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Research Paper

Analysis of the optical and thermal properties of transparent insulating materials containing gas bubbles

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HIGHLIGHTS

- Transparent insulating medium containing gas bubbles was proposed.
- Radiative transfer and thermal conduction models were constructed.
- Bulk transmittance increases first and then decreases with the bubble number.
- Effective thermal conductivity decreases with increasing filling ratio.
- High filling ratio with large bubbles is preferred for good performance.

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ABSTRACT

As a medium of low absorption and low thermal conduction, introducing gas bubbles into semitransparent mediums, such as glass and polycarbonate (PC), may simultaneously improve their light transmission and thermal insulation performances. However, gas bubbles can also enhance light scattering, which is in competition with the effect of the absorption decrease. Moreover, the balance between the visible light transmittance and the effective thermal conductivity should also be considered in the material design. Therefore, a radiative transfer model and the Maxwell–Eucken model for such material were employed to analyze the optical and thermal performances, respectively. The results demonstrate that the transmittance increases when the bubble radius (r) increases with a fixed volume fraction of the gas bubbles (f_v) due to the increased scattering intensity. In addition, the effective thermal conductivity always decreases with increasing f_v. Thus, to achieve both good optical and thermal performances, high f_v with large r is preferred. When $f_v = 0.5$, the transmittance can be kept larger than 50% as long as $r \geq 0.7$ mm. To elucidate the application performance, the heat transfer of a freezer adopting the glass or PC with gas bubbles as a cover was analyzed and the energy saving can be nearly 10%.

1. Introduction

Transparent insulating materials or envelopes have been widely applied in solar energy utilization, building energy conservation and commercial freezers. The most typical representative of transparent insulating materials is silica aerogel, which combines very low thermal conductivity and comparatively high light transmittance [1]. To form a transparent insulating envelope, silica aerogel is usually sandwiched between two glass panels because it is fragile and should not be contacted with water [2–6]. Thus, the thermal insulation and light performances of silica aerogel are suppressed due to the presence of the glass panels. The key to using silica aerogel as the transparent insulating envelope directly is to improve its strength. Yang et al. [7] incorporated Si_3N_4 powder into porous Si_3N_4 ceramic through freeze casting and sintering and later impregnated the porous Si_3N_4 ceramic with silica aerogel to obtain a silica aerogel/porous Si_3N_4 composite, which combines high strength and low thermal conductivity. In addition to silica aerogel, a transparent insulating film consisting of hollow silica nanoparticles dispersed in a polyurethane matrix was prepared by Fuji et al. [8]. These researchers' results showed that the thermal conductivity of the film is 0.029 W/(m·K), and the light transmittance is close to 90%. In addition, a polycarbonate (PC) square section capillary transparent insulating material was reported in Buratti and Moretti [2]; this material must be sandwiched between two glass panels. To eliminate the negative influence of the glass panels, Moretti et al. [9] designed three coextruded PC multi-sheet systems for potential use as the transparent insulating envelope directly.

As mentioned above, there are certain disadvantages in the transparent insulating envelope consisting of the transparent insulating material and the glass panels. Thus, developing a transparent insulating material of structural performance has wide potential

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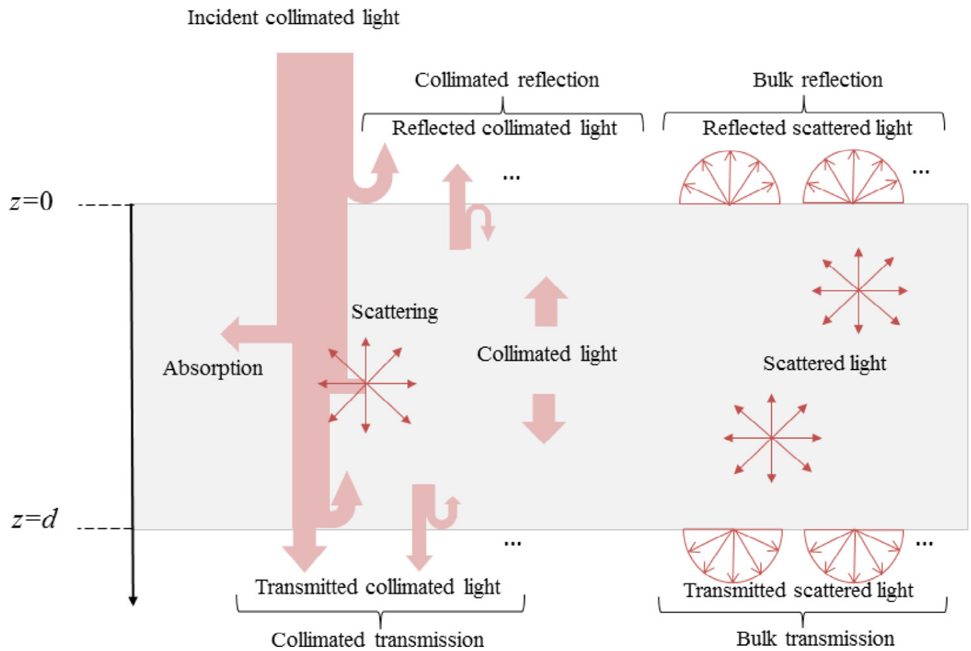

