Optimising the Thermal Performance of Triple Vacuum Glazing with Low-emittance Coatings

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OPTIMISING THE THERMAL PERFORMANCE OF TRIPLE VACUUM GLAZING WITH LOW-EMITTANCE COATINGS

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ABSTRACT

The thermal performance of the triple vacuum glazing with one to four internal glass surfaces coated with a low-e (emittance) coating was simulated using a finite volume model. The simulated triple vacuum glazing 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 decreases 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 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 environment vacuum gap is 0.50 $W.m^{-2}.K^{-1}$ and that with two low-e coatings in the warm facing environment 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.

KEY WORDS: Triple vacuum glazing, low-emittance coating, thermal performance, finite volume model

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. However the first fabricated vacuum glazing was reported by a team of the University of Sydney in 1989 which used a solder glass with a melting point of 450 ºC to seal the periphery of the vacuum gap [2]. Collaborating with Baechli [3], the Fraunhofer Institute for Solar Energy Systems [4] 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)[5, 6] and the German consortium ProVIG [7] 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 ºC) between the indoor and outdoor glass panes. A thermal transmission 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 heat transmission (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 [8]. Due to the high fabrication temperature, many soft coatings and tempered glass cannot be used, since many soft coatings and tempered glass will degrade at this sealing temperature. The second fabrication method was developed by a team at the University of Ulster [9, 10]. 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 [11].

It has been shown that when the vacuum pressure between the two glass sheets is lower than 0.1 Pa, the heat convection and conduction of gas can be ignored [8]. Both analytic and finite element 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 two glass sheets. 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 [8]. 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 low-e coatings. A team of Swiss Federal Laboratories for Material Testing and Research has presented the viability of triple vacuum glazing (TVG) [12]. 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 [13, 14] 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 [12]. An optimized 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. [14] investigated the effect of vacuum gap edge seal material and width, frame rebate depth and glazing size on the thermal performance of the TVG. This paper investigated the effects of emittance of low-e coating on one to four glass surfaces in the two vacuum gaps of 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 [15].

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 $(m^2.K.W^{-1})$
t	Thickness of glass pane (m)
T	Temperature (ºC)
U	Thermal transmission $(W.m^{-2}.K^{-1})$

Greek letters

ε	Hemispheric emittance of a surface
σ	Stefan-Boltzmann constant $(5.67 \times 10^{-8} W.m^{-2}.K^{-4})$

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

2. 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.
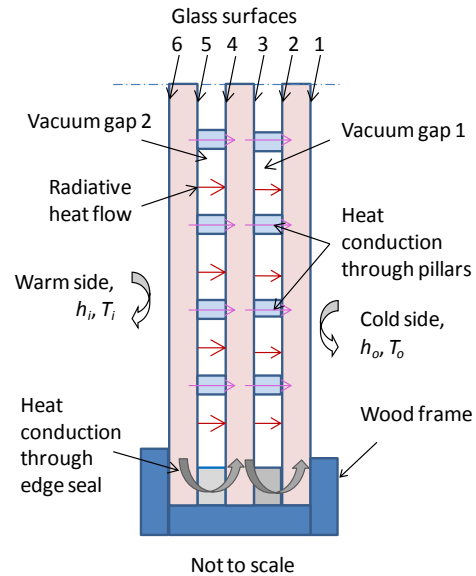

Fig. 1 Schematic diagram of a TVG cross section and heat flow mechanism across the TVG.

The support pillars within the vacuum gaps of TVG were 0.3 mm in diameter with a height of 0.2 mm and were set in square pattern separated by 25 mm. The TVG was rebated by 10 mm within a solid wood frame. 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 4 and 5, 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 2 and 3, 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; 5) 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 Mans et al. [12]. The heat transmissions calculated by both models were in very good agreement.

2.1 ANALYTIC MODEL APPROACH

To ease the analysis of the influence of low-e coating on the TVG thermal performance, the thermal network [12, 14] of a 25 mm by 25 mm unit cell with a pillar in the centre at the centre-of-glazing area is presented in Fig. 2 (a) and (b).
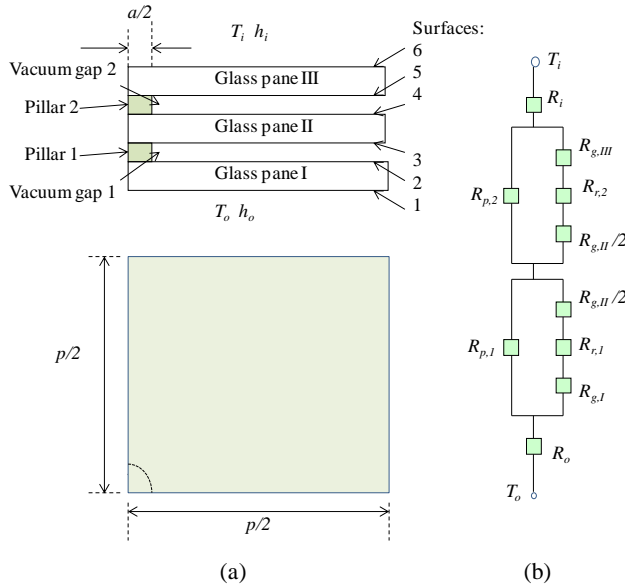

(a)   (b)

Fig. 2 Schematics of a quarter of a unit cell (a) and its thermal network at the central glazing area (b) [14].

