Vacuum Glazing with Tempered Glass Panes

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Abstract: The application of tempered glass has made it possible to significantly reduce the support pillar number within evacuated glazing (EG) since tempered glass (T-glass) is four to ten times mechanically stronger than annealed glass (A-glass). The thermal transmittance (U-value) of 0.4 m by 0.4 m double evacuated glazing (DVG) with 4 mm thick T-glass and A-glass panes with emittance of 0.03 were determined to be 0.3 $Wm^{-2}K^{-1}$ and 0.57 $Wm^{-2}K^{-1}$, respectively (47.4% improvement) using previously experimentally validated finite volume model. The thermal transmittance (U-value) of 0.4 m by 0.4 m triple evacuated glazing (TVG) with 4 mm thick T-glass and A-glass panes with emittance of 0.03 were determined to be 0.28 $Wm^{-2}K^{-1}$ and 0.11 $Wm^{-2}K^{-1}$, respectively (60.7% improvement). The improvement in the U-value of EG with T-glass is due to a reduction in support pillar number, leading to reduction in heat conduction through pillar array. The impact of tempered glass on the thermal transmittance for TVG is greater than that of DVG since radiative heat transfer in TVG is much lower than that in DVG, thus the reduction in heat conduction resulted from the reduction of support pillar number in TVG is much larger than that in DVG.

Key words: Evacuated glazing, A-glass; T-glass, thermal performance and support pillar

1. Introduction

Buildings were responsible for approximately 40% of the total energy consumption in 2014 in the EU according to a recent International Energy Agency (IEA) report (Cuce and Cuce, 2016). Windows are generally considered the weakest component of the building in terms of energy efficiency, and can contribute to 60% of energy loss in the buildings (Jelle et al., 2012; Manz and Menti, 2012). Significant research (Cuce et al., 2015, 2016) has been undertaken to reduce the thermal transmission U-value of windows, such as multi-layer glazing (Wang and Wang, 2016), suspended particle device switchable

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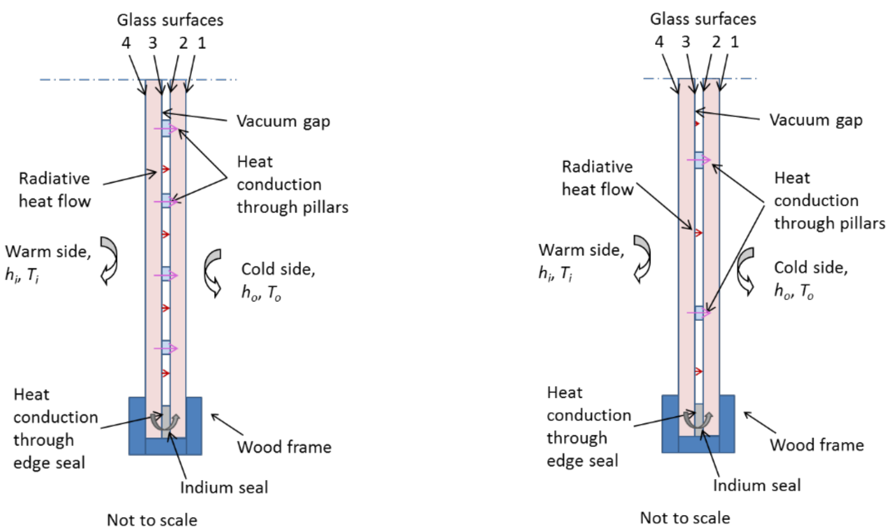
glazing (Ghosh et al., 2016), glazing with suspended films (Frost et al., 1996,), vacuum glazing (Manz, 2008; Collins and Simko, 1998; Fang et al., 2014; Arya, 2014), triple vacuum glazing (Fang et al., 2015), aerogel glazing (Schultz et al., 2005) and hybrid vacuum glazing (Fang et al., 2013). A range of smart glazing technologies have been developed to provide thermal and visual comfort and generate electricity, such as electrochromic vacuum glazing (Fang et al., 2014), insulating glazing with inTVGrated blinds embedded with cooling pipes (Shen, 2016), heat insulating solar glass (Cucu et al., 2016), and PV glazing (Fung and Yang, 2008). Amongst these glazing technologies vacuum glazing provides a promising solution for reducing heat loss through windows due to its extremely low U-value, high solar heat gain and thinner profile compared to other systems. This work focuses on further improving the U-value of EG by applying T-glass with low-e coatings.