Fig. 1. Sketch of light propagation in a semitransparent medium containing gas bubbles.

applications. Gas bubbles, as a medium of low absorption and low thermal conduction, when introduced into semitransparent mediums such as glass and PC, may improve simultaneously their light transmission and thermal insulation performances, and reduce their weights as well. Gas bubbles can be generated through several ways and they can exert complex effects on thermal radiation heat transfer. Thus, a number of studies were motivated. When water is used to cool burning hot surfaces, the generated vapor bubbles may affect the propagation of the radiation from the hot surfaces. To analyze this phenomenon, a theoretical model for the propagation of infrared radiation in a semitransparent liquid containing gas bubbles was proposed by Dombrovsky [10]. Later, this author's group performed an experimental investigation on the radiative properties of polymer coating containing hollow microspheres [11]. During the industrial glass melting process, gas bubbles can form in the glass, and they can affect the radiative properties of the glass. Pilon and Viskanta. [12] presented a general formulation of the radiation characteristics for the semitransparent medium containing gas bubbles and calculated the spectral absorption and extinction coefficients. Randrianalisoa et al. [13] proposed an improved inverse method based on spectral bidirectional transmittance measurements to retrieve the radiative properties of a fused quartz glass containing gas bubbles and used the measured hemispherical transmittance and reflectance to verify his inverse method. In 2014, Cvecek et al. [14] used ultra-short laser pulses to generate gas bubbles in the fused silica successfully, which offered a feasible method to prepare the glass or PC containing gas bubbles.

Note that gas bubbles can enhance the scattering [11–13,15–17], which is in competition with the effect of the absorption decrease. Moreover, the trade-off between the light transmittance and the effective thermal conductivity should also be considered in the material design. Here, a radiative transfer model for a semitransparent medium containing large gas bubbles (with diameters much larger than the wavelengths concerned) with the assumption of independent scattering was constructed to calculate the transmittance and reflectance of the glass or PC containing gas bubbles. To obtain the effective thermal conductivity of the semitransparent medium containing gas bubbles, the Maxwell–Eucken thermal conduction model was adopted. Subsequently, the effects of the volume fraction of the gas bubbles (f_v) and the bubble radius (r) were discussed, and the trade-off mentioned above was analyzed. To elucidate the application performance of the glass and PC containing gas bubbles, a simplified heat transfer model of a freezer was constructed to analyze the effect of the energy saving for the glass and PC containing gas bubbles.

2. Theoretical model

2.1. Radiative transfer model for the semitransparent medium containing gas bubbles

Fig. 1 shows a sketch of light propagation in a semitransparent medium containing gas bubbles. When gas bubbles were introduced in a semitransparent medium, such as polycarbonate (PC) or glass, they can decrease absorption while inducing scattering. The semitransparent medium containing gas bubbles can be considered as a homogeneous medium with the characteristics of absorption and scattering. If it is assumed that the gas bubbles do not contact with the boundaries of the medium, then both the top and bottom surfaces have a characteristic of specular reflection. When the collimated light incident on the top surface of such a medium, a part of the light is reflected by the top surface due to surface reflection, and the remaining collimated light goes into the medium. After undergoing several absorptions and scatterings, the remaining collimated light reaches the bottom surface, and the surface reflection occurs again. Therefore, the collimated light undergoes numerous absorption, scattering and surface reflection. Note that the collimated light scattered by gas bubbles can propagate in any direction, and such light is called the scattered light. As for collimated light in the medium, the scattered light also undergoes numerous absorptions, scatterings and surface reflections. The collimated light leaving the top and bottom surfaces are called the reflected transmitted light and the transmitted collimated light, respectively, and the scattered light leaving the top and bottom surfaces are called the reflected scattered light and the transmitted scattered light, respectively. In this study, all of the reflected collimated light and all of the transmitted collimated light are referred to as the collimated reflection and the collimated transmission, respec-