The thermal resistance associated with the heat flow per m^2 due to heat conduction of each glass pane is given by:

$$R_{g,m} = \frac{t_m}{k_g} \tag{1}$$

where t_m is the thickness of glass pane m, where $m \in (I, II, III)$, k_g is the thermal conductivity of glass.

The thermal resistance associated with radiative heat flow between the glass surfaces within each of the vacuum gaps is:

$$R_{r,1} = (\frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_3} - 1)(4\sigma T_{2,3}^3)^{-1} = (4\varepsilon_{2,3}\sigma T_{2,3}^3)^{-1} \tag{2}$$

$$R_{r,2} = (\frac{1}{\varepsilon_4} + \frac{1}{\varepsilon_5} - 1)(4\sigma T_{4,5}^3)^{-1} = (4\varepsilon_{4,5}\sigma T_{4,5}^3)^{-1} \tag{3}$$

where ε_2, ε_3, ε_4 and ε_5 are the hemispheric emittance of glass surfaces 2, 3, 4, and 5 within vacuum gaps 1 and 2 as shown in Figs. 1 and 2; the $\varepsilon_{2,3}$ and $\varepsilon_{4,5}$ are combined effective emittances of surfaces in vacuum gaps 2 and 1; σ is the Stefan-Boltzmann constant; $T_{2,3}$ and $T_{4,5}$ are the mean temperatures of glass surfaces 2, 3 and 4, 5 respectively in vacuum gaps 1 and 2 in Kelvin. The thermal resistance associated with the heat conduction through the support pillars in vacuum gap n (1 or 2) is determined by equation 4 [8]:

$$R_{p,n} = \frac{p^2}{2k_g a} \tag{4}$$

where a is the radius of the cylindrical pillar. The thermal resistance of the middle glass pane is divided into two equal thermal resistances, therefore the total thermal resistance associated with the heat flow between surfaces 1 and 6 is determined by equation 5:

$$R_{tot} = \frac{R_{p,1}(R_{g,1} + R_{r,1} + \frac{1}{2}R_{g,II})}{R_{p,1} + R_{g,1} + R_{r,1} + \frac{1}{2}R_{g,II}} + \frac{R_{p,2}(R_{g,III} + R_{r,2} + \frac{1}{2}R_{g,II})}{R_{p,2} + R_{g,III} + R_{r,2} + \frac{1}{2}R_{g,II}} \tag{5}$$

The thermal resistances associated with the heat flows R_i and R_o at the glazing surfaces 6 and 1 are the inverse of the surface heat transfer coefficients, i.e. $R_i = 1/h_i$ and $R_o = 1/h_o$. The total heat transmission [12] of the unit cell at the centre-of-glazing area is then given by:

$$U_{tot} = \frac{1}{R_i + R_{tot} + R_o} \tag{6}$$

The heat flow through the entire TVG is the sum of heat flow across the centre-of-glazing area and the heat flow through the edge area including the heat conduction through the edge seal, whose analytic model is presented in literature [8].

2.2 FINITE VOLUME APPROACH

The finite volume model of Fang et al., [13] for DVG was adapted to suit the structure of TVG. The heat transmission calculated for TVG using this finite volume model was in very good agreement with that of Manz et al [12] and Fang et al. [14]. The detailed description for the finite volume model is presented in Fang et al., [15]. The simulated thermal transmission of a standard unit containing a pillar in the centre of a 25 mm by 25 mm centre-of-glazing area was in good agreement with the result calculated using the analytical model with a 1.8% variation [14] which is comparable with the variation (2%) of Manz et al. [12]. With the 85×85 nodes distributed on the *y* and *z* directions on the glazing surface and with 20 nodes on the *x* direction, the thermal transmission of double vacuum glazing at the centre-of-glazing for DVG with emittance of 0.02 was determined to be 0.36 W.m^{-2}.K^{-1} with a glass pane thickness of 6 mm. This is comparable to the findings of Griffiths et al. [10] and Fang et al. [14] Mans et al. [12]. This level of agreement is satisfactory to simulate a practical heat flow with high accuracy.

3. INFLUENCE OF LOW-E COATINGS ON THE THERMAL PERFORMANCE OF TVG

The simulated TVGs consisted of three 4 mm thick glass panes, sealed by two indium alloy based edge seals 6 mm wide and rebated into a solid wood frame with a rebate depth of 10 mm as shown in Fig. 1. The two 0.12 mm wide vacuum gaps were maintained by two pillar arrays with a pillar diameter of 0.3 mm and spaced at 25 mm. The thermal conductivity of indium alloy, glass, pillar and wood frame were 83.7 W.m^{-1}.K^{-1}, 1 W.m^{-1}.K^{-1}, 20 W.m^{-1}.K^{-1} and 0.17 W.m^{-1}.K^{-1} respectively. In the simulation the air temperatures in the hot and cold sides were 20 ℃ and 0 ℃; the glazing surface heat transfer coefficients at the hot and cold sides were 7.7 W.m^{-2}.K^{-1} and 25 W.m^{-2}.K^{-1} respectively in accordance with the requirement of ISO standard 10077-1[16].

