Development of a window with a low heat loss and high visual transmittance

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Summary

As windows with very low heat loss usually comprise multi-pane systems, their visual transmittance is low. This may be unacceptable or undesirable in many domestic applications, due to the loss of both daylight and solar gains. New multi-pane windows are cumbersome to install and require framing arrangements which are difficult to retrofit. A new form of, and manufacturing process for, a contiguously sealed double-glazing with an evacuated gap and internal low long-wave radiative emittance coating is described. This glazing is no heavier than conventional double-glazing, gives good visual transmittance and may be retrofitted to existing buildings. The experimentally measured heat transfer coefficients and visual transmittances of 0.5x0.5metre laboratory fabricated evacuated glazing samples are reported. Theoretical predictions of centre of glazing K-values using a validated model ranged from 0.28 to 2.5Wm^{-2}K^{-1}, for low emittance coatings with emittances between 0.04 and 0.2, support array pillar spacing of between 20 and 50mm, and with pillar radius' between 0.11 and 0.55mm. The general specifications of the experimentally fabricated systems are provided, together with a discussion of the influence of design parameters on overall thermal performance and durability.

Introduction

Advanced glazing systems with very low U-values have employed multiple glass panes, inert gases and numerous low emittance coated surfaces. These systems usually require three or more panes of glass and are twice as wide as standard double-glazing. Their visual transmittance is reduced by the number of glass sheets and multiple low emittance films. They are cumbersome to install and require framing systems that are in general difficult to retrofit. A new form of, and manufacturing process for, a contiguously sealed double-glazing with an evacuated gap and internal low long-wavelength radiative emittance coating, illustrated schematically in Figure 1, has been developed (1). This glazing is no heavier than conventional double-glazing, gives good visual transmittance and due to its narrow width is suitable for retrofit to existing buildings.

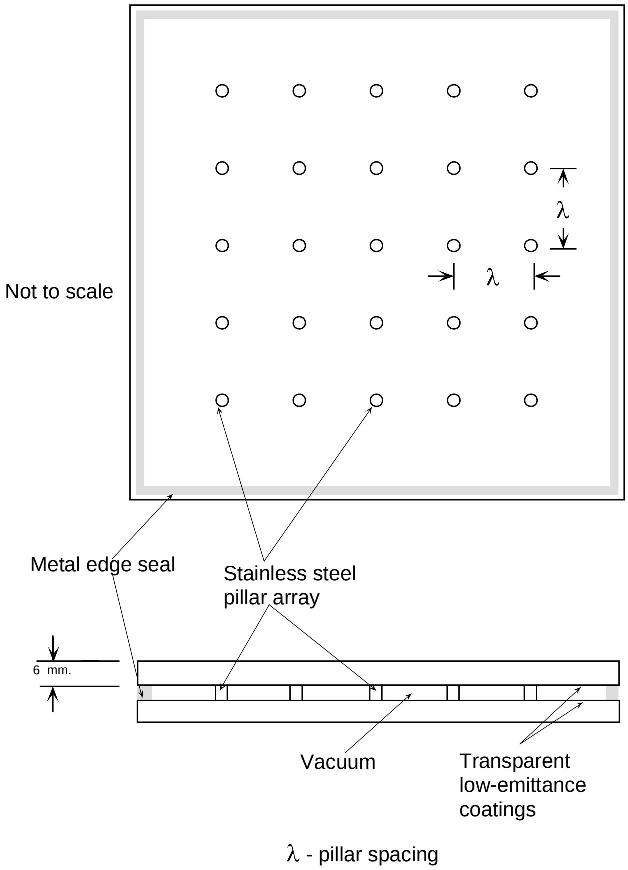

Figure 1: Schematic diagram of a metal-based edge sealed evacuated glazing.

