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Simulating thermochromic and heat mirror glazing systems in hot and cold climates

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Abstract

This paper investigates the potential energy requirements for heating and cooling when using a thermochromic glazing system on a highly glazed tall office building and comparisons are made with the respective performance of two heat mirror units and a clear triple glazed window. The assessment is done with the ESP-r whole building integrated simulation program in order to account for the dynamic optical properties of thermochromic glass in integrated simulations. The glazing systems are assessed for hot, cold and significantly varying between hot and cold climates. Annual heating and cooling energy requirements were quantified and short-period simulations were also run to assess the effect of the glazing systems on indoor temperatures. It was found that thermochromic glazing could significantly reduce cooling loads in hot climates and where cooling could be a significant building energy load (by approximately 30% in comparison with the other glazing systems). On the other hand, thermochromic glass could have a negative impact in cold climates where the use of heat mirror glazing systems could offer the highest energy savings even when compared with the triple glazed window. In seasonally varying climates and for highly glazed office buildings in which simultaneous high internal and solar heat gains are likely to occur, the use of thermochromic glass is an appropriate technique for saving energy and improving thermal comfort.

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"Keywords: thermochromic; heat mirrors; whole building energy simulation; highly glazed office"

1. Introduction

A wide variety of advanced glazing systems have been produced in recent years with the aim of being more energy efficient than the traditional glazing systems by controlling solar heat gains and limiting heat losses through them. In this paper the thermochromic glazing and heat mirror glazing systems are evaluated for their performance in reducing thermal loads with the use of state-of-the-art whole building

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modelling techniques. Their performance is also compared with simulation results of the same building that uses a triple clear glazing system. The study focuses on highly glazed tall office buildings since they tend to be aesthetically attractive to building developers in urbanised cities and they do also easily overheat due to the high simultaneous occurrence of internal and solar heat gains at daytime. The option of internal or external shading will not be considered in this study since it is not practical or desirable to have, for example, external shading in high rise buildings and it is intended to have a building that maintains maximum visibility and daylight penetration through the windows.

Thermochromic glazing has the ability to control the quantity of light and heat entering the building by changing its optical properties (transmittance, absorptance, etc.) when exposed to heat. Thermochromic systems become darker above specific to their manufacturing characteristics glass temperatures, and therefore they have the potential to reduce cooling loads and the risk of overheating in buildings. Most of the relevant papers in the literature focus on electrochromic glazing, which is a type of glass that has a similar function as the thermochromic but the changes of the optical properties are activated by a small amount of electricity. A thorough review of thermochromic coatings was done by [1]. Only a limited number of whole building energy simulations for thermochromic systems have been reported in the literature. Saeli et al. [2] used the EnergyPlus program to assess the energy savings from thermochromic glazing units across several European and North African climates. Their work focused on thermochromic glass that has one transitional temperature (i.e. optical properties change above one specific temperature) while the work presented in our paper will investigate changes in optical properties at several stages that correspond to more than one transition temperatures. Four thermochromic glass types studied by [2] with their single transition temperatures being between 38.5^{o}C and 59 ^{o}C. Xu et al. [3] did use the TRSNSYS simulation tool to compare thermochromic glass that changes optical properties at a single transitional temperature (38.5^{o}C) with traditional white and low-e glass types. The authors report that thermochromic glazing has the potential to offer energy savings only in warm climates where cooling loads are more significant than heating loads. As an extension of the above listed studies, Saeli et al. [4] used EnergyPlus to model the performance of thermochromic glazing for a Southern European climate by using low theoretical single transition temperatures (20^{o}C, 25^{o}C, 30^{o}C and 35^{o}C) for each simulation run. However, the authors have also included a discussion for a potential theoretical hysteresis during the changes of the optical properties between the heating and cooling cycles of the glass (i.e. a different transition pattern during the increase and decrease of the glass temperature). They concluded that the specific type of glazing has a potential to significantly reduce cooling loads if future efforts are focused on reducing the actual transition temperature of the glass.

