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Measured thermal & daylight performance of an evacuated glazing using an outdoor test cell

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HIGHLIGHTS

- An experimental average overall heat transfer coefficient of 1.4 W/m^2 K was found for a vacuum glazing.
- Solar heat gain coefficient of a vacuum glazing was calculated from measured data.
- Measured interior illuminance due to vacuum glazing has been shown to the almost same as double glazing.

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ABSTRACT

Outdoor characterization of thermal and daylight performance of an evacuated (vacuum) glazing has been conducted using an outdoor test cell for clear sunny day, intermittent day and overcast days. An average overall heat transfer coefficient of 1.4 W/m^2 K was found for vacuum glazing. Solar heat gain coefficient of vacuum glazing varied between 0.58 and 0.19. Vacuum glazing has potential to reduce 53% heat loss compared to a same area of double-glazing while offering nearly equal amount of heat gain. Internal daylight illuminance was found to be similar to double glazing indicating that the presence of small pillars inside vacuum glazing had no significant visual impact.

1. Introduction

Energy consumption in buildings is responsible for 40% of global energy in the European Union, contributing to production of up to 35% of greenhouse gases [1]. It is expected that, between 2008 and 2030, the world energy demand will increase by about 50% [2]. In cold climatic area or cold dominated area energy are used mainly for space heating [3]. Single and double-glazing have high overall heat losses that contribute to enhance this energy demand. Low heat loss glazing can reduce these losses, which will also reduce energy demand.

Heat loss through windows is less when convection between the glass panes is inhibited by

(i) the introduction of multiple glazing panes [4–7];
(ii) the use of heavy inert gasses between the panes [8];
(iii) the use of aerogel material [9–14];
(iv) the presence of vacuum between two glass panes [15–17].

Multiple glazing is considered to have more than two glass panes, which make it heavier to use. Expensive inert gas is a barrier for this type of glazing to be widely available [8]. Aerogel material inside aerogel glazing scatters the transmitted light, which makes it less applicable for window [18]. Vacuum glazing is advantageous due to its less weight comparing to the multiple panes glazing; less price compared to heavy inert gasses filled glazing; and high transparency compared to aerogel glazing. A vacuum glazing consists of two sheets of glass separated by a narrow evacuated space [19–21]. The edges of the glass are sealed together hermetically in order that a vacuum <0.1 Pa is maintained between the glass sheets. An array of small support pillars ensures that the glass sheets do not come into contact under the large atmospheric pressure. Internal transparent low-emittance (low-e) coating reduces radiative heat transfer to a sufficiently low level [22,23]. The concept of vacuum glazing was first described in a 1913 patent [24]. Methods of fabrication [25–29], heat transfer [30–38], structural analysis [39–42] and laboratory characterization [43–47] have been reported extensively. Details of vacuum glazing are shown in Fig. 1.

The first reported successful production of vacuum glazing was in 1989 [19]. Since that time, many samples of vacuum glazing

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Nomenclature

A_i	anisotropy index
A_{vacuum}	aperture area of vacuum glazing (m^2)
A_{wall}	interior wall surface area (m^2)
C_{air}	heat capacity of air (kJ/kg K)
h_0	heat transfer coefficient from test cell outer surface (W/m^2 K)
h_i	heat transfer coefficient from test cell inside surface (W/m^2 K)
$I_{beam,h}$	incident beam solar radiation on the horizontal surface (W/m^2)
$I_{dif,h}$	incident diffuse solar radiation on the horizontal surface (W/m^2)
I_{extra}	incident extra-terrestrial solar radiation (W/m^2)
I_{sc}	solar constant (W/m^2)
$I_{ver,global}$	incident solar radiation on the vertical surface of glazing (W/m^2)
k_d	diffuse factor
k_T	clearness index
K_{wd}	thermal conductivity of wood (W/mK)
L_{pl}	thickness of polystyrene (m)
L_{wd}	thickness of wood (m)
M_{tc}	mass of the air inside test cell (kg)
Q_{vacuum}	heat through the vacuum glazing incident solar radiation (W)
k_g	extinction coefficient
N_g	number of glass pane
n	refractive index
SE_{vacuum}	transmitted solar energy through vacuum glazing
$T_{in,tc}$	interior temperature (°C)
$T_{out,tc}$	ambient temperature (°C)
t_g	thickness of glazing (m)
U_{vacuum}	overall heat transfer coefficient of glazing (W/m^2 K)