Traditional glazing thermal simulation models do not accurately predict the thermal behaviour of evacuated glazing systems. To address this inability, finite-difference and finite-element simulation tools based on the “unified model” of Eames and Norton (2) for optics and heat transfer have been developed. The transient three-dimensional model, allows coefficients for convective and radiative heat transfer at the external glass surfaces to be imposed, and predicts the evolution of temperature from set initial conditions. Initial results from a series of experimental and theoretical analyses have been reported by Griffiths et al. (1,3,4). Calorimeter based experiments have been undertaken, and are reported below, to verify the predictions made by the developed computer model. A high temperature glass-sealed evacuated glazing produced at the University of Sydney (5), and recent samples of low-temperature sealed evacuated glazing produced at the University of Ulster (1) have been experimentally tested.

Calorimeter and Solar Transmittance Experiments

The experimental test program undertaken was based on that of Griffiths et al. (4). The calorimeter was however used in the non-illuminated mode, with the hot plate at the rear of the calorimeter box used as the heat source. A constant temperature of 42 ±0.2°C was achieved on the hot plate by circulating heated water from a constant temperature heat source. This gave an average internal air temperature of 36 ±0.2°C while the external laboratory temperature was maintained at 9 ±0.2°C. A retaining frame that extended 7mm over the exterior glass surface was used to locate the glass in position. When steady-state conditions were attained, the experimentally determined overall heat loss co-efficient of the 0.25m^2 framed glazing samples was 2.3Wm^{-2}K^{-1} for the whole system including the frame. The experiments were repeated at four different volume flow rates of the heating plate hot water, to reduce errors and ensure the robustness of the experimental technique. This value agreed well with that predicted by the model, the value is high due to the large edge effects resulting from the small glazing area and simple framing system.

The total solar transmittance through evacuated glazing samples with different low-emittance coatings was measured with a normal incidence Pyrheliometer. The measured value for the solar transmittance (τ_{sol}) of an evacuated glazing with two "k" (6) coated sheets was 0.49, while its visual transmittance (τ_{lux}) was 0.69. Samples have been produced with only one of the sheets coated with "Kappafloat" (6). The measured value of τ_{sol} for these samples was 0.43 while τ_{lux} was 0.71. The results are tabulated in Table 1.

glass	τ_{sol}	τ_{lux}
single sheets		
clear	0.75	0.88
kappafloat	0.47	0.79
double glazing 2x6mm sheets	0.62	0.82
vacuum glazing with low-e films		
kappafloat-kappafloat	0.36	0.66
clear-kappafloat	0.43	0.71
k-k	0.49	0.69

Table 1: Measured values of solar and visual transmittance for three vacuum glazing systems with some comparisons.

Dynamic thermal simulation

Windows are subject to varying internal and external conditions, therefore steady-state predictions have limited use. For accurate predictions of window performance, it is essential to consider conduction, convection, radiation and absorption of solar flux. Large variations in length-scale are inherent in an evacuated glazing system, i.e. the window area may be of several square metres, while the support pillar cross sectional area is of the order of $4 \times 10^{-8} m^2$. (The support pillars are required to maintain a vacuum space between the two sheets of glass. The pillars prevent the two sheets of glass being pushed together by atmospheric pressure.) Analysis using numerical methods with a uniform division of the problem domain would result in a system of equations with over 10^9 variables. This number of variables is unnecessary to obtain an accurate prediction of system temperatures and rates of heat transfer. Therefore a computer model based on the "unified model" of Eames and Norton (2) has been used. It uses an orthogonal array of nodes, and energy balance equations at each node based on the work of Patankar (7). A variant of the Bi-CGstab algorithm is used to solve the matrix of equations (8).

Modelling results

The simulation model was used to determine the change in the overall thermal conductance for scenarios in which different low emittance coatings were present, the pillar diameter varied from 0.2mm diameter to 1mm diameter, and pillar spacing varied between 20mm and 50mm. In addition, an analysis of the effect of radiation suppression near the pillar was undertaken. Boundary conditions used were those adopted in previous work in this area (1,3,4,9). Heat transfer coefficients to the cold and warm environments were 30 and 8.3 $Wm^{-2}K^{-1}$ respectively, with cold and warm environment temperatures of -17.8°C and 21.1°C,