On the other hand, heat mirror glazing systems have less transient behaviour than the thermochromic systems. When compared with a common double glazing unit, heat mirror units have an additional lightweight heat mirror film between the two glass layers. Placing the heat mirror film in the middle of the window creates two cavities (Fig. 1), which could be filled with a variety of gases. Advanced heat mirror films have now been produced by utilising nano-coatings of metal to reflect heat back to its source. Heat mirror glazing systems can be produced with a wide range of glass types and gas fills that allow flexibility for addressing the heat loss, visible light and solar control requirements of different climates.

The idea of using transparent heat mirror films is not new [5, 6] and the initial studies investigated the optical properties when placing mirror layers that incorporate various coatings in different ways on the glazing system. For example in Lampert's work [6, 7] the use of heat mirrors at different positions in glazing systems has been studied and demonstrated. Placing the mirror in the middle of the glazing system and using it for energy saving purposes has been studied experimentally and with stand-alone (i.e. not whole building) modelling approaches, e.g. [8, 9]. On the other hand, the literature reports only a limited number of whole building energy performance comparisons of these glazing systems with other advanced glazing types (e.g. thermochromic).

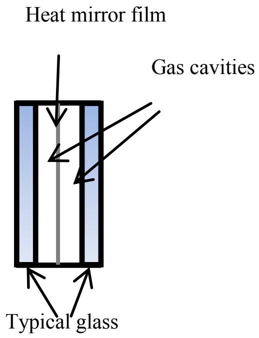

Fig. 1. Single Heat Mirror film and double cavity

Of particular interest is the study by Omar and Al-Ragom [10] who used the ESP-r simulation program to model an office building in Kuwait and compared three commercial argon-filled heat mirror types (HM88 with two and three cavities and HM22) with traditional single and double (clear and reflective) glazing types. The authors concluded that the heat mirror type with the lowest solar transmittance and absorptance (HM22) did offer the highest reductions of peak cooling loads for the specific hot climate of their study.

In our paper the ESP-r integrated whole building simulation program will be used for comparisons between thermochromic glazing that has more than one transition temperatures, specific types of heat mirror glazings and a triple glazing system. Indoor peak and minimum air temperatures for hot summer and cold winter days respectively and annual thermal loads will be investigated with the aid of the simulation program.

2. Thermal and Optical properties of the analysed glazing systems

The ESP-r simulation program can model thermochromic glazing systems by dynamically adjusting their optical properties [11]. ESP-r uses a linear function to modify the relevant optical properties of a thermochromic glazing system at run-time based on the calculated node temperature of the glass. Measured data of thermochromic glass from WINDOW 7.2–LBNL software's database are used in this study to derive the angular and temperature dependent optical properties needed by ESP-r. Fig. 2 shows the variation of solar transmittance through the whole window construction at different thermochromic glass temperatures. WINDOW 7.2–LBNL outputs show that for thermochromic glass confirm the results optical properties are close to be a linear variation of the glass' temperature. ESP-r's assumption of linear optical property changes with glass temperature variations is therefore close to the actual outputs from WINDOW 7.2–LBNL. Inserting the data in ESP-r allows for full scale integrated building energy simulations that provide a large number of performance outputs. While a number of Heat Mirror coatings are available in practice (HM88, TC88, SC75, HM22, etc.) two heat mirror types are modelled in this study: Heat Mirror 88 (HM88) and Heat Mirror 44 (HM44). HM88 has the highest solar transmittance at close to 0^o angles of incidence amongst the other heat mirror panes in the database of WINDOW 7.2–LBNL, which in theory when compared with the rest of the documented heat mirror panes makes it more beneficial for allowing solar gains to enter the building spaces and reducing heating loads. HM44 on the other hand represents a heat mirror pane with low solar transmittance at low angles of incidence, i.e. approximately a third of HM88's solar transmittance, which makes it more appropriate for buildings where solar gains need to be limited. In addition to the thermochromic's glazing system transmittance, Fig. 2 shows the angular solar transmittance of HM88, HM44 and a triple clear glazing system that was also used for the comparisons.

