THERMAL AND OPTICAL ANALYSIS OF A NOVEL GLAZING FAÇADE SYSTEM WITH PARALLEL SLATS TRANSPARENT INSULATION MATERIAL (PS-TIM)

Y Sun; Y Wu; R Wilson; Z Zhu.

Department of Architecture and Built Environment, The University of Nottingham, Nottingham, NG7 2RD, UK

ABSTRACT

With the increase of the awareness of sustainability in the built environment, it has never been stopped to continuously improve the performance of glazing façade systems leading to indoor comfortable and building energy conservation. An innovative façade system where parallel transparent plastic slats are sandwiched in between two glass panes to form a Transparent Insulation Material (PS-TIM) structure is proposed to effectively reduce the coupled convective and radiative heat transfer, therefore increasing the thermal resistance of the façade, meanwhile keep sufficient sunlight penetrating into rooms. A numerical investigation of the thermal and optical performance of this PS-TIM façade were conducted and presented in this paper. The detailed modelling of the thermal characteristics of the PS-TIMs was undertaken using a finite volume Computational Fluid Dynamic (CFD) package FLUENT while the optical simulation is realised by a commercial ray-tracing tool TracyPro. The thermal numerical model was validated with previously published experimental measurements. The CFD predictions show that: an aspect ratio of *A=0.35* can provide full suppression in convection; the PS-TIM structure can reach *35%-46%* reduction of thermal conductance compared with standard double glazing at the same size with no slat installed in the air cavity; In addition, the trade-off analysis between *U-value* and light transmittance at various solar incidence angles have also been investigated. The results provide a better understanding of the benefits of parallel plastic slats Transparent Insulation Material (PS-TIM) in energy saving and also leads to better designs of glazing façade systems.

Keywords: parallel plastic slats Transparent Insulation Material (PS-TIM), Computational Fluid Dynamic (CFD), building simulation, heat transfer, optical performance

1. INTRODUCTION

Since the 60s in the last century, glass has become the most popular façade material for buildings. With the increase of the awareness of sustainability, people paid more attention to improve the poor thermal insulation property of glazing façade. A Transparent Insulation Material (TIM) structure, which is sandwiched in a double-glazed unit, is proposed to reduce the heat transfer through the glazing unit more effectively and meanwhile keep sufficient sunlight penetrating into rooms. The parallel slats structure of TIM (perpendicular TIM) is the most suitable structure for window application and thus selected in this research. As shown in Figure 1 (a), the structure walls that are vertical to glazing panes divide the whole air gap into small cells. These walls provide additional viscous resistance to the onset of free convection and meanwhile interfere the thermal radiation transferred from one side to the other. Therefore, the employment of a well-designed perpendicular TIM structure can effectively reduce the heat transfer coefficient of a double-glazing unit. In the past decades, the thermal behaviours of perpendicular TIM have been researched numerically and experimentally, but most of the studies are focused on their application in solar collectors [1-3]. However, when TIMs are vertically applied for windows or glazing façades, their thermal and optical performances are entirely different but were rarely studied. To address the gap, the work presented in this paper details the optical and thermal analysis of parallel plastic slats TIM (PS-TIM) structures that were sandwiched in between two glazing panes. A two-dimensional model was developed in the commercial CFD package FLUENT to comprehensively explore the convective, conductive and radiative heat transfer that occurs in the double glazing air cavity with and without parallel slats structure. The Nusselt number, which represents the ratio between the pure conduction resistances to a convection resistance, is used to indicate the intensity of convection. Finally, the *U-value* was calculated and ray-tracing technique was used to analyse the optical transmittance under different solar incidence angles.

2. METHODOLOGY

Schematic diagrams illustrating the geometry of a double-glazing unit with and without a PS-TIM structure are shown in Figure 1 (b) and (c), respectively. A double-glazing unit with an air gap of *15mm* width and *300mm* length was researched by adding 4 different geometries of PS-TIM structure (four different interval distances between the parallel slats). The interval distance, which is D_a, varies from *3mm*, *5mm* to *7.5mm* and *10mm*.

Two-dimensional finite volume models were developed in the commercial CFD package FLUENT. To simplify the CFD simulation process, the following assumptions were made: 1) the internal surfaces of the left and right glass panels were set as two isothermal walls with different temperatures to represent the temperature difference between indoor and outdoor environments, while the top and bottom ends were assumed to be adiabatic; 2) the enclosure was filled with air with $Pr = 0.71$, all thermophysical properties (e.g. ρ, C_p, k) of the fluid were assumed to be constant [4-6], except for the fluid density and viscosity, which varies with temperature. The flows in the vertical cavity or cells remain laminar, because the Grasholf Numbers never reach the related critical value [7].

