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Theoretical and experimental study of departure duration of condensate droplets from radiant cooling ceiling surfaces

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A B S T R A C T

In this paper, a mathematical model for predicting the departure duration of the first condensate droplet from a radiant ceiling surface was proposed on the basis of the condensation water mass. The simulation results indicate a dependence of condensation water mass on the apparent contact angle of the substrate, but almost in no relation with the surface temperature. The condensation water mass firstly increases with the increase of the apparent contact angle. It reaches a maximum weight of 522 g/m^2 at an apparent contact angle of 110°, and then decreases. A visualization experiment of condensation on a radiant ceiling panel with a conventional aluminum alloy surface was performed in a climate chamber to measure the departure duration of the droplet. The measured departure duration fluctuates due to the variance of apparent contact angle and the randomness of condensation process, but it decreases sharply with the sub-cooled degree (air dew point minus surface temperature). And the average departure duration is 10 h with a sub-cooled degree of 5 °C. The theoretical model is validated as the average relative biases between the experimental and theoretical results are within 25%.

1. Introduction

Nowadays building energy consumption is still increasing with the development of economy and society, accounting for about 20% of the total energy in China [1]. The air-conditioning system including heating and cooling usually consumes about 30%–60% [1,2] of the total building energy. It is crucial to reduce the energy consumption of the air-conditioning system in buildings. Continuous efforts have been paid in proposing novel appropriate approaches for creating comfortable living conditions with a low energy cost. The radiant cooling ceiling system is such a new solution serving as a high temperature cooling system [3–5]. It has been used in multiple types of buildings, such as office buildings, residential buildings and airports, and its popularity is still increasing [6–8]. Compared with all-air systems, radiant cooling ceiling systems can achieve energy savings by increasing chiller's efficiency due to high temperature cooling and reducing energy consumption of fans [9,10]. Khan et al. [11] investigated the energy consumption of radiant cooling ceiling systems with a dedicated outside air system (DOAS) in a hot and humid climate. A comparison of energy consumption calculated that the radiant systems was 17.5% more efficient than a conventional all-air system. Besides, a side-by-side comparison between radiant and variable air volume systems was conducted in two identical buildings in India. The monitoring data indicated that the radiant system used 34% less energy compared to the variable air volume systems during the two years of operation [12]. Furthermore, previous studies revealed that a radiant cooling ceiling system could achieve better thermal comfort than a conventional all-air system [13–15]. Radiant cooling ceiling system is also claimed as a promising indoor terminal unit for temperature and humidity independent control. As radiant cooling ceiling systems only handle indoor sensible load, indoor moisture load needs to be handled by auxiliary dehumidification systems [16,17].

However, there are condensation risks on the panel surfaces of radiant cooling ceiling systems when applied in a hot and humid climate. Research on avoiding condensation of radiant cooling surfaces has mainly focused on the control strategies and system configuration. It's suggested that the lowest surface temperature of radiant panel should be maintained above the indoor dew point temperature to guarantee no condensation. Yuan et al. [18] studied the inherent correlation between total heat flux capability and panel surface temperature, and proposed a condensation free control logic based on a simplified model of panel surface

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temperature. Ning et al. [19] improved a novel radiant ceiling panel with a uniform surface temperature distribution which is beneficial for condensation control. Xie et al. [20] investigated the influence of water temperature and tube spacing on the non-uniformity of surface temperature for a capillary radiant ceiling panel by a computational fluid dynamics (CFD) simulation. On the other hand, it is also essential to control the indoor moisture level carefully. Seo et al. [21] developed a control logic that a dehumidification ventilation system will be activated to remove indoor moisture facing potential condensation risks. Zhang et al. [22] and Ge et al. [23] studied the optimal pre-dehumidification time with neural network models to eliminate condensation risks during the start-up process where the air conditioning system operated intermittently. However, the condensation issue on a radiant cooling ceiling close to external windows and doors, or wherever the indoor moisture load increases sharply, is sometimes inevitable.