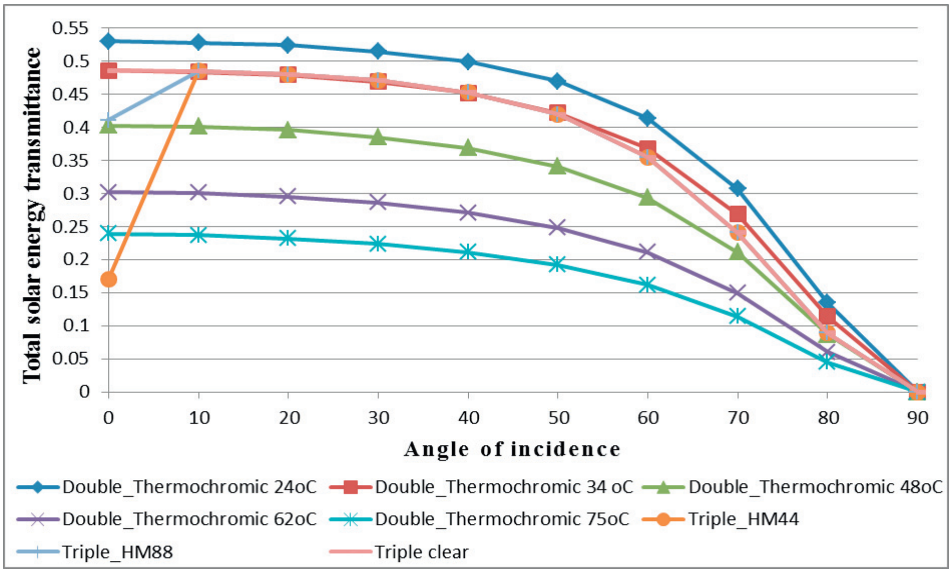

Fig. 2. Total solar transmittance of glazing system (all layers) at different angles of incidence (note: the optical properties of triple clear glazing and thermochromic glazing at 34°C are almost identical at low angles of incidence, while at higher angles the properties of triple clear glazing are almost the same as the properties of HM44)

The alignment of the layers of the above glazing systems and their overall thermal transmittance values (U-values) are listed in Table 1. It should be noted that for all types of glazing constructions in this study the gaps between the window panes were assumed to be filled with 90% argon and 10% air.

Table 1. The simulated glazing systems of the study

Glass type	Layers (from outside to inside)	U-value (W/m^2K)
Thermochromic (double)	7mm Thermochromic – Air/Argon – 6mm clear	2.54
HM88	6mm clear – Air/Argon – HM88 (<0.1mm) – Air/Argon – 6mm clear	1.12
HM44	6mm clear – Air/Argon – HM44 (<0.1mm) – Air/Argon – 6mm clear	1.03
Triple clear	6mm clear – Air/Argon – 6mm clear – Air/Argon – 6mm clear	1.62

3. Location and climates

Three types of climates were used in this study to investigate the energy performance of the glazing systems under different boundary conditions: a) the hot climate of Abu Dhabi, b) the prevailingly cold climate of Berlin, and c) the sub-tropical hot-summer and cold-winter climate of Shanghai. Table 2 shows the relevant monthly heating and cooling degree hours of these climates as they were exported from the climate module of the ESP-r simulation program.

4. Building model parameters

The urban building morphology patterns of the selected locations have been analysed in order to identify common building shapes. Two different portions of urban patterns for each selected city with an area each of approximately 2 km^2 have been initially investigated with Google Maps. After undergoing a number of shape optimisation steps that maximise the potential incident solar radiation falling on the building façade, a shape for the building model has been determined and shown in Fig. 3.

Table 2. Heating and Cooling Degree Hours (base temperature: heating=18°C, cooling=21°C)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Berlin – Heating Degree Hours	11997.8	11905.2	9361.7	6982.2	3478.6	1643	1051.4	1080.8	2576.2	5793.7	9768.8	11579.7	77219.1
Shanghai – Heating Degree Hours	10034.9	7866.2	6290.5	2413.3	148.6	2.8	0	0	0.2	843.8	3213.3	7864.3	38677.9
Shanghai – Cooling Degree Hours	0	0	105.4	182.9	704.9	2512.1	4830.4	4448	2466.5	457.5	1.5	0	15709.3
Abu Dhabi – Cooling Degree Hours	406.9	1029	1925.2	4082.8	7304.3	8505.7	10005.5	10268	8316.6	5645.5	2718.9	898.9	61107.3

The building comprises of 16 floors and the total floor area is approximately 45650 m^2. Since the focus of the study is on highly glazed buildings, 2/3 (66%) of the external surface area was covered by windows.

