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Thermal comfort of standard and advanced glazed building envelopes

Abolfazl Ganji Kheybari [a], Matyas Gutai [b,*], Brandon Mok [b], Giulio Cavana [c]

[a] Transsolar Energietechnik GMBH, Landwehrstraße 60/62, 80336 München, Germany
[b] School of Architecture, Building and Civil Engineering, Loughborough University, Epinal Way, LE11 3TU Loughborough, United Kingdom
[c] Politecnico di Torino, Corso Castelfidardo 39, 10129 Torino TO, Italy

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ABSTRACT

The characteristics of building envelopes impose significant impacts on indoor thermal comfort, especially for buildings that possess higher portions of glazing. As a result, the overall Indoor Environmental Quality (IEQ) is also largely controlled by the glazing scenario. Recent studies present three strategies to mitigate this aspect, by either i) improving the U-value with additional glass layers (insulation-based), ii) utilizing shading devices, or iii) changing the transparency or reflectance of glass (radiation control). In this study, Water-filled Glass (WFG) is presented as a potential fourth strategy. WFG is an innovative technology that utilizes a water layer within an insulated glass unit, to help improve the energy performance of the glazing. Current research primarily focuses on the energy consumption of WFG technology, and its potential to reduce both operational and embodied carbon. However, the potential impact on the thermal comfort of buildings, due to the thermal mass, absorption and radiant heating–cooling properties of its water layer have not yet been analysed in detail.

To build on this, this paper provides comparisons of various standard and advanced glazing technologies clustered in the above strategies, to assess the impact of glazing choice on indoor thermal comfort. This is conducted for both an office and a sunroom scenario using the Analytical Comfort Zone PMV (SolarCal) Method. Seven conventional glass technologies across nine locations were measured, to represent all major inhabited climate regions (Köppen-Geiger A-D).

Results show that WFG-like technologies can provide the highest amount of thermal comfort in up to eight out of nine climates; depending on the structure and in free-floating conditions, up to 26 % thermally comfortable periods can be achieved over an entire year. When this is compared to the base case, an additional 19 % comfortable periods are created. For hotter and more tropical climates (Af, BSk, Bwh), solar-gain focused techniques often function best, such as electrochromic and double glazing with permanent shading.

This study also highlights the importance of thermal mass in glass structures, as well as the advantage of dynamic fluid mass over a static one. The results show that by utilizing WFG, up to 64–145 kWh of energy can also potentially be absorbed annually. In addition to this, this glazing technology offers warmer discomfort periods for many climates during colder seasons. Whilst this initially may seem undesirable, it offers an opportunity for the adoption of passive strategies, as well as heat redistribution to neighbouring thermal spaces, to potentially reduce overall energy usage at the building level.

1. Introduction

The built environment is responsible for i) approximately 39 % of global CO_2e emissions, ii) 30 % of CO_2e emissions in Europe, [1] and iii) about 41.4 % of greenhouse gas emissions in the United Kingdom [2]. The business sector, in particular, is responsible for about 14 % of EU energy consumption [1], and about 17 % in the UK [3]. Since buildings are the place where people spend most of their time, it is fundamental to ensure their high functional performance, with regards to energy consumption and Indoor Environmental Quality (IEQ). These two aspects are intrinsically interconnected [9]. Aside from climatic conditions, the operational energy consumption of a building is determined by three main factors, which ultimately reflect its function: i) building energy systems, ii) the building envelope, and iii) occupant behaviour/IEQ requirements [4]. Considering glass components in particular (e.g., windows, skylights, curtain walls), they have a large impact on these latter two aspects due to their low insulative capacity, and resistance in radiation transfer when compared to opaque elements. Here, these

* Corresponding author.
E-mail address: M.Gutai@lboro.ac.uk (M. Gutai).

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material properties not only can increase energy demand, but may also induce a detrimental effect on thermal comfort. Even for buildings with a low window-wall-area ratio (WWR), windows are responsible from 25-35 % [5] up to 60 % [6] of energy loss in a building, and can also affect thermal and visual comfort of occupants (both IEQ parameters). The importance of such relationships between energy consumption, thermal comfort and glass envelopes is exacerbated for building with high window-wall-ratio or WWRs, e.g., office buildings and glass towers, where the transparent area might reach the 85–90 % of the building façade. This is demonstrated by recent policy trends, which highlight how the evaluation of building performance should be considered as a complex procedure, which considers a variety of aspects other than energy consumption alone, in line with EPBD 2018/844/UE; thermal comfort is suggested to be among the most important factors for achieving overall IEQ.

Among the different parameters that could influence the environmental performance of a glass façade, spectral properties (e.g., reflection and absorption), thermal transmittance (U-value), and solar heat gain coefficient (SHGC) have a high impact on energy consumption, directly influenced by ambient conditions and climate. For example, the influence of SHGC on energy consumption is higher in tropical and arid countries compared to the U-value [7]. With regard to literature highlighting these relations, Vanhoutteghem et.al. analyses the connection between window properties (e.g., proportions, orientation, window size) in relation to room area, thermal comfort, energy consumption and illumination in Denmark. The authors present a strong correlation between window properties (in particular SHGC) and thermal performance related measures [8]. Elghamry and Hassan present a similar study for an arid climate, and conclude that window optimisation can lead to significant energy savings in the building [9]. Koniorczyk et.al. expanded the analysis of correlation between window properties, thermal comfort and energy consumption with additional aspects of human behaviour. Their research concluded that human-related factors cause a larger uncertainty in results than any other design factor [10]. Finally, Ko et al. found a positive psychological effect on the comfort sensation due to the presence of windows in an occupied space, with 12 % more occupants satisfied in a space with windows compared to without [11]. Studies also indicate the impact of window characteristics and outside view on occupants' satisfaction and wellbeing [12,13]. As shown, glazing is largely responsible for the energy efficiency and thermal comfort of the entire indoor environment.

