Improvements in triple vacuum glazing design

Yueping Fang, Trevor J. Hyde, Neil Hewitt

School of the Built Environment, University of Ulster, BT37 0QB,
Newtownabbey, N. Ireland, UK

Abstract: The design optimization of the thermal performance of triple vacuum glazing (TVG) was undertaken using a finite volume model. This included optimization of the pillar positioning in the two vacuum gaps and optimization of each glass pane thickness. The pillar arrays in the two vacuum gaps were positioned so that they were not aligned with each other when viewed through the window but were interspaced. Due to the increased length of the heat conduction path from one side of the 0.4 m by 0.4 m glazing to the other through the two support pillars arrays and the glass panes, the U-value at the centre-of-glazing area is reduced from 0.55 $W.m^{-2}.K^{-1}$ to 0.44 $W.m^{-2}.K^{-1}$. When using thinner glass panes in a TVG, the pillar separation needs to be reduced, e.g. for 6 mm thick glass panes, the permissible pillar separation is 35 mm based on a 0.32 mm pillar diameter; for 2 mm glass panes, the pillar separation needs to be 15 mm based on 0.16 mm diameter pillars. It was found that for a 0.4 m by 0.4 m TVG, reducing the glass thickness of three glass panes from 6 mm to 2 mm decreases the lateral heat conduction through the two edge sealants. For a 0.4 m by 0.4 m TVG, notwithstanding a reduction in the pillar separation and pillar diameter due to the reduced glass thickness, the U-value at centre-of-glazing area increased from 0.35 $W.m^{-2}.K^{-1}$ to 0.44 $W.m^{-2}.K^{-1}$; however the U-value of total glazing area reduced from 0.84 $W.m^{-2}.K^{-1}$ to 0.67 $W.m^{-2}.K^{-1}$, since the decreased lateral heat conduction at the edge area dominates the heat flow across the total glazing area. For a 1 m by 1 m TVG, reducing the glass thickness from 6 mm to 2 mm increases the U-value at the centre-of-glazing area from 0.33 $W.m^{-2}.K^{-1}$ to 0.43 $W.m^{-2}.K^{-1}$ and increases the U-value of the total TVG area from 0.51 $W.m^{-2}.K^{-1}$ to 0.59 $W.m^{-2}.K^{-1}$, since the decreased thermal resistance due to reducing the glass pane thickness dominates the heat flow through the total glazing area.
Key words: triple vacuum glazing,

1. Introduction

The window is generally considered the weakest building component in the building façade in terms of thermal insulation. Due to the demand for natural daylight, windows must maintain maximum transparency. To keep proper ventilation, in many areas of the world, window must be designed with proper thickness and weight to facilitate window control. To reduce heat lost though windows as a result of the relatively high thermal conductivity (1 $W.m^{-1}.K^{-1}$) of a glass compared to other building components, multi-layer of glass panes with low-emittance (low-e) coatings and heavy gas filled gaps have been commonly used (EN ISO 10077-1). The heat transmission U-value of a typical double glazing with one hard low-e coating with emittance of 0.16 with an air filled gap is 2.2 $W.m^{-2}.K^{-1}$. The highly efficient passive house design requires the heat transmission U-value of windows (including frame and glass) is lower than 0.8 $W.m^{-2}.K^{-1}$ in accordance with new European standards (Anon, 2013). It has been reported (EN ISO 10077-1, 2006) that the U-value of a triple glazing with three 4 mm thick glass panes and two 12 mm wide argon filled gaps (4-12-4-12-4) (two panes with coatings with an emittance of

0.05) can be reduced to 0.8 W.m^{-2}.K^{-1}. These glazings would typically have a total thickness of 36 mm and can then meet the passive house requirement.