3.1 TVG WITH FOUR LOW-E COATINGS

With these boundary conditions and configuration parameters the thermal performance of TVG with four low-e coatings with 0.03 and 0.18 emittance were calculated. The use of four coatings within the TVG is the best case scenario. With the boundary conditions above and configuration parameters, the 3-D isotherms of the 0.4 m by 0.4 m TVG with four 0.03 emittance coatings were calculated and are illustrated in Fig. 3, which show the temperature gradient across the three glass panes due to the high thermal resistance of the two vacuum gaps.
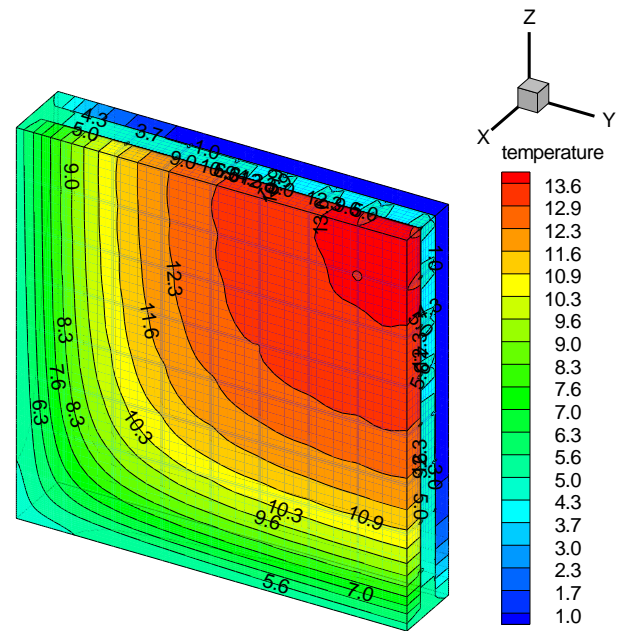

Fig. 3 Isotherms of TVG with four 0.03 emittance low-e coatings.

For a TVG with four low-e coatings of 0.03 emittance, the U-values of the centre-of-glazing and total glazing areas are 0.22 W.m^{-2}.K^{-1} and 0.64 W.m^{-2}.K^{-1}, which are comparable to the result of Manz et al. (2006). The mean surface temperature difference between the indoor and outdoor glass panes is 10.8 °C, that between the indoor and middle glass panes is 7.5 °C and that between the outdoor and middle glass panes is 3.3 °C. For a TVG with four low-e coatings of 0.18 emittance, the U-values of the centre-of-glazing and total glazing areas are 0.41 W.m^{-2}.K^{-1} and 0.80 W.m^{-2}.K^{-1}. The mean surface temperature difference between the indoor and outdoor glass panes is 9.4 °C, that between the indoor and middle glass panes is 5.8 °C and that between the outdoor and middle glass panes is 3.6 °C. Thus the temperature difference between the indoor and outdoor glass panes with an emittance of 0.03 is 1.4 °C higher than that with an emittance of 0.18. Equations 2 and 3 show that although the effective emittances $\varepsilon_{2,3}$ and $\varepsilon_{4,5}$ of the two opposite surfaces within vacuum gaps 1 and 2 are equal, a difference in the mean temperatures $T_{2,3}$, and $T_{4,5}$ of glass surfaces 2, 3 and 4, 5 in vacuum gaps 1 and 2 results in a difference in the thermal resistances $R_{1,r}$, and $R_{2,r}$ of vacuum gaps 1 and 2. The thermal transmission U-values at the centre-of-glazing and total glazing areas of the TVG with four low-e coatings with emittance of 0.03 and 0.18 rebated within a solid wooden frame with a 10 mm rebate depth are shown in Fig. 4. For comparison, the U-values of DVG with two low-e coatings with emittances of 0.03 and 0.18 rebated within a solid wood frame with a 10 mm rebate depth are also included in Fig. 4.
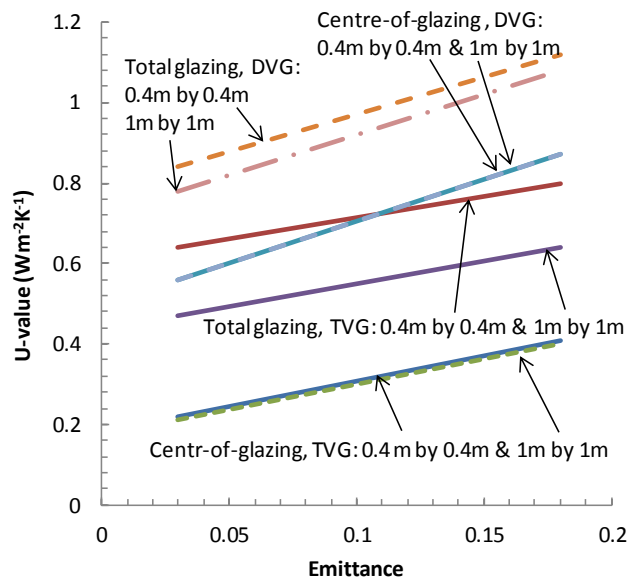
Fig. 4 U-value of the TVGs with four low-e coatings with various emittances of low-e coatings.