The significant theoretical and experimental work have been done for EG sealed by solder glass and indium alloy as sealant (Collins and Simko, 1998; Fang et al., 2016). The solder glass technique has been very mature which has been used by Nippon Sheet Glass for commercialized EG. The melting point of typical solder glass is about 450 ^{o}C, which restrict the application of T-glass into evacuated glazing, since at such high temperature, T-glass will lose temper. However applying T-glass into evacuated glazing can significantly reduce the number of support pillar, since T-glass is four to ten times stronger than annealed glass. The lower the pillar number, the lower the heat flow through the pillars within evacuate glazing. Consequently, strenuous work have been undertaking to reduce the melting point of T-glass, with melting point of 380 ^{o}C achieved to date. Panasonic Company has commercialised evacuated glazing with T-glass using this technique.
DVG samples were successfully fabricated using indium a sealing material with a melting temperature of about 156°C (Hyde et al., 2000). LandVac Glass company has independently developed a low temperature sealing technique and used in their production line for evacuated glazing and now the company has a big portion of glazing market in China. Both techniques have been proved to be viable for T-glass evacuated glazing, but both have advantages and disadvantages which will be discussed in our future paper. In this paper, the potential thermal performance of DVG and TVG with T-glass under ISO winter conditions is investigated. This work will contribute to the development and application of evacuated glazing with T-glass since many building codes require the use of T-glass.

2. Methodology

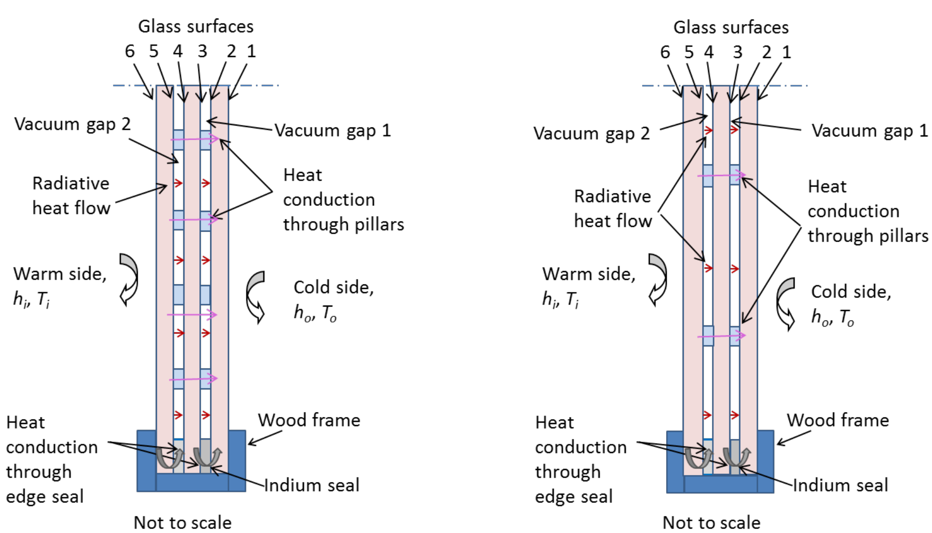
2.1 Heat transfer through DVG and TVG

Figures 1 shows the configurations (not to scale) of DVG which comprise two A-glass (Fig. 1a) and two T-glass (Fig. 1b). The pillar separation of the DVG in Fig. 1(b) with T-glass glass is twice those of the DVG with A-glass in Fig. 1(a). Figures 2 shows the configurations (not to scale) of TVG which comprise three A-glass (Fig. 1a) and three T-glass (Fig. 1b). The pillar separation of the TVG in Fig. 2(b) with T-glass glass is twice those of the TVG with A-glass in Fig. 2(a). Heat conduction though pillar arrays and edge seal, radiative heat transfer between internal surfaces of vacuum gap, convective heat transfer on the warm and code side glass surfaces are presented in Figs. 1 and 2.



(1a) (1b)

Fig. 1 Schematics of DVG with A-glass (1a) and T-glass (1b) glass. The pillar separation in Fig. 1b is twice that in Fig. 1a.



(a) (b)

Fig. 2 Schematics of TVG with A-glass (2a) and T-glass (2b) glass. The pillar separation in Fig. 2b is twice that in Fig. 2a.

Analytical and finite element models of heat transfer through DVG and TVG have been experimentally validated (Collins and Simko, 1998; Fang et al., 2016). They are employed to analyze the heat transfer though the U-value of DVG and TVG and their comparison in this work.

2.2 Analytical and finite volume model of DVG and TVG

Analytical models of DVG and TVG have been investigated by teams at Sydney (Collins and Simko, 1998) and at the Swiss Federal Laboratories (Manz et al., 2006), which were compared with numerical models developed by Sydney, Swiss and Ulster University teams independently (Fang et al., 2014). The simulation results by both analytic and finite volume models (FVM) were experimentally validated (Collins and Simko, 1998; Fang et al., 2014). The details of this work can be accessed in the literature. The analytical models clearly show that the larger the pillar separation, the lower the heat conduction contribution to the total heat transfer through the pillar arrays of DVG and TVG. This work modified these validated models to suit the specifications of DVG and TVG with a pillar separation twice that of conventional DVG and TVG with A-glass.

