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Impact of convection on thermal performance of aerogel granulate glazing systems

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ABSTRACT

Among currently available window systems, aerogel granulate glazing systems are considered promising for achieving good thermal and visual comfort in buildings. In aerogel granulate glazing systems, it is important to evaluate how convection in the granular-filled cavity affects their thermal performance because double glazing systems, which have a similar structure, show variable thermal properties related to the convection effect. In this study, it is shown that the granular-filled cavity hardly influences the air permeance, and therefore, convection can occur in such cavities. Nevertheless, a mock-up of commercially available aerogel granulate window shows practically identical window *U*-values in hot box measurement with various tilt angles. In other words, convection in the granular cavity does not affect the thermal performance of aerogel granulate glazing systems. The center-of-glass *U*-values are 0.28 and 0.69 W/(m^2 K) for aerogel thickness of 60 and 30 mm, respectively. The total window *U*-values (using a wood frame) are 0.69 and 0.84 W/(m^2 K) for aerogel thickness of 60 and 30 mm, respectively. Furthermore, the granular aerogel in the cavity subsided by ∼3% of its total volume after the hot box measurement. The risks posed by this subsidence under actual conditions should be assessed in later research.

1. Introduction

In the building envelope, windows usually have higher thermal transmittance (i.e., *U*-value) compared to those of opaque parts such as roofs and walls. This is not preferable from an energy-saving viewpoint. Therefore, many studies have focused on thermally insulated windows. Double or triple glazing systems have been widely used to achieve better energy performance in buildings. These glazing systems have cavities in which air and/or other low-thermal-conductivity gases such as argon or xenon are filled [1]. By also utilizing low emissivity (low-E) coatings to minimize thermal radiation, the center-of-glass *U*-value of double and triple glazing systems can be reduced to less than 1.3 and 0.8 W/(m^2 K), respectively [2].

Aerogel granulate glazing systems have recently been considered a promising alternative for thermally insulated windows. Aerogel granulate glazing systems can be produced more easily than the abovementioned multipane systems while achieving the same or better thermal performance. For example, by packing aerogel granules with low thermal conductivities (13–27 mW/(m K)) [3,4] into the cavity between two glass panes, a lower *U*-value than that of double glazing systems can be readily achieved. In fact, some current commercial products have center-of-glass *U*-values of 0.25–1.38 W/(m^2 K), some of which are close to those of opaque parts [2,5,6]. Therefore, aerogel granulate glazing systems are considered advantageous relative to multipane systems. Nevertheless, the translucent appearance of aerogel granulate glazing systems restricts their application as the transparent parts of the building envelope. Therefore, satisfactory application cases for buildings should be discussed further.

The convection effect is characteristic of multipane systems (e.g., double or triple glazing systems), which changes the *U*-value of the glazing system when, e.g., the cavity angle or temperature difference is changed. The convective heat transfer coefficient is given as follows [7]:

$$h_c = Nu\left(\frac{\lambda}{d}\right) \quad (1)$$

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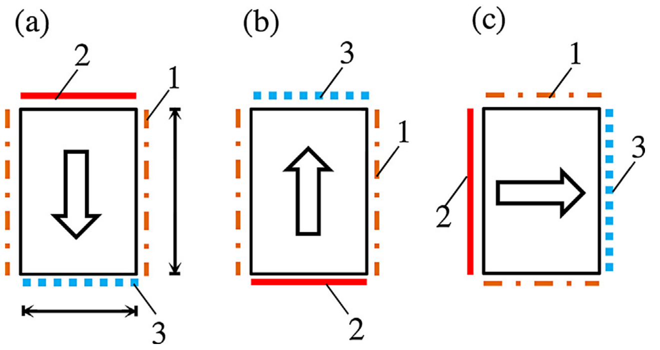

Fig. 1. Illustration of heat flow in rectangular glazing cavity. L_v and L_h are the cavity dimensions in the vertical and horizontal directions. "1" denotes the adiabatic boundary; "2," the hot side; and "3," the cold side. (a) Downward, (b) upward, and (c) horizontal heat flow.

where h_c is the convective heat transfer coefficient; Nu, the Nusselt number; λ, the thermal conductivity of the gas filled in the cavity (W/(mK)); and d, the thickness of the gas-filled cavity. The Nusselt number for a glazing system can be calculated for different geometries (usually rectangular cavities with a specific aspect ratio, L_h/L_v), cavity angles, temperature differences, etc. Three different cases of heat flow direction are shown in Fig. 1: downward, upward, and horizontal. The downward heat flow in Fig. 1(a) does not cause convection, and therefore, $Nu = 1$. In other cases, the Nusselt number can be expressed as a function of the Rayleigh number (Ra), cavity vertical length (L_v), and cavity horizontal length (L_h) as follows [7]:

