Effect of Sky Clearness Index on Transmission of Evacuated (Vacuum) Glazing

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Abstract

Glazing transmittance variation with clearness index has higher influence than incident angle for soar energy application. This work presents variation of vacuum glazing transmittance with clearness index. Clearness index and transmittance was calculated from measured one year (2014) solar radiation and glazing transmittance data in Dublin, Ireland. Clearness index below 0.5 offer single value of transmittance whereas above 0.5 clearness index glazing transmittance varies with clearness index. For different azimuthal orientation, clearness index associated with vertical plane glazing transmittance has been proposed. In Dublin for south facing vertical plane, vacuum glazing has 35% transmittance below 0.5 clearness index. Yearly usable single transmitted solar energy and solar heat gain coefficient for vertical plane south facing vacuum glazing are 87 W/m^2 and 0.22 respectively.

Keywords: Glazing; Clearness index; Vacuum glazing; Transmission; Solar heat gain coefficient; Adaptive

Nomenclature

I

Incident global solar radiation on the vertical surface of glazing (W/m^2)

$I_{beam,h}$

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)

$I_{global,h}$

Incident global solar radiation on the horizontal surface of glazing (W/m^2)

I_0

Extraterrestrial solar radiation (W/m^2)

I_{sc}

Solar constant (W/m^2)

k_b

Anisotropy index

k_d

Diffuse fraction

k_T

Clearness index

N_g

Number of glass pane

n

Refractive index

n_d

Number of day

SHGC

Solar heat gain coefficient

TSE_{vacuum}

Transmitted solar energy through vacuum glazing (W/m^2)

Greek symbols

δ

Declination angle

ω

Hour angle

φ

Latitude

θ

Incidence angle

1 Introduction

Reduction of building energy consumption can be possible by using advanced adaptive glazing technologies [1–4]. Solar heat gain control and low heat loss are the two major types of advanced glazings, which are gaining more importance in research due to their potential application in building cooling and heating energy demand reduction respectively. Solar heat gain control glazing such as electrochromic [5–7], suspended particle device [8–14], liquid crystal [15,16], thermochromic [17,18], gasochromic [19,20] and thermotropic [21,22] control the entering solar heat by changing their states from “transparent” to “opaque”. Thus, these types of glazing reduce the cooling load demand of building. These glazing are more suitable for hot climatic area and summer time in cold climatic area. Low heat loss glazing such as vacuum glazing [23,24], aerogel [25–27], and multiple pane glazing [28] reduce the heat passing from the room to outside thus reduce the heating load demand of building. These glazing are suitable for cold climatic area and wintertime in composite climate to reduce a building's heating energy demand [24].

Low heat loss vacuum glazing is advantageous compared to aerogel glazing due to its high transparency. Vacuum glazing is also advantageous compared to other multiple panes glazing due to its low weight and elimination of convective heat transfer between two panes [24]. In vacuum glazing, two glass panes are separated by a vacuum. Small pillars between the two glass panes withstand the outside atmospheric pressure [29–33] as shown in Fig. 1. The overall heat transfer coefficient of vacuum glazing is low compared to double-glazing [24]. The idea of vacuum glazing was first introduced by Zoller in 1913 and was granted with a patent in 1914 [34]. A vacuum tight thermally insulating edge sealing process makes the fabrication of a vacuum glazing complicated compared to other glazing technologies. To avoid deformation from the high temperature, the sealing should be performed below the softening temperature of the glass, which is generally low (for example, the softening temperature of common soda-lime glass is lower than 600 °C [35].

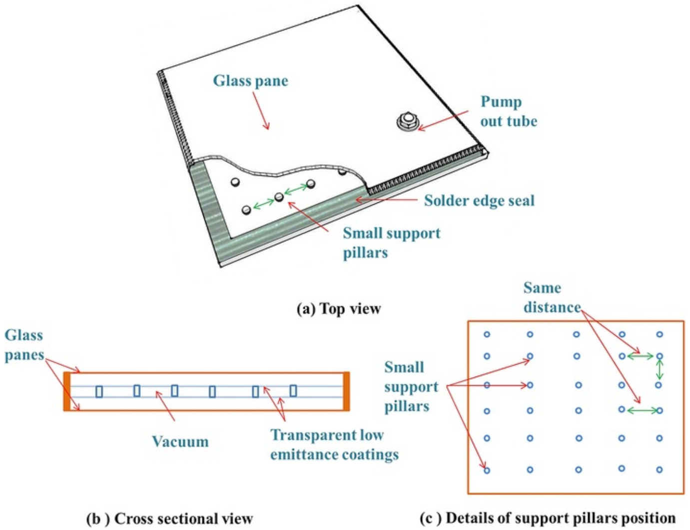

Fig. 1 Schematic details of vacuum glazing.

