Thermal Performance of Vacuum Insulated Window Shutter Systems

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Abstract: Windows are a major area of heat loss in buildings losing up to 10 times more energy compared to other building elements. Thermal shutters are used to improve the energy performance of windows in both hot and cold climatic conditions. The performance of thermal shutters however greatly depends on the thermal insulation and construction detailing, specifically cold-bridging, through the shutter, as well as between the shutter and window frames. This study evaluates the effects of cold-bridging, trickle ventilation and the size of the air cavity, between the vacuum insulated shutter and the window, on the performance of window thermal shutters. Thermal simulations are conducted in VOLTRA (Thermal analysis software) to assess the conditions. The results indicate that although thermal shutters reduce heat-loss through windows, their performance could be significantly affected by cold-bridging by up to 90%. The additional thermal resistance due to the air cavity and the ventilation through the trickle vent appeared to be much less significant compared to the effects of thermal bridging.

Keywords: Windows; Thermal Shutter; Vacuum Insulation; Thermal Bridging; Heat Loss

1. Introduction

Buildings are responsible for consuming approximately 40% of energy and emitting 36% of CO_2 in the EU [1]. Reducing energy consumption in buildings is one of the main areas that require energy efficient interventions for reducing their carbon footprint and achieving the emission targets as set in the Paris Agreement [2]. Thermally insulating building envelopes can help in reducing the space heating energy consumption and achieving energy efficiency in buildings. Windows are often the thermally poor performing element in the building envelope and can have heat transfer coefficients (U-value) up to 10 times high in comparison of an insulated roof [3]. Window thermal shutters can be used to reduce heat loss, solar shading and glare [4]. Thermal shutters can improve the thermal performance of a double-glazed window by 25%-30% [5] and can be a non-intrusive option for internally upgrading windows of historic buildings without any change in the external façade. Thermal performance of timber-framed sash windows can be improved cost effectively using thermal shutters instead of replacing it with standard double glazing. Heat loss through windows can be reduced up to 60% by using window shutters insulated with conventional thermal insulation materials [6]. Further decreases in heat loss would need greater thickness of a shutter's thermal insulation material, which may not be aesthetically desirable nor ideal for achieving smart windows. To address this issue, alternative materials are required to be employed.

Previously, Phase Change Materials (PCMs) have been investigated as one of the options in external window shutter application in summer climatic conditions and was found to have reduced the heat gain through windows by 23.29% [7]. Use of PCM in an aluminum hollow blade internal window shutter was investigated by Silva et al. [8] and found to have reduced the heat flux by 10W/m2 in the measurement chamber in summer climate conditions in a Mediterranean region. Vacuum Insulation Panels (VIPs), an advanced thermal insulation material, have been suggested to improve the performance of thermal window shutters relative to PCMs(?) without any effect on overall thickness [9,10]. VIPs have a thermal conductivity that is potentially 5-8 times lower compared to that of a conventional thermal insulation material [11,12,13]. VIP insulation is a suitable window shutter application due to its low thermal conductivity, thinner section and damage protection inside the outer cover of thermal shutter. However, the issue of thermal bridging for VIP insulated thermal window shutters has been highlighted to have significant impact on the overall window thermal performance [9]. This paper further investigates the effects of thermal bridging and air gap/cavity between the window and the shutter and presence of shutter trickle vent on thermal performance of VIP insulated window shutter.

2. Methodology

Static thermal simulations were conducted in VOLTRA, which is a thermal analysis software used for simulating three-dimensional transient heat transfer [14]. A 1000 x1000 mm double-glazed window with 50 mm aluminum frame and an overall U-value of 1.4 W/m2K was modelled. The simulations were done for a VIP window shutter, with a thermal conductivity of 0.006 W/mK, for the following combination scenarios:

Geometry:
- Bare window (without thermal shutter)
- Window and internal shutter with VIP insulation

Ventilation:
- No ventilation/trickle vent
- Trickle ventilation (500mm)