Compared to gas filled triple glazing, the U-value of either double or triple vacuum glazing (TVG) can be easily meet the requirement (U-value less than 0.8 W.m^{-2}.K^{-1}) of passive house. With two low-e coated glass panes with emittance of 0.16 or 0.05, the U-value of a typical double vacuum glazing (DVG) with total thickness of 8.2 mm can be reduced to 0.8 W.m^{-2}.K^{-1} or 0.4 W.m^{-2}.K^{-1} respectively. With two low-e coatings with an emittance of 0.16 or 0.05, the U-value of a TVG with total thickness of 12.4 mm and diameter of 0.4 mm can be reduced to 0.57 W.m^{-2}.K^{-1} or 0.25 W.m^{-2}.K^{-1} respectively (Fang et al., 2010). So both DVG and TVG can easily meet the passive house requirement for windows with much smaller thickness compared to gas filled triple glazing. DVG has been successfully developed by a team at the University of Sydney (Collins and Simko, 1998) using a solder glass to seal the vacuum gap and by a team at the University of Ulster using an indium alloy as the vacuum gap sealant (Hyde et al., 2000; Zhao et al., 2007). TVG has been successfully fabricated and thermally characterized at the University of Ulster (Arya et al., 2012). The experimentally determined U-value was in good agreement with the predictions. This paper presents a novel design method for improving the thermal performance of TVGs using a finite volume model.

2. An new approach for pillar positioning in a TVG

As shown in Fig. 1(a), heat transfer through a TVG includes i) heat transfer from the warm side air to the warm side glass pane, ii) heat conduction from the warm side glass pane to the middle glass pane though the pillar array within vacuum gap 1 and the edge seal bounding vacuum gap 1; iii) radiative heat transfer between surfaces 5 and 4 and between surfaces 3 and 2; iv) heat conduction from the middle glass pane to the cold side glass pane through the pillar array within vacuum gap 2 and through the edge seal bounding vacuum gap 2.

For conventional TVG (Mans et al., 2006; Fang et al. 2010), two pillar arrays are designed to align with each other within the two vacuum gaps, giving a direct conduction path across the glazing. To increase the length of the heat conduction path through the two pillar arrays and glass panes, the pillar arrays are designed to be offset from one another, i.e. interspaced rather than above each other as shown in Fig. 1(b). Using a finite volume model which has been experimentally validated in previous work (Fang et al., 2009), U-values of the TVG as shown in Fig. 1(a) and (b) subject to the ambient conditions required by ISO standard (EN ISO 10077-1, 2006) have been calculated. The air temperatures at the warm and cold sides were 20 ^{o}C and 0 ^{o}C; the surface heat transfer coefficients at the warm and cold side glass surfaces were 7.7 W.m^{-2}.K^{-1} and 25 W.m^{-2}.K^{-1}. The simulated TVG1 as shown in Fig. 1(a) and TVG2 as shown in Fig. 1(b) comprised three 4 mm thick glass panes separated by two vacuum gaps each with an array of support pillars with a diameter of 0.4 mm. The emittance of the low-e coating at surfaces 5, 4 and 3 was 0.16 and that at the non coated surface 2 was 0.837. The width of the two edge seals bounding vacuum gaps 1 and 2 was 6 mm. The rebate depth of the wood frame was 10 mm. The thermal conductivities of the indium edge seal, support pillar, glass sheet and wood frame are 83.7 W.m^{-1}.K^{-1}, 20 W.m^{-1}.K^{-1}, 1 W.m^{-1}.K^{-1} and 0.17 W.m^{-1}.K^{-1} respectively (Holman, 1989).

