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Study on the reduction of condensation risks on the radiant cooling ceiling with superhydrophobic treatment

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ABSTRACT

In this paper, the size of droplets departing from the superhydrophobic surface and conventional aluminum alloy surfaces was studied experimentally. It showed that the coalescence-induced jumping condensate droplets departing from the superhydrophobic surface has a radius of below 300 μm, and the radii of the gravity-induced falling droplets from conventional aluminum alloy surfaces range from 2000 μm to 7000 μm. During droplets' dripping from radiant ceiling to human skin, numerical simulation also indicated that the change of the droplet size is rather small and can be neglected. Furthermore, the human sensory threshold size for fallen droplets was found to be a radius of 325 μm via a psychological experiment conducted with 30 volunteers. Therefore, these results revealed that the superhydrophobic surface can significantly reduce condensation risks of radiant cooling ceiling systems. This is because the radii of coalescence-induced fallen condensate droplets from superhydrophobic surfaces are below this threshold, whereas gravity-induced falling droplets from conventional radiant ceiling surfaces can be perceived with a probability of over 95%.

1. Introduction

The basic task of an air conditioning system is to provide a suitable indoor environment with respect to factors such as temperature and humidity. As a result of China's rapid economic development, energy consumption of buildings is now accounting for nearly 20% [1] of this country's total energy consumption. Furthermore, the air-conditioning system including heating and cooling consumes about 30%~60% [1,2] of the total building energy. Thus creating comfortable living conditions at a low energy cost becomes an important challenge for HVAC engineers, requiring new solutions. The radiant cooling ceiling system is such a new solution. It has been used in multiple types of buildings, such as office buildings, residential buildings, and airports, and its popularity is still increasing [3,4]. Compared with conventional all-air systems, radiant cooling ceiling systems can achieve energy savings by increasing chiller efficiency, reducing energy consumption of fans and so on [5–7]. Hao et al. [8] investigated the energy consumption of radiant cooling ceiling systems combined with a desiccant dehumidification system in a hot and humid climate. The results indicated that the combined system can save 68.5% energy of the chiller and 39.0% energy of the fans compared with all-air systems. In addition, previous studies indicated that indoor occupants with radiant cooling ceiling systems perceived better thermal comfort than those with all-air conditioning systems [9–12]. As radiant cooling ceiling systems only handle the indoor sensible heat load, the indoor moisture load needs be handled by auxiliary dehumidification systems [13,14].

However, radiant cooling ceiling systems pose moisture condensation risks on the panel surface when applied in the hot and humid climate. Thus, various control strategies were developed to avoid condensation on radiant cooling surfaces. Seo et al. [15] developed a control strategy using a dehumidification ventilation system with an outdoor cooling mode. Facing potential condensation risks, the dehumidification control in the ventilator is activated to recirculate the indoor air and remove moisture. Zhang et al. [16] and Ge et al. [17] indicated that the pre-dehumidification is an effective method to prevent condensation on radiant cooling surfaces where the air conditioning system operates intermittently. And neural network models were developed to predict the optimal pre-dehumidification time for radiant cooling ceiling systems. However, these control strategies can never eliminate condensation risks on the part of the radiant cooling ceiling surfaces closest to the external windows and doors, where it is easy for outdoor air

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Nomenclature

C_D	Drag coefficient, Eq. (6)
$c_{p,w}$	Thermal capacity, (J/kgK)
D_{AB}	Mass diffusivity, (m^2/s)
g	Acceleration of gravity, (m/s^2)
h_{fg}	Latent heat of vaporization, (J/kg)
m	Mass, (kg)
Nu	Nusselt number, Eq. (4)
Pr	Prandtl number, (−)
r	Droplet radius, (m)
Re	Reynolds number, (−)
Sh	Sherwood number, Eq. (2)
Sc	Schmidt number, (−)
T	Temperature, (°C)
t	Time, (s)
v	Droplet falling speed, (m/s)

Greek symbols

θ	Apparent contact angle, (rad)
λ	Thermal conductivity, (W/mK)
ν	Kinematic viscosity, (m^2/s)
ω	Vapor mass fraction
ρ	Density (kg/m^3)

Subscripts

w	water
a	air

to infiltrate into buildings.