Air gap size:
- 50 mm
- 100 mm
- 150 mm
- 200 mm

Walling construction:
- Typical cavity insulated wall
- Adiabatic walls

Overall, 18 combination scenarios were simulated. The internal and external temperatures were considered as 20 °C and 0 °C, respectively, to reflect winter conditions in an oceanic climate. Table 1 summarises the simulation conditions and material properties. For the purpose of the ventilation through the trickle vent, a constant inlet/outlet ventilation was considered between outside and the cavity between the window and the shutter. According to CIBSE Guide A (CIBSE 2015) [15], the ventilation rate for small openings and cracks can be calculated from the equation (1):

$$q_{vc} = l_c \, k_1 \, (\Delta p)^n \quad (1)$$

where, q_{vc} is the volumetric flow rate through the crack ($L.s^{-1}$), l_c is the length of the crack/opening (m), Δp is the pressure difference across the opening (Pa) and k_1 is the flow coefficient per unit length of the opening ($L.s^{-1}.m^{-1}.Pa^{-n}$). The figures for the k1, n and Δp were defined as 0.8, 0.6 and 0.7 respectively, using Appendix 4.A2 and Table 4.14 of the CIBSE Guide A document [15]. The ventilation rate through a 500mm trickle vent was therefore calculated as: 0.5 x 0.8 x (0.7) 0.6 = 0.32 $L.s^{-1}$.

Table 1. Simulation inputs and parameters

Material	Thermal conductivity (W/mK)	Thickness/size (mm)	Temperature (°C)
Outside	-	-	0
Inside	-	-	20
Brick	0.90	100	-
Cavity insulation	0.035	80	-
Concrete	0.85	140	-
Gypsum board	0.50	15	-
Glazing	0.036*	20	-
Shutter (VIP)	0.006	50	-
Shutter frame	0.5	50	-
Air cavity between shutter and window	-	50 ,100, 150 and 200	-
Trickle vent		500	

* Additional inside (0.13 m^2K/W) and outside (0.04 m^2K/W) surface resistance BS EN ISO 10077-1 BSI (2017)[16] should be considered for U-value calculations.

3. Results and Discussion

According to the results, heat loss through the bare window was 26.65 W. The heat loss significantly reduced by around 75%, 67%, 59% and 53% for the 50, 100, 150, and 200 mm air gap, respectively, when the thermal shutter was deployed. Table 2 summarises the results for different cavity widths (unventilated air cavity) when the shutter was on for a typical insulated cavity wall.

Table 2. Heat-loss values for the shutter with insulated cavity wall and no trickle vents

Cavity width/air gap (mm)	Heat loss through the window (W)
Bare window-base case	26.65
50	6.61
100	8.75
150	10.92
200	12.44

The results indicate that there is a direct relationship between heat losses through the window and the cavity width. The heat loss increased significantly by around 90% from 6.61 W, for the 50 mm air gap, to 12.44 W, for the 200 mm air gap. This seems to be due to the excessive heat losses through the surrounding surfaces around the window and the shutter, indicating thermal bridging. Figure 1 and Figure 2 also illustrate the heat loss and temperature ranges through the windows, shutters and walls. These figures show higher temperatures corresponding to higher heat-losses/thermal bridging around the perimeter of the shutters and windows. The blue colours at the centre of the shutters in Figure 1 (50mm, 100mm) indicate considerably lower losses through shutters, relative to the teal and green colouring (150mm, 200mm). The figures show lower losses when the air cavity is reduced, in line with the numerical results shown in Table 1. Overall, the results confirm the findings of earlier studies [4,9] on the effects of thermal bridging on the performance of the thermal shutters.

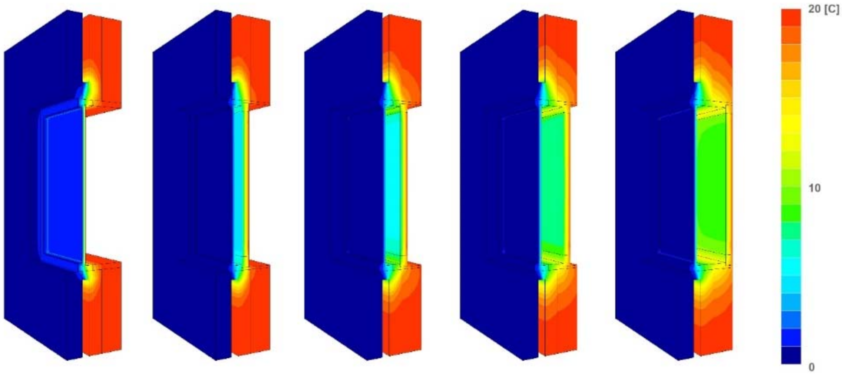

Figure 1. Temperature ranges (°C) in window systems with insulated cavity wall for (from left to right): bare window, window & shutter 50mm, 100mm, 150mm and 200mm unventilated air cavity.