Internal heat gains from lights and equipment were scheduled in the simulation inputs only on weekdays from 9am to 18pm. Heat gains from lights were taken to be 10 W/m^2 [12] while with the improvements on the energy efficiency of office equipment nowadays (flat screens, use of laptops, power saving mode for printers, etc.) equipment heat gains were set to 6 W/m^2. Occupants were also assumed to be present only on weekdays from 9am to 13pm and from 14pm to 18pm. A low occupant density and a moderate office work activity was assumed in all spaces. An average infiltration rate of 0.5 ACH has been assigned for each space in this study and for each hour of the simulation.

The systems used for space heating and cooling were assumed to be ideally sized for covering the required energy demand. It was assumed that the heating system will operate from 1st of October to 30th of April while the cooling system will operate from 1st of May to 30th of September. In both heating and cooling periods the systems were configured to be only ON on weekdays from 8am to 18pm. The set-points for heating and cooling were configured in different ways for each climate to account for the local conditions, e.g. only setback heating set-points were assumed for the climate of Abu Dhabi. The details of the heating and cooling control set-points are described in Table 3.

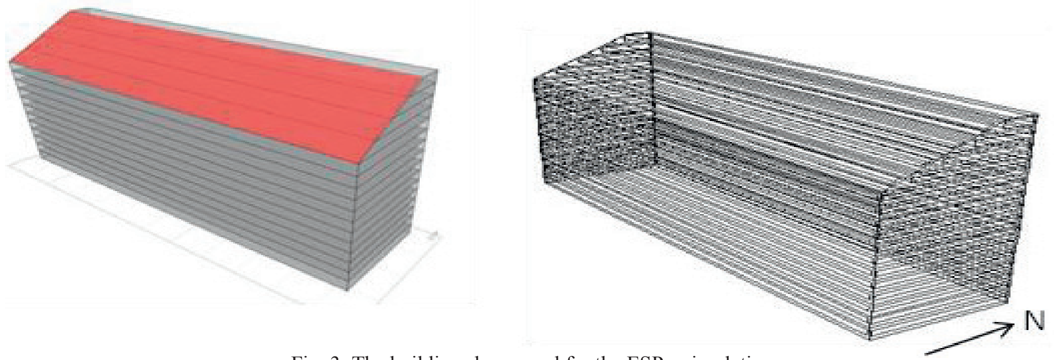

Fig. 3. The building shape used for the ESP-r simulations

Table 3. Heating and Cooling set-points following the general climate characteristics of each location

	1st of October to 30th of April (Weekdays, 8am - 18pm)	**1st of May to 30th of September (Weekdays, 8am - 18pm)**
Berlin	Heating at: 22°C	Setback control for heating at: 16°C for the potential occurrence of cold periods (passive cooling is assumed to be maintaining indoor temperatures below 30°C)
Abu Dhabi	Setback control for heating at: 16°C. Cooling at: 26°C, since cooling may also be needed during this period.	Cooling at: 24°C
Shanghai	Heating at: 22°C (in case of short periods of overheating, passive cooling is assumed to be maintaining indoor temperatures below 35°C)	Cooling at: 24°C

The energy requirements for the heating and cooling systems when operating under the rules of the setback controllers were not presented in this study. This is because the setback controllers are rarely active during these setback periods and when compared with the peak periods there is no need for significant amounts of thermal energy in the building.

5. Results and discussion

5.1. Annual thermal energy requirements

The annual simulation results revealed that out of all glazing systems of this study the thermochromic glazing is the best energy saving option for highly glazed buildings in which cooling loads can be significant. This is evident from both Figs. 4a and 5 where it can be seen that when thermochromic glass was used, the annual cooling loads were reduced by about 30% in comparison with the resulted cooling loads for the rest of the glazing systems, e.g. for Abu Dhabi's case the cooling requirements were reduced to about 70 kWh/m^2 instead of being approximately 100 kWh/m^2. The use of heat mirror and triple glazing systems did result to similar annual cooling requirements for the building, however, some minor additional energy savings were offered by the HM44 glazing system case in Abu Dhabi's climate (Fig. 4a). While heating energy requirements were not the major energy load for the specific highly-glazed building it was noticed that in cold climates (e.g. Berlin) the thermochromic glass case resulted in higher heating energy requirements than the triple and heat mirror glazing systems of this study. Overall, lower annual requirements for heating were noticed for the cases where heat mirror glazing systems were used (Fig. 4b).

