The Influence of Isolation on the Thermal Performance of Triple Vacuum Glazing

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Abstract
The thermal performance of triple vacuum glazing subjected to various solar insolation levels was simulated using a finite volume model. Simulation results show that with increasing insolation, the temperatures of the three glass panes increase; however the rate of temperature increase of the middle glass pane is the largest. This is due to the high thermal insulation provided by the vacuum gaps either side of the middle glass pane; consequently the heat absorbed from the sun by the middle glass pane cannot be easily transferred to the indoor and outdoor environments. For 0.5 m by 0.5 m and 1 m by 1 m triple vacuum glazing exposed to isolation levels greater than 200 W.m⁻² and 180 W.m⁻² respectively with four 0.03 emittance coatings, the middle glass sheet temperature is larger than that of the indoor and outdoor glass sheets. Thus the heat absorbed from solar radiation by the middle glass sheet flows to both the indoor and outdoor glass sheets. When the insolation is less than 200 W.m⁻² and 180 W.m⁻² for 0.5 m glazing and 1 m by 1 m glazing respectively, the heat flows from the indoor glass sheet to the middle glass sheet and then to the outdoor glass sheet. For a 0.5 m by 0.5 m triple vacuum glazing with four 0.18 emittance coatings, when insolation is greater than 400 W.m⁻², the middle glass sheet temperature is higher than that of indoor glass sheet.

Introduction
Double vacuum glazing was first patented by Zoller (1913). Since then, many patents have been reported, however only recently was the first successful fabricated vacuum glazing reported by a team from the University of Sydney (Collins and Robinson, 1991). This vacuum glazing used solder glass with a melting point in the region of 450 °C as a vacuum edge seal. Since then a team at the University of Ulster (Hyde et al., 2000, Griffiths et al., 1998) employed an indium based alloy with a melting point of less than 200°C to seal the evacuated space between the glass sheets, making possible the use of a large range of soft low-emittance (low-e) coatings and tempered glass which would otherwise degrade at high sealing temperatures. Using the low temperature indium based edge seal, samples have been fabricated with a heat transmission U-value of 0.90 W.m⁻².K⁻¹ in the centre-of-glazing area for a 0.5 m by 0.5 m sample. More recently research into new sealing techniques (Wittwer V., 2005), outgassing (Minaai et al., 2005; Ng and Collins, 2005), thermal performance modeling and experimental validation (Collins and Simko, 1998; Fang et al., 2005, 2006, 2009a, 2009b, and Zhao et al., 2007) and vacuum glazing application (Trushevski and Mitina, 2008) has been published in peer reviewed scientific journals.

In an attempt to further reduce the heat transmission through the glazing, the concept of triple vacuum glazing as shown in Fig. 1 was presented by a team of Swiss Federal Laboratories for Material Testing and Research with basic mechanical design constraints discussed (Manz et al., 2006). A heat transmission of 0.2 W.m⁻².K⁻¹ in the centre-of-glazing area was predicted when using a stainless steel pillar array with a pillar diameter of 0.3 mm and the four glass surfaces within the two vacuum gaps coated with low-e coatings. The thermal performance of the entire triple vacuum glazing was simulated by Fang et al., (2010) varying parameters such as edge seal width, edge seal material and frame rebate depth. With such a low thermal transmission and consequently a potentially high temperature differential from one side of the glazing to the other, the level of insolation has an important bearing on the thermal performance of the triple vacuum glazing. In the work presented in this paper, a three-dimensional finite volume model was developed to simulate the thermal performance of the entire triple vacuum glazing with the support of...
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The simulated triple vacuum glazing comprised three glass sheets with the four internal glass surfaces coated with low-emittance (low-e) coatings as shown in Fig. 1. A finite volume model (Eames and Norton, 1993) extensively validated experimentally in previous research (Fang et al., 2006) was modified to analyse heat transfer through a triple vacuum glazing under standard winter conditions (EN ISO, 2000) and various insulations. The simple analytic model (Collins and Simko, 1998) developed to predict heat transfer through each individual support pillar of a vacuum glazing was not used in this analysis since the pillar array was incorporated and modeled directly in this analysis since the pillar array was not used in previous research (Fang et al., 2006).

Methodology

The simulated triple vacuum glazing was modulated to analyse heat transfer through a triple vacuum glazing under standard winter conditions (EN ISO, 2000) and various insulations. The simple analytic model (Collins and Simko, 1998) developed to predict heat transfer through each individual support pillar of a vacuum glazing was not used in this analysis since the pillar array was incorporated and modeled directly in the finite volume model. In the model, a square cross section pillar with the same cross sectional area represents the circular cross section pillars of the fabricated system since the pillars with the same cross section conducted similar amounts of heat under same conditions (Holman, 1989). A mesh refined to provide a high density of nodes in and around the pillar was used to enable an accurate prediction of heat transfer in this area. The simulated glazing system comprised four low-e coated glass panes with an emittance of 0.03 and 0.18 separated by two vacuum gaps. Due to symmetry considerations, only one quarter pane of the triple vacuum glazing was modeled to represent the thermal performance of the entire glazing.