Effect of changing glazing coating emittance

Two systems were simulated, in (i) both sheets were coated with the same low emittance film as the system manufactured by Collins and Robinson (10). In (ii) one surface was coated with a low emittance film which had been deposited using sputtering techniques, the other was a clear pane of glass with an emittance of 0.9 as the system manufactured by Griffiths et al, (1). Reducing the value of the coating emittance increases the insulating properties of the evacuated glazing, as shown in Figure 2. It can be seen that the use of a coating with a very low emittance of 0.04 on one sheet of glass, instead of two coatings with an emittance of 0.2, gives a better performance. It is also evident that there is little to be gained from using two 0.04 emittance coated glass sheets. A sputtered low-emittance coating that can withstand the temperatures required in the low temperature manufacture of vacuum glazing systems developed at the University of Ulster (1), which maintains a high visual transmittance and reduces multiple reflections between films has been developed specifically for this application (11).

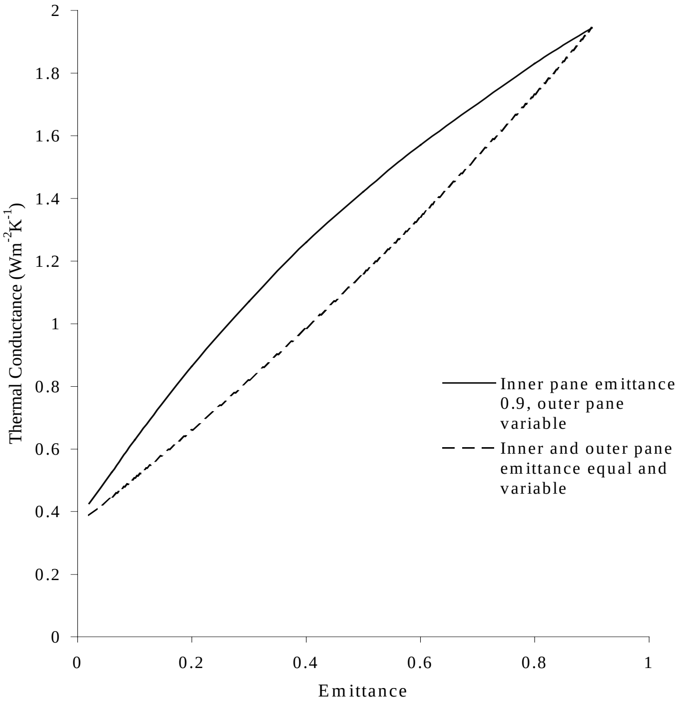

Figure 2: Performance of vacuum glazing where a) both panes have the same low-emittance coating, and b) where the exterior pane only has a low-emittance coating with an inner pane emissivity of 0.9. The internal and external temperatures were set at 21.1°C and -17.8°C while the internal and external heat transfer coefficients were set at 8.3 and 30 $Wm^{-2}K^{-1}$ respectively. Pillar spacing was 40mm and pillar diameter was 0.32mm.

Effect of pillar array separation and pillar radius on thermal performance

A quarter pillar model was created to predict the effect of varying the pillar separation and pillar radius, as shown in Figure 3. The use of a quarter pillar model with adiabatic boundaries was to reduce the required computational effort. The nature of the pillar array is analogous to an array of point contacts between the glass surfaces (9). The analytical approach determines that the thermal conductance of a single pillar is dependent upon the thermal conductance, k, of the infinitely large glass sheets and the radius, a, of the pillar, with $C_{pillar}=2ka$. The thermal conductance of the pillar array is determined by multiplying C_{pillar} by the inverse of the pillar separation, λ, squared, i.e., C_{array}

