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Transmittance of transparent windows with non-absorbing cap-shaped droplets condensed on their backside

Keyong Zhu [a], Yong Huang [a], Jeremy Pruvost [b], Jack Legrand [b], Laurent Pilon [c,*]

[a] Beihang University School of Aeronautical Science and Engineering, No. 37, Xueyuan Road, Beijing 100191, China
[b] LUNAM Université, Université de Nantes, CNRS, GEPEA, UMR6144, Blvd de l'Université, CRTT - BP 406, 44602 Saint-Nazaire Cedex, France
[c] University of California, Los Angeles Mechanical and Aerospace Engineering Department, 420 Westwood Plaza, Los Angeles, CA 90095-1597, USA

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ABSTRACT

This study aims to quantify systematically the effect of non-absorbing cap-shaped droplets condensed on the backside of transparent windows on their directional-hemispherical transmittance and reflectance. Condensed water droplets have been blamed to reduce light transfer through windows in greenhouses, solar desalination plants, and photobioreactors. Here, the directional-hemispherical transmittance was predicted by Monte Carlo ray-tracing method. For the first time, both monodisperse and polydisperse droplets were considered, with contact angle between 0 and 180°, arranged either in an ordered hexagonal pattern or randomly distributed on the window backside with projected surface area coverage between 0 and 90%. The directional-hemispherical transmittance was found to be independent of the size and spatial distributions of the droplets. Instead, it depended on (i) the incident angle, (ii) the optical properties of the window and droplets, and on (iii) the droplet contact angle and (iv) projected surface area coverage. In fact, the directional-hemispherical transmittance decreased with increasing incident angle. Four optical regimes were identified in the normal-hemispherical transmittance. It was nearly constant for droplet contact angles either smaller than the critical angle θ_{cr} (predicted by Snell's law) for total internal reflection at the droplet/air interface or larger than 180°-θ_{cr}. However, between these critical contact angles, the normal-hemispherical transmittance decreased rapidly to reach a minimum at 90° and increased rapidly with increasing contact angles up to 180°-θ_{cr}. This was attributed to total internal reflection at the droplet/air interface which led to increasing reflectance. In addition, the normal-hemispherical transmittance increased slightly with increasing projected surface area coverage for contact angle was smaller than θ_{cr}. However, it decreased monotonously with increasing droplet projected surface area coverage for contact angle larger than θ_{cr}. These results can be used to select the material or surface coating with advantageous surface properties for applications when dropwise condensation may otherwise have a negative effect on light transmittance.

1. Introduction

The effects of water droplets condensate on the transmittance of plane parallel slabs or films of various semi-transparent materials (e.g., glass or plastic) have been investigated both experimentally and theoretically [1–16]. There exist two types of condensation namely (i) *filmwise condensation* referring to the formation of a liquid film covering the window and (ii) *dropwise condensation* corresponding to discrete droplets forming, growing, and potentially coalescing on the window [1]. Filmwise condensation on the backside of a window increases transmittance and reduces reflectance compared with a dry window thanks to the fact that the refractive index mismatch between air and water is smaller than between air and glass [16–19]. On the other hand, water droplets condensed on the backside of windows are known to decrease their transmittance because of backscattering and/or absorption of the incident radiation by the droplets [1,9,10].

In practice, dropwise condensation reduces the solar energy input and the overall energy efficiency of greenhouses used for growing various plants [20]. In addition, droplet condensing inside greenhouses can cause damages and diseases to plants as they drip from the windows [6,7]. Dropwise condensation has also negative effects in other solar energy applications such as solar desalination where visible and infrared solar radiations are absorbed by salty water to evaporate freshwater which condenses and flows along an inclined windows before being collected [21]. The same is likely true in some microalgal culture systems, such as raceways or ponds covered by plastic sheets or glass plates [22] to

* Corresponding author.
E-mail address: pilon@seas.ucla.edu (L. Pilon).

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grow microalgae and convert carbon dioxide and sunlight, in the photosynthetically active radiation (PAR) region (400–700 nm), into biomass.

Several approaches have been explored to favor the formation of filmwise rather than dropwise condensation. For example, anti-condensation (or anti-drop) agents deposited on the window's backside can increase its wettability so that filmwise condensation prevailed to facilitate drainage of the condensate along the window surface [4–7]. Anti-dust measures can also be used to reduce static build-up on the window's outer surface by providing a conduction path to the ground [4].

This study aims to assess the effects of non-absorbing cap-shaped droplets condensed on the backside of transparent windows on their directional-hemispherical transmittance and reflectance. Particular attention was paid to the effects of light incident angle, as well as droplet size distribution, spatial arrangement, contact angle, and projected surface area coverage. The results will provide guidelines for material selection in order to minimize the effect of dropwise condensation on window transmittance.