A recent innovative solution within the glass industry is the use of a fluid medium within the glazing unit, which is able to dynamically control the associated heat flux of the associated space; this represents a flexible solution that is especially applicable for intermediate and seasonal climatic conditions. Within this, Water-filled Glass (WFG) is an innovative technology that utilizes a water layer within an insulated glass unit, to improve the energy performance of the glazing (by forming a fluid–solid envelope). In addition to reducing energy consumption, WFG has a significant impact on the thermal comfort of buildings, due to the thermal mass, absorption and radiant heating–cooling properties of its water layer; this permits the reuse of absorbed heat, to improve the performance of the glazing without a substantial increase of its embodied carbon (i.e., making the addition of external shadings redundant) [14,15]. Existing research that demonstrates the effectiveness of WFG in this manner includes Santamaria et.al. who denote that WFG windows can improve overall thermal comfort and microclimate, by presenting a scaled-type prototype of a log cabin. The results show that the space equipped with WFG had around a 10 °C lower temperature difference between day and night compared to that of the reference cabin [16]. Sutton and McGregor present measurements on thermal comfort for their Solarwall project in Tasmania. Their results show better thermal comfort for users is created, when compared to other techniques [17]. Wang and Lei also evaluate the impact of a water-wall on thermal comfort, by using it as a ventilation device and connecting it to a transparent solar chimney. The results show that the surface temperature of such a water-wall can contribute to increasing ventilation and thermal comfort [18].

Overall, several studies presented by literature investigate the effect of different glazing techniques on thermal comfort. While these studies consider both standard [19,20] and more advanced techniques [21–23], they are often limited to specific geographic and climatic conditions. This suggests that a comprehensive analysis involving different glazing techniques (conventional, advanced, and innovative) in different climatic contexts could represent a suitable tool for comparative purposes, especially ones that provide a dynamic evaluation of climate specific solutions across an annual timeframe. The expected outcomes of such a study could be a recommendation of the optimal glass solution for each climate, which would reduce transmittance in heating dominated climates, and decrease SHGC in cooling dominated ones. For this reason, this paper presents a comparative analysis between the thermal comfort capabilities of standard (double glass), hybrid (double glass with automated shading or with permanent shading), advanced (electrochromic, solar protection glass), and innovative (WFG, SWFG) glazing techniques. This is done via PMV-based comparisons (SolarCal method) of different glazing configurations in two simulated case studies, on a hourly, seasonal, and annual scale. Overall, this will enable the comprehensive study of thermal comfort patterns, and the distribution of comfort/discomfort hours throughout the year. An additional assessment of the excess solar load (which is currently being wasted) experienced by windows has also been undertaken, of which the concept could significantly increase the operational efficiency of the entire building, as well as the thermal condition of other adjacent indoor zones.

In terms of novelty resulting from this paper, the first aspect comes from the comprehensive analysis of seven window types in nine locations on thermal comfort, which is presented here for the first time. A second aspect is also introduced via the evaluation of thermal comfort of WFG and its impact on a linked hybrid envelope using simulation techniques. Finally, a third aspect of novelty results from the analysis of thermal mass in glass structures, in particular the advantage of dynamic mass over static to achieve a rapid flow of energy distribution, and to create better adaptability and indoor microclimate of the entire building.

The rest of the contribution is divided as follows: Section 2 introduces the methodology used, and the case study setup. Section 3 displays the results of the study, discussed in depth in Section 4. Finally, in Section 5 and 6, recommendations for future research and conclusions are presented.

2. Methodology

The Methodology chapter is divided into three main parts. The first part provides an overview of the routine to calculate the PMV, according to the Analytical Comfort Zone Method (SolarCal method) described in ANSI ASHRAE 55 Standard, for which applicability conditions are met. The second part describes the different glass options considered to evaluate the effect of the glazed element of the envelope on occupant's thermal comfort. The third part describes the case study in terms of building geometry, location, and software set up.

2.1. Evaluating thermal comfort

Among the available protocols to estimate the thermal comfort of indoor spaces, Fanger's model is one of the most used and developed [24,25] and is adopted by several international standards [24] including ISO 7730, ASHRAE Standard 55-92, CEN CR 1752, and EN 16798-1. This model calculates the heat balance between the occupant and the environment under steady state conditions [26], and uses the Predicted Mean Vote (PMV) as a theoretical index that describes the comfort perception of subjects exposed to environmental conditions [25,27]. PMV expresses the thermal sensation of occupants of indoor spaces on a 7-point scale [28], with comfort conditions for PMV values in a range between −0.5 and +0.5 [25].

The general equation for PMV can be seen below in Eq. (1) below.

$$PMV = \left(0.303 \cdot e^{-0.036M} + 0.028\right) \cdot L \quad (1)$$

where M is the metabolic rate, and L is the thermal load on the body, defined as the difference between internal heat production and heat loss to the environment. To account for the impact of the effective radiant field experienced on the occupant, this can be quantified by Eq. (2) [29].

$$ERF = f_{eff} h_r (MRT - T_a) \quad (2)$$

where f_{eff} is body surface exposed to radiation from environment, h_r is the radiation heat transfer coefficient, and T_a is the external air temperature. However, this formula does not account for the shortwave radiation component, which is significant in highly glazed buildings. As such, this is quantified as E_{solar} (shortwave solar radiant flux) in Eq. (3):

$$\propto_{LW} ERF_{solar} = \propto_{SW} E_{solar} \quad (3)$$

where E_{solar} is the sum of three exchange fluxes after the influence of fenestration is considered, α_{SW} is short-wave absorptivity, and α_{LW} longwave radiation absorptivity. E_{solar} can be categorised into direct beam solar energy (E_{dir}), diffuse solar energy from sky vault (E_{diff}), and solar energy reflected upward from the floor (E_{refl}). These are shown in Eqs. (4)–(6):

$$E_{dir} = \left(\frac{A_p}{A_D}\right) f_{bes} T_{sol} I_{dir} \quad (4)$$

where A_p is the projected area of the mannequin exposed to direct beam radiation, A_D is the surface area of the mannequin (often calculated with the DuBois area formulation), and f_{bes} is the fraction of body exposed to sunlight (from 0 to 1). T_{sol} refers to solar transmittance, specifically the proportion of incident shortwave radiation that enters the internal space after façade and shading are considered.

$$E_{diff} = 0.5 f_{eff} f_{svv} T_{sol} I_{diff} \quad (5)$$

where f_{svv} is the fraction of sky vault in view. I_{diff} accounts for the diffuse irradiance experienced on the upward surface; this will be affected by the surrounding orography and obstructions to sky, and the consequent radiation reflected from these.

$$E_{refl} = 0.5 f_{eff} f_{svv} T_{sol} I_{TH} R_{floor} \quad (6)$$

where I_{TH} is the total outdoor solar radiation on the horizontal, filtered by both T_{sol} and f_{svv}. R_{floor} is the total albedo of the floor (assumed constant throughout the internal environment). This value can be increased to consider both the short-wave reflected energy and the long-wave radiation from the floor surfaces.

