difference between the inlet and the outlet of the panel is small enough. The condition was maintained for eight hours to simulate the normal working period of radiant cooled ceiling panels used in offices, starting from the time when the temperature of blank samples is lower than the air dew point in the ceiling area.

2.4. Quantification of condensation risk
The condensation risk is evaluated by occupants’ perception of condensate. Hence, the quantification of condensation risk is to find the threshold size of droplets that is visible and sensible to people. A normal vision acuity in Snellen Chart is 6/6 meters, which means a man needs to discriminate two contours separated by 1 arc minute [23]. A theoretical angular resolution of a normal eye with a given pupil diameter of 2.4 mm and wavelength of light of 560 nm is 0.98 arc minute [24], which is similar to the above value. So, the angular resolution of 1 arc minute is used to calculate the spatial resolution. Since the ceiling is about 1 meter away from occupants standing in the room, the diameter of the minimum object on the ceiling people can see is about 300 µm. According to a sensory investigation conducted with 30 subjects, the sensory threshold for dripping droplets to people was found to be a radius of 325 µm, or a diameter of 650 µm [22].

2.5. Image analysing
The diameter of droplets was obtained through analyzing the condensate image of testing samples. The software Fiji [25], which is a popular image processing tool in biology and material science, was employed to analyze the captured images. The machine learning based Trainable Weka Segmentation tool [26] and the function of Particle Analyze was used to account the diameter distribution of droplets automatically.

3. Results and discussions

3.1. Analysis of superhydrophobicity.
As shown in figure 2(a), micro-bumps with diameter of 1.5 µm - 2.5 µm were formed on the superhydrophobic aluminium sheet. Nano-pillars can be seen on the micro-bumps shown in figure 2(b). The aluminum substrate was functionalized with superhydrophobicity by this two-tier roughness. The measured contact angle of the superhydrophobic aluminium sheet is 169°, and the contact angle hysteresis is less than 5°.

![Figure 2](image.png)

**Figure 2.** Micro-structures on the surface of the superhydrophobic aluminum sheet.

3.2. Experimental conditions
The average temperature in the ceiling area was 25.1°C during the experiment. The average relative humidity in the ceiling area was 79.9%. The relevant air dew point was 21.4°C. The average temperature of blank samples was 13.5°C.

3.3. Condensate on testing samples

3.3.1. Jumping-induced droplets detachment on the superhydrophobic aluminum sheet

As shown in figure 3, the detachment of tiny condensate droplets occurred on the superhydrophobic aluminum sheet from the early stage to the late stage of the experiment. Five groups of droplets circled by dashed ellipses at the time of 19 min, which may contain two, three, or four droplets, disappeared after one minute. Similarly, four groups of droplets containing two or four droplets at the time of 7 h 40 min disappeared from the camera view after one minute. It can be seen that a droplet always disappeared together with its neighbor droplets. The diameter of the disappeared droplets ranged from 30 µm to 80 µm, which is two orders of magnitude smaller than the capillary length of water. The condensation regime on the superhydrophobic aluminum sheet, that is the detachment behavior of groups of droplets and the detachment size of droplets, indicated that jumping-induced detachment of tiny droplets was continuously occurring in the observation area during the eight-hour experiment.

![Figure 3](image)

**Figure 3.** Jumping-induced detachment of droplets on the superhydrophobic aluminum sheet.

3.3.2. Condensate on the superhydrophobic and the pure aluminum sheet

The image of condensate drops on the superhydrophobic aluminum sheet and the pure aluminum sheet at each hour is shown in figure 4. It can be seen that there are no droplets larger than 200 µm on the superhydrophobic aluminum sheet because tiny droplets detach from the surface after coalescing with neighbor droplets. However, drops on the pure aluminum sheet grew continuously hour by hour, and finally formed the largest drop with a diameter near 4 mm.

The diameter of the max droplet on the superhydrophobic and the pure aluminum sheet against condensation time is shown in figure 5. The vertical axis is scaled as logarithmic since there is a difference of two orders of magnitude between the size of droplets on two sheets. The max diameter is analyzed and accounted per minute for the superhydrophobic aluminum sheet while it is measured per ten minutes for the pure aluminum sheet. The maximum diameter of droplets on the superhydrophobic aluminum sheet oscillates between 60 µm and 100 µm, except for the time during 5 h and 5.5 h when the diameter grows from 100 µm to the peak value of 150 µm. The oscillation of the max diameter is caused by the periodical growth and jumping-induced detachment of tiny droplets. The condensation regime on the superhydrophobic aluminum sheet reaches a steady state from the first half hour when the max diameter reaches the upper limit of the oscillation. The steady condensation regime can also be found in figure 4 where the size distribution of condensate droplets at different time changes a little in visual. But, different to that on the superhydrophobic surface, the diameter of the max droplet on the pure aluminum sheet increases against the condensation time. In the first hour, the max diameter continuous to increase over time, but after that, it begins to increase step by step. This is because at the beginning a droplet grows through both the condensate water and the coalescence with neighbor droplets, but when the droplet grows larger, the influence of the condensate water on the size becomes smaller since the condensate rate remains almost unchanged or even smaller due to the increasing thermal resistance between the vapor and the cooled surface. At this stage, a droplet grows slowly and
steadily through condensate water before coalescing with neighbor droplets, but after a coalescence, the size of the coalesced droplet suddenly increases, resulting in the step change of the max diameter.

Figure 4. The image of condensate drops on the superhydrophobic aluminum sheet and the pure aluminum sheet during the 8-hour experiment. Scale bar is 250 µm and 2 mm respectively.

Figure 5. The diameter of the max droplet on the superhydrophobic and the pure aluminum sheet.

4. Conclusion
Condensation experiment was performed using a superhydrophobic aluminum sheet and a pure aluminum sheet under the indoor temperature of 25°C ± 0.5°C and the relative humidity of 80% ± 5% in a climate chamber. These aluminum sheets were affixed on a cooled ceiling panel which is cooled by
chilled water of 6°C for eight hours. The average temperature of the superhydrophobic and pure aluminum sheet was 13.5°C, which was 7.9°C lower than the air dew point. The size of the maximum drop in the observation area of the superhydrophobic aluminum sheet was less than 100 µm during most time of the experiment, and the size of the max drop which appeared at the time 5.5 h was 151 µm. The value is smaller than the people’s visual threshold of 300 µm and sensible threshold of 650 µm. Different to the condensation regime on the superhydrophobic aluminum sheet, droplets were growing continuously on the pure aluminum sheet and finally formed the largest drop with a diameter near 4 mm at the end of the experiment. The results indicated that the size of condensate droplets in the observation area of the superhydrophobic aluminum sheet in a long-time condensation under the experimental condition was smaller than the visual and tactile perceptual threshold of people. It is possible to employ the superhydrophobic surface to reduce condensation risks of radiant cooled ceiling panels. It should also be noted that only a small part of area on the superhydrophobic aluminum surface and only one humidity condition was studied in this research, further work still needs to be done to study the condensation performance of different areas of the superhydrophobic aluminum surface under a wider range of conditions to get a comprehensive understanding of condensation preventing potential of superhydrophobic surface when applied in ceiling cooling panels in buildings.

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