**Modelling and experimental validation for the thermal performance**

**of a hybrid vacuum glazing**

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**Abstract**

 The thermal performance of a hybrid vacuum glazing (HVG) with dimensions of 0.4 m by 0.4 m was modelled using a finite volume model (FVM). The HVG is the combination of a conventional double vacuum glazing (DVG) and a third glass sheet separated a gas filled cavity. The DVG integrated within the HVG comprises two 4 mm thick glass sheets both coated with a low-emittance (low-e) coating with emittance of 0.16, separated by an array of stainless steel support pillars with a diameter of 0.4 mm and a height of 0.2 mm, spaced at 25 mm within the vacuum gap, sealed around their periphery by a 6 mm wide indium based sealant. The thermal performance of both DVG and HVG were characterised using a guarded hot box calorimeter (GHBC).

 The simulation results showed that for the 0.4 m by 0.4 m HVG with the configuration parameters listed above, the thermal transmission U-value of the centre-of-glazing area was 0.64 W.m-2.K-1. Before integration with the third glass sheet, the U-value of the centre-of-glazing area of the DVG with dimensions of 0.4 m by 0.4 m was 0.85 W.m-2.K-1. No low-e coating was employed on the third glass sheet. The U-value of the HVG calculated using the analytic model was in good agreement with that predicted using the FVM with a deviation of less than 1%. Using the GHBC, the experimentally determined U-value of the centre-of-glazing area of the HVG was 0.66 W.m-2.K-1 which was in very good agreement with the prediction by the FVM with a deviation of 3.1%.

**Key words:** hybrid vacuum glazing (HVG), double vacuum glazing (DVG), U-value, finite volume model (FVM)

**1. Introduction**

 Due to gaseous heat conduction and convection within the double glazing, the heat transmission U-value of a double glazing cannot be reduced further. Zoller [1] first presented the concept of double vacuum glazing (DVG) with two glass sheets, which eliminates gaseous heat conduction and convection. Although many concepts for fabricating vacuum glazing were subsequently patented, the first DVG was successfully fabricated by a team at the University of Sydney in 1989 [2], which used solder glass as the edge sealant with a melting point of 500 °C. A U-value of 0.80 W.m-2.K-1 in the centre-of-glazing area of the DVG with 0.25 mm diameter support pillars has been achieved for samples up to 1 m by 1 m fabricated in the laboratory [3]. Using an indium based alloy with a melting temperature of less than 200 °C as an edge seal, DVG was successfully fabricated by a team at the University of Ulster [4]. Due to the low temperature for forming the edge seal, tempered glass can be used in the DVG, since high temperature above 350°C would cause the glass to lose temper. A U-value of 0.86 W.m-2.K-1 at the centre-of-glazing area of the DVG with 0.4 mm diameter support pillars has been achieved experimentally [5]. Irrespective of the sealing technique used, the core principle for designing a vacuum glazing is the optimisation of the minimal number of pillars and the smallest pillar diameter which leads to a bearable tensile and shear stress within the glass sheets due to atmospheric pressure acting on the glazing surfaces.

 Since the emittance of low-e coatings cannot be reduced to zero, the radiative heat flow across the vacuum glazing cannot be reduced to zero. Additionally, the heat conduction through the edge seal and support pillars within the vacuum glazing still exists, thereby limiting the U-value achievable for DVG. Two methods which can further reduce the U-value of vacuum glazing systems have been presented: i) adding a second vacuum gap within the glazing, i.e. triple vacuum glazing (TVG) and ii) including a third glass sheet with a gas filled gap within the glazing system, i.e. hybrid vacuum glazing (HVG). TVG was firstly presented by a team of Swiss Federal Laboratories for Material Testing and Research [6]. Theoretical analysis of the design principles [6] and thermal performance of the TVG [7] have been undertaken. Recently TVG [8] has been successfully fabricated at the University of Ulster. The theoretic thermal performance analysis for a solder glass sealed HVG has been undertaken by Collins et al., [9]. In the present work, the thermal performance of a HVG using a low temperature fabrication technique was systematically analyzed using both analytic and finite volume models, and subsequently compared with TVG and DVG performance. A HVG was fabricated using an indium based sealant for the vacuum gap and a thermal spacer bar integrated with butyl rubber as the sealant of the air filled gap. The U-value of the fabricated HVG was experimentally determined, which was in very good agreement with the predictions with a deviation of 3.1%.