Fig, 4 shows that if using 0.18 emittance low-e coatings, the difference in U-value between the 0.4 m by 0.4 m or 1 m by 1 m DVG and TVG is larger than that if using 0.03 emittance low-e coatings. The difference in U-value at the total glazing area between the 1 m by 1 m TVG and DVG is larger than that between the 0.4 m by 0.4 m TVG and DVG. Fig. 4 also shows that the difference in U-value of the total glazing area between the 0.4 m by 0.4 m and 1 m by 1 m TVGs is much larger than that between the 0.4 m by 0.4 m and 1 m by 1 m DVG, since lateral heat conduction through the edge area of the TVG is larger than that of the DVG. This indicates that larger size TVGs have a greater advantage over smaller size DVGs in comparison to the DVG.

3.2 TVG WITH THREE LOW-E COATINGS

In the first stage of TVG fabrication, a low-e coated glass is used with one coating in one vacuum gap and with two coatings in the second vacuum gap with a 10 mm frame rebate depth within a solid wood frame. In the simulation, two methods for setting the orientation of the low-e coatings were considered. In method 1, one coating was set at both surfaces 2 and 3 in the cold side vacuum gap and one coating was set at surface 5 in the warm side vacuum gap as shown in Fig. 1; in method 2, one coating was set at surface 2 and one coating was set at both surfaces 4 and 5. The U-values at the centre-of-glazing and total glazing areas of the TVGs with 0.4 m by 0.4 m and 1 m by 1 m dimensions and three low-e coatings with emittance between 0.03 and 0.18 with setting methods 1 and 2 were calculated and are presented Fig. 5.
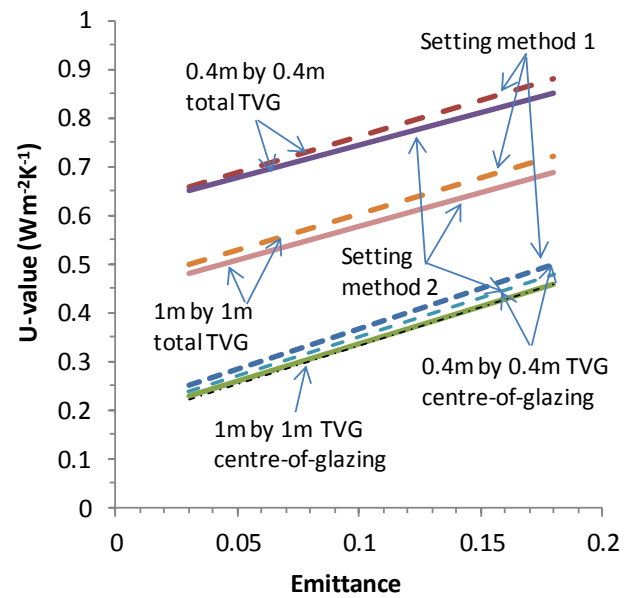

Fig. 5 U-value at centre-of-glazing and total glazing areas of TVGs with three low-e coatings.

Fig. 5 shows that for the TVG with three low-e coatings, the difference in U-values at the centre-of-glazing area between 0.4 m by 0.4 m and 1 m by 1 m TVG with setting methods 1 and 2 is negligible. The difference in U-values of the total glazing areas of the 0.4 m by 0.4 m and 1 m by 1 m TVGs with 0.18 emittance coatings is larger than that with 0.03 emittance coatings, although this difference is very small. These results indicate that when using three 0.18 emittance coatings in a TVG, setting method 2 provides lower thermal transmittance than setting method 1; when using three 0.03 emittance coatings, the setting method is less important compared to using 0.18 emittance coatings. For 0.4 m by 0.4 m TVG with three 0.03 emittance coatings, the difference in U-value of the total glazing area between the setting method 1 and 2 is negligible.