It was assumed that for the cold climate of Berlin the building spaces are ideally cooled by natural means, however, simulation results reveal that such highly glazed office spaces where heat gains peak up during daytime they tend to significantly overheat and would require significant amounts of mechanical cooling. This could explain the low values of the results for the heating requirements in Fig. 4b. In such cases, i.e. when overheating is expected in highly glazed buildings, thermochromic glazing could have the potential to reduce the overall space energy requirements. This can be confirmed by the results of Fig. 5 for Shanghai. The specific climate of Shanghai has in total 38678 heating degree hours per year and 15709 cooling degree hours (Table 2), which in theory could mean that energy requirements for heating would have been much higher than those for cooling. However, due to the large amount of glazing in this simulated case and the amount of internal heat gains during daytime while heating and cooling systems operate, the simulation results show that a lot more energy is annually required for cooling than for space heating purposes (Fig. 5). It is also evident from the results in Fig. 5 and the values in Table 2 that the oversimplified heating and cooling degree day/hours calculation methods would have lead to wrong conclusions for the amount of heating and cooling required in such types of highly glazed buildings. The analysis in the next section will further discuss simulation results for minimum and maximum indoor air temperatures as predicted for the models that incorporate the different glazing systems of this study.

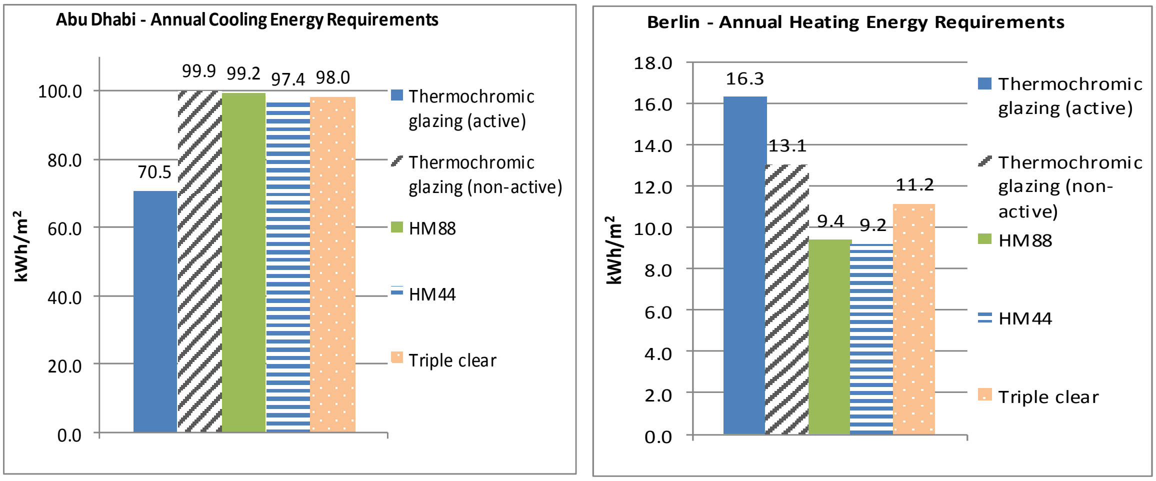

Fig. 4. (a) Annual cooling energy requirements for Abu Dhabi; (b) Annual heating energy requirements for Berlin