The adjusted ERF for short wave radiation can be seen in Eq. (7):

$$ERF_{solar} = \left(0.5 f_{eff} f_{svv} \left(I_{diff} + I_{TH} R_{floor}\right) + \frac{A_p f_{bes} I_{dir}}{A_D}\right) T_{sol} \left(\frac{\propto_{SW}}{\propto_{LW}}\right) \quad (7)$$

To produce final solar adjusted comfort measurements (ΔMRT and PMV_{adj}), the ERF_{solar} is substituted back into Eq. (2). To solve these equations numerically, the overall conceptual workflow can be seen below in Fig. 1.

2.2. Glass options

Table 1 lists the seven glass options investigated in the present study, providing construction data (Glazing System Setting), operational settings (Shading/Switchable window control), thermal and solar properties, and categorization of the main strategy used to manage the energy flow through the component (Energy Management Category). The latter component is divided into i) improving U-value (insulation), ii) controlling the incident solar radiation (shading), iii) controlling the solar gains (radiation control), iv) use of a fluid medium (Fluid Flow).

Three base glass options are investigated within this study. The first is a standard double glass option with Low-E coating (Base_2G), assumed to represent industrial standard for newbuild projects. The next base case (Base_2G + AS) is the same window in terms of composition, but features an automated shading system with a 75 % shading fraction (Fc = 0.25) when incident total radiation (IT) is higher than 200 W/m2 (according to German Industrial standard DIN 4108–2). For the third base case (Base_2G + PS), the same shading fraction is used and set as constant during the year (permanent shading). These latter two cases are unique compared to the other options, since the glass is combined with a shading device which is not strictly part of the glass unit itself. Whilst this difference was acknowledged by the authors, the inclusion of these was still deemed beneficial as it offers a valuable control reference to the other options with inbuilt dynamic solar gain controlling functions (e.g., Base_EC4st or SWFG).

Two other advanced glass options are also included in the study: the SHGC option is a solar protective glass with a selective coating (SHGC =

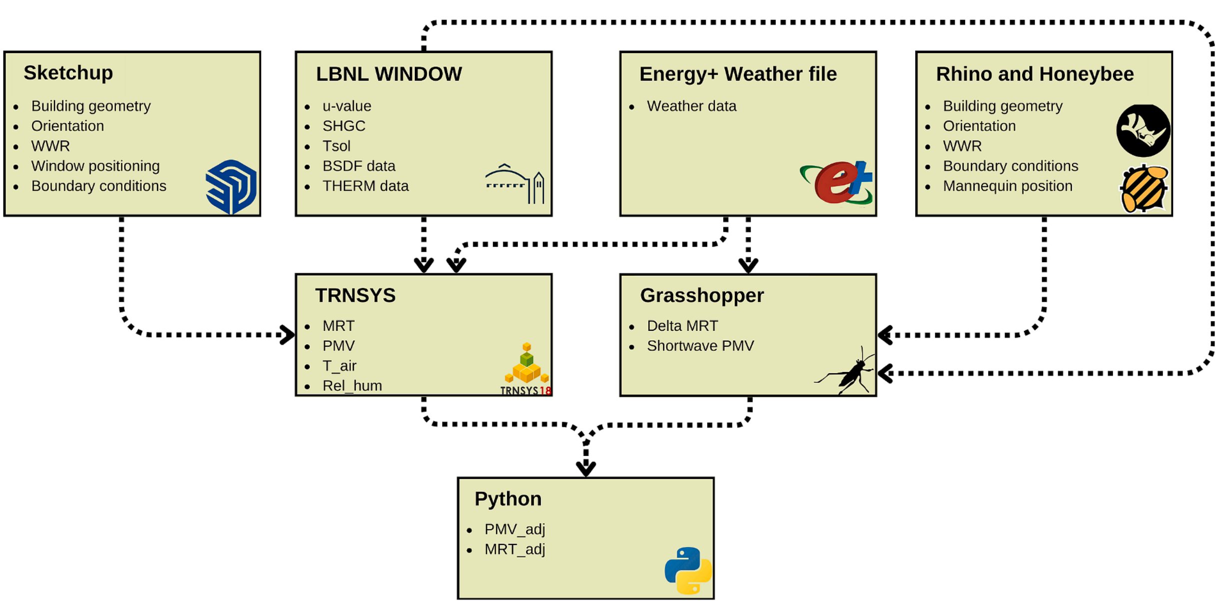


Fig. 1. Conceptual workflow for thermal comfort assessment.

Table 1
Glass options.