3.3 TVG WITH TWO LOW-E COATINGS

The U-values of 0.4 m by 0.4 m and 1 m by 1 m TVGs with two low-e coatings with emittances between 0.03 and 0.18 were calculated and are presented in Figs. 6 and 7. Three setting methods of the two low-e coatings were considered. Setting method 3: one coating set in each of the two vacuum gaps at surfaces 5 and 2 (defined in Fig. 1); Setting method 4: two coatings in the outdoor side vacuum gap at surfaces 3 and 2; Setting method 5: two coatings in the indoor side vacuum gap at surfaces 4 and 5. The U-value of 0.4 m by 0.4 m and 1 m by 1 m TVGs with 0.03 emittance coatings using the three setting methods are compared in Fig. 8.
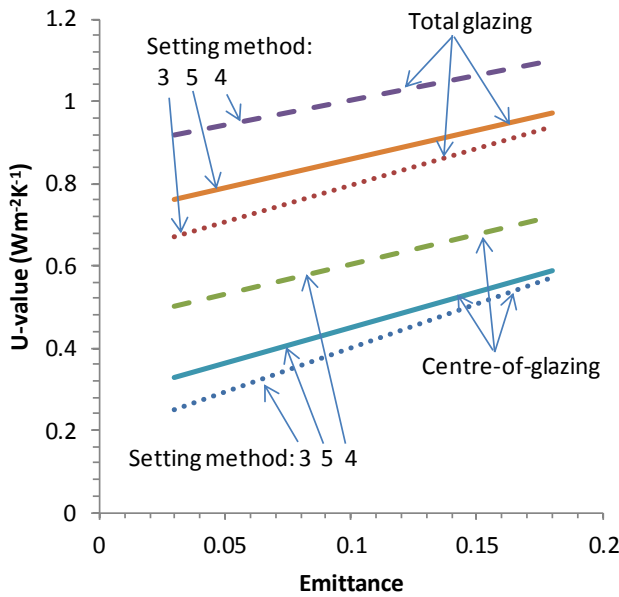
Fig. 6 U-values at the centre-of-glazing and the total glazing areas of the 0.4 m by 0.4 m TVGs with two low-e coatings in setting methods 3, 4, 5.

Fig. 6 shows that for 0.4 m by 0.4 m TVG with two coatings, setting one coating in both of the vacuum gaps (setting method 3) gives the lowest U-value, while setting the two coatings in the vacuum gap at the outdoor side (setting method 4) gives the highest U-value; the U-value of the TVG with two coatings in the indoor side vacuum gap (setting method 5) is in between. These are reflected by the temperature differences between the indoor and outdoor glass panes in setting methods 3, 4, 5, which are 10.5 $^{\circ}$C, 8.6 $^{\circ}$C and 9.3 $^{\circ}$C respectively. These results are in good agreement with those calculated using equations 1 to 6 of the analytic model explained in section 2.1. The U-values at the centre-of-glazing of the 0.4 m by 0.4 m TVGs with emittance of 0.03 when using setting methods 3, 4, and 5 are 0.25 $W.m^{-2}.K^{-1}$, 0.5 $W.m^{-2}.K^{-1}$ and 0.33 $W.m^{-2}.K^{-1}$ respectively; those of the total glazing area are 0.67 $W.m^{-2}.K^{-1}$, 0.93 $W.m^{-2}.K^{-1}$ and 0.76 $W.m^{-2}.K^{-1}$ respectively.

In Fig. 7, the U-values at the centre-of-glazing area of 1 m by 1 m TVGs with emittance of 0.03 in setting methods 3, 4, and 5 are calculated to be 0.25 $W.m^{-2}.K^{-1}$, 0.39 $W.m^{-2}.K^{-1}$ and 0.33 $W.m^{-2}.K^{-1}$ respectively; those of the total glazing area are 0.5 $W.m^{-2}.K^{-1}$, 0.68 $W.m^{-2}.K^{-1}$ and 0.59 $W.m^{-2}.K^{-1}$ respectively. These indicate that when using two coatings in TVG, the one coating should be set in each of the vacuum gaps. Comparing Figs. 5 and 6, it can be seen that the difference in U-values for setting methods 3, 4 and 5 for the 0.4 m by 0.4 m TVG is larger than that for the 1 m by 1 m TVG. This means that for 0.4 m by 0.4 m TVG with two low-e coatings, the influence of setting method is more significant compared to the 1 m by 1 m TVG. This is due to increased lateral heat transfer

through the edge area of the 0.4 m by 0.4 m TVG compared to that of the 1 m by 1 m TVG.
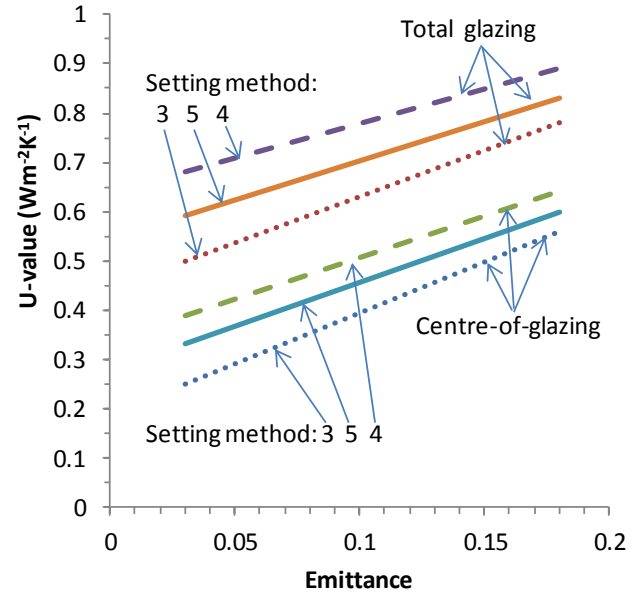