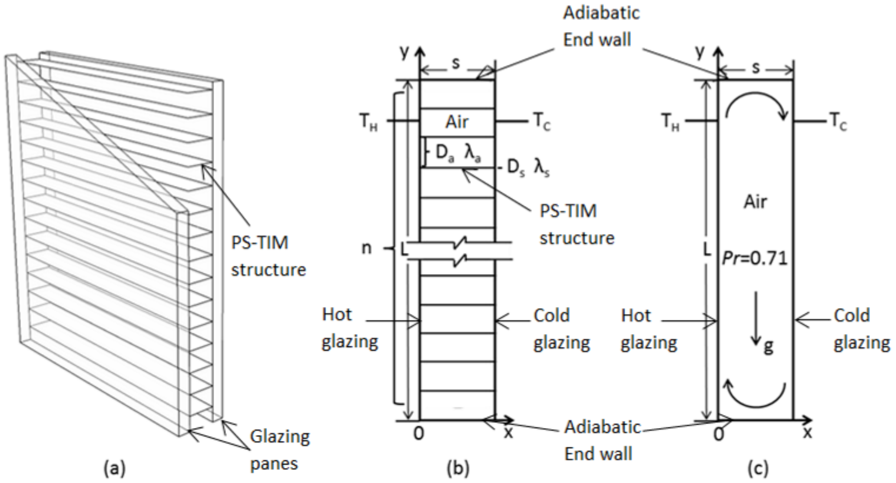

Figure 1: (a) PS-TIM structure in a double-glazing (b) 2D schematic diagram illustrating the geometry of the air gap with PS-TIM structure (c) 2D schematic diagram illustrating geometry of air gap without PS-TIM structure

In order to evaluate the effect of parallel slats structure on the convection, the radiative heat transfer between the two glazing panes was separated initially. It was only included when calculating the overall performance of the heat transfer through the air cavity and the *U-value*. The discrete ordinates (DO) radiation model was used to solve the radiative transfer equation.

Four temperature differences between the two glazing panes (*10K*, *20K*, *30K* and *40K*) were set as the boundary conditions, but the mean temperature of the two isothermal surfaces was kept at 10^oC. And in order to provide a more accurate consideration of the boundary layers, the mesh size was defined as smaller near the boundaries (*0.025mm×0.025mm*), and then gradually increased toward the centre. Extensive mesh independent studies were undertaken. Iterative convergence was achieved when the normalized residuals were less than 10^{-3} for the continuity, and 10^{-7} for the energy and momentum equations.

The module validation was undertaken using the experimental date published by Lee and Korpela [8]. The simulated results well matched, as the percentages of difference of the Nusselt numbers in the same Grashof numbers were less than *4%*.

The estimated result of local convective heat flux and combined convective and radiative heat flux were calculated from the converged temperature field. The results of convective heat flux at the boundaries were used to express the local Nusselt number (*Nu*) as follows:

$$Nu = \frac{(\frac{\partial T}{\partial x})_w s}{\Delta T} = \frac{qs}{\lambda_a \Delta T} \tag{1}$$

where $(\frac{\partial T}{\partial x})_w$ is the air temperature gradient on the wall and q(W/m^2) is the average convective heat flux that transfers across the two surfaces. ΔT(K) is the temperature difference between the hot and cold surfaces.

3. RESULTS AND DISCUSSION

In this section, the simulation results concerning the convective, conductive and radiative heat transfer of the PS-TIM structure in the double-glazing air cavity are discussed. And the overall *U-value* and optical performance of the novel PS-TIM system are presented.

3.1 Aspect ratio for convective suppression

The PS-TIM structure is proposed to suppress the convective heat transfer in the air cavity of a double-glazing unit. However, it is useful to understand the free convection that occurs in a single air cavity at various dimensions firstly to improve our understanding of the underlying convective suppression. In this section, the aspect ratio of a double-glazing units (where $A = \frac{L}{s}$ is illustrated in Figure 1(c)) and the aspect ratio of a PS-TIM cell ($A = \frac{D_a}{s}$ is shown in in Figure 1(b)) to provide convective suppression are investigated.