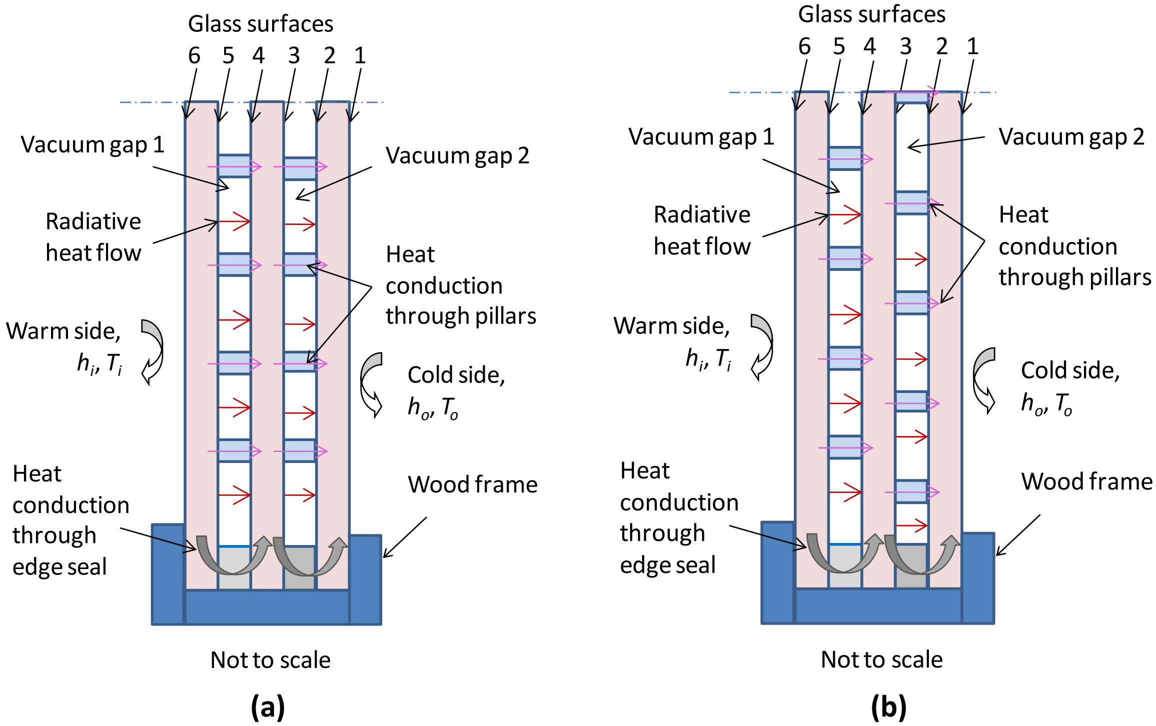


Fig. 1 Schematics of TVG1 (a) and TVG2 (b).

The isotherms of TVG1 have been reported in Fang et al., 2010. The 3-D isotherms of the TVG2 are presented in Fig. 2. The isotherms of surfaces 5, 4, 3, and 2 are shown in Figs. 3 and 4.