Fig. 7 U-values at the centre-of-glazing and the total glazing areas of the 1 m by 1 m TVGs with two low-e coatings in setting methods 3, 4, 5.
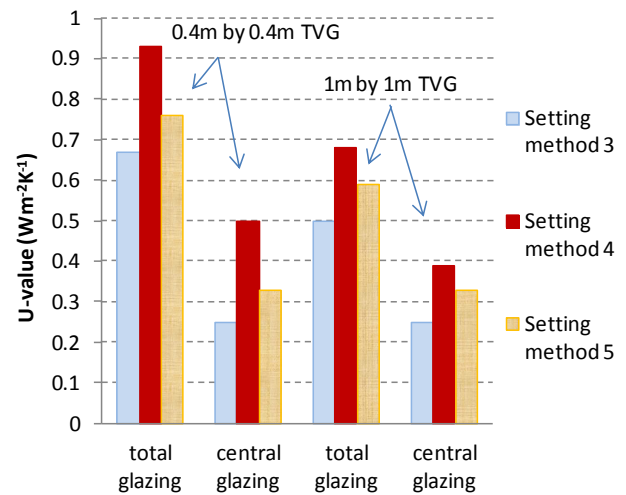

Fig. 8 Comparison of U-value of TVGs with two 0.03 emittance coatings using different setting methods.

Fig. 8 shows that with setting methods 3 and 5, the U-values at the centre-of-glazing of 0.4 m by 0.4 m and 1 m by 1 m TVGs with two 0.03 emittance coatings are approximately the same; while with setting method 4, the U-value at the centre-of-glazing of 0.4 m by 0.4 m TVG is larger than that of the 1 m by 1 m TVG. This is because in method 4, there is increased lateral heat conduction from

the indoor glass pane to the middle and outdoor glass panes compared to that in methods 3 and 5, and therefore the U-value at the centre-of-glazing area of 0.4 m by 0.4 m TVG is larger than that of 1 m by 1 m TVG.

3.4 TVG WITH ONE LOW-E COATING

When using only one coating with an emittance of 0.03 in the 0.4 m by 0.4 m TVG, the U-values at the centre-of-glazing and total glazing areas were calculated and illustrated in Fig. 9. Two setting methods were considered: a) one low-e coating in the outdoor facing vacuum gap on surface 2; b) one low-e coating in the indoor facing vacuum gap on surface 5. The U-values of 0.4 m by 0.4 m and 1 m by 1 m TVGs with both setting methods are compared in Fig. 10.
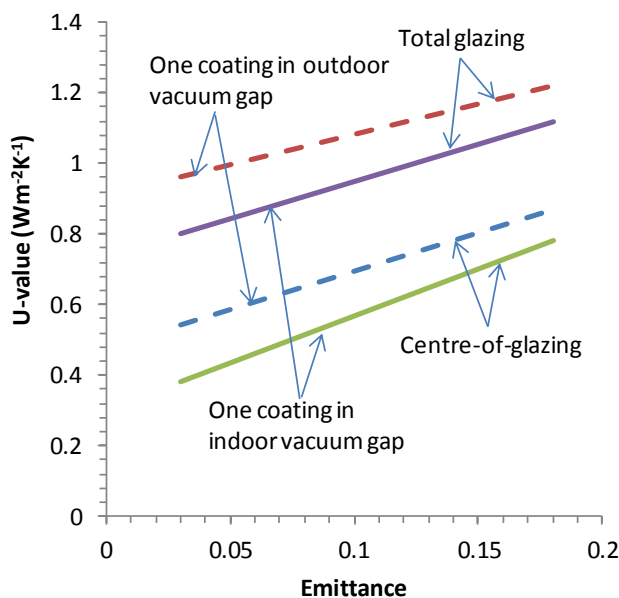

Fig. 9 U-values of 0.4 m by 0.4 m TVGs with one low-e coating in the indoor and outdoor side vacuum gaps.

Figs. 9 and 10 shows that for 0.4 m by 0.4 m and 1 m by 1 m TVGs, the U-values at both the centre-of-glazing and total glazing area with one coating in the outdoor vacuum gap are larger than those with one coating in the indoor vacuum gap. The difference in U-value of the total glazing area from using the two setting methods is larger for the 0.4 m by 0.4 m TVG compared to the 1 m by 1 m TVG. Fig. 10 also shows that with one coating in the indoor vacuum gap, the U-value at the centre-of-glazing area of the 0.4 m by 0.4 m and 1 m by 1 m TVGs are approximately same, but with one coating in the outdoor vacuum gap, the U-value at the centre-of-glazing area of the 0.4 m by 0.4 m TVG is larger than that of the 1 m by 1 m TVG. This is because: firstly, without a coating in the indoor side vacuum gap, radiative heat transfer across the indoor side vacuum gap is much larger than with a coating