Figure 2 shows the relationship between the variation of the Nusselt number and different aspect ratio at different Grashof numbers of a single air cavity. The right hand side of the graph represents the performance of air cavity in a conventional double-glazing unit with the aspect ratio increase from 1 to 100. While the left hand side represents the performance of a cell of the PS-TIM structure, whose aspect ratio changes from *0.1* to *1*. It can be seen that the Nusselt number reaches the peak value when the aspect ratio is equal to *1*. This means that a shape of square provides the smallest viscous resistance to the onset of free convection. In the range of *A=1* to *100*, with the increase of aspect ratio, the Nusselt number decreases, but there is no significant difference of the Nuseelt number when the aspect ration increase from 40 to 100. This indicates that the shape of the vertical space has an important influence on the free convection until it becomes sufficiently tall. In the range of *A=1* to *100*, a high Grashof number leads to a high Nusselt number. This means that a higher temperature difference increases the convection in the cavity; therefore the convective heat transfer cannot be fully suppressed. On the other hand, the left hand side of Figure 2 shows the aspect ratio is less than 1, which means the height of the cavity is smaller than its width to create a cell in the shape of horizontal rectangle. With the decrease of the aspect ratio from *1* to *0.1*, the Nusselt number declines sharply until it reaches *Nu=1* when *A=0.35*. This indicates that it is capable of achieving full convection suppression in the PS-TIM cell other than in the vertical slot. This is because the increased viscous resistance is along the direction of the temperature gradient in the cell while it is perpendicular to the direction in the vertical slot. Thus, the convection in the cell can be fully suppressed once the resistance is sufficiently high no matter what the temperature difference between the two panes is.

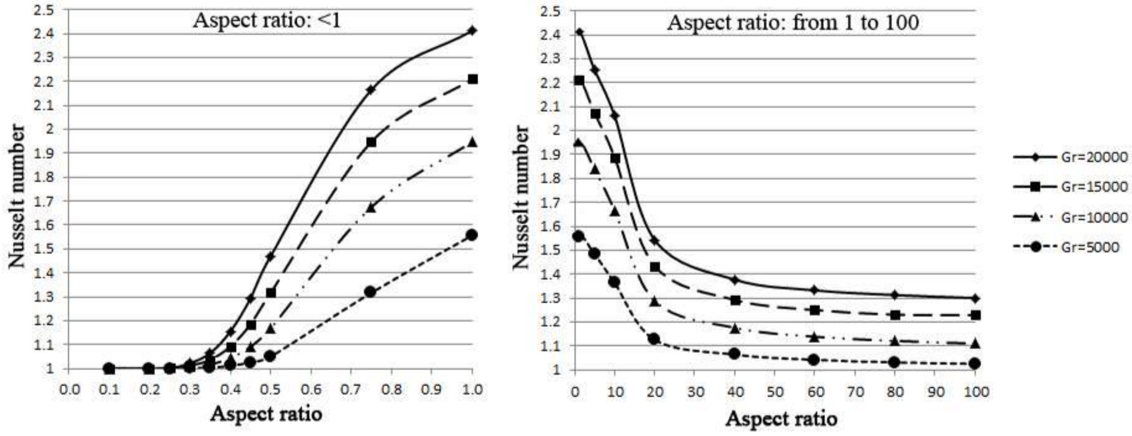

Figure 2：Relationship of the Nusselt number vs Aspect ratio for different Grashof number

3.2 The convection that occurs in the PS-TIM structures

From section 3.1, it can be seen that creating small horizontal rectangle cells leads full convection suppression within air cavity. The application of adding horizontal slats in the air cavity of a double-glazing unit to create a PS-TIM structure with small cells were further studied. Four different PS-TIM structures were analysed and also compared with no-slat cavity.

The relative average Nusselt numbers of an air cavity of a double-glazing unit with and without different geometries of PS-TIM structures ($D_a=3mm$, *5mm*, *7.5mm* and *10mm*) are shown in Figure 3 (left). The free convection within *3mm*- and *5mm*-cell structures is fully suppressed, when the Grashof number increases from *5000* to *20,000*, however, it increases with the increase of the Grashof number in *7.5mm*- and *10mm*-cell structures. The *3mm*-, *5mm*- and *7.5mm*-cell structures can effectively reduce the average Nusselt number and hence reduce convective heat transfer rate, when compared with the air cavity without slat at the same Grashof number. For the *7.5mm*-cell structure, though its Nusselt number increases with Grashof number, but it only reaches *1.2*. This indicates that the convective heat transfer is not significant [8]. The *10 mm*-cell structure provides less convection suppression as the average Nusselt numbers are similar to or larger than that of no-slat, this is because the viscous resistance of *10mm*-cell is less than the tall vertical air cavity of double glazing.