$$Nu = f(Ra, L_v, L_h) \tag{2}$$

Further, the Rayleigh number is defined as

$$Ra = \frac{\rho^2 d^3 g \beta c_p \Delta T}{\mu \lambda} \tag{3}$$

where ρ is the mass density (kg/m^3); g, the gravitational acceleration (m/s^2); β, the thermal expansion coefficient of gas (1/K); c_p, the specific heat capacity at constant pressure (J/(kgK)); ΔT, the temperature drop across a cavity (K); and μ, the dynamic viscosity (Pas). If the cavity is composed of a material with permeability k (m^2), the Rayleigh number can be modified by keeping the same dimensions and introducing the permeability as follows [8]:

$$R'_a = \frac{\rho^2 k d g \beta c_p \Delta T}{\mu \lambda} \tag{4}$$

When a substance like aerogel granules is packed into the cavity between the panes, it will cause a change in the U-value owing to the reduction of the convection effect. However, to the best of our knowledge, the permeability of aerogel granules in a cavity has not yet been investigated, probably owing to the difficulty of measuring the gas permeability in aerogel granules. Barnyakov et al. [9] reported the water vapor adsorption speed of an aerogel. They showed that water adsorption at 25 °C and 7% RH reached saturation in a few hours. Stahl et al. [10] reported relatively high water vapor transmission using a mixture of aerogel granules for a rendering application. These previous studies have suggested that an aerogel granular cavity might show high permeability. Then, the question of how convection impacts the thermal performance of aerogel glazing systems arises. Previous studies have reported that convection has some impact when using porous materials (e.g., rock wool) [11]. The heat transmittance of aerogel granular windows has been experimentally investigated (e.g., [4,6,12]). The impact of a rim seal on the heat transmittance of aerogel windows has also been discussed [13,14]. However, to the best of our knowledge, the impact of convection on aerogel glazing systems has not yet been well investigated experimentally.

Aerogel granules have been reported to have low thermal conductivities of 15–25 mW/(mK) compared to values of 1.2–1.4 W/(mK) for bulk silica. The significant reduction in heat transfer in aerogel granules can mainly be attributed to a strong Knudsen effect within the nanopores of aerogels. The Knudsen effect can be expressed as follows [15–17]:

$$\lambda_{gas} = \frac{\lambda_{gas,0}}{1 + 2\beta Kn} \tag{5}$$

where λ_{gas} is the gas thermal conductivity in the pores (W/(mK)); $\lambda_{gas,0}$, the gas thermal conductivity in the pores at STP (standard temperature and pressure) (W/(mK)); β, a coefficient characterizing the molecule–wall collision energy transfer (in)efficiency (value: 1.5–2.0); and Kn, the Knudsen number, defined as $Kn = \sigma_{mean}/\delta$, i.e., the mean free path of gas molecules σ_{mean} (m) divided by the characteristic pore diameter δ (m). Kn is expressed as follows:

$$Kn = \frac{k_B T}{\sqrt{2}\pi d^2 p \delta} \tag{6}$$

where k_B is the Boltzmann constant ($k_B \sim 1.38 \times 10^{-23}$ J/K); T, the temperature (K); d, the gas molecule collision diameter (m); and p, the gas pressure in pores (Pa). A small pore size (i.e., small δ) can lead to a higher value of Kn and, in turn, a lower value of λ_{gas}. The mean free path of air is ~69 nm at ambient pressure [18], whereas the aerogel granule pore size range is several to tens of nanometers [19–21]. The smaller the pore diameter, the less frequently will the gas molecules collide with each other before hitting the pore walls. Therefore, as the molecule collision probability decreases, so does the gaseous thermal conductivity. However, aerogel granules have an open cell structure, and the aerogel granular cavity of aerogel glazing systems consists of many cohered granules with large voids between them. This may impact convection in aerogel granulate glazing systems.

This study aims to investigate the effect of convection on the thermal performance of aerogel granulate glazing systems. Further, the moisture permeance of aerogel granules is compared with those of conventional insulation materials because an approximately linear relationship was observed between water vapor permeability and air permeability with some building materials [22]. Furthermore, hot box measurements were performed to evaluate the thermal performance of the granulate glazing systems.

2. Experimental

2.1. Samples

2.1.1. Glazing assemblies

Two commercially available aerogel granulate glazing systems were tested. The tested samples had the same structure except for their different aerogel granular cavity thickness of 30 and 60 mm. As shown in Eq. (1), the cavity thickness is an important parameter when discussing convection. The glazing systems consist of 6-mm-thick heat-strengthened glasses. The rim seal is composed of a stainless steel spacer and a dual-seal sealant joint—one was a two-component silicone sealant that was hardened after mixing and then injected into the joint space to produce alcohol gas during hardening, and the other was a butyl sealant by which the stainless spacer was adhered to each pane. Therefore, the structure of the tested aerogel granulate glazing systems was that typically specified for insulated glazing systems. Two types of aerogel granules were used in each cavity—small granules with a diameter of 0.7–1.2 mm and large granules with a diameter of 1.2–4.0 mm. Table 1 lists the properties of these granules. A previous study