In the finite volume model, the rate of radiative heat transfer between each of the finite volume surfaces with areas \( S \) and mean surface temperatures \( T_1 \) and \( T_2 \), that form the two plane parallel glass surfaces containing the vacuum with hemispherical emittance \( e_1 \) and \( e_2 \), was determined (Collins and Simko, 1998) using:

\[
Q_{\text{radiation}} = e_{\text{effective}} \alpha S (T_1^4 - T_2^4) \quad (1)
\]

Where the effective emittance, \( e_{\text{effective}} \), was determined by:

\[
e_{\text{effective}} = \frac{1}{e_1} + \frac{1}{e_2} - 1
\]

Radiation reflectance was assumed to be independent of the wavelength, angle of the incident radiation and surface temperature. The error associated with calculating emittance using equation 2 in this research is about 4% (Zhang et al., 1997). This ignores dependence on surface temperature, the wavelength and angle of incidence of the radiation.

As can be seen from Fig. 2, solar radiation absorbed in each finite volume can be determined by:

\[
dI_{\text{absorbed}} = I_m (A_L - A_{L,1}) dx dy \quad (3)
\]

where \( A_L \) and \( A_{L,1} \) are the intensities of solar radiation at the two surfaces of the finite volume determined using equation 4.

\[
A_L = 1 - e^{-C_L z_L}
\]

where \( C_L \) is the extinction coefficient of glass which is a measure of how well it absorbs electromagnetic radiation (Duffie and Beckman, 1991). Duffie and Beckman (1991) reported that the extinction coefficient of glass varies from 32 m\(^{-1}\) for “greenish edge” glass to 4 m\(^{-1}\) for “white white” glass. In this work \( C_L \) was assumed to be 30 m\(^{-1}\). \( Z_L \) is the path length through the glazing from the front glass surface.

It was assumed that each low-e coating absorbs 10% of the incident solar radiation (Hollands et al., 2001). The radiation absorbed within each finite volume was calculated and included in the energy balance for each finite volume.

Thermal performance of triple vacuum glazing under solar radiation

The thermal performance of a triple vacuum glazing with 0 Wm\(^{-2}\) and 500 Wm\(^{-2}\) insolation was simulated by using the finite volume model described in section 2. The isotherms of the simulated triple vacuum glazing are presented in Fig. 3. The boundary conditions of the simulated triple vacuum glazing are listed in table 1. The other parameters of the glazing are listed in table 2. Fig. 3a shows the temperature gradient from the indoor to the outdoor glass sheets. The large temperature difference between each of the glass sheets was caused by the high thermal insulation provided by each vacuum gap. The heat conduction through the support pillars can be clearly seen. The mean temperature at the centre-of-glazing area is clearly higher than at the edge area due to conduction through the edge seal. Fig. 3b shows that the middle glass sheet temperature is higher than both the indoor and outdoor glass sheets, since the heat absorbed by the middle glass sheet cannot transfer directly to the indoor surface.
to the indoor or outdoor glass sheets due to the high thermal insulation of the two vacuum gaps at either side of middle glass sheet.

With various insolutions incident perpendicular to the outdoor glass surface, the thermal performance of 0.5 m by 0.5 m and 1 m by 1 m triple vacuum glazings with a 6 mm wide indium edge seal were simulated using the boundary conditions of EN ISO 10077-1 (2000) listed in Table 1 and the results are presented in Fig. 4. All other configuration parameters are shown in Table 2.

Fig. 4 shows that for the 0.5 m by 0.5 m triple vacuum glazing, with 0 W.m\(^{-2}\) insolation, the temperatures of the outdoor, middle and indoor glass panes are 0.9 °C, 6.2 °C and 15.2 °C respectively. When the insolation is 900 W.m\(^{-2}\), the temperatures of the outdoor, middle and indoor glass panes are 15.5 °C, 72.4 °C and 45.8 °C respectively. For 1 m by 1 m triple vacuum glazing, with 0 W.m\(^{-2}\) insolation, the temperatures of the outdoor, middle and indoor glass panes are 0.6 °C, 6.3 °C and 16.3 °C respectively. When insolation is 900 W.m\(^{-2}\), the temperatures of the outdoor, middle and indoor glass panes are 14.6 °C, 81.4 °C and 47.9 °C respectively.