alt-text: Fig. 1

Vacuum glazing was first fabricated successfully in the early 1980s [36]. Thermal performance of this glazing was poor as a vacuum pressure below 0.1 N/m^2 is required to eliminate the gaseous conduction [37]. A laser was used to fuse two sheets of glass together successfully within a vacuum chamber to form a periphery edge seal for the vacuum gap [36–38].

To manufacture successful vacuum glazing, a fabrication technique was developed by Robinson and Collins, which was commercialized in 2000 by Nippon Sheet Glass (NSG) under brand name of SPACIA [23]. High temperature solder glass (melting point 450 °C) edge sealing was employed to produce this product, which restricts the choice of inner pane low-e coating. Low temperature indium alloy edge sealing (melting point 200 °C) enable low-e coating [35] to be used. Details of vacuum glazing edge sealing process can be found elsewhere [39,40]. A finite volume model to calculate the thermal performance of vacuum glazing with various frames [41], low-e coatings [42,43], glazing size, glass thickness [44], and vacuum pressure inside glazing [45] were predicted and validated experimentally [46,47]. To obtain low heat loss switchable glazing, investigation was performed using vacuum electrochromic [42,48,49] and vacuum suspended particle device combinations have been employed [50].

Thermal characterisation of vacuum glazing has been conducted under outdoor weather conditions in Sydney, Australia [51] and in Dublin, Ireland [24] has also been performed. Building energy performance due to glazing is dependent on glazing transmittance. Available glazing transmittance value is only suitable for normal solar incidence. Due to diurnal variation of solar radiation, incident angle also changes. Thus, glazing transmission is not a constant parameter; it changes with incident angle [52–54]. For building energy calculation, clearness index is more influential than incident angle as clearness index directly related with incident solar radiation. Glazing transmission changes for clearness index has been theoretically calculated by Waide and Norton [55]. They observed that below a critical clearness index for particular locations the transmission was largely invariant as the diffuse component.

The clearness index (k_T) is defined as the ratio between total solar radiation and the corresponding extraterrestrial radiation (H_0) [56,57]. Clearness index is an effective parameter for solar energy application, as it requires only measured global solar radiation [58]. Knowledge of glazing parameter such as transmission, transmitted solar energy (TSE), and solar heat gain coefficients (SHGC) is essential for building designer and architecture. First time the correlation between vacuum glazing transmission, TSE through vacuum glazing, and SHGC of vacuum glazing has been investigated with clearness index. Results from this investigation are suitable for calculation of building energy using vacuum glazing with less error in northern latitude area.

2 Methodology

Fig. 2 indicates the vertical plane vacuum glazing and different solar radiation incident on it. Glazing transmission throughout a day is not constant but changes. Transmission through vertical plane vacuum glazing can be written as Equation (1) [24].

$$\tau_{vacuum} = \left[k_d \left\{k_T R_b \left(1-k_d\right) + \left(1-\cos\ \beta\right)\left(1-k_T\left(1-k_d\right)\right)\right\} + R_b\left(1-k_d\right) + R_g \frac{1-\cos\ \beta}{2}\right] \times \tau_{dir} R_b \left(1-k_d\right)\left(1+k_d k_T\right) + \frac{\tau_{dif} k_d}{2}\left(1+\cos\ \beta\right)\left(1-k_T\left(1-k_d\right)\right) + \frac{\tau_g R_g \left(1-\cos\ \beta\right)}{2} \quad (1)$$

where Clearness index $k_T = \frac{I_{global,h}}{I_0}$, diffuse factor $k_d = \frac{I_{dif,h}}{I_{global,h}}$, $I_0 = I_{sc}\left(1+0.033\ \cos\frac{360 n_d}{365}\right)\left(\cos\ \varphi\ \cos\ \delta\ \cos\ \omega + \sin\ \varphi\ \sin\ \delta\right)$, and

$$\tau = \frac{1}{2}\left[\frac{1-\left\{\frac{\sin(\theta-n)}{\sin(\theta+n)}\right\}^2}{1+\left(2n_g-1\right)\left\{\frac{\sin(\theta-n)}{\sin(\theta+n)}\right\}} + \frac{1-\left\{\frac{\tan(\theta-n)}{\tan(\theta+n)}\right\}^2}{1+\left(2n_g-1\right)\left[\frac{\tan(\theta-n)}{\tan(\theta+n)}\right]^2}\right] \times \exp\left(\frac{-k_g N_g t_g}{\cos\ \theta}\right)$$