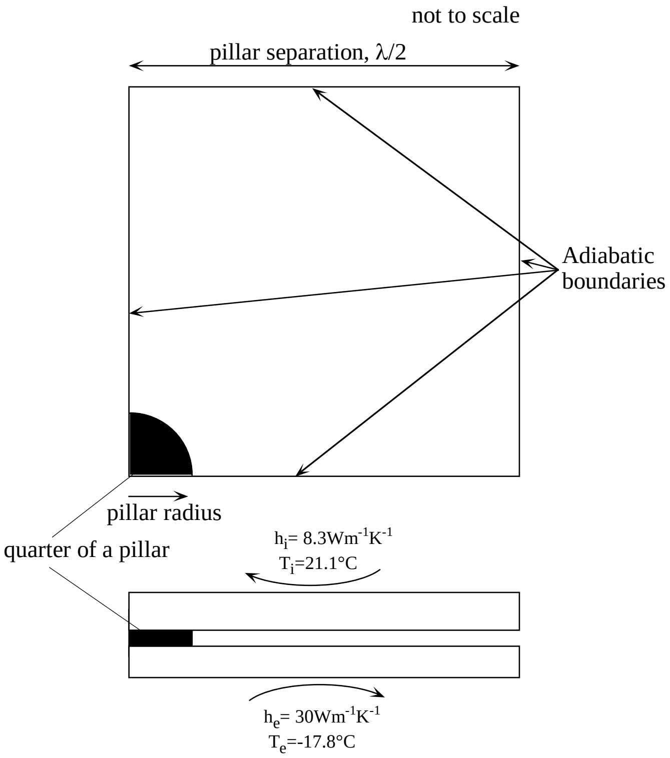

Figure 3: Schematic of the model used to determine the thermal performance of vacuum glazing with varying pillar separation and pillar radius.

= C_{pillar}/λ^2 (10). The results determined using the computer model are presented in Figure 4. These compare well with those obtained using the analytical approach. Increasing the pillar radius results in a higher rate of heat transfer through each pillar and thus total heat transfer increases. Increasing the pillar separation leads to a decrease in the total thermal conductance, due to the reduction in number of pillars required per unit area of glass.

Analysis of the suppression of radiative heat transfer near the pillar

In traditional multiple glazing systems the centre region glass surface temperatures are relatively uniform. In vacuum glazing the pillar array constitutes a thermal short-circuit between the two glass panes resulting in non-uniform outer glass surface temperatures for 4mm thick panes. The predicted and measured temperature differences on the external surfaces of an evacuated glazing using 6mm
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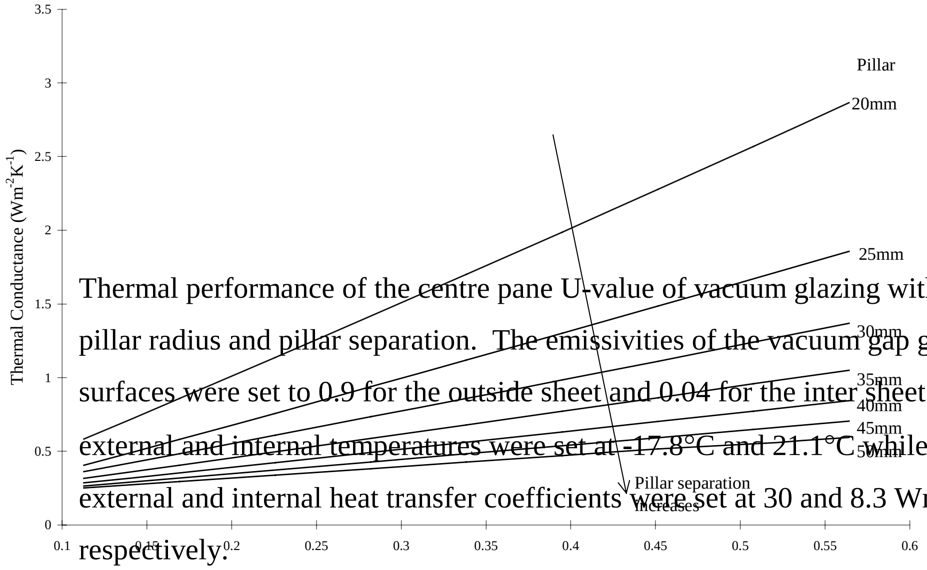
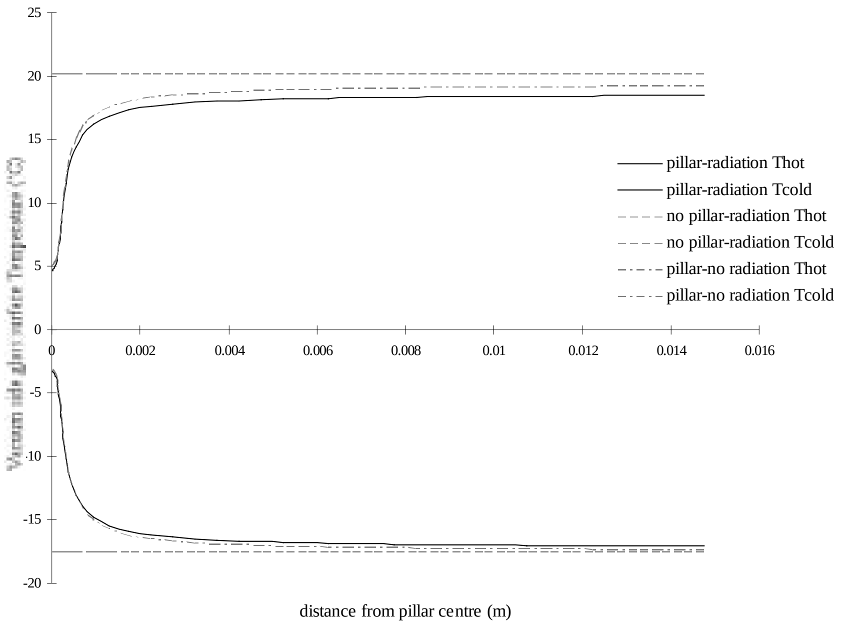