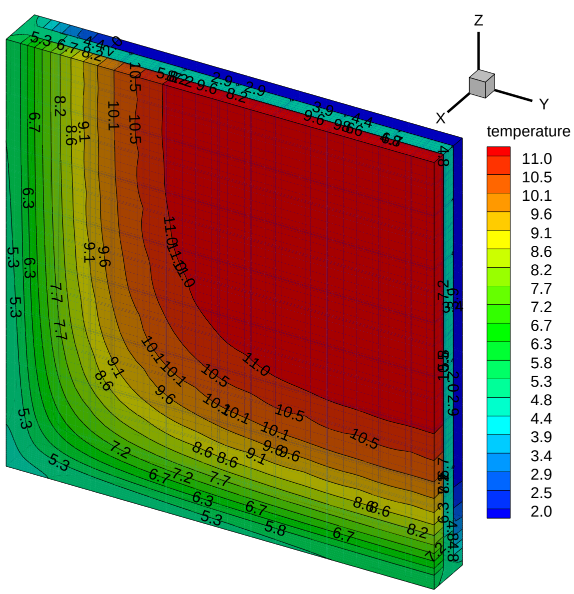
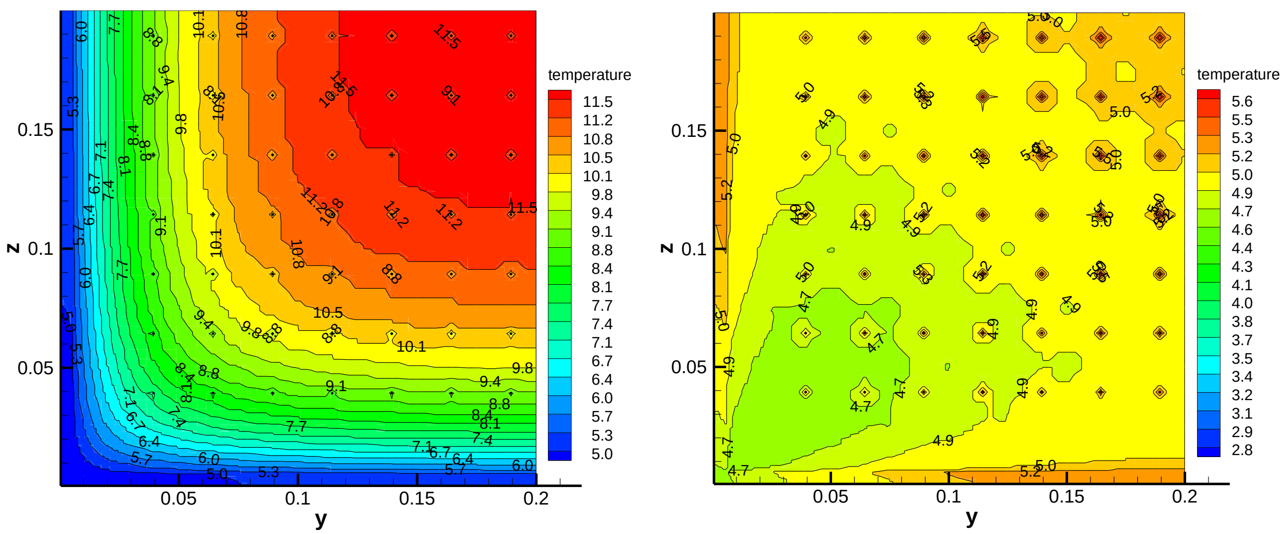
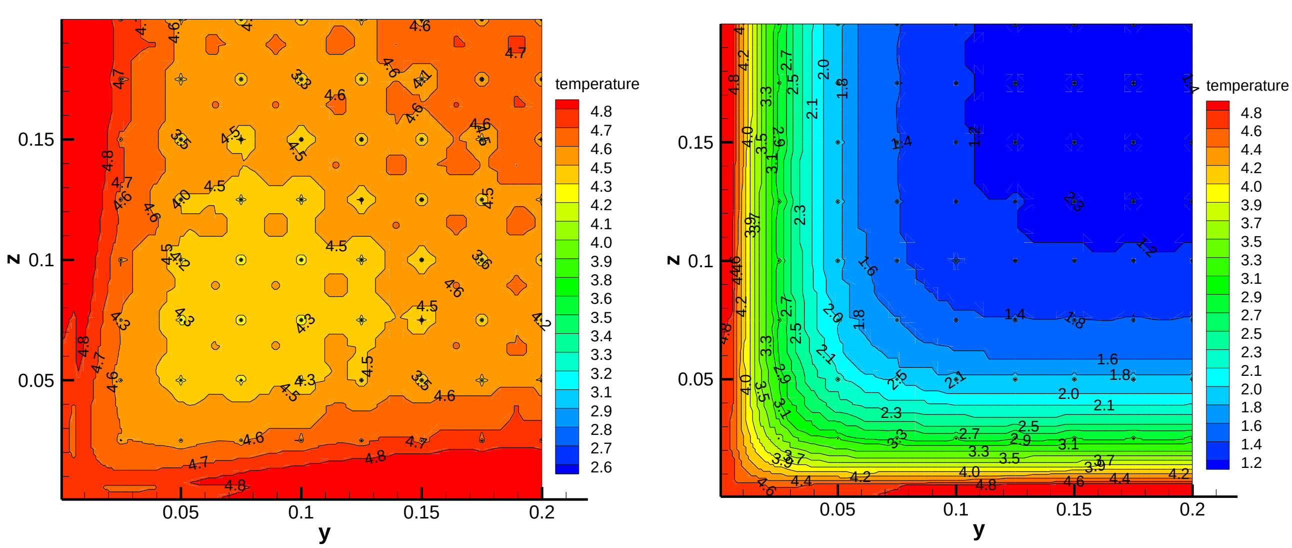


Fig. 2 3D isotherms of the TVG2.



(3a) (3b)

Fig. 3 Isotherms of surfaces 5 (3a) and 4 (3b) in vacuum gap 1.



(4a) (4b)

Fig.4 Isotherms of surfaces 3 (4a) and 2 (4b) in vacuum gap 2.