**2. Analytic model approach**

 The HVG as shown in Fig. 1 is the combination of a conventional DVG and a third glass sheet, separated by a gas filled cavity and an edge spacer bar sealed with butyl rubber. The DVG investigated within the HVG comprises two 4 mm thick sheets of glass coated with a low-e coating with emittance of 0.16, separated by an array of stainless steel support pillars with a diameter of 0.4 mm and a height of 0.2 mm, spaced at 25 mm within the vacuum gap. The vacuum gap was sealed by a 6 mm wide indium alloy sealant. The 12 mm wide air gap between the DVG and the third glass sheet is sealed by a 6 mm wide edge spacer bar integrated with a butyl rubber sealant. The total thickness of the HVG was approximately 24 mm. The overall heat transfer through the HVG includes 1). heat flow from the indoor side environment to the glass sheet facing the indoor side environment; 2). radiation between two glass surfaces bounding the vacuum gap and the air filled gap; 3). conduction through the pillar array within the vacuum gap and through the edge seal for both the vacuum gap and the air filled gap; 3). heat transfer across the air gap by convection and conduction; 4). heat flow from the cold side glass pane to the outdoor side ambient.



**Fig. 1** Schematic diagram of a hybrid vacuum glazing



**Fig. 2** Schematics of a quarter of a unit cell with a pillar at the centre.

 The heat transmission U-value of a 25 mm by 25 mm cell with a pillar in the centre was investigated. Considering the symmetrical shape of the unit cell, it is appropriate to consider a quarter of the cell to represent the thermal network of a full cell. As shown in Fig. 2(A), a quarter of the pillar is shown at the corner of the square cell. The thermal network of the quarter unit cell is shown in Fig. 2(B). The thermal resistance due to heat conduction of each glass pane is given by:

 (1)

where *dm* is the thickness of the glass sheet *m*, where *m *(*I, II, III*), *A* is the area of the unit cell of the glazing (so *A = p2*); *kg* is the thermal conductivity of glass.

 The thermal resistance due to radiative heat flow between the glass surfaces within the vacuum gap and air filled gap is given by:

  (2)

where *εj* and *εk* are the hemispheric emittances of the glass surfaces *j* and *k* opposite each other within the vacuum gap and the air filled gap; *σ* is the Stefan-Boltzmann constant and *Tjk* is the mean glass surface temperature in the gaps in Kelvin. The thermal resistance due to heat conduction through the support pillars in the vacuum gap is determined by equation 3 [3]:

 (3)

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 between the outdoor and indoor glass pane surfaces is determined by equation 4:

 (4) Where *Rair,gap* is the thermal resistance of the air gap, which is determined by the thermal resistance *Rair* due to heat conduction and convection through the air gap and the thermal resistance due to radiative heat transfer between the two glass surface bounding the air gap, i.e.

 (5)

 (6)

The British and European standard BS EN 673 [10] recommends that

 (7)

Where *s* is the width of the air gap, λ is the thermal conductivity of the air, *Nu* is the Nusselt number:

 (8)

Where *K* is a constant, *Gr* is the Grashof number, Pr is the Prandtl number, *n* is an exponent.

 (9)

 (10)

Where *∆T* is the temperature difference between the glass surfaces bounding the air gap. For the air in the glazing gap, ρ is the density, *μ* is the dynamic viscosity and *c* is the specific heat capacity. *Ta* is the average temperature of the glass sheets bounding the air gap. If *Nu* is less than 1, then the *Nu* number is selected to be 1. For vertical glazing: *K* is 0.035, *n* is 0.38 [10].

