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Light transfer through windows with external condensation

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ABSTRACT

This study investigates systematically light transfer through windows supporting cap-shaped droplets on their external face. The presence of such droplets may have negative effects on the conversion efficiency of solar cells, distorts image quality of lenses, or hinders visibility through windows and windshields. Here, the directional-hemispherical transmittance was predicted by the Monte Carlo ray-tracing method. The droplets were monodisperse or polydisperse randomly distributed on the outside face of optically smooth windows. For nonabsorbing droplets, the diameter and size distribution did not have a significant effect on the window directional-hemispherical transmittance. The latter was nearly independent of contact angle for incident angle $\theta_i \leq 30°$. However, the directional-hemispherical transmittance decreased monotonously with increasing incident angle and droplet contact angle for contact angle $\theta_c \leq 70°$ to reach a minimum at a contact angle $\theta_{c,min}$ beyond which it increased with increasing contact angle before reaching a plateau at large contact angles. This was attributed to total internal reflection at the back window/air and droplet/air interfaces. For absorbing droplets, the normal-hemispherical transmittance decreased significantly with increasing droplet contact angle, mean diameter, polydispersity, and projected surface area coverage due to strong absorption within the droplets. Moreover, the normal-hemispherical transmittance decreased with increasing contact angle for $\theta_c < 90°$ and remained constant and independent of the droplets' absorption index, mean diameter, and contact angle for $\theta_c \geq 90°$. Finally, Analytical expressions for the upper and lower bounds of the normal-hemispherical transmittance as a function of droplet contact angle, optical properties, and projected surface area coverage were derived.

1. Introduction

The presence of droplets on the outside face of a window is common occurrence in numerous circumstances. In such situations, droplets are undesirable as they hinder visibility. For example, outside condensation on windows can be observed (i) on poorly insulated windows in air-conditioned buildings under hot and humid climates [1,2] or (ii) on well-insulated windows – with U-value less than 1.2 W/m^2.K – on clear and humid nights when the window external surface temperature falls below the dew point [3-5]. Outside condensation reduces the visibility through the window and has been identified as a factor limiting adoption of more energy efficient windows [5]. Two types of surface coatings have been explored to reduce outside condensation on well-insulated windows namely (1) a low-emissivity coating (e.g., SnO_2:F) to reduce radiation cooling and increase the window outside surface temperature and (2) a hydrophilic coating (e.g., TiO_2) to ensure that condensed water forms a transparent water film instead of strongly scattering droplets [2,4].

Similarly, outside condensation on vehicle windshields and from water sprayed by other vehicles driving on wet roads can significantly reduce road visibility, particularly at night and despite the use of wipers [6]. Dropwise condensation also occurs on lenses of cameras used for scientific observations [7,8] and surveillance [9]. Finally, the presence of water droplets on photovoltaic solar cells from dew or rain could decrease the efficiency of solar cells due to light absorption and reflection by the water droplets [10,11].

The present paper aims to investigate systematically light transfer through windows supporting cap-shaped droplets on their outside face. The effects of incident angle and of droplet size distribution, contact angle, projected surface area coverage, and absorption index were investigated. The results will provide guidelines for the design and material selection of building and car windows, camera lenses, and solar cells in order to reduce the negative effects of droplets on window transmittance and system performance.

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Nomenclature

A_n	normal absorptance
d	droplet diameter, µm
d_m	mean diameter of droplets, µm
d_p	projected diameter of droplets on the window, µm
f_A	droplet projected surface area coverage
H	thickness of the window, mm
k	absorption index
L	length of the window, mm
M	number of photon bundles
n	refractive index
R	reflectance
T	transmittance
W	width of the window, mm

Greek symbols

θ_c	contact angle, °
θ_i	incident angle, °
λ	wavelength, µm
ρ_{ij}	reflectivity of the interface i/j
σ	standard deviation of droplet diameter, µm
τ	transmissivity

Subscripts

a	refers to air
d	refers to droplet
f	refers to film
w	refers to window
dh	refers to directional-hemispherical
nh	refers to normal-hemispherical