Recently, the influence of surface materials of the radiant cooling ceiling on the moisture condensation phenomenon has been studied for reducing condensation risks. Yin et al. [18] analyzed the condensation on radiant cooling panels constructed with different materials by experiment, and the results showed that the gypsum radiant panel performs best in avoiding condensation risks when compared with the metal panel and the plastic capillary panel. As for condensation risks of radiant cooling ceilings, the process culminating in the condensate negatively affecting indoor occupants comprises three stages: condensate droplets departing from ceiling surfaces, droplets evaporating during dripping and the perceiving of fallen droplets, as shown in Fig. 1. On a conventional radiant cooling ceiling surface with an apparent contact angle of below 90°, condensate droplets grow until they approach the critical radius, and then fall off due to gravity [19]. The radii of fallen droplets from conventional radiant cooling ceilings are around the capillary length (i.e., 2700 μm) [20,21]. Currently, superdrophobic surfaces (hereinafter SHS) with apparent contact angles of over 150° are attracting considerable attention because of their potential in decreasing the radii of the droplets departing from SHS to a microscopic length [22–24]. As long as the size of droplets departing from radiant cooling ceilings is below the human sensory threshold size for fallen droplets, the fallen droplets are imperceptible to indoor occupants. However, the radius range of the fallen droplets from both conventional radiant cooling ceiling surfaces and SHS throughout the whole condensation process has not been investigated thoroughly. Additionally, there have been no explicit results in relation to the evaporation of a droplet during dripping and the human sensory threshold size for fallen droplets.

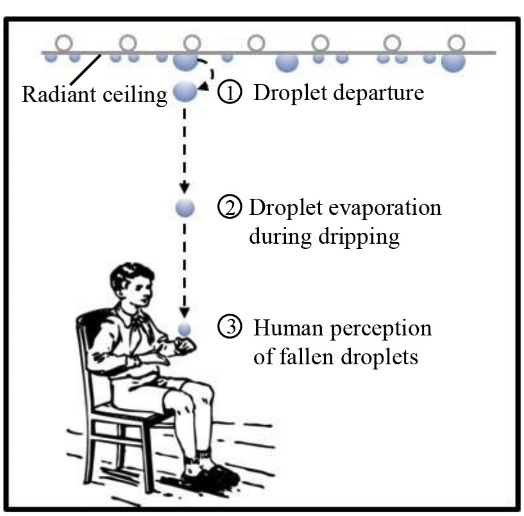

Fig. 1. Three stages of the process culminating in the condensate droplets on the radiant cooling ceiling negatively affecting indoor occupants.

Similar to the perception of thermal comfort, which can be characterized using the ASHRAE thermal sensation scale with seven levels of comfort, from cold to hot [25], the sensory threshold size for fallen droplets is also a watershed. If a droplet size is below this threshold, a person cannot perceive the fallen droplet. Otherwise the fallen droplet can be perceived. On the basis of this idea, the sensory threshold size is defined in psychophysics as a droplet size at which the fallen droplet can be perceived by indoor occupants with a probability of 50% [26,27].

This paper deals with the reduction of condensation risks on the radiant cooling ceiling with superhydrophobic treatment. The size of condensate droplets departing from superhydrophobic surfaces and conventional aluminum alloy surfaces was studied experimentally. Numerical simulation was performed to analyze the droplet evaporation during the dripping process from radiant ceiling to human skin. Furthermore, the sensory threshold size for fallen droplets was investigated via a psychological experiment conducted with 30 volunteers. The experimental results pinpointed the detection possibilities corresponding to the sizes of the coalescence-induced and gravity-induced falling droplets. This study is beneficial for determining the feasibility of superhydrophobic treatment on radiant cooling ceilings to reduce condensation risks.

2. Size of departing droplets from radiant cooling ceilings

2.1. Sample preparation and experimental apparatus

As shown in Fig. 2, the radiant cooling ceiling always adopts metal panels for better performance of heat transfer. A superhydrophobic copper sheet (SHS) was fabricated through procedures described by Chen et al. [28] to study the phenomenon of moisture condensation on the radiant ceiling surface with the superhydrophobic treatment. In brief, a 30 mm × 50 mm × 0.1 mm copper sheet was incubated in an alkaline solution of 2.5 M NaOH and 0.13 M $(NH_4)_2S_2O_8$ for 60 min. After that, the copper sheet was incubated in a 20 g/L ethanol solution of stearic acid for 24 h. In addition, eight conventional aluminum alloy sheets (H1-8) with various contact angles were fabricated by variable modification with a low surface energy chemical.