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Enhancing the thermal performance of triple vacuum glazing with low-emittance coatings

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ABSTRACT

The thermal performance of triple vacuum glazing (TVG) with one to four internal glass surfaces coated with a low-e (emittance) coating was simulated using a finite volume model. The simulated TVG comprises three, 4 mm thick glass panes with two vacuum gaps, sealed with indium metal and separated by an array of stainless steel pillars, 0.2 mm high, 0.3 mm diameter and spaced at 25 mm. The simulation results show that decreasing the emittance of the four low-e coatings from 0.18 to 0.03 reduces the heat transmission *U*-values at the centre-of-glazing area from 0.41 W m^{-2} K^{-1} to 0.22 W m^{-2} K^{-1} for a 0.4 m by 0.4 m TVG rebated by 10 mm within a solid wood frame. When using three low-e coatings in the TVG in a heating dominated climate, the vacuum gap with two low-e coatings should be set facing the warm environment, while the vacuum gap with one coating should face the cold environment. When using two low-e coatings with an emittance of 0.03, the *U*-values at the centre-of-glazing area with one coating in both vacuum gaps is 0.25 W m^{-2} K^{-1}; that with two coatings in the cold facing vacuum gap is 0.50 W m^{-2} K^{-1} and that with two low-e coatings in the warm facing vacuum gap is 0.33 W m^{-2} K^{-1}. Thus setting one low-e coating in both vacuum gaps is better than setting two coatings in the same vacuum gap. The thermal performance of fabricated 0.4 m by 0.4 m TVGs with two and three low-e coatings were experimentally characterised and were found to be in very good agreement with simulation results.

1. Introduction

The concept of vacuum glazing was first patented by Zoller [1]. Since the publishing of the patent nearly 90 years ago, there have been many further patents on vacuum glazing [2,3]. However the first fabricated vacuum glazing was reported by a team at the University of Sydney in 1989 which used a solder glass with a melting point of 450 °C to seal the periphery of the vacuum gap [4]. Since then a number of edge sealing techniques have been proposed such as a Spring Band Edge Seal [5], a novel solder glass sealing process [6] and an Alkali Silicate Edge Seal [7]. Collaborating with Baechli [8], the Fraunhofer Institute for Solar Energy Systems [9] developed an edge seal for vacuum glazing based on a sputtered metallic layer and a soldering technique, but this work has not been published in a scientific journal. Recently, EverSealed Windows Inc. (US) [10,11] and the German consortium ProVIG [12] designed a vacuum glazing where a thin, flexible strip of metal is bonded to the glass using ultrasonic welding or a soldering process. This flexible edge seal was designed to accommodate the differential thermal expansion of the glass panes when subjected to a large temperature difference (e.g. 35 °C) between the indoor and outdoor environments. A thermal transmission (*U*-value) of 0.5 W m^{-2} K^{-1} for vacuum glazing using these technologies has been achieved. However, such technologies are still in the development stage.

Using the method developed by the University of Sydney, samples up to 1 m by 1 m with a *U*-value of 0.80 W m^{-2} K^{-1} in the centre-of-glazing area with a pillar diameter of 0.25 mm have been produced in the laboratory [13]. Due to the high fabrication temperature, many soft coatings and tempered glass cannot be used, since both will degrade at this sealing temperature. The second fabrication method was developed by a team at Ulster University [14,15]. In this method, an indium based alloy with a melting temperature of less than 200 °C was used as the edge sealant, making the use of a wide range of soft coatings and tempered glass possible. For 0.4 m by 0.4 m samples, a *U*-value of 0.86 W m^{-2} K^{-1} at the centre-of-glazing area with a pillar diameter of 0.4 mm has been achieved experimentally [16].

It has been shown that when the vacuum pressure between the glass sheets is lower than 0.1 Pa, the heat convection and conduction of gas can be ignored [13]. Both analytic and finite element

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Nomenclature

a	radius of support pillar (m)
h	surface heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
p	pillar separation (m)
R	thermal resistance (m^{-2} K^{-1} W^{-1})
t	thickness of glass pane (m)
T	temperature (°C)
U	thermal transmission (W m^{-2} K^{-1})

Greek letters

ε	hemispheric emittance of a surface
σ	Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
Δ	mean surface temperature difference between glass panes I, II, III.