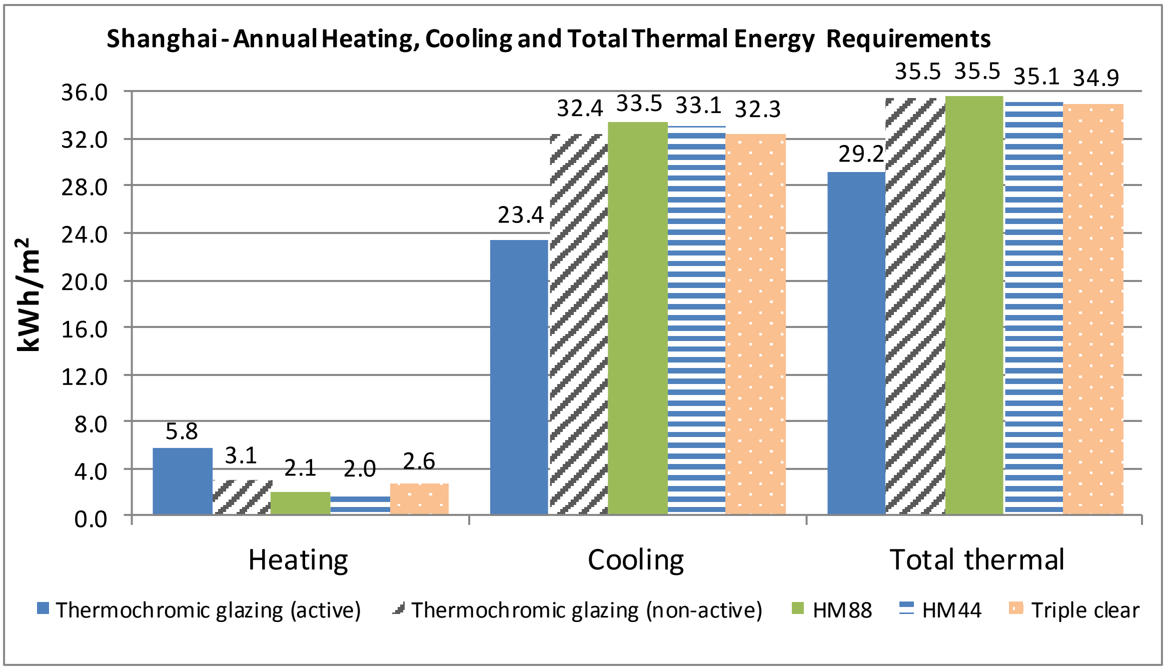

Fig. 5. Annual thermal (heating and cooling) energy requirements for Shanghai

5.2. Indoor air temperatures

Short-period simulations were also run with the ESP-r program at “free-float” conditions, i.e. without having any heating or cooling for conditioning the building spaces, in order to analyse the indoor air temperatures during hot and cold days. The results for the top floor of the building were analysed and presented in Figs. 6 to 8 since this floor has the largest percentage of exposed to the ambient environment surfaces.

It can be seen from Figs. 6 and 7 that when the heat mirror, triple and double (i.e. thermochromic non-active) glazing systems are used during the summer there is occurrence of severe overheating in the building spaces. On the other hand, the thermochromic glazing system is able to prevent a large amount of solar gains from entering the building and reduces significantly the indoor air temperatures during the hot periods of the year (Fig. 6 and Fig. 7). It is however evident that even by using thermochromic glazing systems in such types of highly glazed buildings it is necessary to apply additional energy saving techniques for further reducing the building’s cooling energy requirements.

A simulation was also run for a cold day in Berlin’s climate. Less extreme temperatures than those in Figs. 6 and 7 were noticed and the results show that heat mirror glazing systems could improve indoor air temperatures in the winter by approximately 1-3^{o}C when compared with the results for thermochromic glazing (Fig. 8). When compared also with the typical clear triple-glazed system, heat mirror glazing systems do demonstrate better indoor air temperature improvements by approximately 1-2^{o}C (Fig. 8). These results could be explained by the better thermal properties (e.g. U-values in Table 1) of heat mirror systems than the rest of the glazing systems of this study. Thermal properties are more significant than the optical properties in such cold days and climates since solar radiation values are generally low during these cold periods.