Case Name	Window Type	Glazing System Settings	Shading / Switchable Window Control	U_g	SHGC [%]	T_{sol} [%]	T_{vis} [%]	Energy Management Category
Base_2G	Insulating double glazing	16mm Gap filled with argon, Low-E	No shading, always transparent	1.4	62%	43%	62%	Insulation
Base_2G+AS	Insulating double glazing	16mm Gap filled with argon, Low-E	Automatic 2-step radiation-based control, When IT < 200 W/m2 = Clear, When IT ≥ 200 W/m2 = Shaded (Fc = 0.25)	1.4	62%	43%	62%	Insulation + Shading
Base_2G+PS	Insulating double glazing	16mm Gap filled with argon, Low-E	Always Shaded	1.4	62%	43%	62%	Insulation + Shading
Base_SHGC0.2	Solar protection double glazing (SHGC ≥ 0.2)	16mm Gap filled with argon, solar protection	No shading, always transparent	2.16	20%	15%	20%	Insulation Incorporated radiation control
Base_EC4St	Electrochromic Window	Double glazing system 16mm Gap filled with argon, Low-E	Automatic 4-step illuminance-based control, When E < 600lx = Clear, When 600 lx ≤ E < 800lx = Low-tinted When 800 lx ≤ E < 1000lx = Mid-tinted When E ≥ 1000lx = Full-tinted	1.3	43%	29%	44%	Incorporated radiation control
WFG	Water Filled Glazing	15mm Gap filled with clear water	Always clear, 0% dyed	2.9	55%	27%	44%	Fluid Flow
SWFG	Smart Water Filled Glazing	15mm Gap filled with dyed water	Always clear, 0-40% dyed Automatic 3-step illuminance-based control 0% (Clear), 20%, and 40%	2.9	54%	22%	35%	Fluid Flow

0.2), that aims to control the solar gain experienced through the glass façade. This option differs from other glasses, in the sense that it is a mirror glass with lower transparency, but it has been included to evaluate the potential offered by solar protective glass options. The other option (Base_EC4st) is an electrochromic glass with Low-E coating and 4-step illuminance-based control.

Finally, two options for glasses incorporating a fluid medium are considered: basic WFG option with the water infill constituting of clear water (WFG), and Smart-Water-Filled-Glass (SWFG), which is characterized by a coloured water infill, from clear (0 %) to semi-dark (20 %) and dark (40 %) opacity. This investigates the shading effect of the water medium.

2.2.1. Building considerations

To evaluate the effect of different glazing options on occupant's thermal comfort, two case studies have been simulated. The first is a theoretical glass extension (sunroom) attached to a residential dwelling. Such an extension is characterized by a 15.0 m^2 gross floor area (3 m length, 5 m width, and 3 height), with a total glazed area of 39.2 m^2. As shown in Fig. 2, the roof, East, West, and equatorial-facing envelope surfaces of the room are considered glazed, whilst the remaining wall and the floor are considered opaque made of concrete, with the addition of an insulation layer for the floor. These surfaces represent the connecting surfaces to the existing building, thus they have been considered as adiabatic. The orientation of the largest glass façade was assumed to be equatorial (South-facing in Northern hemisphere, and North-facing in the Southern one), which would be a typical case for a sunroom or conservatory. The glass is further divided into 3 panes on the South-facing façade and roof, and into 2 panes on the East and West orientations. Table 3 shows the different areas of each transparent element, whilst the U-values and SHGC for the glass facades are shown in Table 2.

In terms of mechanical systems, it was assumed that the space does not have any heating or cooling system installed, as is typical for sunroom scenarios. An infiltration rate of 0.5 ACH was considered, and a ventilation rate of 5 ACH assumed during the day, while during night this is reduced to 3 ACH and 1 ACH in summer and winter seasons respectively. These values took into consideration the enhanced flexibility available to control the ventilation (through the occupant opening various windows). Regarding internal gains, 130 W/m2 for a person, and artificial lighting gain of 2 W/m2 (controlled by available daylight setpoint of 300–500 lx) have been considered. In the case of WFG, an independent hydronic system is installed, with a water pump to move the water between panels and a storage tank. This pump system was considered to not provide any ambient heating or cooling effect, and was only responsible for water flow. Finally, the occupancy hours for the sunroom have been set from 06:00 to 23:00. The authors acknowledge the quite extensive occupation time simulated, but since the aim of the present work is to evaluate pattern of thermal comfort conditions (and

Table 2
Area of each glazed surface.

Surface	Number of Partitions	Surface areas
Roof	3	5.04,2.24,5.04 m^2
East-facing	2	3.64,3.64 m^2
South-facing	3	5.04,2.24,5.04 m^2
West-facing	2	3.64,3.64 m^2

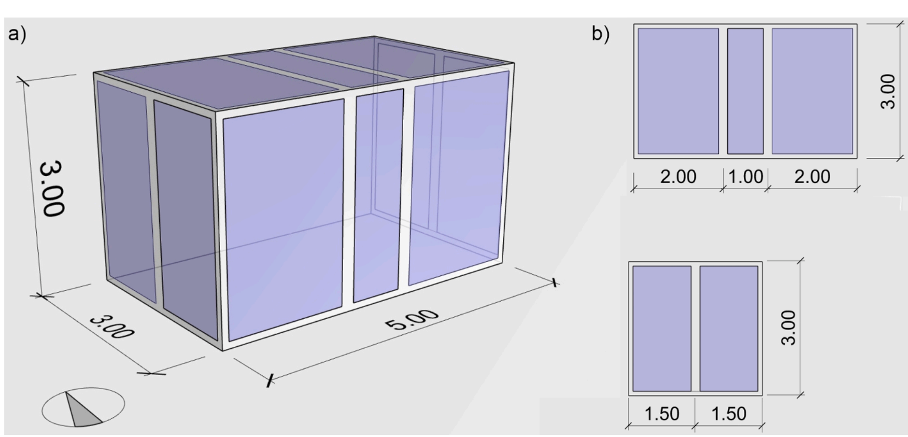


Fig. 2. Simulation Model for sunroom.

not energy consumption), this was deemed a suitable assumption. The authors also recognize that the model has high window-wall ratio, which may seem atypical. There were two reasons for this. First, this was to give a clear presentation of the impact of glass on thermal comfort and present a clear comparison between glass types (i.e. by eliminating other variables from the model e.g. opaque walls). Second, the design follows an existing building type of 'sunroom' or 'conservatory', which is common in different countries and climates (e.g. in Europe, Canada, United States, Australia and New Zealand) and is gaining popularity in other countries (e.g. as glass extensions). Therefore, the simulation setup picked this kind of design as a typical building extension form which also is an ideal building part to assess impact of glazing options on thermal comfort.