3. Simulated U-values of DVG and TVG with T-glass

The U-value of DVG and TVG (0.4 m by 0.4 m and 1 m by 1 m) with a 10 mm rebate depth in a solid wood frame were calculated under ISO standard winter boundary conditions (ISO, 2017) using a finite volume model. The evacuated glazing samples were assumed to have 6 mm wide metal edge seal and an array of support pillars with 0.4 mm diameter. The boundary conditions and parameters of DVG and TVG are listed in table 1.

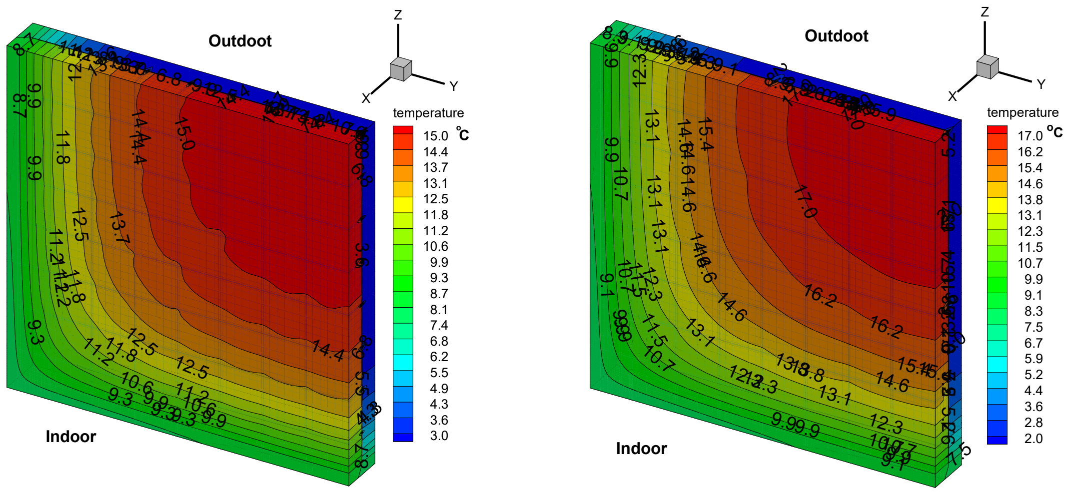
Table 1

	Ambient temperature (°C)	Heat transfer coefficient ($Wm^{-2}K^{-1}$)
Warm side	20	7.7
Cold side	0	25

The thermal conductivities of the metal edge seal, glass panes, stainless steel pillars and wood frame are 83.7 $Wm^{-1}K^{-1}$, 1 $Wm^{-1}K^{-1}$, 20.0 $Wm^{-1}K$-1 and 0.14 $Wm^{-1}K^{-1}$, respectively.

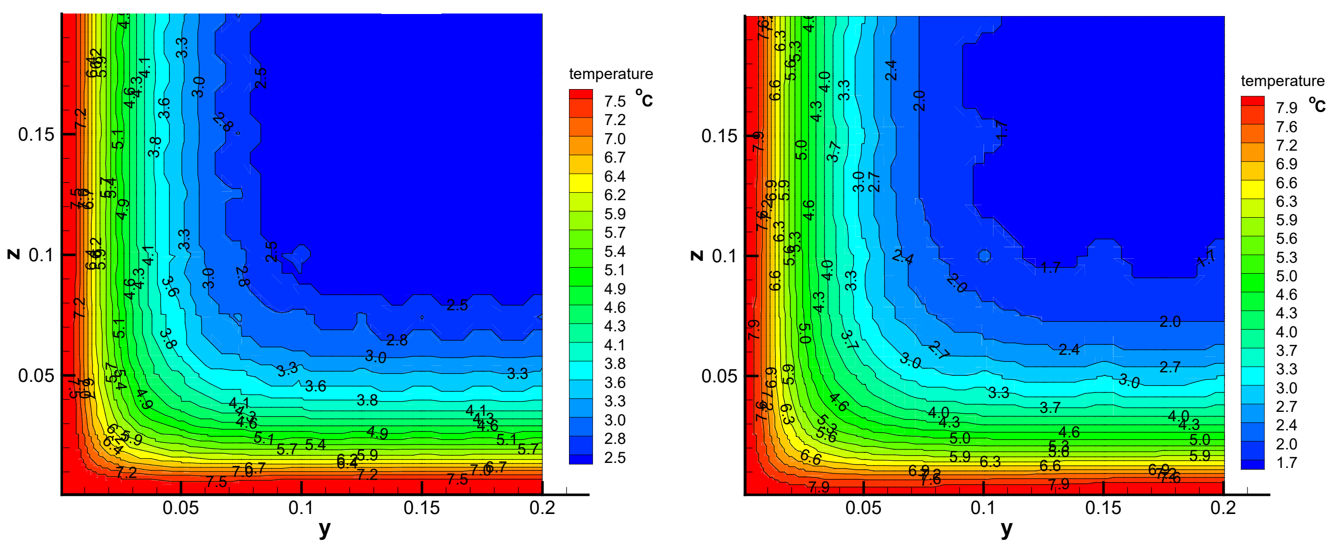
3.1 The U-value of DVG with T-glass panes