With increasing insolation, the temperatures of the three glass panes increase, however the rate in increase of the middle glass pane temperature is the greatest. Due to the high thermal insulation of the vacuum gap, the heat absorbed from solar radiation by the middle glass pane cannot easily flow to the indoor or outdoor glass pane. For 0.5 m by 0.5 m triple vacuum glazing, when the insolation is greater than 200 W.m\(^{-2}\), the middle glass pane temperature is greater than that of the indoor glass pane; for the 1 m by 1 m triple vacuum glazing, when insolation is greater than 180 W.m\(^{-2}\), the middle glass pane temperature is greater than that of the indoor glass pane, thus the heat absorbed from solar radiation by the middle glass pane flows to the indoor and outdoor glass panes.

The outdoor glass pane temperature of the 0.5 m by 0.5 m triple vacuum glazing is greater than that of the 1 m by 1 m triple vacuum glazing; the indoor glass pane temperature of the 0.5 m by 0.5 m triple vacuum glazing is lower than that of the 1 m by 1 m triple vacuum glazing. The middle glass pane temperature of the 0.5 m by 0.5 m triple vacuum glazing is lower than that of 1 m by 1 m triple vacuum glazing. This is because the heat flow from the indoor glass pane to the indoor and outdoor glass panes of the 0.5 m by 0.5 m glazing is greater than that of the 1 m by 1 m glazing system as the thermal conductance of the 0.5 m by 0.5 m glazing is greater than that of the 1 m by 1 m glazing system. Due to the edge conductance influence, the larger the glazing size, the lower the heat transmission of the total glazings area will be (Fang et al., 2010).

The temperature variations of the three glass panes of triple vacuum glazing with low-e coatings of emittance 0.03 and 0.18 subject to various levels of insolation are presented in Fig. 5. This figure shows that subjected to the same insolation level, the indoor glass sheet temperature of the glazing with 0.03 emittance is
higher than that of the glazing with 0.18 emittance coatings, (a maximum difference of 1.9 °C occurred at an insolation of 900 W.m⁻²), while the outdoor glass sheet temperature of the glazing with 0.03 emittance is lower than that with 0.18 emittance coatings (a maximum difference of 1.7 °C occurred at an insolation of 900 W.m⁻²); i.e. the temperature difference between the indoor and outdoor glass sheets of the triple vacuum glazing with 0.03 emittance coatings is larger than that with 0.18 emittance coatings. The middle glass sheet temperature of triple vacuum glazing with 0.03 emittance is larger than that of glazing with 0.18 emittance by 22.6 °C at an insolation of 900 W.m⁻², i.e. when emittance value of four low-e coatings within the triple vacuum glazing are 0.03 and 0.18, the middle glass sheet temperature of the triple vacuum glazing with emittance of 0.03 is significantly larger than that with emittance of 0.18. This is because the radiative heat flow across the vacuum gap of triple vacuum glazing with 0.03 emittance is much lower than that with 0.18 emittance. For a triple vacuum glazing with four 0.03 emittance coatings, when the insolation increases to 200 W.m⁻², the middle glass sheet temperature is higher than that of indoor glass sheet; for the triple vacuum glazing with four 0.18 emittance coatings, when insolation increases to 400 W.m⁻², the middle glass sheet temperature is higher than that of indoor glass sheet.

Conclusions
Simulation results showed that with increasing insolation, the temperatures of the three glass panes increase; however the rate of temperature increase of the middle glass pane is the largest. Due to the high thermal insulation of the vacuum gaps either side of the middle glass pane, the heat absorbed from the sun by the middle glass pane cannot easily transfer to the indoor and outdoor environments. For 0.5 m by 0.5 m triple vacuum glazing, when the insolation is larger than 200 W.m⁻², the middle glass pane temperature is lower than that of the indoor glass pane; for the 1 m by 1 m triple vacuum glazing, when insolation is larger than 180 W.m⁻², the middle glass pane temperature is larger than that of the indoor glass pane. Thus the heat absorbed by the middle glass pane from the solar radiation flows to both the indoor and outdoor glass panes.

For triple vacuum glazing with four low-e coatings of emittance of 0.03 and 0.18, the temperatures both of the indoor and outdoor glass sheets of the two triple vacuum glazing exhibits approximately 2 °C of a difference when the insolation is 900 W.m⁻², however there is a significant temperature difference between the middle glass sheets of the two triple vacuum glazing.

When subjected to an insolation of 900 W.m⁻², the middle glass sheet temperature of the glazing with 0.03 emittance is 22.6 °C larger than that with 0.18 emittance coatings. When the insolation is less than 400 W.m⁻² for 0.5 m by 0.5 m triple vacuum glazing with four 0.18 emittance coatings, the heat flows from the indoor glass pane to the middle glass pane, then to the outdoor glass pane. When the insolation is higher than 400 W.m⁻², the middle glass sheet temperature is higher than that of indoor glass sheet. The heat flows from the middle glass sheet to the indoor glass sheet, then to the indoor environment.

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References