For the second building model, this corresponded to an office of 17.5 m^2 gross area with 3 m height. This can be seen in Fig. 3 below. The size of the room was 3.5 m by 5.5 m, and the glass façade was 3.3 m by 2.8 m (9.24 m^2 area). The façade was assumed to be equatorial (South-facing in Northern hemisphere, for all seven cities), with the rest of the surfaces (interior walls, ceiling, floor) considered adiabatic. The properties of internal walls, floor and ceiling are also shown in Fig. 2, with simulated U-values of 0.3, 0.6 and 0.6 W/m^2K respectively.

The room was designed to be a functional office environment for one employee. Internal heat gains were set for working hours (Mon-Fri: 8:00–18:00) as 130 W for a person, 140 W for a computer and 5 W/m^2 for artificial lighting (controlled by available daylight lighting setpoint of 300–500 lx). Infiltration was assumed as $n = 0.25$ ACH, with an increase to $n = 1.45$ ACH during working hours. Optional night ventilation was assumed as an efficient cooling alternative during summer, as outdoor temperature fell below room temperature.

2.2.2. Considerations for climate and cities

The above-described structures have been strategically considered in different cities, to include locations from each major Köppen-Geiger climate region. Offices with high WWR and glass façade extensions are common in these climates, which justified a comprehensive investigation. The selected nine cities are listed below in Table 3 and Fig. 4. With regards to cold climates (Köppen-Geiger E), glass strategies which focus on reducing the risk of overheating (shading and radiation control) are considered not to be viable, with previous research also indicating WFG suffers from the same limitation [15]. As such, locations in such climate were not included in the study.

The cities within each climate region were chosen based on their existing building stock characteristics: preference was given to locations where high WWRs is a likely scenario (and therefore is a good representation of the study).

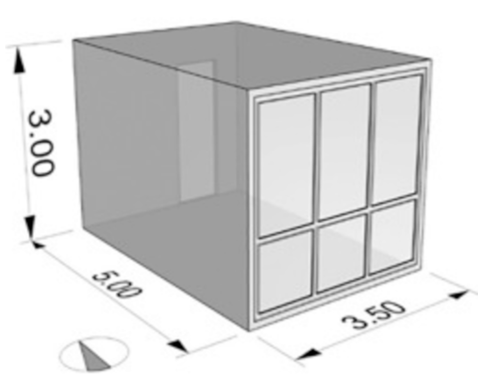
2.2.3. Simulation considerations

The simulation setup for TRNSYS followed the same conditions as in previous publications [15], with TRNSYS Type 77 model being used for the energy simulation. For WFG and SWFG, the window configurations for the water layer were set up in LBNL Window software (v.7.6). The optical properties were defined first in Optics 6, and then exported to the LBNL Window to define the water layer as a new shading material. The thermal conductivity of water is also based on different temperatures (0–50 °C) as a new gap in the Window library. The characteristics of the glass are shown in Table 2. The energy model has been validated through experiments with physical prototypes and monitoring of an experimental building, presented in detail in the earlier publication [27].

For preparing the necessary data for an annual dynamic simulation, window properties for every window configuration were imported as BSDF (Bidirectional Scattering Distribution Function) data sets (in addition to other thermal information of layers and gaps) from LBNL Window into TRNSYS via the trnBSDF tool. BSDF data generated by the Window contains solar and visible transmission and reflection data, in the format of a Klems matrix (145 × 145). This method of modelling is one the most accurate models for a window with a complex fenestration system, in order to calculate radiative heat fluxes through a glazing system. This detailed window model in TRNSYS makes it possible to calculate the absorbed solar radiation and temperature for each layer and gap specifically. As shown in Fig. 5, the simulation for WFG utilizes a virtual (dummy) layer that provides the absorption properties identical to the water layer with the given thickness.

To calculate the thermal comfort in each scenario, some key assumptions were made within both TRNSYS and Grasshopper. These were mainly to produce a conservative assessment of the impact of ERF on the occupant. For the office, the mannequin was assumed to be low-res standing, to simulate the use of a standing desk. This would maximise the impact of the body surface area exposed to sunlight (f_{bes}). The mannequin was also set to be facing sideways at a 135-degree angle to the plane of the window. This is a typical positioning within an office building, to avoid glare on the screen, and discomfort to the occupant's eyes from the sun. The metabolic factor was set to 1.2, and clo was set to 1, to reflect the likely implementation of a dress code in the office (adaptive comfort opportunities related to clothing would be minimal). For the sunroom, clo was set to 0.5 in the winter periods, and 1 in the summer (to reflect a higher degree of adaptive comfort). The mannequin was assumed to be seated, with a met of 1.

For both cases, the mannequin was also assumed to be positioned as close to the window as is realistic (0.5 m away). This is because both longwave and shortwave radiation is influenced by distance from the



Component	Material	Thickness (m)
External wall	Expanded polystyrene	0.15
	Reinforced concrete	0.25
	Gypsum	0.0125
Dry wall	Steel structure	0.1
	Acoustic insulation	0.1
	Plasterboard	0.025
	Paint (double coat)	-
Ceiling/Floor	Finishing (timber MDF)	0.012
	Expanded polystyrene	0.03
	Reinforced concrete	0.25
	Gypsum	0.0125
	Paint (double coat)	-
Door (0.9x2.4m²)	Veneered Door	-
Window	See options in Table 2	

Fig. 3. Simulation Model for Office.

Table 3
Selected cities and climates.