Figure 4: Thermal performance of the centre pane U-value of vacuum glazing with varying pillar radius and pillar separation. The emissivities of the vacuum gap glass surfaces were set to 0.9 for the outside sheet and 0.04 for the inter sheet. The external and internal temperatures were set at -17.8°C and 21.1°C while the external and internal heat transfer coefficients were set at 30 and 8.3 Wm^{-2}K^{-1} respectively.

As can be seen from Figure 5 there is a temperature difference of over 10K on the vacuum faces of the glass in the area immediately adjacent to the pillar, extending out 2mm from the pillar axis. If a very low, low-emittance coating (ε=0.04) is utilised, there is a negligible change in the predicted surface temperature compared to a system in which radiative heat transfer is totally suppressed. This demonstrates the dominance of pillar array conduction in determining the rate of centre-pane heat transfer when good low emittance coatings are present. The computer model predicted that thermal radiation between the two sheets contributed no more than 30% to total thermal conductance across the centre of the vacuum glazing when one of the panes had a low emittance coating of 0.04. Figure 6 shows the finite-volume model predicted variation in radiative heat transfer across the vacuum gap as distance from the pillar increases. There is a sharp reduction in radiative heat transfer near the pillar, the effect of this is very small compared to the total value of radiative heat transfer when the area effects are included. The suppression of radiation around the pillar is thus small and while there may be important micro effects on thermal stress at the pillar-glass interface, (particularly when subject to relatively high thermal differences between the warm and cold sides), the effect on overall centre-region thermal conductance is minimal.



Optimal System Performance

Figure 5: Variation of temperature with distance from the pillar on the vacuum faces of the two glass sheets for three scenarios, a) with pillars and radiation, b) a pillar but without radiation, and c) without a pillar but with radiation. The emissivities of the vacuum gap glass surfaces were set to 0.9 for the outside sheet and 0.04 for the inner sheet. The external and internal temperatures were set at -17.8°C and 21.1°C while the external and internal heat transfer coefficients were set at 30 and

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The best thermal performance in an evacuated glazing system arises from pillar diameters as small as can be fabricated, spaced as far apart as possible. The choice of the pillar diameter and separation, is however governed more by the mechanical stresses imposed on the system by atmospheric pressure (5). 0.3mm diameter pillars spaced at 50mm can be utilised if 4mm tempered glass is used instead of standard float glass. The low temperature fabrication technique developed at the University of Ulster allows the use of tempered glass and soft, very low emittance films (ε=0.04). Predictions of heat transfer for the University of Ulster system, which is subject to a patent, would give a centre-pane U-value of $0.28Wm^{-2}K^{-1}$ (when the external and internal heat transfer coefficients from the glass surfaces are 30 and $8.3Wm^{-2}K^{-1}$ respectively), with a visual transmittance of 0.71.