in the indoor side vacuum gap; Secondly, increased radiative heat transfer from the indoor glass pane to the middle glass pane is then conducted through the edge seal to the outdoor glass panes by lateral heat transfer, leading to an increased U-value at the centre-of-glazing of the 0.4 m by 0.4 m TVG compared to the 1 m by 1m TVG. When the single coating is set in the indoor vacuum gap in both 0.4 m by 0.4 m and 1 m by 1 m TVGs, the lateral heat transfer through the edge seal is much smaller than that when the single coating is set in the outdoor vacuum gap. This indicates that the low-e coating at the indoor glass pane is very important for reducing the radiative heat transfer across the indoor side vacuum gap and lateral heat transfer through the edge seal of the indoor side vacuum gap of the TVG.
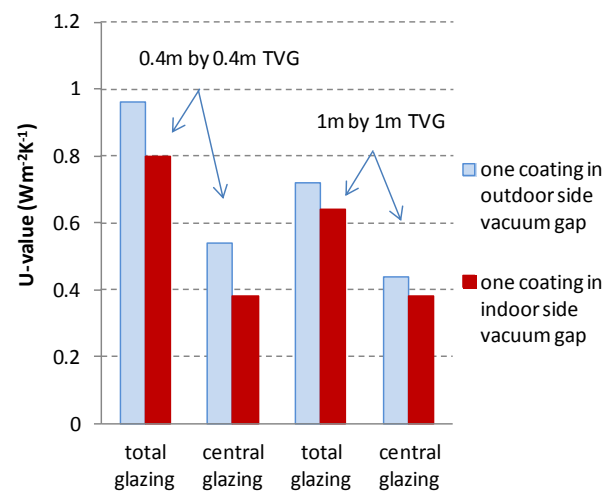

Fig. 10 U-values of TVGs with one 0.03 emittance low-e coating.

3.5 COMPARISON OF THERMAL PERFORMANCE OF TVG WITH ONE, TWO, THREE AND FOUR LOW-E COATINGS

The U-values of the 0.4 m by 0.4 m and 1 m by 1 m TVGs with one coating at surface 5, two at surfaces 2 and 5, three at surfaces 3, 4, and 5 and four at surfaces 2, 3, 4 and 5 with emittance of 0.03 and 0.18 are compared in Figs. 11 and 12. Based on the number of coatings within the TVG the setting methods giving a lowest thermal transmittance are selected.
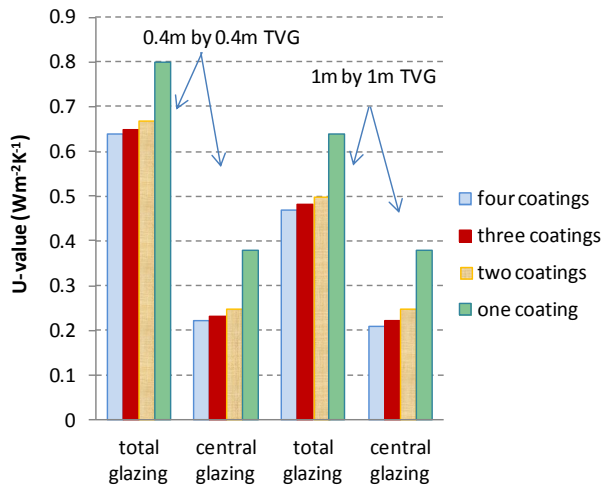
Fig. 11 Comparison of U-values of TVG with one, two, three and four 0.03 emittance coatings.
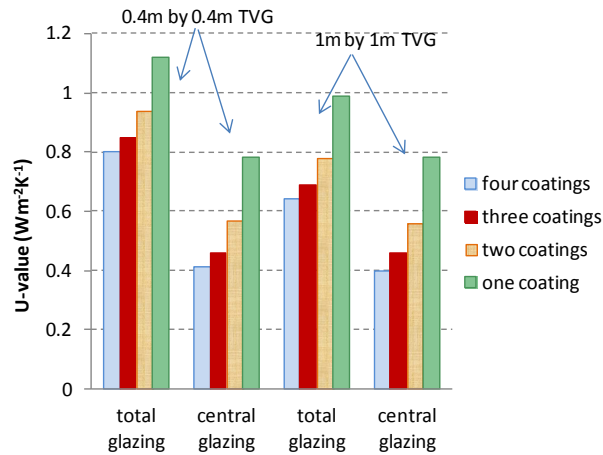

Fig. 12 Comparison of U-values of TVG with one, two, three and four 0.18 emittance coatings.

Figures 11 and 12 show that the U-value decreases with increasing the number of low-e coatings. The difference in U-value between TVGs with one and two coatings is much larger than that of the TVGs with two and three coatings. The difference in U-value at both the centre-of-glazing and total glazing areas of TVGs with two and three low-e coatings is larger than that of TVGs with three and four low-e coatings. This indicates that the impact of the number of low-e coatings on the thermal performance of TVG decreases, with an increasing number of coatings. In Fig. 10, the difference in U-value at centre-of-glazing and total glazing areas of TVGs with three and four 0.03 emittance coatings is small. Therefore when applying 0.03 emittance coatings, using two coatings (one in both vacuum gaps) is more practical than using three low-e coatings in the TVG due to increased solar heat gain and visible light transmission. Comparing Fig.

11 and Fig. 12 it can be seen that the difference in U-value of TVG as a result of increasing the number of 0.18 emittance coatings is larger than that as a result of increasing the number of 0.03 emittance coatings. This is because the U-value of the TVG with 0.03 emittance coatings is much lower than that with 0.18 emittance coatings. When using 0.18 emittance coatings in a TVG, applying three coatings is practical in terms of thermal performance improvement.