Greek symbols

α	absorptance
τ	transmittance
τ_v	vertical global transmittance
τ_{dir}	direct transmittance
τ_{diff}	diffuse transmittance
θ	incident angle

have been produced under the "SPACIA" brand using high temperature (450 °C) solder glass edge sealing [19–23]. This high temperature process degrades both soft low-e coatings and tempered glass [23]. An indium alloy edge seal technique [25,26] at temperatures less than 200 °C enables soft low-e coating and tempered glass to be used. So far, all the vacuum glazing's thermal behavior and overall heat transfer coefficient were studied under controlled environment using hotbox calorimeter [22,23,41,42]. Potential behavior of switchable vacuum glazing was also investigated earlier [7,48–51].

Outdoor characterization of vacuum glazing has only been performed once to look at the effects of a known, periodically applied temperature difference on the long-term mechanical and thermal integrity performance of the glazing [52].

Vacuum glazing is considered as a part of building energy saving component specially applicable for cold climate area. Thus, outdoor thermal characterization is essential to investigate its actual performance under dynamic conditions. Till now, no outdoor characterization was investigated to find out overall heat transfer coefficient, solar heat gain coefficient and daylighting performance using vacuum glazing.

In this work, an outdoor test cell was employed which offered to measure the overall heat transfer coefficient, and solar heat gain coefficients of a vacuum glazing under an uncontrolled dynamic condition. Internal illuminance of this vacuum glazing was measured and compared with double-glazing. This article provides important knowledge on the heat gain and heat loss of vacuum glazing under Dublin climatic conditions. Engineers and building designers can refer to the results of this study for evaluating the thermal performance of this kind of vacuum glazing for similar type of climatic locations.

2. Experiment

A sample of SPACIA vacuum glazing shown in Fig. 2 was provided by Nippon Sheet Glass, of dimensions 0.35 m × 0.2 m with a 0.002 m vacuum space between two 0.003 m thick glass panes, support pillars were set 0.02 m apart each other and one of the panes has low-e coating facing onto the vacuum space. The edge of the glazing was sealed with solder glass. A see through photograph of double-glazing and vacuum glazing in Fig. 2 indicates the small pillars are completely invisible in naked eyes. Presence of low-e coating inside the vacuum glazing reduces the transmission of near infrared solar radiation. In the visible range, the average solar transmission of this vacuum glazing was 72% and double-glazing was 78%. A transmission spectrum of the vacuum and double-glazing were performed using AvaSpec-ULS2048L Star Line Versatile Fiber-optic spectrometer is shown in Fig. 3.

Using Fresnel equation [53] the reflection from the vacuum glazing can be possible by using Eq. (1).

$$R = \left(\frac{n_g - n_{air}}{n_g + n_{air}}\right)^2 \quad (1)$$

where the refractive index of vacuum glazing (n_{gv}) and air (n_{air}) are 1.52 and 1.0 respectively. Absorption for different combinations are described in Table 1.

A test cell was used to measure the thermal behavior of vacuum glazing as shown in Fig. 4 [6,7]. T type thermocouples were employed to measure temperatures. A Kipp and Zonen model SMP11 pyranometer was used to measure solar radiation incident on the vertical surface.

An illuminance sensor has been employed to measure the inside illuminance [54]. The experiment was performed from July to November 2014 in Dublin, Ireland (53.34 °N, 6.25 °W).

3. Methods of thermal characterization

Solar heat gain and thermal transmission are the two primary modes of net heat flow through windows [55]. Thermal transmission is measured by overall heat transfer coefficient (*U*-value) and solar heat gain is measured by solar heat gain coefficient (SHGC), which measures the fraction of solar radiation admitted through the glazing.

3.1. Solar heat gain coefficient

Solar energy transmitted through vacuum glazing can be written as Eq. (2) [56]