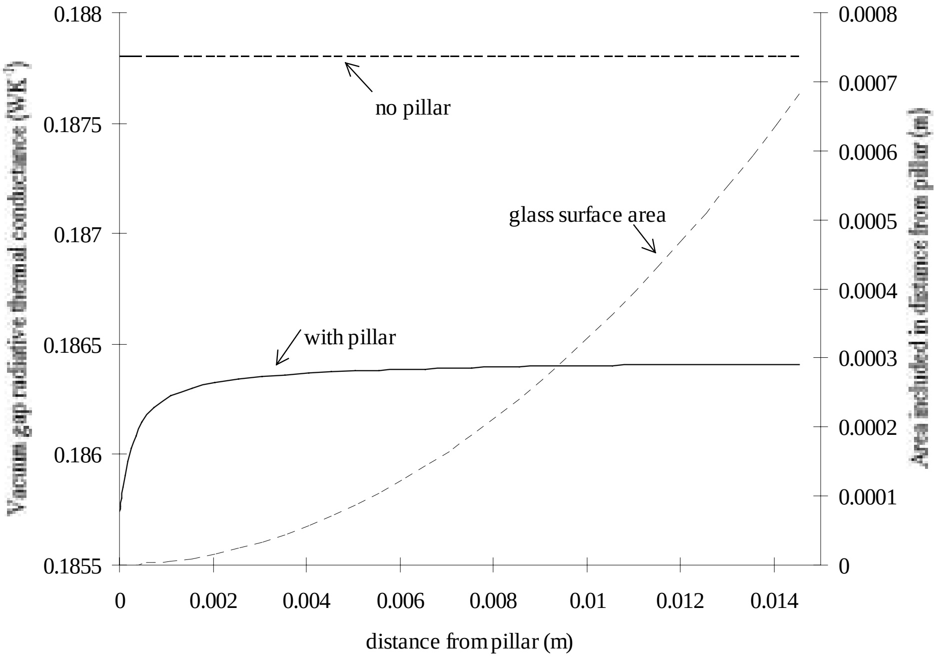

Figure 6: Variation of radiative heat transfer with distance away from the pillar for two scenarios, a) with a pillar, b) without a pillar.

Conclusion

The validation of the developed model should make it possible to reduce the level of experimental characterisation required for new designs of vacuum glazing and frames. The experimentally determined U-value for the 0.5x0.5m k-k coated evacuated glazing produced at the University of Ulster was $2.3Wm^{-2}K^{-1}$, this was similar to that predicted by the thermal simulation model. The solar and visual transmittances measured for systems with two "k" coatings were good, while the systems fabricated from a silver coated glass pane and a non-coated glass pane, gave lower solar transmittance values and higher visual light transmittance. The suppression of radiation around a pillar while significant in the region adjacent to the pillar, does not significantly alter the overall thermal conductance of the vacuum gap.

The low-temperature fabrication procedure for vacuum glazing developed at the University of Ulster will permit the use of 4mm tempered glass with increased pillar spacing and very low emittance coatings. This makes possible the production of glazing systems with a centre-pane U-values of as low as $0.28Wm^{-2}K^{-1}$ while maintaining a visual transmittance of over 0.7.

Acknowledgements

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Nomenclature

a	radius of the pillar contact with the glass	m
C_{pillar}	energy flow through a single pillar	WK^{-1}
C_{array}	energy flow through the pillar array	$W^{-1}K^{-1}$
h_e	combined external surface radiative and convective heat transfer co-efficient	$Wm^{-2}K^{-1}$
h_i	combined internal surface radiative and convective heat transfer co-efficient	$Wm^{-2}K^{-1}$
k	thermal conductivity of the glass	$Wm^{-1}K^{-1}$
T_i	internal air temperature	°C
T_e	external air temperature	°C
T	temperature	K
ε	emittance	-
λ	pillar separation	m
τ_{sol}	solar transmittance	-
τ_{lux}	visual transmittance	-

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