Subscripts

1 to 6	refer to surfaces of glass panes shown in Fig. 1
I, II, III	refer to the first, second and third glass panes
i,o	refer to warm and cold ambient temperatures
g	glass
m	glass pane number of the TVG
n	vacuum gap number
p	pillar
r	radiation
tot	total resistance of triple vacuum glazing

models have proved that the heat transfer in the centre-of-glazing depends on the heat conduction through the support pillar arrays and radiative heat flow between the glass sheets. Infrared thermographs reveal a small variation in glass surface temperature that occurs over the support pillars [17]. To further reduce heat transfer through the centre-of-glazing area, two possible approaches could be considered. The first is to reduce the pillar diameter or increase the spacing, however beyond certain limits, the glass will fracture. The minimum diameter is restricted by mechanical rules outlined by Collins and Simko [13]. The second possible approach is to reduce radiative heat transfer by reducing the emittance of the low-e coating. The lowest emittance of a soft low-e coating achieved so far is 0.02. When these approaches are at limiting values, the principle way to further reduce the heat transmission of vacuum glazing is to add a second vacuum gap by integrating a third glass sheet with a low-e coating. A team of Swiss Federal Laboratories for Material Testing and Research has presented the viability of triple vacuum glazing (TVG) [18]. The mechanical design constraints were investigated and a *U*-value of 0.2 W m^{-2} K^{-1} in the centre-of-glazing area was predicted when using an array of stainless steel pillars with a diameter of 0.3 mm and four low-e coatings within two vacuum gaps. Based on the finite volume model which has been experimentally validated using double vacuum glazing (DVG) samples [19,20] a three-dimensional finite volume model to simulate the thermal performance of the entire TVG was developed. In this model, the support pillar arrays within the two vacuum gaps were incorporated and modelled directly. The circular cross section of the pillar in a fabricated system was modelled as a square cross section pillar of equal area in the model. It has been proven that the heat flow through the square and circular support pillars with the same cross sectional areas is the same [18]. An optimised mesh is generated with a high density of nodes in and around the pillar to provide high accuracy for the heat transfer calculation. Using this finite volume model, Fang et al. [20] investigated the effect of vacuum gap edge seal material and width, frame rebate depth and glazing size on the thermal performance of the TVG. In previous research on DVG, this finite volume model has been employed to investigate the effect of hard and soft low-e coatings on the thermal performance of DVG and has been experimentally validated [21].

The objective of this paper is to theoretically and experimentally investigate the effects of the emittance value and the number and location of the low-e coated surfaces within the vacuum gaps on the thermal performance of the TVG. Based on the investigation results, optimisation for the low-e coating position on glass surfaces 2–5 (Fig. 1) within two vacuum gaps is then achieved when using one to three low-e coatings in the TVG.

2. Research methodology

The methodology adopted in this research was to use analytic and finite element models to investigate the thermal performance of TVG with a range of low-e coatings. A number of TVGs with various coating setting methods were fabricated and their *U*-values experimentally determined by using a guarded hot box calorimeter developed at Ulster University. The experimentally determined *U*-values are compared with the simulation results.

2.1. Heat transfer through TVG

The schematic diagram of a TVG cross section showing heat transfer mechanisms through the glazing components is shown in Fig. 1, which is not to scale. The support pillars and vacuum gap widths are significantly exaggerated.

Fig. 1 shows the heat transfer across the TVG by: (1) conduction and radiation from the indoor ambient to the glass pane surface 6, (2) conduction across the indoor side glass pane to surface 5; (3) radiation between surfaces 5 and 4, conduction through the pillar array within vacuum gap 2 and heat conduction through the edge seal of vacuum gap 2; (4) conduction across the middle glass pane from surface 4 to surface 3; (5) radiation between surfaces 3 and 2, conduction through the pillar array within vacuum gap 1 and conduction through the edge seal of vacuum gap 1; (6) conduction across the outdoor glass pane from surface 2 to surface 1; (7) convection and radiation from the cold side surface 1 to the cold ambient. The analytic and finite element models for analysing the heat flow through the centre-of-glazing were established by Manz et al. [18]. The heat transmissions calculated by both models were in very good agreement.

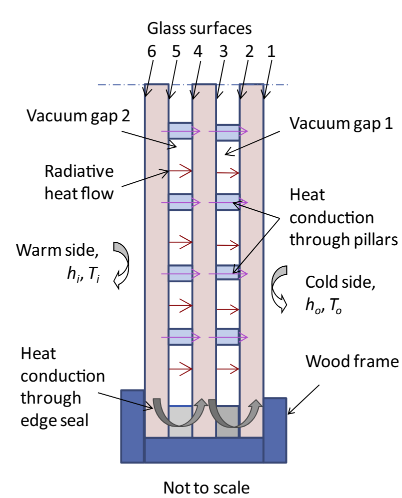

Fig. 1. Schematic diagram of a TVG cross section and heat flow mechanism across the TVG.