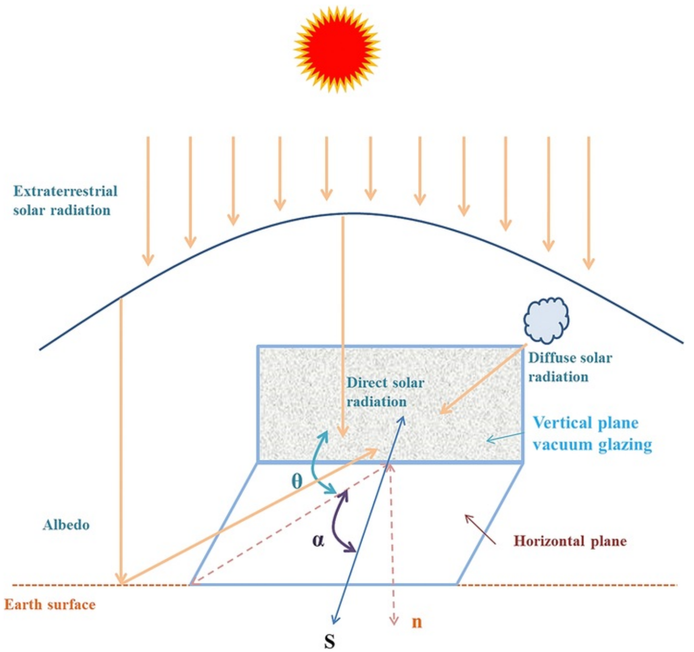

Fig. 2 Schematic diagram of a south facing vertical plane vacuum glazing with incident angle and solar elevation angle.

alt-text: Fig. 2

$\tau = \tau_{dir}$ when $\theta = \theta_{dir}$,

$\tau = \tau_{dif}$ when $\theta = \theta_{dif} = 59.68 - 0.1388\beta + 0.001497\beta^2$ [59]

and $\tau = \tau_g$ when $\theta = \theta_g = 90 - 0.5788\beta + 0.002693\beta^2$ [59]

Transmitted solar energy (TSE) for a vertical plane vacuum glazing can be written as Equation (2) [55].

$$TSE_{vacuum} = \left(I_{beam,h} + I_{dif,h} k_b\right)\tau_{dir} R_b + I_{dif,h}\left(1+k_b\right)\tau_{dif,h}\frac{(1+\cos\ \beta)}{2} + I_{global,h}\rho_g \tau_g \frac{(1-\cos\ \beta)}{2} \quad (2)$$

Dynamic SHGC can be written as Equation (3) [14,50]

$$SHGC = \frac{SE_{vacuum}}{I_{ver,global}} \quad (3)$$

3 Experiments

One SPACIA vacuum glazing as shown in Fig. 3 was provided by Nippon Sheet Glass. The dimension of this glazing was 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. Details of experiment procedures are described in Ghosh et al. [24] and was performed in the year of 2014. A transmission spectrum of the vacuum glazing was performed using AvaSpec-ULS2048L Star Line Versatile Fiber-optic spectrometer under indoor condition. A Kipp and Zonen model SMP11 pyranometer was used to measure global solar radiation incident on the vertical surface.

Fig. 3 Photograph of vacuum glazing.

alt-text: Fig. 3

4 Results

Fig. 4 represents the vacuum glazing transmission spectra.