2. Background

2.1. Experiments

Briscoe and Galvin [1] investigated experimentally the transport of monochromatic light at 650 nm through five types of glass windows with water droplets condensed on their backside. The windows consisted of 1.1 mm thick clean and unclean glass window as well as three glass windows coated, on their backside, with polymethyl methacrylate (PMMA or acrylic), polystyrene, and polyethylene (PE). The associated droplet contact angle was measured at 0°, 50.9°, 64.8°, 90.0°, and 99.7°, respectively. In all cases, the surface area coverage of droplets was estimated to be 55%, corresponding to the equilibrium coverage accounting for droplet coalescence on a vertical substrate [23–25]. The authors measured the normal-hemispherical reflectance of each window held vertically under dry or dropwise condensation conditions. The normal-hemispherical reflectance $R_{nh,650}$ of the window with droplet condensation was found to increase from about 5% to 24% as the contact angle increased from about 0° to 100°. Simultaneously, the normal-hemispherical transmittance $T_{nh,650}$ decreased with increasing contact angle. Note that absorption by the glass window and the polymeric films can be neglected at the wavelength considered, so that $T_{nh,650} = 1- R_{nh,650}$.

Pollet and Pieters [4] measured the directional-hemispherical transmittance of visible light at 632.8 nm through three types of vertical glass plates namely (i) a 4 mm thick single glass plate, (ii) a 4 mm thick single glass plate with a low-emissivity SnO_2 coating, and (iii) a 8 mm thick double glass plate, along with three types of vertical polyethelene films including (iv) a 150 µm thick single-layer ordinary low-density PE film, (v) a 180 µm thick three-layer anti-drop polyvinyl-ethyl vinyl acetate (PE-EVA) film, and (vi) a 180 µm thick three-layer anti-dust PE-EVA film. The authors reported that condensed water droplets reduced the directional-hemispherical transmittance of all glass plates and PE-based films for light incident angles ranging from 0 (normal) to 75°. For example, the transmittance of the low-density PE film decreased by up to 23% under normal incidence due to the presence of droplets. However, the directional-hemispherical transmittance of the anti-drop PE-EVA film was not affected by water condensation and featured the largest transmittance under condensation conditions. The authors attributed the different effects of dropwise condensation on the directional-hemispherical transmittance to the shape of droplets which were much flatter on the glass windows than on the PE films. They also observed wide variations in the shape, size, and spatial distributions of the droplets condensed on the glass plates and PE films. Droplets condensed on the PE films without anti-drop agents approached more closely the cap-shaped than those on the glass slabs. However, the authors did not measure either the contact angle or the surface area coverage of the droplets because of their irregular shapes.

Geoola et al. [6,7] designed an experimental greenhouse and measured the total hemispherical transmittance of solar radiation (collimated and diffuse) over the wavelength range 305–2800 nm through 140 µm thick cladding materials with and without condensation on the inner surface. Three types of low-density PE films were investigated namely (i) ultraviolet (UV)-stabilized PE films, (ii) UV- stabilized and infrared-modified PE films, and (iii) ultraviolet-stabilized as well as infrared- and anti-drop-modified PE films. The total hemispherical transmittance of the anti-drop PE film was larger under condensation conditions by about 3.5% than under dry conditions. By contrast, the total hemispherical transmittance of the two other types of PE films without anti-drop agents was lower by about 14–19% between dropwise condensation and dry conditions. Unfortunately, the authors did not report the contact angle and surface area coverage of the droplets condensed on the different PE films.

Cemek and Demir [8] investigated experimentally the total hemispherical transmittance of solar radiation in mini-greenhouses with and without dropwise condensation on the inner surface. Four kinds of covering materials were tested namely (i) PE films with no additives, (ii) UV-stabilized PE films, (iii) IR-absorbing PE films, and (iv) double-layer PE films with no additives, all with a thickness of 150 µm. The authors measured the number and diameter of droplets on the oblique ceiling and vertical sidewall of the greenhouses and calculated the volume and surface area coverage of droplets assumed to be cap-shaped. The mean droplet diameter on the greenhouse's ceiling made of PE films with no additives, UV-stabilized PE films, and IR-absorbing PE films were 2.6 mm, 2.0 mm, and 2.6 mm, respectively with surface area coverage of 46%, 29%, and 38%. Droplets diameter on the greenhouse vertical sidewalls, for the same three PE films, were 1.2 mm, 1.2 mm, and 2.6 mm with surface area coverage of 48%, 16%, and 23%, respectively. The total hemispherical transmittance of solar radiation was larger by about 9% under dry conditions compared with condensation conditions for all types of PE films. The total hemispherical transmittance of double-layer PE films was the lowest while that of PE films with no additives was the highest both under dry and condensation conditions. The authors indicated that high surface area coverage and volume of condensate led to a reduction of the total hemispherical transmittance.

Overall, previous experimental measurements have established that water droplet condensation on the backside of windows decrease their directional-hemispherical transmittance, compared with dry conditions except for some anti-drop films [1,4,6–8]. In addition, it was also established that the normal-hemispherical transmittance decreases with increasing contact angle. Only contact angles up to 90°–100° were explored [1]. To the best of our knowledge, window materials with large contact angles were not considered.

2.2. Modeling

Hsieh and Rajvanshi [9] analyzed theoretically light transfer by the ray-tracing method at wavelengths between 500 nm and 2.5 µm for a 2.286 mm thick absorbing glass slab supporting, on its backside, a single hemispherical water droplet, i.e., with contact angle of 90°. The droplet radius varied from 0.25 mm to 1.25 mm. The droplet size was found to have a negligible effect on both