3.3 Thermal conductance of air gap with the PS-TIM structures

In this section, a "convective-conductive-radiative" model was used to investigate the thermal conductance (where $h = \frac{\lambda_a}{s} \cdot \frac{D_a n}{L} + \frac{\lambda_s}{s} \cdot \frac{D_s(n-1)}{L}$, see Figure 1 for symbols representation) of the air cavity with four different PS-TIM structures. The reduction in heat transfer effect is quantified by using the thermal conductance ratio $h_{PS\text{-}TIM}/h_{no\text{-}slat}$. It can be seen in Figure 3 (right), all of the four PS-TIM structures are able to provide a reduction in thermal conductance at different Gr numbers, even including the *10mm* one (which cannot provide convection suppression as mentioned in the previous section). This is because the added interfering walls blocks the long-wave radiative heat transfer between two glazing panes caused by temperature difference. The smaller the cell's height, the smaller the thermal conductance is. The *3mm*-cell structure can reach *35%-46%* decrease of thermal conductance while a *10mm*-cell structure can reduce it by *16%-18%*. Meanwhile, for *3mm*-, *5mm*- and *7.5mm*-cell structures, with the increasing of temperature difference, the reduction rate grows. But 10mm-cell structure changes in an opposite trend. This is because 10mm-cell can only suppress the radiative heat transfer, but has a less convective thermal resistance than no-slat at higher temperature differences.

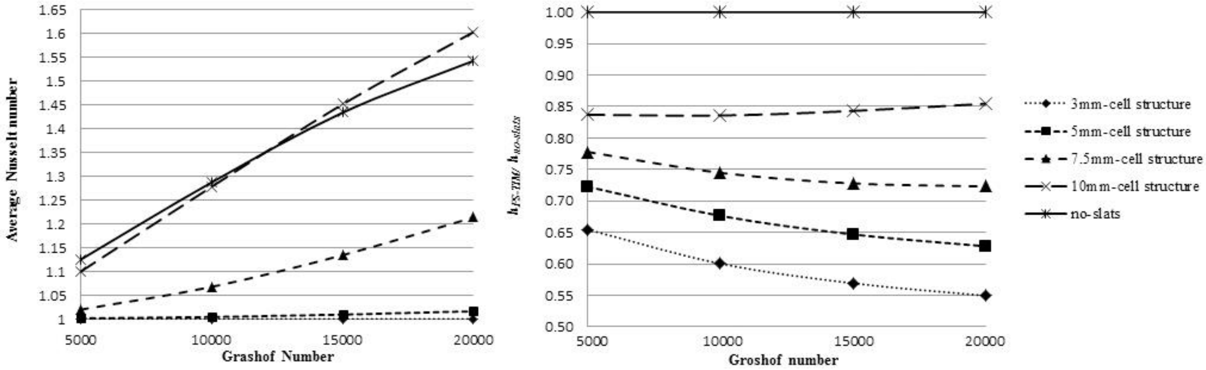

Figure 3. (left) Average Nusselt number vs Grashof numbers for different PS-TIM structure types, (right) Thermal conductance reduction of different PS-TIM structure types vs various temperature differences (D_s=0.1mm, λ_s= 0.15W/mK and ε=0.65)

3.4 An overall consideration of U-value and light transmittance of these four different types PS-TIM

The overall heat transfer between the air gaps under standard testing conditions EN 673 (i.e. temperature difference of *15K* between two panes, average panes temperature of *10^{o}C*) was simulated by FLUENT and discussed in this section. The *U-values* of four PS-TIM structures are shown in Figure 4 (left). The ray-tracing simulation results of the transmittance of these four TIM systems at five different solar incidence angles (*15°, 30°, 45°, 60° and 75°*) are shown in Figure 4 (right).