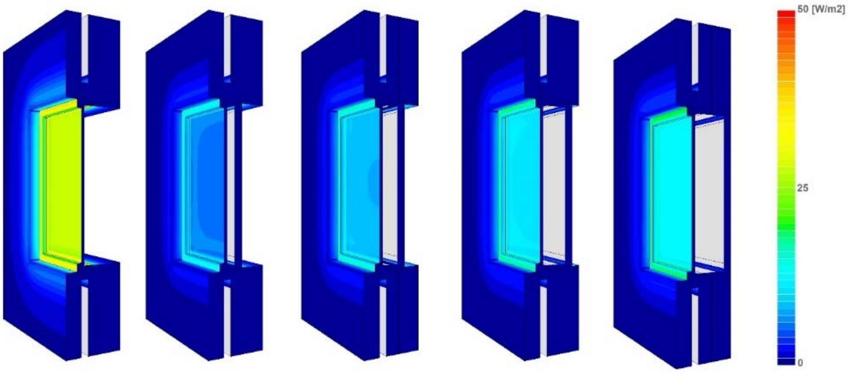

Figure 2. Heat-loss ranges (W/m^2) in window systems with insulated cavity wall for (from left to right): bare window, window & shutter 50mm, 100mm, 150mm and 200mm unventilated air cavity.

Table 3 summarises the results for different unventilated air cavity sizes when the walls and surrounding surfaces around the window and shutter were changed to near-zero conductivity of 0.0001 W/mK. Unlike the above figures, the amount of heat-losses through the window remained almost constant regardless of the size of the air gap. According to the BS EN 13125 (BSI 2001) [17], for the "Class 5" airtight shutter an additional R-Value of 0.17 m2.K.W^{-1} should be considered to recognise the insulating effect of the air gap between the window and the 'external' shutters. The additional thermal resistance is also considered for internal devices such as internal blinds. The additional thermal resistance of the air gap seems to be correct in theoretical conditions when thermal bridging is zero or negligible; however, the presence of thermal bridging significantly deteriorates the performance of the shutters. Indeed, the main criteria that BS EN 13125 is referring to are the air cavity, between the shutter and window, and the air permeability of the shutter. No reference has been made to thermal bridging in the standard, which appears to be a significant issue in the performance of shutters and other similar products.

Table 3. Heat-loss values for shutter with adiabatic walls and no trickle vents

Cavity width (mm)	Heat loss through the window (W)
Bare window-base case	26.65
50	4.23
100	4.18
150	4.28
200	4.31

Table 4 and Table 5 show the heat losses through the window for the normal and adiabatic walls when a 500mm trickle vent was introduced to the window. As stated above, in the methodology section, a permanent inlet/outlet ventilation of 0.32 $L.s^{-1}$ was considered to simulate the effects of trickle ventilation on the performance of the shutters. According to the results, the losses through the windows were reduced for all simulated scenarios. This appears to be due to the losses through ventilation, meaning that although the overall heat losses increased, these were reduced through the windows.

Table 4. Heat-loss values for the shutter with insulated cavity wall and trickle vent (500mm)

Cavity width (mm)	Heat loss through the window (W)
Bare window-base case	26.65
50	5.83
100	7.78
150	9.83
200	11.31

Table 5. Heat-loss values for shutter with adiabatic walls and trickle vent (500mm)

Cavity width (mm)	Heat loss through the window (W)
Bare window-base case	26.65
50	3.67
100	3.60
150	3.68
200	3.70

Figure 3 and Figure 4 illustrate the losses through the shutters and windows with a ventilated air cavity. The heat-losses have been reduced significantly through the window when the shutter is deployed. Similar to the above figures (1 &2), the losses are significantly lower for smaller air cavities indicating the negative effects of thermal bridging.