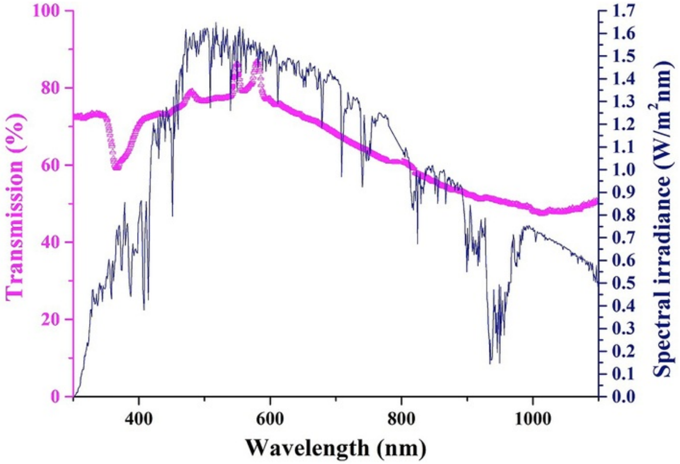

Fig. 4 Transmission spectra of vacuum glazing.

alt-text: Fig. 4

Using Fresnel Equations (4) and (5) absorption reflection of the vacuum glazing can be found. Table 1 represents the properties of vacuum glazing.

$$A_{vacuum} = 1 - (T_{vacuum} + R_{vacuum}) \quad (4)$$

$$R_{vacuum} = \left(\frac{n_{vacuum} - n_{air}}{n_{vacuum} + n_{air}}\right)^2 \quad (5)$$

Table 1 Vacuum glazing properties.

alt-text: Table 1

Vacuum glazing spectral properties	Solar transmission (278–1100 nm)	64%
	Solar absorption	32%
	Visible transmission (380–700 nm)	72%
	Visible absorption	24%
	NIR spectrum absorption (700–1100 nm)	8%

South facing vertical plane vacuum glazing transmission was measured on the 1st of January and on the 1st of July as shown in Fig. 5. During wintertime, transmission through vacuum glazing is higher due to lower elevation angle.

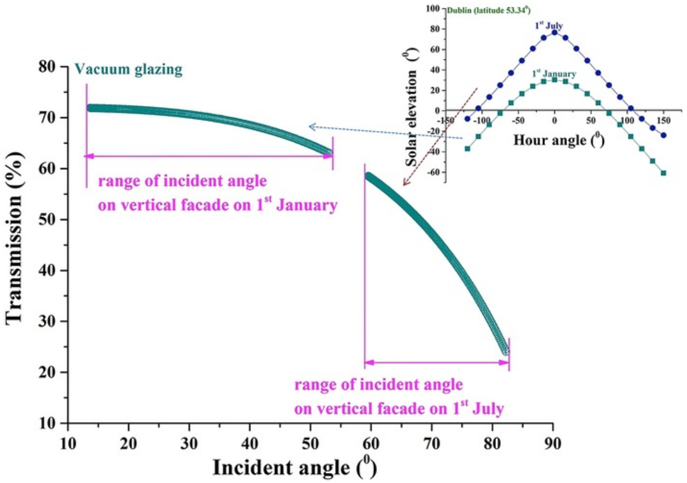

Fig. 5 Variation of vacuum glazing (62% transparent) transmission for different incident angle on 1st of July and on 1st of January.

alt-text: Fig. 5

The variation of vacuum glazing transmittance with clearness index is represented in Fig. 6. Below a clearness index of 0.5, isotropic diffuse transmission was dominant. Above 0.5 clearness index, direct incident solar radiation was dominant and glazing transmittance was linearly correlated with clearness index. In western European location, it is possible to use only one single transmittance value for vertical plane glazing which is associated with isotropic diffuse solar component. This single value will reduce large computational time and/or resources for building design studies [55]. In Dublin, for below 0.5 clearness index, south facing vertical plane vacuum glazing transmission of 35% was found which could be used for building performance using vacuum glazing over the year with negligible error. For different azimuthal direction and below particular clearness index, one single glazing transmittance can be used with less than 1% error, which is listed in Table 2.

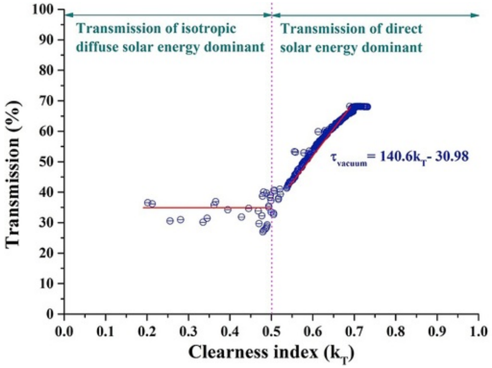

Fig. 6 Variation of vacuum glazing transmittance with clearness index.

alt-text: Fig. 6

Table 2 The clearness index limits for the use of a yearly usable single transmittance, transmitted energy and SHGC value for vertical plane vacuum glazing.