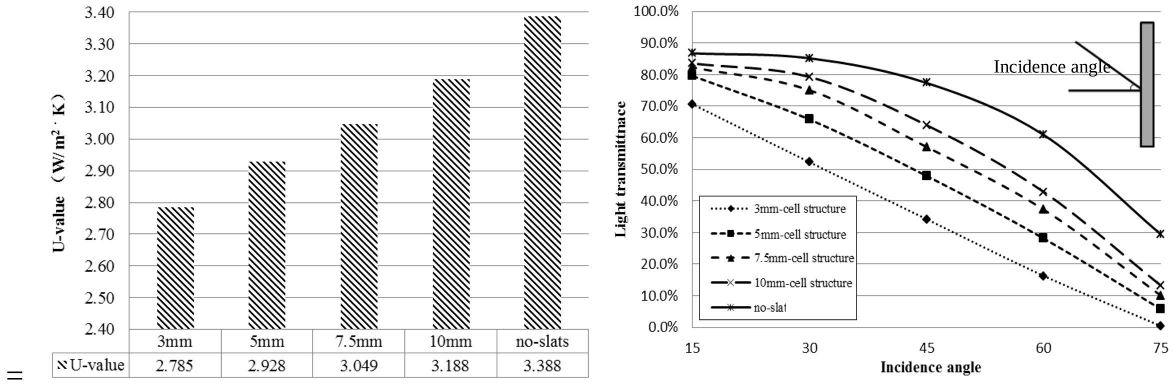

Figure 4. (left) U-value of different PS-TIM structure types; (right) Light transmittance at different incidence angles of different PS-TIM structure types

It can be seen in Figure 4, generally, adding TIM structure and reducing the slats interval distance from *10mm* to *3mm* leads to a gradually reduction of *U-value*, while this also results in a decrease of light transmittance. The *7.5mm* cells and *10mm* cells have a better light transmittance than the *3mm* and *5mm* ones. By compared with air gap without TIM structure, they only have *5%-10%* loss of light transmittance for a low incidence altitude angle (*15°* and *30°*) and *20%* for high incidence altitude angle, and reduce the U-value by *10%* and *5%*, respectively. These systems will be able to provide sufficient daylight transmitted into room for both lighting and passive heating requirements in the wintertime (where the solar incidence angle is low). On the opposite, *5mm* and *3mm* cells have better thermal resistance, but the light transmittances drop *10%* and *20%* respectively compared with *7.5mm* cells.

Thus, for a mild climate with a small temperature difference between indoor and outdoor environment with large daylight requirement, *10mm* and *7.5mm* cells would be recommended. For climate with large temperature difference, but less daylight requirement, *3mm* and *5mm* cells may provide good insulation and a certain degree of shading.

4. CONCLUSION

A detailed research of the thermal and optical simulation of parallel slats TIM (PS-TIM) structure that has been sandwiched in two glazing panes has been conducted. The following conclusion can be obtained: 1) When the aspect ratio of a PS-TIM structure's cell is less than *0.35*, the free convection is fully suppressed despite the temperature difference between the two surface panes; 2) In practice, design a suitable interval distance of the parallel slats in the air cavity to maintain the Nusselt number less than *1.2* can provide good reduction of the convective heat transfer coefficient; 3) The results of a convection, conduction and radiation model show that a *3mm*-cell structure can reach *35%-46%* decrease of thermal conductance while a *10mm*-cell structure can reduce it by *16%-18%*; 4) An overall consideration of light transmittance and U-value has been analysed. This study will provide a general guidance for architects and engineers to apply parallel slats TIM on windows or glazing facades.

ACHNOWLEDGEMENTS

This work was supported by the Faculty of Engineering, University of Nottingham and the China Scholarship Council through a joint PhD studentship to Yanyi Sun.

REFERENCES

1. Kaushika, N.D. Padmapriya, P. Arulanantham, M. Sharma, P.K. : Transparent insulation characteristics of honeycomb and slat arrays. Energy, Vol 19 (10), pp. 1037-1041, 1994.
2. Kumar, P. Kaushika, N.D. : Convective effects in air layers bound by cellular honeycomb arrays. Journal of Scientific & Industrial Research, Vol 64, pp. 602-612, 2005.
3. Arulanantham, M. Kaushika, N. D. : Coupled radiative and conductive thermal transfers across transparent honeycomb insulation materials. Applied Thermal Engineering, Vol 16 (3), pp. 209-212, 1996.
4. Collins, M. Tasnim, S. Wright, J.: Numerical analysis of convective heat transfer in fenestration with between-the-glass louvered shades. Building and Environment, Vol 44 (10), pp. 2185-2192, 2009.
5. Avedissian, T. Naylor, D.: Free convective heat transfer in an enclosure with an internal louvered blind. International Journal of Heat and Mass Transfer, Vol 51(1–2), pp. 283-293, 2008.
6. De Giorgi, L. Bertola, V. Cafaro, E.: Thermal convection in double glazed windows with structured gap. Energy and Buildings, Vol 43 (8), pp. 2034-2038, 2011.
7. Dalal, R. Naylor, D. Roeleveld, D.: A CFD study of convection in a double glazed window with an enclosed pleated blind. Energy and Buildings, Vol 41 (11), pp. 1256-1262, 2009.
8. Lee, Y. Korpela, S. A.: Multicellular natural convection in a vertical slot. J. Fluid mech, Vol 126, pp. 91-121, 1983.