 The thermal resistances *Ri* and *Ro* at the indoor and outdoor glazing surfaces are the inverse of the surface heat transfer coefficients, i.e. *Ri=1/hi*and *Ro=1/ho*. The total U-value of the unit cell at the centre-of-glazing area is then given by:

 (11)

 The heat flow through the entire HVG is the sum of the heat flow across the centre-of-glazing area and the heat flow through the edge area including the heat conduction through the edge seal.

**3. Numerical modeling approach**

 The governing equation solved by the finite volume model (FVM) is the Fourier’s equation:

 (12)

Where *T* is the temperature of each finite volume of glass or support pillars, *t* is the time parameter,  which is the thermal diffusivity, *k* is the thermal conductivity, *ρ* is the density and *c* is the specific heat capacity.

 Equation 12 was solved using the Galerkin approach [11]. Since the internal glass surfaces within the vacuum and air filled gaps are parallel, the view factor between the two internal glass surfaces is 1, the radiative heat transfer between the two surfaces is given by:

 (13)

 In the simulation, the outdoor and indoor air temperatures are 0 ºC and 20 ºC respectively and the overall heat transfer coefficients of the outdoor and indoor glazing surfaces 25 W.m-2.K-1 and 7.7 W.m-2.K-1 respectively [12].

 In the developed FVM, the node numbers of the brick element in the x, y and z directions are 40, 350 and 350 respectively to represent the geometry of the HVG. The small pillars were directly integrated in the FVM with the physical parameters of stainless steel. The brick element number within and around the pillars and edge seal area was refined to be much denser than other areas to achieve more accurate results and reduce CPU time. The cylindrical pillars with radius *a* of the spherical cross sectional area in the practical sample were replaced by square pillars with a width of  such that the area of the spherical and square cross sections are the same. It has been proved that both pillars with the same cross sectional area conduct similar amounts of heat under the same boundary conditions [13]. Due to symmetry conditions, it is sufficient to simulate one quarter of the HVG.

 The BS EN standard [10] systematically presents the approach calculating the thermal transmission of the gas filled gap within a double glazing as described in above section. The air gap in the FVM was treated with an effective material with a thermal resistance calculated by equations 5 to 10, which combines the influence of radiative heat transfer, air conduction and convection. The effective thermal conductivity of the air gap is given by:

 (14)

Where *s* is the air gap width.

 The accuracy of simulations with the specified mesh number was tested for both a DVG and an air filled double glazing separately. The accuracy of this treatment for DVG has been undertaken in the past [14]. The accuracy of the treatment for air filled double glazing was tested in this work. A 25 mm by 25 mm unit cell with an air filled gap was simulated using a mesh of 40×40×20 nodes. The 20 nodes (*x* direction) were distributed in a graded mesh through the double glazing thickness of 20 mm (two 4 mm thick glass sheets and a 12 mm wide air gap). The U-value of the unit cell of the air filled double glazing without low-e coatings was determined to be 2.70 W.m-2.K-1, which is in good agreement with the typical U-value of 2.71 W.m-2.K-1 of an air filled double glazing without low-e coatings calculated using the software Window 6.3 [15] of the Lawrence Berkeley Laboratory.