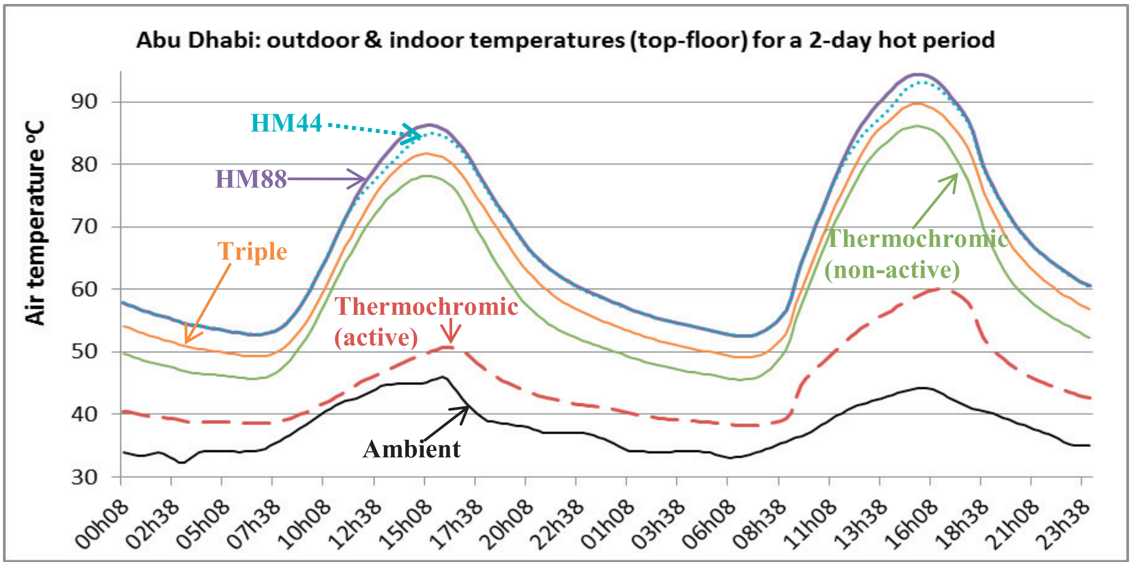

Fig. 6. Indoor air temperatures in Abu Dhabi’s climate during two hot summer days (top floor)

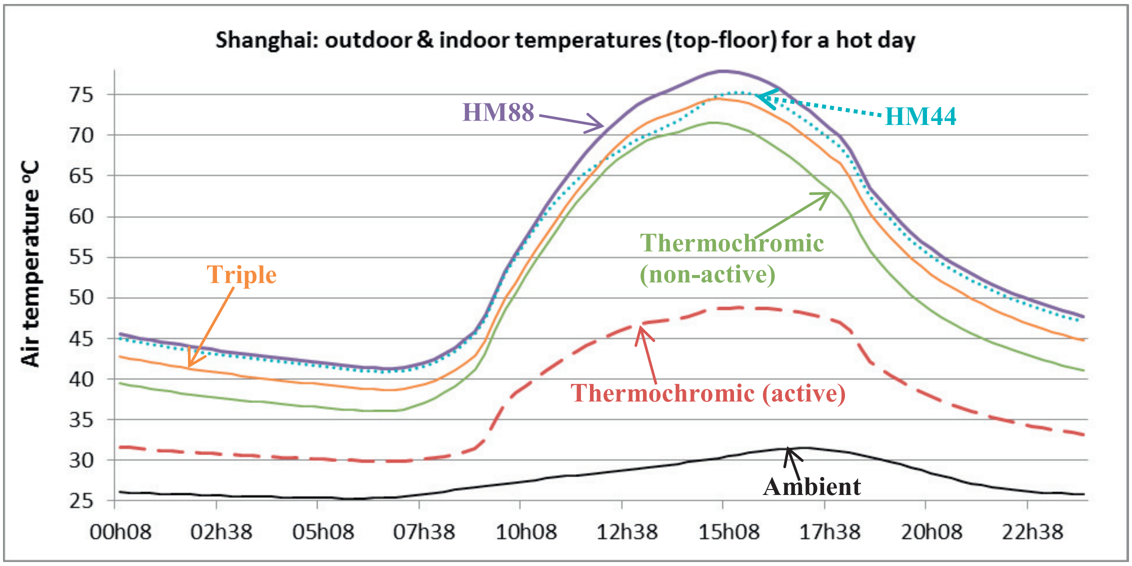

Fig. 7. Indoor air temperatures in Shanghai's climate during a hot summer day (top floor)