City	Country	Latitude	Longitude	Altitude (m)	Avg. ground temperature (Celsius)	Climate region (Köppen-Geiger)
Singapore	SIN	1.37	103.98	16	27.5	Af
Dubai	UAE	25.2	55.27	44.2	27.2	Bwh
Shanghai	CHN	3.23	121.47	4	25.1	Cfa
London	UK	51.5	0.12	11	10.8	Cfb
Rome	IT	41.9	12.49	21	15.8	Csa
Tokyo	JPN	35.67	139.65	40	15.2	Cfa
Torrens	USA (CA)	33.83	118.34	27	22.9	BSk
New York	USA (NY)	40.71	74	10	11.9	Cfa
Beijing	CHN	39.9	116.4	44	12.7	Dwa

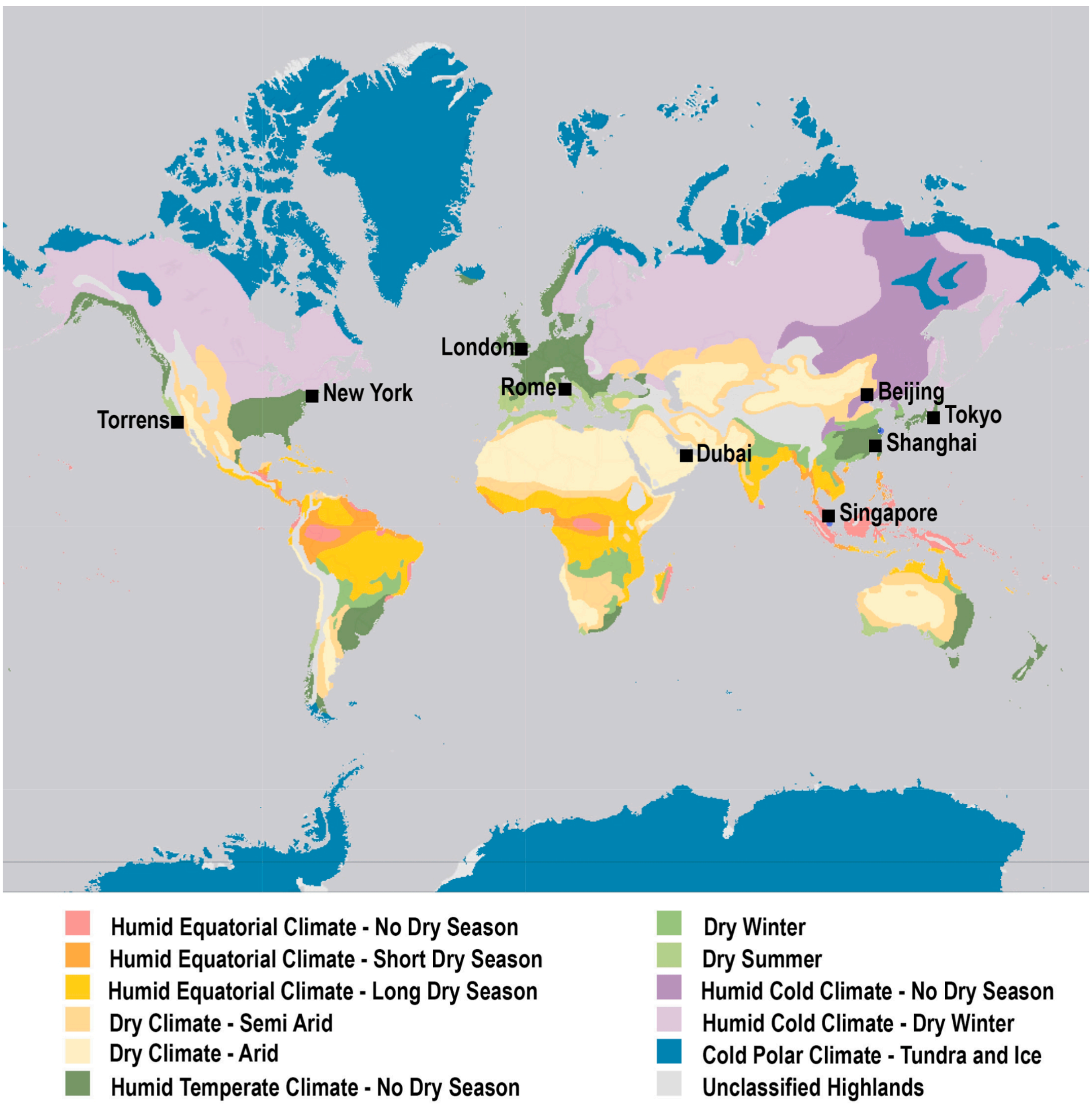


Fig. 4. Selected cities and climate regions (world map).

window, and as such this would present the most conservative case for comfort (full impact of radiative gain).

3. Results

The following chapter will be split into two sections, to evaluate the thermal comfort findings across different time scales (annual, hourly, and seasonal) for each case study.

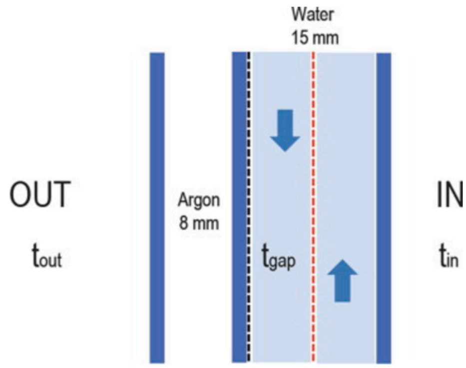


Fig. 5. Layout of WFG. The virtual (dummy) layer is shown with red dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. Overall annual thermal comfort evaluation

Figs. 6 and 7 display the percentages of occupied hours in each thermal comfort category according to PMV values. This is for the sunroom and office respectively.

For humid equatorial climates and subtropic deserts such as Dubai and Singapore, it is challenging to provide a glazing technique that can independently provide holistic thermal comfort all year round (in a free-floating scenario). Here, most of the occupied hours are characterized by a discomfort condition (warm or hot). For Dubai, less than 7 % comfort for the office was experienced across all techniques, and less than 8 % for the sunroom. Due to the climate experienced, windows that have greater control over the solar gains and reflectance perform slightly better than those which are designed to retain solar energy and reduce heat dispersion (insulative). The best performing window in Dubai was SWFG for the sunroom (8 %) and EC for the office (6 %). The worst performing technique was Base_2G for both sunroom (0 %) and office (2 %).