Since the mechanical strength of T-glass is four to ten times stronger than A-glass, even if the pillar separation is significantly increased, the tensile stress on the external surface of glass panes above support pillars will not cause mechanical fracture within the service time of the evacuated glazing. Collins et al., (1999) reported that for 4 mm thick A-glass, the usual pillar space is between 20 to 25 mm and for 4mm T-glass, the pillar spacing can be increased to 54 mm. In this work, the pillar space of 50 mm is employed for both DVG and TVG with 4 mm thick T-glass panes. The 3-D isotherms on the warm and cold side glass panes of DVG with A-glass and T-glass panes coated with low-e coatings of 0.03 emissivity were calculated using the FVM and presented in Figs. 3 and 4.



(3a) (3b)

Fig. 3 3-D isotherms of DVG with A-glass (3a) and T-glass (3b) with 0.03 emittance low-e coatings.



(4a) (4b)

Fig. 4 Isotherms of the cold side glass panes of DVG with A-glass (4a) and T-glass (4b).

Figure 3(a) shows that the mean temperature at the centre-of-glazing area of DVG with A-glass is 15ºC and Fig. 3(b) shows the temperature at the centre-of-glazing area of DVG with T-glass is 17ºC which is clearly higher than that of the DVG with A-glass. Fig. 4(a) shows that the mean temperature at the centre-of-glazing region of the cold side surface of DVG with A-glass is 2.5ºC and Fig. 4(b) shows that the mean temperature at the centre-of-glazing area of the cold side surface of the DVG with T-glass is 1.7 ºC. Since the temperature of the warm side glass pane of the DVG with T-glass is higher than that of the DVG with A-glass and the temperature of the cold side glass pane of the DVG with T-glass is lower than that of the DVG with A-glass, DVG with T-glass provides enhanced insulation properties than DVG with A-glass panes.

In Figure 5, the dotted lines are the temperature lines on the cold and warm side glass surface right above one row of support pillars of the DVG with A-glass and the solid lines are the temperature lines on the cold and warm side glass surfaces right above one row of support pillars of the DVG with T-glass. The emittance of low-e coating on the A-glass and T-glass are 0.03.

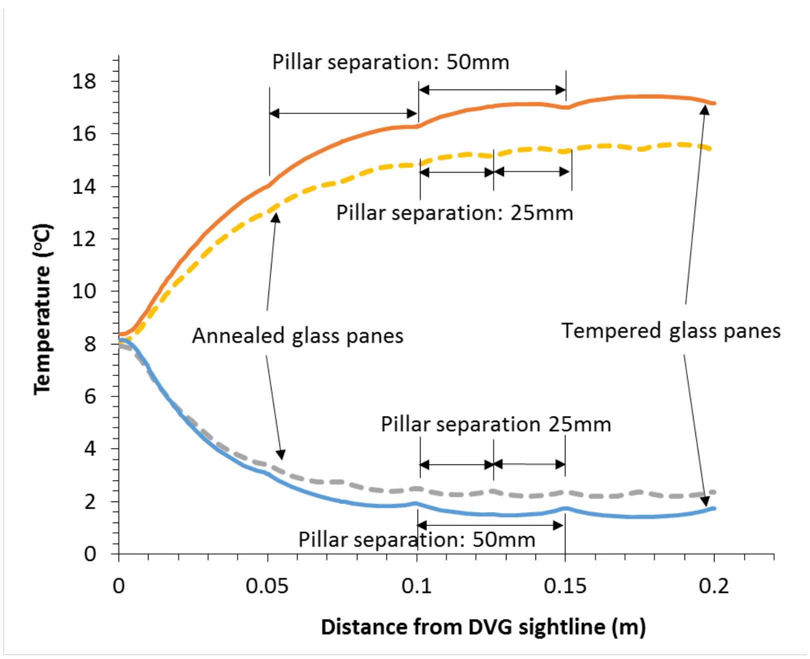


Fig. 5 Comparison of temperature profiles of the 0.4 m by 0.4 m DVG with A-glass and T-glass coated with 0.03 emittance coatings.