 

**Fig. 3** Isotherms of HVG with vacuum gap facing the indoor environment.

 The 3-D isotherms of the HVG with the vacuum gap facing the indoor (setting method 1) and outdoor environments (setting method 2) are presented in Figs. 3 and 4. A low-e coating is used on the internal surfaces of the two glass sheets bounding the vacuum gap; no low-e coating is used on the internal glass surfaces bounding the air gap. In Fig. 3,the temperature difference between the two glass sheets bounding the vacuum gap is 8.7 ºC; that between the two glass sheets bounding the air gap is 1.1 ºC; In Fig. 4, the temperature difference between the two glass sheets bounding the vacuum gap is 6.9 ºC; that between the two glass sheets bounding the air gap is 1.7 ºC. The 3-D isotherms of the DVG illustrated in Fig. 5 show that the temperature difference between the two glass sheets is 9.7 ºC. Comparing Fig. 5 to Figs. 3 and 4, it can be seen that inclusion of the third glass sheet reduces the temperature difference between the two glass sheets bounding the vacuum gap by 1 ºC in Fig. 3 and 2.8 ºC in Fig. 4, thereby the temperature-induced stress within the glazing is reduced. This is an advantage of HVG compared to the DVG.

 

**Fig. 4** Isotherms of HVG with vacuum gap facing the outdoor environment.

 Both Figs. 3 and 4 show that the temperature difference between the glass sheets bounding the vacuum gap is much larger than that of the glass sheets bounding the air gap, since the thermal resistance of the vacuum gap is much larger than that of air gap. The mean temperature of the indoor glass sheet of the HVG with setting method 1 as in Fig. 3 is 1.4 ºC larger than that of the indoor glass sheet of the HVG with setting method 2 as in Fig. 4. The temperature difference between the indoor and outdoor glass sheets in Fig. 3 is 9.8 ºC and in Fig. 4 is 8.6 ºC. The thermal resistance of HVG with a vacuum gap setting as in method 1 is larger than that with vacuum gap setting method 2.



**Fig. 5** Isotherms of DVG before integration with the third glass sheet of a HVG.

**4. HVG sample fabrication and characterization**

 A DVG was fabricated using the pump-out method [5] and subsequently the third glass sheet was added with the edge spacer bar as shown in Fig. 1. The parameters of the sample configuration are the same as those detailed in the first paragraph of section 2. The DVG and HVG were characterized using a guarded hot box calorimeter using a vacuum gap setting method 1. The ambient conditions in the guarded hot box calorimeter are listed in Table 1. The method of determining the U-value is described elsewhere [14].

 The experimental determined U-values of the HVG with a vacuum gap setting methods 1 (as shown as HVG1) are compared with the predictions in Table 2. The predicted U-values of the centre-of-glazing and total glazing areas of both HVG with a setting method 2 (as shown as HVG2) and TVG with two low-e coatings within the vacuum gap facing the indoor environment are presented in Table 2 for comparison.

**Table 1** Ambient conditions in the guarded hot box calorimeter and measured U-values of DVG and HVG with the vacuum gap setting method 1.

|  |  |  |
| --- | --- | --- |
| Sample type | Air temperature (oC) | Heat transfer coefficient at the sample surface (W.m-2.K-1) |
| Hot box | Cold box | Hot box | Cold box |
| DVG | 19.0 | -0.3 | 5.79 | 17.91 |
| HVG | 18.8 | -0.3 | 6.84 | 18.63 |

**Table 2** Comparison of the predicted and experimentally determined U-values of the HVG with the vacuum gap settings of method 1 and method 2.

|  |  |  |
| --- | --- | --- |
| 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  |
| DVG | 0.85 | 1.05 | 0.86 | 1.10 |
| HVG 1 | 0.64 | 0.90 | 0.66 | 0.91 |
| HVG 2 | 0.77 | 0.98 | - | - |
| TVG | 0.57 | 0.99 | - | - |

 It can be seen from Table 2 that the experimentally determined U-values of the centre-of-glazing and total glazing areas of the HVG are in very good agreement with the simulation results with deviations of less than 3.1%. For 0.4 m by 0.4 m HVG with a vacuum gap setting of method 1, the U-value at the centre-of-glazing and total glazing areas are lower than that of the DVG by 0.21 and 0.15 W.m-2.K-1 respectively. This is another advantage of HVG against DVG. In comparison with TVG, it can be seen that although the U-value of the centre-of-glazing area of TVG is lower than that of HVG, the U-value of the total glazing area of the TVG is higher than that of HVG. This is due to higher rate of heat conduction through the edge seal of TVG compared to DVG.