For continental climates such as Beijing (Dwa), WFG variants and EC perform the best for the sunroom, with 23–24 % comfortable periods. The remaining techniques only achieved 6–9 % comfort; insulative based techniques here result in overheating and loss of thermal comfort. Similar cases are shown for the sunroom in Cfa climates (Shanghai and Tokyo), whereby WFG variants and EC are again the best performers (20–23 %), with 7–14 % experienced by the remaining techniques. For the office, all techniques were found to have similar performance (10–12 %) in Beijing, but in Shanghai WFG technologies hold the highest comfort (16–17 %) compared to the rest (12–16 %). In Tokyo, all techniques exhibit a similar performance to each other (17–20 %), except for Base_2G (13 %), and Base_2G+AS (15 %).

For Cfb climates such as London, WFG and SWFG hold the highest comfort levels (21–22 % for the office, with EC providing a similar performance (20 %). Due to the cold weather clusters and perceptions, techniques such as Base_2G do not function suitably here, with a 7 % comfort. Instead, the best functioning techniques here are ones that focus on solar gain control. Similar findings are presented for the sunroom, with techniques such as SWFG, EC, SHGC_0.2, and Base_2G+PS, performing best (17 %, 17 %, 18 %, and 19 % respectively), and Base_2G (11 %) Base_2G+AS (14 %) performing worst. Similar findings are presented for the final location Canberra, which is also a Cfb climate.

4. Discussion

4.1. Comparison of glass options

People spend more than 90 % of their time indoors [30], and as such it is crucial to understand how to best improve the thermal comfort of the indoor environment, across each different climatic region globally. Since the specifics of what defines thermal comfort will vary for a number of reasons geographically, this study focuses on providing guidance for which glazing technique can help maximise comfort, to reduce the need for deployment of HVAC systems. This will ensure that operational emissions are reduced throughout the life cycle of the building, and also achieve the various benefits associated with thermal neutrality and comfort.

First, the base case (Base_2G) performs the worst out of all techniques investigated, when evaluated on its ability to provide thermal comfort. For the office, this corresponds to 0–9 % across all climates, and for the sunroom 0–13 %. This can be accredited to its permeability to solar radiation, creating an inclination to overheat the indoor space, which usually results in strong warm sensations perceived throughout the year. This is especially true for the majority of climates around midday, and for cities located in cold climates like London and Beijing. Consequently, the results suggest to consider alternatives to standard double glazing, across all climates for high WWR ratio buildings. This is also found in a similar study for a classroom scenario [31].

Again, Base_2G+AS is also largely not recommended for high WWR structures in most climates, as strong overheating is normally observed during periods of warmer outdoor temperatures (commonly April to September). For the sunroom, comfort ranges from 0-14 % and for the office 0–15 %. Whilst a simplified control was used here to dictate the shading condition at any timestep, future studies should seek to offer a more detailed adaptive schedule, as this may improve the quantification of expected comfort.

For Base_EC4st, this technique performs admirably across the study, with 0–25 % total neutral periods for the sunroom, and 0–21 % for the office. Whilst this may appear as an effective solution to general thermal

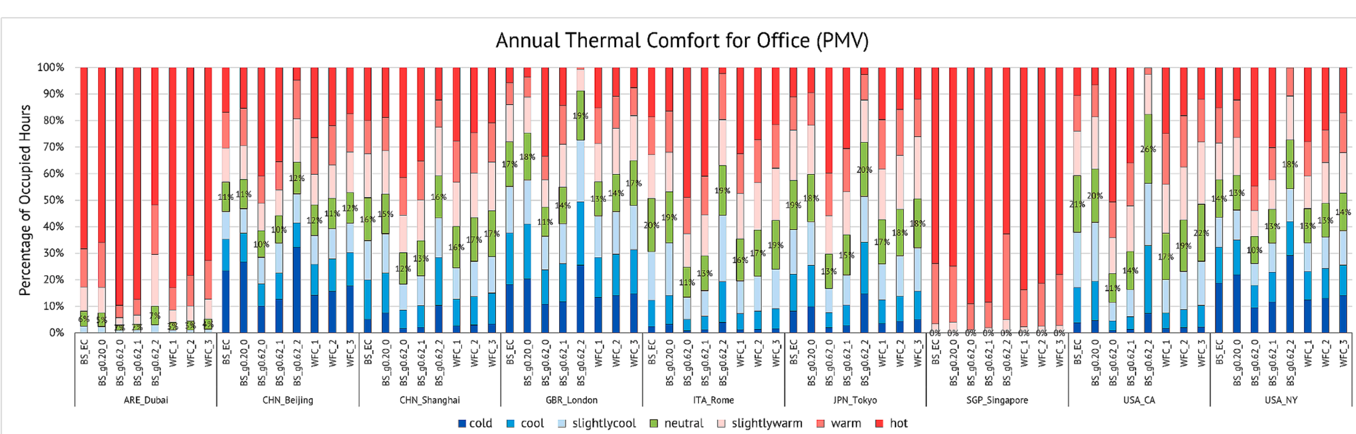


Fig. 6. Annual Thermal comfort evaluation for office.

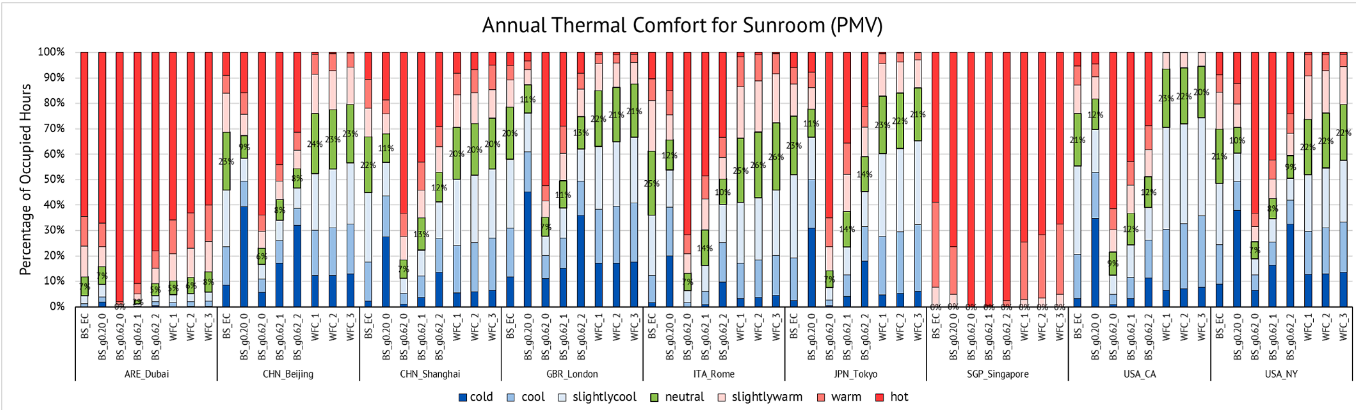


Fig. 7. Annual Thermal comfort evaluation for sunroom.