Natural convection flows arise from the combined buoyancy effects of thermal and mass diffusion in buildings. Condensation on a radiant cooling ceiling involving the natural convection is relatively a slow process [24,25]. The departure duration of droplet usually takes several hours from the beginning of the condensation to the first condensate droplet departure from a radiant ceiling. This provides a quantitative requirement for the responsiveness of control strategy due to thermal inertia of the radiant system and a limited dehumidifying ability of the air system. Yin et al. [26] experimentally examined the growth rate of average droplet radius on a plastic capillary panel varying with inlet temperature of chilled water. It's indicated that the departure duration of droplet is affected by the largest droplet radius instead of the average value. Mei et al. [27,28] and Sikarwar et al. [29] simulated the processes of nucleation, growth due to direct condensation, coalescence, and fall-off of droplets on the underside of horizontal substrate. The dropwise condensation of water vapor was studied correspondingly. Nevertheless, the condensation on radiant ceiling arises from natural convection between humid air and panel surface rather than condensation in pure water vapor. And the great amount of computation becomes an obstacle in application. Because the departure duration of droplet is closely correlated to the condensation water mass, the frost melting water retention on a vertical substrate was investigated theoretically and experimentally by Liang et al. [30]. The experimental results indicated that the retained water mass of the superhydrophobic fin decreases by 75.82% compared with that of the bare fins.

However, there are seldom studies on the departure duration of condensate droplet from a radiant ceiling surface due to the complexity and randomness of the condensation process. In this paper, a theoretical model based on the condensation water mass, which took the surface characteristics of apparent contact angle into account, was developed for predicting the departure duration of the first condensate droplet from a radiant ceiling panel. Meanwhile, a series of condensation experiments with different sub-cooled degrees were conducted on a radiant ceiling with a conventional aluminum alloy surface. The experimental results helped to investigate the mass of condensation water and the departure duration of droplet. The present research would be beneficial for a better operation and control of radiant cooling systems.

2. Theoretical analysis

2.1. Critical size of the gravity-induced falling droplet

As shown in Fig. 1, metal panels are usually adopted as the radiant cooling ceiling for a better heat transfer performance. When the panel surface temperature is below dew-point temperature, condensate droplets grow and coalesce underneath the radiant ceiling. And they fall off due to gravity upon approaching the critical size. The condensation phenomenon is significantly influenced by the wettability of a surface. It is always characterized by the contact angle (θ), which indicates the degree of wetting when a solid and liquid interact. When an interface exists between a liquid and a solid, the angle between the surface of the liquid and the outline of the contact surface is described as the contact angle. In the case of complete wetting (spreading), the contact angle is 0°. The solid is partially wetting if θ is between 0° and 90°, and it is partially non-wetting as θ is above 90°. In the case of super-hydrophobic materials with so-called lotus effect, the contact angle approaches the theoretical limit of 180°.

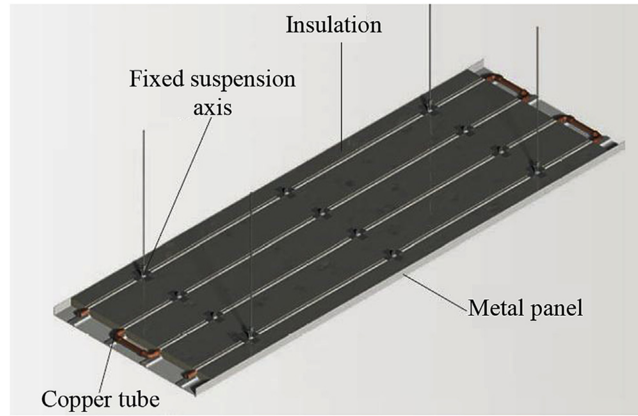

Fig. 1. Schematic of a radiant cooling ceiling panel.

Here we investigate the critical size of the gravity-induced falling droplet from a horizontal radiant ceiling surface. The capillary length is a characteristic length scale for an interface between water and air which is subject both to gravitational acceleration and to a surface force in the interface, which is expressed as:

$$l_{cap} = \sqrt{\frac{\gamma}{(\rho_w - \rho_a)g}} \tag{1}$$

where γ represents the surface tension of water; ρ_w and ρ_a are the density of water and air, respectively; g is the gravitational acceleration.

The shape of a pendent droplet depends on the equilibrium between the forces of surface tension, gravity, and pressure. It was described by the classical Young-Laplace equation of capillarity [31]. According to the hypothesis of rotational symmetry of pendent droplets underneath horizontal surfaces, solving the three-dimensional shape of the droplet is simplified into solving its profile. It can be written as the following ordinary differential equations as a function of arc length s, as shown in Fig. 2.

$$\frac{dx}{ds} = \cos\varphi \tag{2a}$$

$$\frac{dz}{ds} = \sin\varphi \tag{2b}$$

$$\frac{d\varphi}{ds} = \frac{2}{b} + \frac{z}{l_{cap}^2} - \frac{\sin\varphi}{x} \tag{2c}$$

$$\frac{dV}{ds} = \pi x^2 \sin\varphi \tag{2d}$$