 For a 0.4 m by 0.4 m HVG with a vacuum gap setting method 2, its U-values at the centre-of-glazing and total glazing areas are 0.13 and 0.08 W.m-2.K-1 higher than those of the HVG with a vacuum gap setting method 1. With a vacuum gap setting method 2, heat is transferred from the indoor environment across the air gap to the middle sheet of glass, then across the vacuum glazing through the vacuum gap and edge seal to the outdoor environment. With a vacuum gap setting method 1, heat is transferred across the vacuum gap and edge seal, then across the air gap and the edge seal to the outdoor environment. With a setting method 1, the vacuum gap more efficiently resists the transfer of heat from the indoor glass sheet to the middle glass sheet than that of the air gap in setting method 2. So in practical applications of HVG, the HVG with a vacuum gap setting method 1 performs better than that with the vacuum gap setting method 2, i.e. the vacuum gap should be set facing the indoor side environment.

**5. Conclusions**

 Thermal performance of HVG was modelled using an analytic and finite volume models and experimentally determined using a guarded hot box calorimeter, the results of which are in very good agreement with a deviation of less than 3.1%. The investigated HVG comprised a conventional DVG and a third 4 mm thick clear glass sheet separated by a warm edge spacer and sealed with butyl rubber. The DVG integrated within the HVG consisted of two 4 mm thick glass sheets with a low-e coating with emittance of 0.16, separated by an array of support pillars with a diameter of 0.4 mm and a height of 0.2 mm. An indium based alloy with a width of 6 mm sealed the vacuum gap. The experimentally determined U-values of the centre-of-glazing and total glazing areas were reduced from 0.86 and 1.10 W.m-2.K-1 for the DVG to 0.66 and 0.91 W.m-2.K-1 of the HVG with setting method 1. This is one of the advantages of the HVG against DVG. The temperature difference across the glass sheets bounding the vacuum gap of the HVG was reduced by 1 ºC with the vacuum gap setting method 1 and by 2.8 ºC with the vacuum gap setting method 2 compared to the DVG. Thus the temperature-induced stress within the two glass sheets bounding the vacuum gap is reduced, so the durability of the vacuum gap is improved. This is another advantage of HVG against DVG.

 Compared to conventional gas filled triple glazing using two low-e coatings with an emittance of 0.16 and typical U-values of 1.0 W.m-2.K-1, the HVG with two low-e coatings offers an improved U-value of 0.66 W.m-2.K-1 with a reduction in glazing thickness. Compared to conventional air filled double glazing with two low-e coatings with an emittance of 0.16 and with a typical centre-of-glazing U-value of 1.7 W.m-2.K-1, the HVG offers improved thermal performance and with a total glazing thickness similar to conventional double glazing.

 The U-values at the centre-of-glazing and total glazing areas are lower by 0.13 and 0.08 W.m-2.K-1 respectively for a HVG with a vacuum gap setting method 1 compared to a HVG with a vacuum gap setting method 2. Vacuum gap setting method 1 is more resistant to the flow of heat into the glazing than the air gap facing the indoor side environment. So in the practical application of HVG, the vacuum gap should be set facing the indoor side environment.

 With two low-e coatings within the vacuum gap at the indoor side, the U-value of centre-of-glazing area of the HVG is 0.07 W.m-2.K-1 higher than that of TVG with the specified parameters, but the U-value of the total glazing area is lower than that of TVG. This is because the heat conduction through the edge seal of the HVG is less than the heat conduction through the thin metal edge seal of the TVG. The edge spacer bar of the HVG is nonmetal, has a low thermal conductivity and is thicker than the indium seal of TVG. Nevertheless for a larger size HVG and TVG, the scenario could be different, further optimization work for the HVG design and its application under various environments will be undertaken in the next stage.

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