Fig. 2 shows the significant temperature difference across the three glass panes, as a result of the high insulation provided by the two vacuum gaps. From Fig. 3 (a) and 3(b), the mean temperature difference between surfaces 5 and 4 in vacuum gap 1 was determined to be 5.6 ^{o}C; from Figs 4(a) and 4(b), the mean temperature difference between surfaces 3 and 2 in vacuum gap 2 was determined to be 2.8 ^{o}C. In vacuum gap 1, both surfaces 5 and 4 are low-e coated; in vacuum gap 2, only surface 3 was low-e coated with surface 2 non coated, the thermal resistance of vacuum gap 1 is larger than that of vacuum gap 2, leading to the temperature difference across the vacuum gap 1 being larger than that across the vacuum gap 2. Fig. 3(a) and Fig. 4(b) show that the temperature variations at surfaces 5 and 2 are influenced by heat conduction through the pillar arrays in vacuum gaps 1 and 2 respectively. Fig. 3(b) and Fig. 4(a) shows that the temperature variations at surfaces 4 and 3 are influenced by the pillar arrays in both vacuum gaps 1 and 2, due to interspacing of the pillars. This indicates that after the heat conducted though pillar array in vacuum gap 1, it laterally conducted along the centre glass pane, then conducted though the second pillar array in vacuum gap 2, then onto the surface 2. The added length of lateral heat conduction path laterally along the centre glass pane increased the thermal resistance at the centre-of-glazing area of the TVG. The predicted U-values of the total and at the centre-of-glazing areas are listed in Table 1. For comparison purposes, the U-values of TVG1 and TVG2 with dimensions of 1 m by 1 m with a pillar diameter of 0.4 mm are also simulated and presented in Table 1.

Table 1 Predicted U-values of TVG1 and TVG2 subject to EN ISO (10077-1, 2006) ambient conditions.

U-value	Total glazing $W.m^{-2}.K^{-1}$	Centre-of-glazing $W.m^{-2}.K^{-1}$	Total glazing $W.m^{-2}.K^{-1}$	Centre-of-glazing $W.m^{-2}.K^{-1}$
	0.4m by 0.4 m		1m by 1 m	
TVG1	0.86	0.55	0.71	0.54
TVG2	0.83	0.44	0.67	0.43

Table 1 shows that the U-value at the centre-of-glazing area of TVG2 is 20% lower than that of TVG1; this is due to the increased length of the heat conduction path for the glazing with the interspaced pillars. The U-value of the total glazing area of the 0.4 m by 0.4 m TVG2 is 3.5% lower than that of TVG1. The U-value of the total glazing area of the 1 m by 1 m TVG2 is 5.6% lower than that of TVG1. So the improvement of U-value due to interspacing of the pillars in two vacuum gaps of 1 m by 1 m TVG is larger than that for a 0.4 m by 0.4 m TVG, since the larger lateral heat conduction through the edge seal compromised the improvement caused by interspacing the pillars in 0.4 m by 0.4 m TVG compared to 1 m by 1 m TVG.

3. Effect of thickness of glass sheets on the thermal performance of TVG

The influence of glass thickness on the thermal performance of DVG has been systematically investigated (Fang et al., 2007). For a TVG, the relationship between glass sheet thickness and U-value is even more important due to the additional glass panes. When selecting different glass thicknesses, the pillar separation and pillar radius need to be changed to keep the stress caused by atmospheric pressure exerted at the glass surfaces and temperature difference within a bearable stress limitation, while keep the heat transfer across the glazing system minimal. Collins and Simko, 1998 presented four criteria which govern the selection of glass thickness, pillar radius and pillar separations when designing a DVG. These are:

- conical indentation fractures in the glass around the pillars do not occur;
- compressive stresses in pillars is less than a set value which is determined by the pillar material. For stainless steel pillar, it is 1.3GPa which is determined by the physical property of stainless steel;

- the maximum external tensile stress above the pillars less than 4MPa, which is one half of the maximum bearable stress of glass (Standards association of Australia, 1989, Fischer-Cripps et al., 1995) based on finite element analysis and experimental testing;
- the thermal conductance of the pillar array is less than a given value. The minimal value of conductance is determined by equation 1 (Collins and Simko, 1998) with the greatest pillar separation and smallest pillar radius that satisfy the three stress related design criteria above.