Both dotted and solid temperature lines in Figure 5 are periodical. The variation period of the dotted lines is 25 mm and that of solid lines is 50 mm. These resulted from the heat conduction through the support pillars of DVG with 25 mm pillar spacing for DVG with A-glass and with 50 mm pillar spacing for the DVG with T-glass. The distance between the two solid lines at the cold and warm side glass panes is clearly larger than that of between the two dotted lines, which indicates the DVG with the T-glass (corresponding to solid lines) exhibits apparently higher thermal insulation than the DVG with A-glass (corresponding to dotted lines). The U-value of 0.4 m by 0.4 m and 1 m by 1 m DVG with A-glass and T-glass are calculated using FVM and presented in table 2. In table 2, U stands for U-value, the subscript "T,c" stand for " centre-of-glazing area of T-glass pane", "A,c" stands for "centre-of-glazing area of A-glass panes", "T,t" stands for " total area of T-glass pane", "A,t" stands for "total glazing area of A-glass panes" and "Imp" represents "improvement".

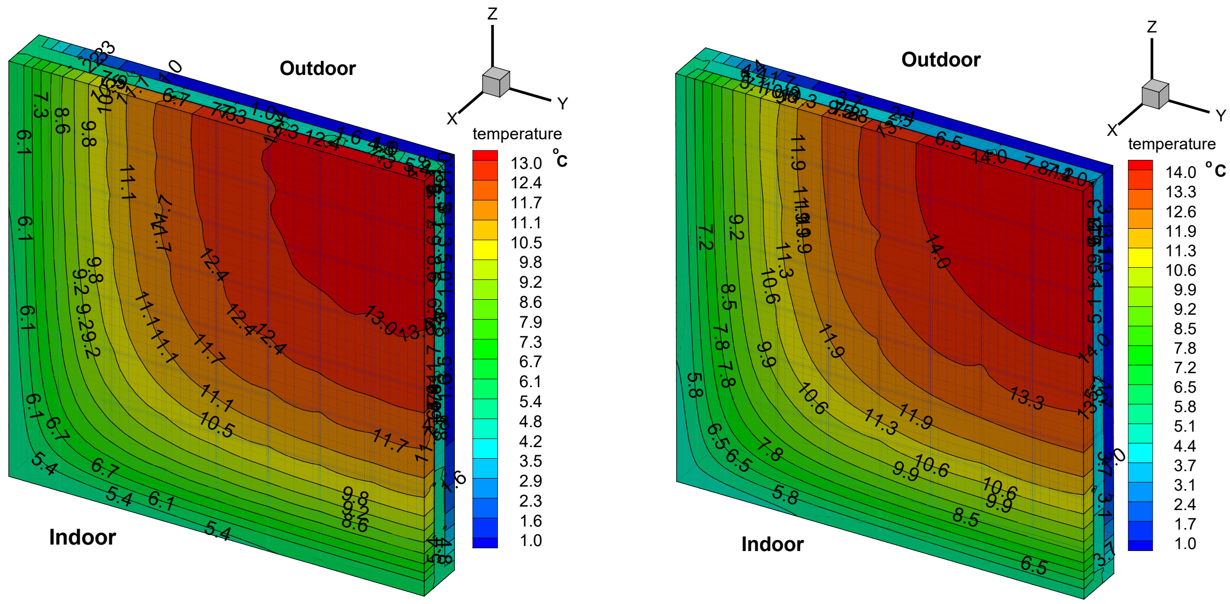
Table 2. U-values of 0.4 m by 0.4 m (A_1) and 1 m by 1 m (A_2) DVG with T-glass and A-glass coated with low-e coatings of 0.03 emissivity.

Glazing size	U centre-of-glazing (W m^{-2} K^{-1})		Imp. (%)	U total glazing (W m^{-2} K^{-1})		Imp. (%)
	$U_{T,c}$	$U_{A,c}$		$U_{T,t}$	$U_{A,t}$	
A1	0.30	0.57	47.4	0.53	0.73	27.4
A2	0.30	0.57	47.4	0.48	0.69	30.4

Table 2 shows that the improvement in the U-value at the centre-of-glazing area of both 0.4 m by 0.4 m and 1 m by 1 m DVG with T-glass compared to DVG with A-glass is 47.4% and the improvement in the U-value of total glazing area of 0.4 m by 0.4 m DVG due to the use of T-glass compared to DVG with A-glass is 27.4%. Due to the influence of heat conduction through the edge seal, the improvement (27.4%) in the U-value of total glazing is lower than that (47.4%) at the centre-of-glazing area, but it is still considerably good performance improvement. The improvements in the U-value of total glazing area of 1 m by 1 m DVG with T-glass compared to DVG with A-glass is 30.4%. Replacing A-glass with T-glass panes in 1 m by 1 m DVG achieves a larger improvement (30.4%) in the U-value of total glazing are compared to that (27.4%) of a smaller sized DVG.