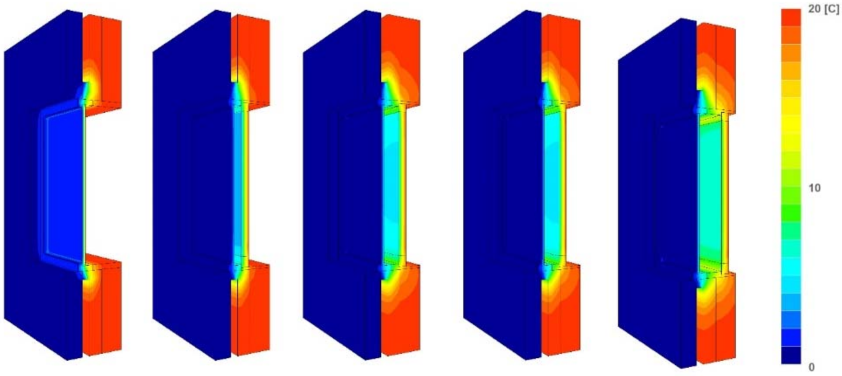

Figure 3. Temperature ranges (°C) for (from left to right): bare window, window & shutter 50mm, 100mm, 150mm and 200mm ventilated air cavity under adiabatic conditions.

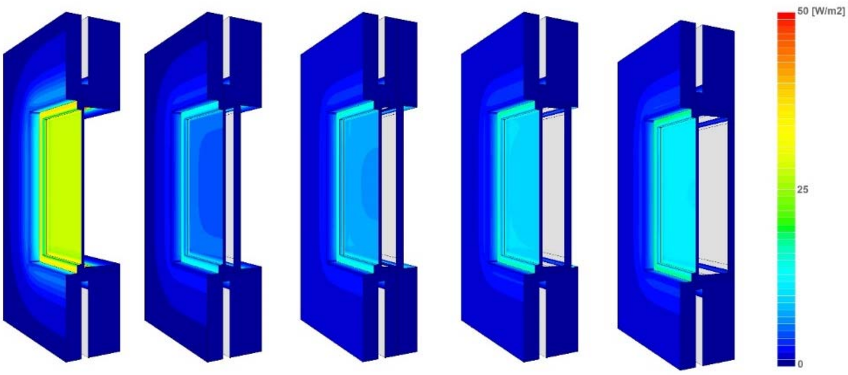

Figure 4. Heat-loss ranges (W/m²) for (from left to right): bare window, window & shutter 50mm, 100mm, 150mm and 200mm ventilated air cavity under adiabatic conditions.

4. Conclusions

Windows are one of the main areas of heat-loss in buildings. Thermal window shutters could significantly reduce heat-losses through windows; however, the performance of shutters greatly depends on various issues including the type of insulation used, thermal bridging and the ventilation rate that itself relates to the airtightness of both the windows and shutters as well as the presence of controlled trickle ventilators. This paper studied the effects of air cavity gap and trickle ventilation on the performance of a window shutter made of Vacuum Insulation Panels (VIP). The results indicate that there is a direct relationship between the air cavity sizes (between the window and shutter) and heat losses through the windows. The heat loss through the window was reduced by nearly 50% when the cavity between the shutter and window was reduced from 200 mm to 50 mm. This indicates the significant effect of cold-bridging on the performance of thermal shutters. Therefore, the additional heat loss due to cold bridging outweighs the additional thermal resistance due to the increased air gap. The results also indicates that overall thermal performance is slightly deteriorated when trickle vent was introduced. The significance of trickle vent sizes and ventilation rates require more investigation. No meaningful changes in the performance were observed for different unventilated cavity sizes when the walls were changed to adiabatic. The results therefore indicate that to achieve the best performance for an airtight shutter, the size of the cavity between the window and the shutter and/or the thermal bridging through the surrounding walls should be minimised.

Conflicts of Interest: The authors declare no conflict of interest.

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