$$C_{pillar,array} = 2k_{glass}a / p^2 \quad (1)$$

Precious studies have shown that under the same ambient conditions, the mean temperature differences of two glass panes bounding the vacuum gaps 1 and 2 within a TVG is lower than that with a DVG (Fang et al., 2010), so the stress used by temperature difference between these two glass panes within a TVG is lower than that of a DVG. The above design principles developed under vacuum conditions are applied to design the TVG. Thermal performance of TVG with various glass thicknesses were simulated. Pillar diameters and separations are varied with the glass thicknesses. For 2 mm, 3 mm, 4 mm, 5 mm and 6 mm thick glass panes, the values of pillar separation, pillar radius and minimal conductance of the pillar array determined using the above four restrictions are listed in table 2. The combination of glass pane thickness, pillar radius and separation in table 2 are employed for TVG in this simulation work.

Table 2 Pillar radius and pillar separation for varying glass pane thicknesses.

Glass pane thickness (mm)	Pillar radius (mm)	Pillar separation (mm)
2	0.08	15
3	0.10	20
4	0.13	25
5	0.15	30
6	0.16	35

U-value of 0.4 m by 0.4 m TVG2 as shown in Fig. 1(b) with three same glass pane thicknesses of 2 mm, 4 mm and 6 mm were simulated using the finite volume model and results are illustrated in Fig. 5. Surfaces 5, 4, and 3 as shown in Fig. 1 were low-e coated with an emittance of 0.16.

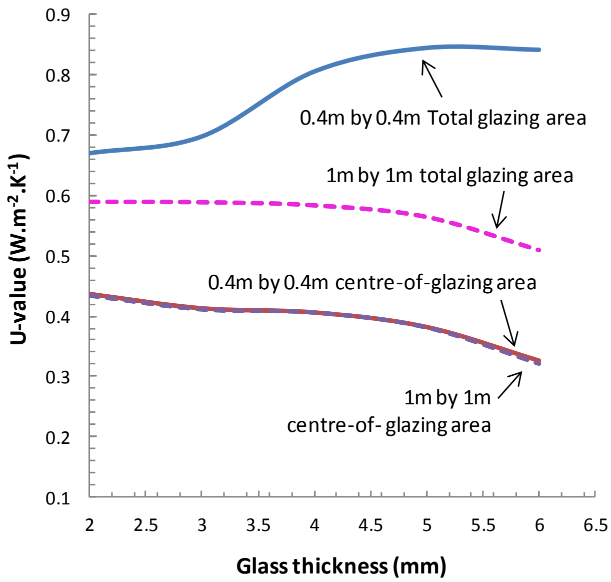


Fig. 5 U-value variations for the 0.4 m by 0.4 m and 1 m by 1 m TVG with various glass pane thicknesses and surfaces 5, 4 and 3 low-e coated.

Fig. 5 shows that for a 0.4 m by 0.4 m TVG, by increasing the glass pane thickness from 2 mm to 6 mm, the U-value of the centre-of-glazing area decreases from 0.44 $W.m^{-2}.K^{-1}$ to 0.35 $W.m^{-2}.K^{-1}$ and for 1 m by 1 m TVG, the U-value at the centre-of-glazing area decreased from 0.43 $W.m^{-2}.K^{-1}$ to 0.34 $W.m^{-2}.K^{-1}$. This is because with increasing glass pane thickness, the total thermal resistance at the centre-of-glazing area increases, thus the thermal conductance and thermal transmission U-value at the centre-of-glazing area decrease. These results are comparable with the results developed by Manz et al., (2006) using an analytic model. Fig. 5 also shows that increasing the glass thickness from 2 mm to 6 mm increases the U-value of the total glazing area from 0.67 $W.m^{-2}.K^{-1}$ to 0.84 $W.m^{-2}.K^{-1}$. This is due to increase in lateral heat conduction along the thicker glass panes and subsequently through the edge seals to the cold side glass pane, thus increasing the total glazing U-value. The rate of increase in the U-value of the total glazing area for glass thicknesses ranging from 2 mm to 4 mm is faster than that for glass thickness ranging from 4 mm to 6 mm. This is because in the range from 4 mm to 6 mm, the increased thermal resistance at the central-glazing-area due to increasing glass pane thickness reduced the effect of lateral heat conduction on the heat flow through the total glazing area.