alt-text: Table 2

Inclination	Azimuthal orientation	Transmittance	Transmitted solar energy (W/m^2)	SHGC	Clearness index
Vertical	North	35	87	0.22	0.7
	South	35	87	0.22	0.5
	East	35	87	0.22	0.6
	West	35	87	0.22	0.6
	North east	35	87	0.22	0.6
	North west	35	87	0.22	0.6

Correlation between calculated clearness index and calculated transmitted solar energy (TSE) through vacuum glazing has been presented in Fig. 7. TSE was calculated using Equation (2). TSE is dependent on glazing transmission. Thus, below 0.5 clearness index, vertical plane south facing vacuum glazing offer single yearly useable transmitted solar energy of 87 W/m^2, which can be used for building energy calculation with less than 1% error. For other azimuthal direction different threshold clearness index is possible and below this clearness index solar energy of 87 W/m^2 can be used with less than 1% error. Vertical plane vacuum glazing single solar energy for different azimuthal direction and threshold clearness index for that particular azimuthal direction are listed in Table 2.

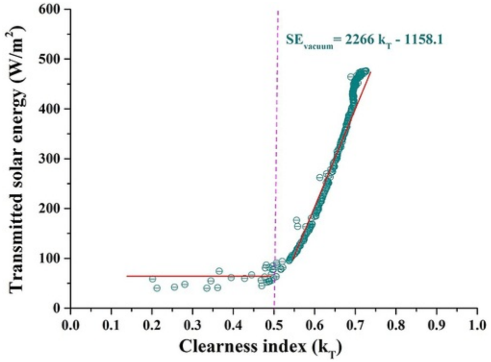

Fig. 7 Variation of transmitted solar energy with clearness index.

alt-text: Fig. 7

Fig. 8 shows the correlation between clearness index and vacuum glazing SHGC. As glazing transmittance is an influential parameter for TSE and SGHC a linear correlation has been found for above 0.5 clearness index. Below 0.5 clearness index, SHGC for south facing vertical plane vacuum glazing was 0.22. Vertical plane vacuum single SHGC for different azimuthal direction and threshold clearness index for that particular azimuthal direction are listed in Table 2.

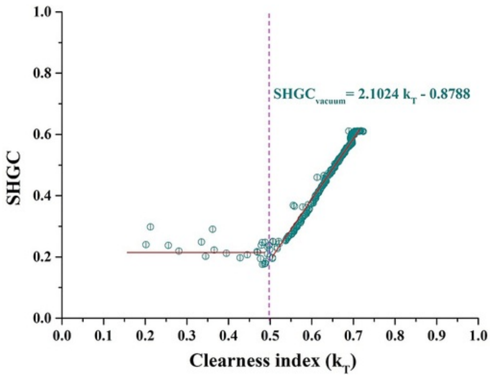

Fig. 8 Variation of solar heat gain coefficient with clearness index.

alt-text: Fig. 8

5 Conclusions

Clearness index is an influential parameter, which need only one single measured data to evaluate. Correlation between clearness index and glazing transmittance, transmitted solar energy (TSE) and solar heat gain coefficients (SHGC) has been evaluated for vacuum glazing. Vertical plane vacuum glazing transmission changes with clearness index. Below clearness index 0.5 majority of transmission is isotropic diffuse and above 0.5, glazing transmission is isotropic direct type. However, one single value of transmission, SHGC, and TSE is possible to use for calculation while clearness index is below 0.5. In Dublin, a south facing vertical plane vacuum glazing below 0.5 clearness index offer 35% glazing transmittance, 87 W/m^2 TSE and 0.24 SGHC and this can be used all over the year with less than 1% calculation error. Building engineer and designer based on their own requirement can use these values without complicated calculation.

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Highlights

- The variation of vacuum glazing transmittance with clearness index is reported.
- Transmittance dependent TSE and SHGC were evaluated for varying clearness index.
- Below 0.5 clearness index, one single glazing transmittance was found.

Queries and Answers

Query: Please provide the grant number for "Higher Education Authority", if any.
Answer: No number available

Query: Reference [60] have been renumbered as [59].
Answer: thanks for correction

Query: Please confirm that given names and surnames have been identified correctly.
Answer: Yes

Query: Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact v.natarajan.2@elsevier.com immediately prior to returning your corrections.
Answer: Yes