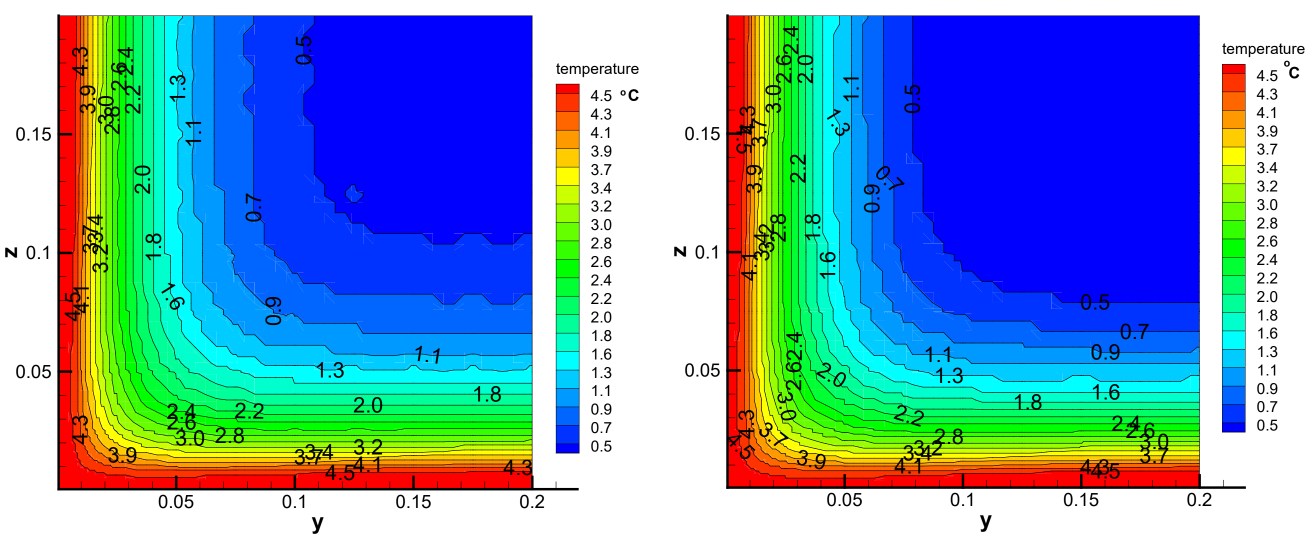
3.2 The U-value of TVG with T-glass

The 3-D isotherms of TVG facing the warm and cold side for TVG made with A-glass and T-glass coated with low-e coatings of 0.03 emissivity were calculated and presented in Figures 6 and 7.



(6a) (6b)

Fig. 6 3-D Isotherms of TVG with A-glass (6a) and T-glass (6b).



(7a) (7b)

Fig. 7 Isotherms of the cold side glass panes of TVG A-glass (7a) and T-glass (7b).

Figures 6(a) and 6(b) shows that the mean temperature (14 °C) at the centre-of-glazing region of the warm side pane of the TVG with T-glass shown in Fig. 6(b) is higher than that (13 °C) of the TVG with A-glass shown in Fig. 6(a). Fig. 7 shows that the T-glass TVG has a larger area with a temperature less than 0.5°C shown in Fig. 7(b) than TVG with annealed glass shown in Fig. 7(a). Consequently, the temperature difference between the warm and cold side glass of the T-glass TVG is significantly larger than that of the A-glass TVG, thus it provides enhanced thermal insulation compared to the A-glass TVG.

In Figure 8, the dotted lines are the temperature lines on the cold and warm side glass surface right above one row of support pillars of the TVG with A-glass panes, and the solid lines are the temperature lines on the cold and warm side glass surfaces right above one row of support pillars of the DVG with T-glass. Both T-glass and A-glass panes had low-e coatings of 0.03 emissivity.