For 1 m by 1 m TVG, increasing the glass thickness from 2 mm to 6 mm decreases the U-value of the total glazing area from 0.59 $W.m^{-2}.K^{-1}$ to 0.51 $W.m^{-2}.K^{-1}$ due to the increased thermal resistance of the thicker glass panes. Although lateral heat conduction increases with increased glass thickness, the rate of increase in thermal resistance at the centre-of-glazing area is larger than the rate of increase in lateral heat conductance, leading to the heat flow across the total glazing system and thus total glazing U-value decreasing. The rate of decrease in the U-value of the total glazing area for glass thicknesses from 4 mm to 6 mm is faster than that for 2 mm to 4 mm. This is because in the range from 4 mm to 6 mm, the influence of increased lateral heat flow on the heat flow through the overall glazing area is less than the decreased heat conduction through the central-glazing-area as a result of increasing glass pane thickness. These results are comparable with the results calculated using an analytic model developed by Simko and Collins, (1998) and relevant simulation results by Fang et al., 2010.

The temperature profiles along the central line of 0.4 m by 0.4 m TVG calculated using the finite volume model and presented in Fig. 6 show that the temperature difference between the outdoor and indoor glass panes at the edge of the TVG with 2 mm glass panes is the lowest and that of the TVG with 6 mm glass panes that highest. This is due to the increased thermal resistance of the 6 mm thick glass panes compared to that of the 2 mm glass pane. In the area ranging from 0 to 0.1 m from the glazing edge towards the centre, the rate of increase in the indoor glass pane surface temperature of the TVG with 2 mm glass panes is much larger than that of the TVG with 6 mm glass panes. The mean temperature difference between the indoor and outdoor 2 mm thick glass panes is larger than that between the 6 mm glass panes. This is a result of the thermal resistance of the TVG with 2 mm glass panes is lower than that of the TVG with 6 mm glass panes. The temperature profiles of the indoor glass surface temperatures along the central line above the support pillars show that the temperature variation (0.1 ^{o}C) of the 2 mm thick glass pane caused by heat conduction though the pillars is larger than that of the 4 mm and 6 mm glazing panes, due to lower thermal resistance of thinner glass panes. It has been reported that the temperature variation caused by support pillars on the surface of double vacuum glazing with 4 mm glass panes is 0.4 ^{o}C (Collins and Simko, 1998).

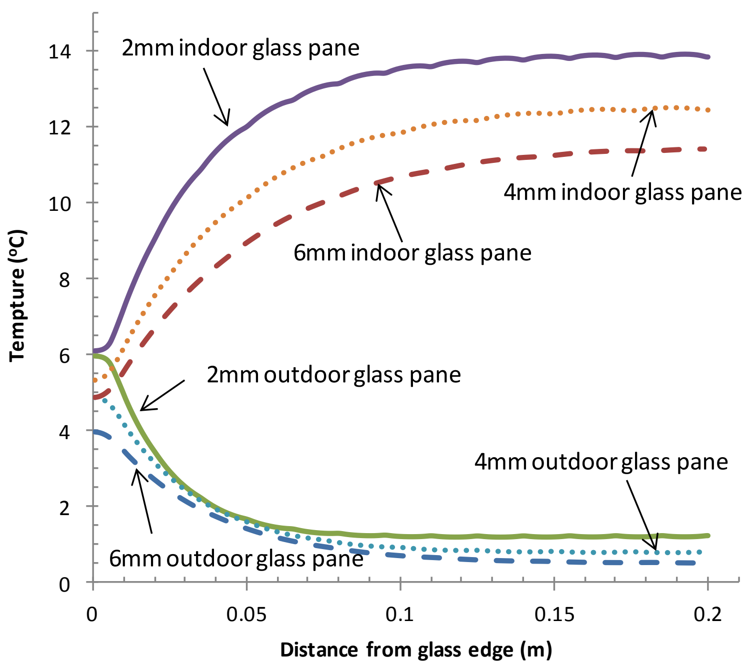


Fig. 6 The temperature profiles along the central line of the 0.4 m by 0.4 m TVGs with three 2 mm, 4 mm and 6 mm thick glass panes.