4. EXPERIMENTAL VALIDATION OF THE THERMAL PERFORMANCE OF TVG WITH TWO AND THREE LOW-E COATINGS

Two 0.4 m by 0.4 m TVG with three, 4 mm thick glass panes were fabricated using the method detailed by Arya et al. [17]. Three low-e coated glass panes with emittance of 0.18 were used within the first TVG and two low-e coated glass panes with emittance of 0.18 in the second TVG. The U-values of the TVG were experimentally determined using a guarded hot box calorimeter [12]. Two tests were undertaken for the first TVG, i) the three coatings were set at surfaces 2, 3 and 5, which is referred to as TVG1; ii) the three coatings were set at surfaces 2, 4, and 5, which is referred to as TVG2. Two tests were undertaken for the second TVG: iii) two coatings were set at surfaces 2 and 3, which is referred to as TVG3; iv) two coatings were set at surfaces 4 and 5, which is referred to as TVG4. The experimentally determined U-values are presented in Table 1. The ambient conditions are listed in Table 2. A double vacuum glazing was fabricated using the pump out method [11] and characterised using the guarded hot box and presented in Table 1 as a comparison.

Table 1 Comparison of the predicted and experimentally measured U-values of the TVG with two and three 0.18 emittance low-e coatings.

Number of coatings	DVG & HVG	Predicted U-value (W.m⁻².K⁻¹)		Measured U-value (W.m⁻².K⁻¹)	
		Central glazing	Total glazing	Central glazing	Total glazing
2	DVG	0.85	1.12	0.88	1.16
3	TVG1	0.50	0.88	0.53	0.91
	TVG2	0.46	0.85	0.48	0.88
2	TVG3	0.72	1.10	0.77	1.14
	TVG4	0.57	0.94	0.60	0.97

Table 2 Ambient conditions in the guarded hot box calorimeter.

Sample type	Air temperature (°C)		Surface heat transfer coefficient (W.m^{-2}.K^{-1})	
	Hot box	Cold box	Hot box	Cold box
DVG	19.0	-0.3	5.79	17.91
TVG1	18.2	-0.3	6.59	14.94
TVG2	18.2	-0.3	6.59	15.13
TVG3	17.5	-0.3	9.41	19.41
TVG4	17.6	-0.3	8.62	17.12

Table 1 shows that the experimentally determined and predicted U-values are in very good agreement. Although the U-values at the centre-of-glazing area of the 0.4 m by 0.4 m TVG are much lower than that of the DVG, the difference in U-value of the total glazing areas between the DVG and TVG is less than that at the centre-of-glazing area. This is because the lateral heat conduction through the edge of TVG is larger than that of DVG, which compromises the U-value of the total glazing area of the TVG. As there is no low-e coating in the indoor side vacuum gap for TVG3, the edge effect is larger than that for TVG4 with two low-e coatings in the indoor side vacuum gap. For 1 m by 1 m DVG and TVG, the scenario would be different. Similar to the discussion in section 3.3, the U-values at the centre-of-glazing and total glazing area of the 1 m by 1 m TVG in setting methods 4 and 5 are much lower than that of 1 m by 1 m DVG compared to 0.4 m by 0.4 m TVG and DVG, since the influence of the edge effect within 1 m by 1 m TVG is much lower than that within 0.4 m by 0.4 m TVG. This leads to a lower U-value for the total glazing area of 1 m by 1 m TVG compared to that of the DVG. The experimental validation for a larger sample with dimensions of 1 m by 1 m will be undertaken in the next stage of the work.

5. CONCLUSIONS

The influence of emittance and location of low-e coatings on the thermal performance of 0.4 m by 0.4 m and 1 m by 1 m TVGs with a 10 mm frame rebate were simulated using a finite volume model. The TVG comprised three 4 mm thick glass panes with two vacuum gaps and a 6 mm wide indium alloy edge seal. The two vacuum gaps were separated by support pillars with a diameter of 0.3 mm, height of 0.2 mm and spaced at 25 mm. The simulation results show that for a 0.4 m by 0.4 m TVG with three low-e coatings, the vacuum gap with two low-e coatings should be set facing the warm (indoor) side, while the vacuum gap with one coating should face

the outdoor side. This is due to the greater thermal resistance of the vacuum gap with 2 low-e coatings at the warm indoor environment.

With two 0.03 emittance coatings within a TVG, the U-value 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 outdoor side vacuum gap is 0.50 W.m^{-2}.K^{-1} and that with two low-e coatings in the indoor side vacuum gap is 0.33 W.m^{-2}.K^{-1}. Setting one low-e coating in each of the vacuum gaps gives significantly lower thermal transmittance compared to setting both coatings in the same vacuum gap. If using one low-e coating in TVG it should be set in the indoor side vacuum gap. The location of low-e coatings within the TVG is significant for achieving a low U-value. The first coating in the vacuum gap at the indoor glass pane most efficiently reduces radiative heat flow across the TVG. The impact of the second, third and fourth low-e coatings on reducing heat flow across the TVG decreases accordingly. This conclusion can be practically applied in the fabrication of TVG. Without incurring extra cost, the correct setting of low-e coating secures better thermal performance of the TVG. The use of a single low-e coating in a TVG significantly compromised the advantage of two vacuum gaps, thus it is not practical for the TVG applications.

ACKNOWLEDGEMENT

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