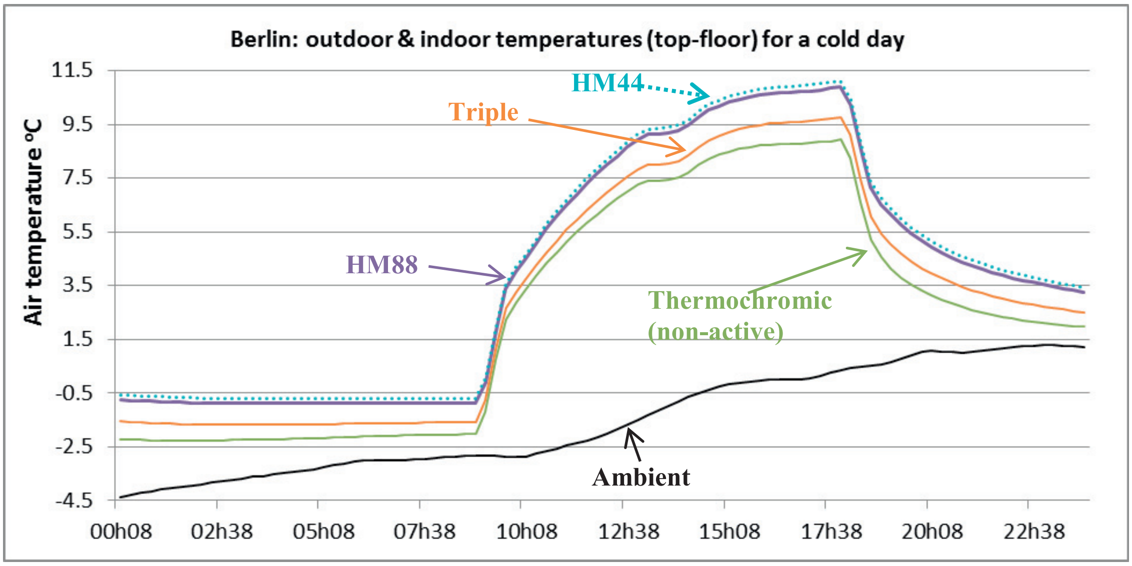

Fig. 8. Indoor air temperatures in Berlin's climate during a cold winter day (top floor). Thermochromic was not active that day.

Figs. 6 to 8 show indoor air temperatures that increase from approximately 9am to 18pm due to the simulation settings for the internal heat gains, i.e. for the presence of occupants and equipment use during usual working hours and while there is an additional contribution of heat gains from solar radiation.

6. Conclusions

The general conclusion from this analysis is that the thermochromic glazing would be a suitable passive design choice in highly glazed spaces with high internal heat gains and with high risk of occurrence of overheating. The thermochromic glass could maintain indoor air temperatures during hot periods well below the potential high temperatures that would occur with other types of glazing systems. It was found for the cases of this study that cooling energy requirements could be significantly reduced when using thermochromic glazing in warm or hot climates. In cold climates, however, the thermochromic glazing system affects indoor temperature in a negative way and causes an increase of the energy requirements for heating, in particular in spaces where summer overheating is not an issue of concern.

When comparing heat mirror glazing systems with triple-layer clear glazing it was found that the heat mirror systems are more suitable in cold climates while triple glazing could be a better choice in climates and buildings where both heating and cooling energy requirements are significant (e.g. for buildings that are not highly glazed in Shanghai's climate). However, the differences between the overall energy performance of these two types of systems were not significant.

Having low energy and highly glazed office buildings in warm climates is proven to be a challenge for building designers and advanced technologies should be adapted in the design. Thermochromic glazing systems have proven to be a passive system that could contribute towards achieving such low energy building designs. Future work should aim to quantify the potential uncertainties on the simulation results if different heating and cooling control systems and strategies are used. The changes on these systems and their schedules could have consequences on the performance of thermochromic glass due to potential time-shifting of the relevant thermal energy loads, which could therefore lead to changes on the temperature and optical properties of the thermochromic glass. Integrated building energy simulation could be a significant tool for quantifying such uncertainties and could assist in determining the most optimum energy efficient design for advanced glazing types (size, type, orientation, etc.) under the potential uncertainties. Future efforts should also incorporate investigations on the payback period of the analysed glazing systems under different uncertainty scenarios.

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