4. Conclusion

The thermal performance of 0.4 m by 0.4 m TVG with different pillar settings and various glass pane thicknesses was simulated. When the support pillars in the two vacuum gaps are not aligned above each other but are interspaced (TVG2), the U-value at the centre-of-glazing area is 20% lower than that of TVG1 where the pillars are aligned above each other. This is due to the increased length of the heat conduction path though the two pillar arrays and glass panes in TVG2 compared to TVG1. The U-value of the total glazing area of TVG2 is 3.5% lower than that of TVG1, since heat conduction through the edge area reduced the influence of the decreased heat conduction at the centre-of-glazing area as a result of the interspaced pillars. The U-value of the total glazing area of 1 m by 1 m TVG2 is 5.6% lower than that of TVG1. The improvement in U-value due to the interspaced pillars in the two vacuum gaps for 1 m by 1 m TVG is larger than that for 0.4 m by 0.4 m TVG, since the influence of heat conduction through the edge seal on the heat transfer through the total glazing area is less for 1 m by 1 m TVG compared to 0.4 m by 0.4 m TVG.

The influence of glass thickness on the thermal performance of 0.4 m by 0.4 m and 1 m by 1 m TVG was simulated. The pillar separation and diameters corresponding to various glass pane thicknesses were selected in accordance with the principles determined for a minimal U-value and bearable level of stress and strain within the glass panes and support pillars. For a 0.4 m by 0.4 m glazing size, the U-value at the centre-of-glazing area of TVG with 2 mm thick glass panes was 0.44 $W.m^{-2}.K^{-1}$, while for a TVG with 6 mm glass panes was 0.35 $W.m^{-2}.K^{-1}$. For 1 m by 1 m glazing size, the U-value at the centre-of-glazing area of the TVG with 2 mm thick glass panes was 0.43 $W.m^{-2}.K^{-1}$, while that for a TVG with 6 mm glass panes was 0.33 $W.m^{-2}.K^{-1}$.This is due to the increased thermal resistance at the centre-of-glazing area of the TVG with 6 mm glass panes compared to the TVG with 2 mm glass panes.

For a 0.4 m by 0.4 m glazing size, the U-value of the total glazing area of the TVG with 2 mm thick glass panes was 0.67 $W.m^{-2}.K^{-1}$, while for a TVG with 6 mm glass panes was 0.84 $W.m^{-2}.K^{-1}$. This is due to the increased lateral heat conduction along the 6 mm thick glass panes compared to the 2 mm thick glass panes of the TVG. For 1 m by 1 m glazing size, the U-value of the total glazing area of the TVG with 2 mm thick glass panes was 0.59 $W.m^{-2}.K^{-1}$, while that for TVG with 6 mm glass panes 0.50 $W.m^{-2}.K^{-1}$. Although lateral heat conduction along the 6 mm thick glass panes is larger than that along the 2 mm thick glass panes, the effect of lateral heat conduction on the total heat flow across the total 1 m by 1 m TVG system is lower than that of 0.4 m by 0.4 m TVG as the increased thermal resistance resulting from increased glass thickness dominates the total heat flow through the overall 1m by 1 m TVG system, leading to the total heat flow of the TVG with 6 mm glass panes being less than that with 4 mm glass panes.

Simulations indicate that for both 0.4 m by 0.4 m and 1 m by 1 m TVGs, the thicker the glass panes, the lower the U-value at the centre-of-glazing area. Nevertheless for a 0.4 m by 0.4 m TVG, the thicker the glass panes, the higher the U-value of the overall glazing system, this is due to increased lateral heat conduction dominates the total heat flow though the glazing system; for 1 m by 1m TVG, the thicker the glass panes, the lower the U-value of the overall glazing system, this is due to the increased thermal resistance at the centre-of-glazing area dominates the total heat flow across the glazing system. Thus unlike a conventional double glazing, when comparing thermal performance of a TVG, it is not accurate to compare the U-value at the centre-of-glazing area only. It is more accurate to compare the U-value of both the total glazing and centre-of-glazing areas for small size TVG system. The simulation results here provide a theoretical basis for selection of glass pane thickness when designing a TVG under various scenarios.

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