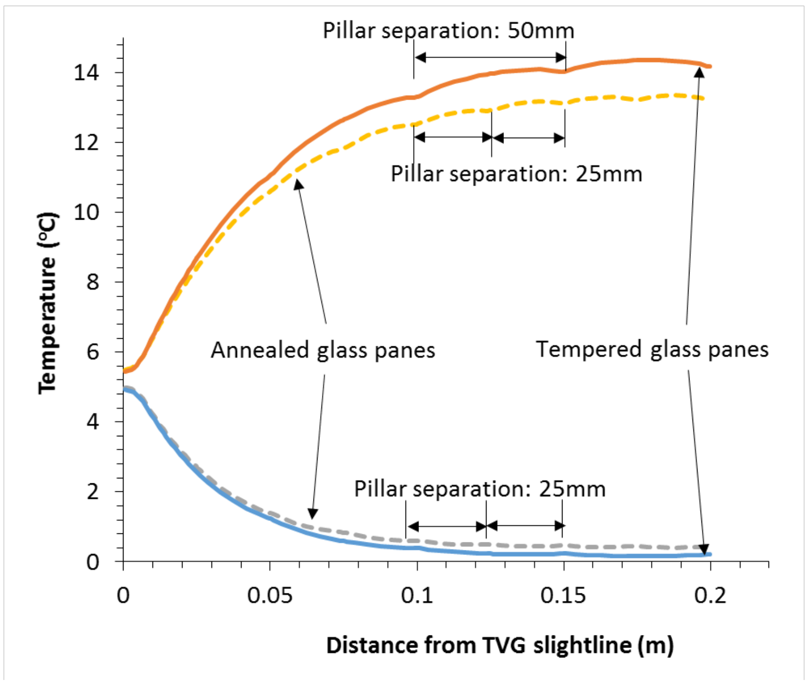


Fig. 8 Comparison of the temperature profiles of 0.4 m by 0.4 m TVG with A-glass and T-glass.

In Figure 8 both dotted and solid temperature lines are periodically distributed. The variation period of the dotted lines is 25 mm and that of solid lines is 50 mm. These resulted from the heat conduction through the support pillars of TVG with 25 mm pillar spacing for TVG with A-glass and with 50 mm pillar spacing for the TVG with T-glass. The distance between the two solid lines at the cold and warm side glass panes is clearly larger than that of between the two dotted lines, which indicates the TVG with the T-glass (corresponding to solid lines) exhibits apparently higher thermal insulation than the TVG with A-glass (corresponding to dotted lines). The U-values of 0.4 m by 0.4 m and 1 m by 1 m TVG with A-glass and T-glass are calculated using FVM and presented in table 3.

Table 3 U-values of 0.4 m by 0.4 m (A_1) and 1 m by 1 m (A_2) TVG with T-glass and A-glass.

Glazing size	U centre-of- glazing ($W\ m^{-2}\ K^{-1}$)		Imp. (%)	U- total glazing ($W\ m^{-2}\ K^{-1}$)		Imp. (%)
	$U_{T,c}$	$U_{A,c}$		$U_{T,t}$	$U_{A,t}$	
A_1	0.11	0.28	60.7	0.57	0.69	17.4
A_2	0.11	0.28	60.7	0.40	0.52	23.1

Table 3 shows that the improvements in the U-value at the centre-of-glazing area of both 0.4 m by 0.4 m and 1 m by 1 m TVG with T-glass compared to TVG with A-glass is 60.7% and the improvements in the U-value of the total glazing of 0.4 m by 0.4 m TVG due to the use of T-glass compared to TVG with A-glass is 17.4%. The improvement (17.4%) in the U-value of total glazing is lower than that (60.7%) at the centre-of-glazing area, the influence of heat flow through the edge seal is significant compared to DVG in table 2. The improvements in U-value of total glazing of 1 m by 1 m TVG with T-glass compared to DVG with A-glass is 23.1%. Replacing A-glass with T-glass panes in 1 m by 1 m TVG achieves a larger improvement (23.1%) in U-value of total glazing compared to that (17.4%) of a smaller sized TVG.

4. Further work on DVG with T-glass

Despite the fact that fabricated DVG with tempered glass panes coated with two low-e coatings with emissivity of 0.16 exhibited a U-value significantly lower than the best performing conventional double glazing (0.69 $Wm^{-2}K^{-1}$ compared to 1.0 $Wm^{-2}K^{-1}$), challenges during the fabrication process may prevent adoption of the fabrication methodology by industry for production lines. To predict the potential maximum bending of the glass panes between the support pillars, finite element software (ABAQUS) was used to simulate a vacuum glazing with the same specifications of the fabricated sample; (a pillar diameter of 0.4 mm, height of 0.15 mm, spacing of 50 mm, Young's Modulus of 70 GPa and Poisson's Ratio of: 0.22) the results of which are presented in Figure 11. Due to bending of the glass panes under atmospheric pressure, the glass panes would approach each other, however a minimum separation of 0.05 mm would be maintained between the panes at a pillar spacing of 50 mm. Although this separation is acceptable the distortion caused by roller wave could still result in contact points between the glass panes. Chemically toughened glass panes may help to solve this problem as the chemical toughening process does not affect the flatness of the glass panes (XINOLOGY, 2018).