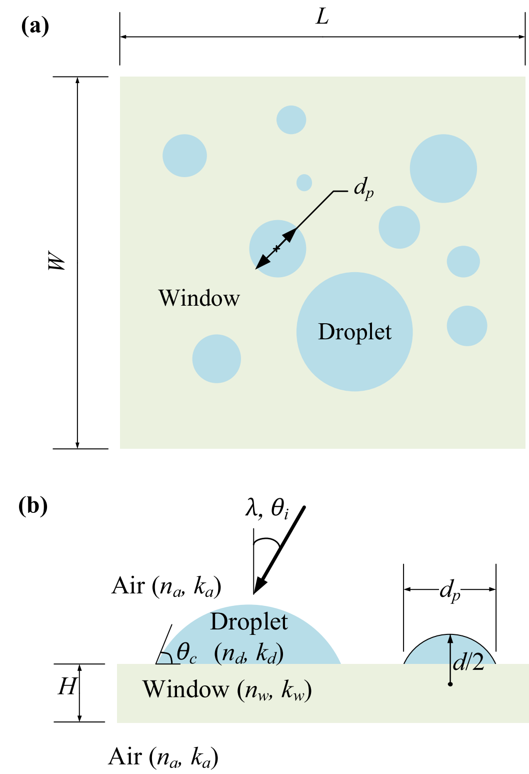

Fig. 1. (a) Top view of the semitransparent window (n_w, k_w) of dimensions $L \times W \times H$ supporting polydisperse absorbing cap-shaped droplets (n_d, k_d) for contact angle θ_c, diameter d, and projected diameter d_p. (b) Cross-section of the semitransparent window supporting absorbing droplets exposed to collimated incident radiation at angle θ_i and wavelength λ.

2. Analysis

2.1. Problem statement

Fig. 1(a) and 1(b) respectively show the top and side views of polydisperse droplets randomly distributed on the outside face of a window of length L, width W, and thickness H. Collimated monochromatic radiation of wavelength λ was incident on the outside face of the window at a polar angle θ_i. Photons were reflected, transmitted, or absorbed by the window with refractive and absorption indices, respectively denoted by n_w and k_w, or by the droplets with refractive and absorption indices denoted by n_d and k_d, respectively. In the present study, the dimensions of the window supporting randomly distributed monodisperse or polydisperse droplets were $L = W = 5$ mm, and $H = 3$ mm. Unless otherwise noticed, the refractive and absorption indices of the surrounding air were taken as $n_a = 1.0$ and $k_a = 0$, and the refractive indices of the window and droplets were taken as $n_w = 1.5$ and $n_d = 1.33$, respectively. The window and droplet absorption indices k_w and k_d were taken as parameters as they can vary strongly with wavelength. Finally, the projected surface area coverage f_A was defined as the fraction of the glass window covered by the normal projection of droplets with diameter d and contact angle θ_c whose projected diameter d_p can be expressed as

$$d_p = d \sin[\min(\theta_c, 90^\circ)]. \tag{1}$$

2.2. Methods

Monodisperse or polydisperse and randomly distributed droplets were generated on the outside face of the window by using the same methodology as that developed in our previous study focused on light transfer through windows supporting droplets on their back side [12,13]. The procedure was described in detail in Ref. [12] and need not be repeated. Similarly, simulations of light transfer through windows supporting droplets on their outside face was based on the same assumptions as that used in Ref. [12,13] in order to make the problem mathematically tractable. In brief, all interfaces were assumed to be optically smooth and Snell's law and Fresnel's equations prevailed. Here also, Monte Carlo ray-tracing method [14,15] was used to predict the directional-hemispherical reflectance, transmittance, and absorptance of windows exposed to collimated radiation and supporting droplets on their outside face [12,13]. In all simulations reported in this paper, the total number of photon bundles simulated was $M = 10^6$ in order to achieve numerical convergence.

3. Results and discussion

A parametric study was performed to investigate systematically the effects of (i) incident angle θ_i, (ii) normal droplet size distribution, (iii) contact angle θ_c, (iv) projected surface area coverage f_A, and (v) droplet absorption index k_d on the normal-hemispherical transmittance and reflectance of semitransparent windows supporting either nonabsorbing ($k_d = 0$) or absorbing ($k_d > 0$) droplets.

3.1. Nonabsorbing droplets on transparent window

3.1.1. Effect of droplet diameter and size distribution

Fig. 2 shows the directional-hemispherical transmittance for nonabsorbing ($k_d = 0$) droplets and transparent ($k_w = 0$) window (a) as a function of incident angle θ_i for contact angle $\theta_c = 60°$ and $\theta_c = 120°$, and (b) as a function of contact angle θ_c with incident angle $\theta_i = 30°$ and $\theta_i = 60°$. Fig. 2 compares predictions