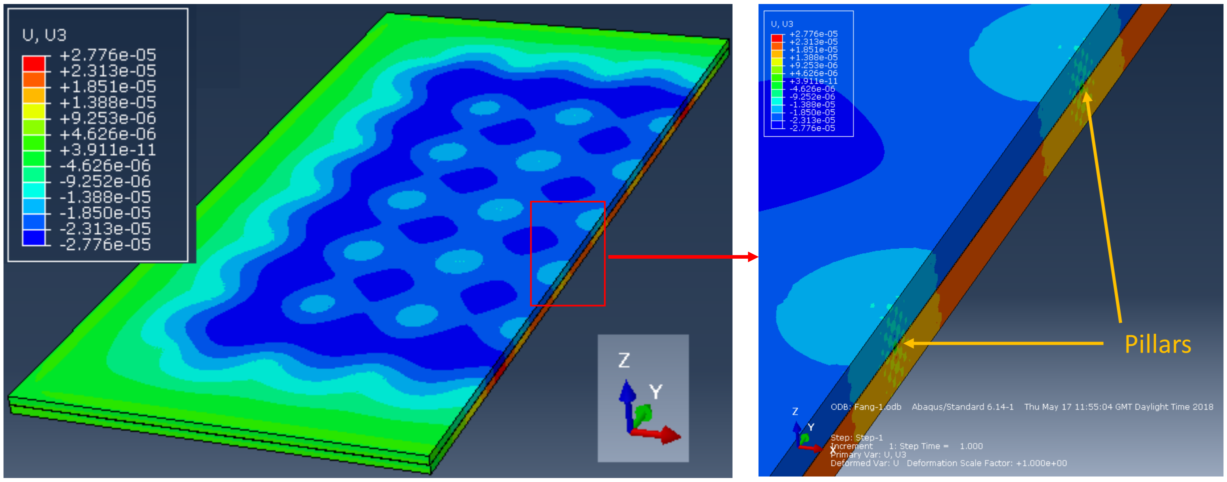


Fig. 9 Bending profile for DVG with T-glass under atmospheric pressure.

5. Conclusions

Evacuated glazing is a thin glazing with high insulation characteristics suitable for application in energy efficient buildings and retrofitting to existing buildings, minimising heat lost or gain through windows. The fabrication of EG at low temperature allows the use of tempered glass in the fabrication of evacuated glazing without losing the mechanical properties of T-glass. The use of T-glass in evacuated glazing enables the increase of space between the support pillars without compromising the inTVGrity of glazing. The increased pillar spacing reduces the number of pillars thereby reducesing the heat transfer across the glazing. Using annealed glass in vacuum glazing allows a pillar spacing of 25 mm (for a 0.4mm diameter pillar) without creating micro cracks in the glass at contact points, but research has shown that by using tempered glass in vacuum glazing it is possible to increase pillar spacing to over 50 mm.

In this work, the U-value of DVG and TVG was predicted for a glazing size of 0.4 m by 0.4 m and 1 m by 1 m. The simulated glazing used T-glass and A-glass separated by support pillar array spaced at 50 mm and 25 mm. The simulation showed that DVG made of A-glass with an emissivity of 0.03 had a thermal transmittance of 0.57 $Wm^{-2}K^{-1}$ at the centre-of-glazing region while this reduced to 0.3$Wm^{-2}K^{-1}$ for DVG made of tempered glass (47.4% reduction). TVG using A-glass with an emissivity of 0.03 had a thermal transmittance of 0.28 $Wm^{-2}K^{-1}$ at the centre-of-glazing region while this reduced to 0.11 $Wm^{-2}K^{-1}$ for TVG with T-glass (60.7% reduction).

It is apparent that using tempered glass in DVG and TVG can improve the thermal performance, however, the improvement for TVG was greater. Heat transfer by radiation in TVG is much lower than that in DVG therefore the heat conduction through the pillar array is more significant in TVG compared to DVG and as a result by reducing the number of the support pillars in TVG, the reduction in heat transfer across the total glazing would be larger.

The reduction in the thermal transmittance of larger sized DVG and TVG caused by the application of T-glass is greater than that of smaller sized glazing. The impact of heat transfer through the edge seal is larger in smaller sized DVG and TVG, thus the impact of the heat transfer through the support pillars on the overall thermal transmittance of 1 m by 1 m DVG and TVG is greater than that across the 0.4 m by 0.4 m DVG and TVG.

Nomenclature

T Temperature (ºC)

U Thermal transmission (W.m^{-2}.K^{-1})

Subscripts

1 to 6 Refer to surfaces of glass panes shown in Figs. 1 and 2

A,c Annealed glass and centre-of-glazing

A,t Annealed glass and total glazing area

i,o Refer to warm and cold side ambient

T, c T-glass and centre-of-glazing

T, t Tempered glass and total glazing area

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