comfort, electrochromic glazing often presents certain limitations, such as a low recyclability content due to external coatings, and a higher associated embodied carbon. As embodied carbon is predicted to form 50 % of the built environment's emissions by 2035, it is crucial that awareness is created of these potential limitations of the technology. It should be noted that Base_EC4st has basically an inbuilt shading function, which is helpful to perform better than non-shaded options in this study such as WFG.

In almost all climate types, WFG and SWFG are also demonstrated to achieve high levels of thermal comfort within the free-floating scenarios modelled: 0–26 % comfort experienced in the office, and 0–22 % for the sunroom. As suggested, there is typically a 0–4 % comparative difference in thermal comfort between a completely transparent water layer and a coloured one. The WFG-like technologies best perform in humid and Mediterranean based climate types. This is because the outdoor temperature and solar radiation is not too high to offset, and the mild seasonal periods create the capacity for thermal comfort to be managed through heat capture. Whilst such technologies perform well in providing comfort around midday (hottest periods), Spring and Autumn typically result in overheating. This is caused by the techniques' ability to retain solar gain within the water layer. However, this propensity may be considered useful in winter (characterized by cooler ambient temperatures), depending on the availability and practicality to utilize this heat in each location.

In hotter climates such as Dubai and Singapore (Bwh, Af), all glazing techniques perform poorly for both the sunroom and office, with the simulated scenarios showing low level of thermal comfort. This is due to an excessive amount of solar gain entering the room and high outdoor air temperatures; as expected, the two strategies performing best in terms of thermal comfort here are the ones that minimise solar gains: (i) electrochromic glass, through increasing the reflectance of the glass (Base_EC4st), and (ii) double glass with permanent shading (Base_2G+PS).

It is noteworthy to mention that there are some similarities in the results, specifically in two cases: i) similarities for the same glass option in different cities and ii) similarities between different glass options within the same city (e.g. cities with hot climate like Singapore or Dubai). It is understood that these similarities exists, and the results may appear repetitive. However, this was deemed as relevant contribution to knowledge mainly because of the following reasons. First similarities between results for the same glass option underlined the importance of radiation in determining the most suitable technique. Second, similarities between different glass options within the same city (Singapore, Dubai) highlighted the impact of high amounts of glazing in those locations. Naturally, glass as a driving factor of energy consumption is acknowledged in general.

Tables 4 and 5 below display the best performing techniques for each location, with regards to both the sunroom and office.

Table 4
Best performing glazing type in terms of thermal comfort for each climate (office).

Location	Climate	Glazing Type (best/second to best)	% of comfortable periods out of total occupied hours (%)	Additional comfort compared to base case (Base_2G)
Singapore	Af	N/A	0 %	0 %
		N/A	0 %	0 %
Dubai	Bwh	Base_2G+PS	7 %	5 %
		Base_EC4st	6 %	4 %
Shanghai	Cfa	SWFG	17 %	5 %
		WFG	17 %	5 %
Tokyo	Cfa	Base_2G+PS	20 %	7 %
		Base_EC4st	19 %	6 %
New York	Cfa	Base_2G+PS	18 %	8 %
		SWFG	14 %	4 %
London	Cfb	Base_2G+PS	19 %	8 %
		SHGC_0.2	18 %	7 %
Rome	Csa	Base_EC4st	20 %	9 %
		SWFG/2G+PS/ SHGC_0.2	19 %	8 %
Canberra	Cfb	Base_2G+PS	26 %	15 %
		SWFG	22 %	11 %
Beijing	Dwa	WFG/SWFG/ 2G+PS	12 %	2 %
		EC/SHGC	11 %	1 %

4.2. Impact of shortwave radiation on comfort

Due to the modular/linear nature of the methodology used, it is possible to isolate the impact of shortwave radiation on the occupant for each scenario. This can be done through comparing the PMV results obtained from solely longwave radiation, and the PMV_{adj}. With the inclusion of shortwave radiation experienced, the overall comfortable periods decrease by up to 12 % for the office, and 10 % for the sunroom. This was an expected result, and is supported by similar studies [32–34]. For the latter, the minimized presence of non-opaque sections (typical when considering the function of the structure), means that overheating is expected to occur in certain periods, even with adaptive comfort controls (e.g., changing the level of clothing insulation throughout the year). Whilst the actual periods of overheating may be overestimated due to the extended occupation hours, the impact of shortwave radiation is mainly felt during the hours of sunlight, and as such this would likely not have a significant effect on the outcome.

For the office, even though the amount of glazing is lowered, the lack of adaptive clothing comfort means that overheating still occurs. In addition, the occupant can seldom remove themselves from the office scenario, unlike the sunroom to provide adaptive comfort.

Table 5
Best performing glazing type in terms of thermal comfort for each climate (sunroom).

Location	Climate	Glazing Type (best/second to best)	% of comfortable periods out of total occupied hours (%)	Additional comfort compared to base case (Base_2G)
Singapore	Af	N/A	0 %	0 %
		N/A	0 %	0 %
Dubai	Bwh	SWFG	8 %	8 %
		Base_EC4st /SHGC_0.2	7 %	7 %
Shanghai	Cfa	Base_EC4st	22 %	15 %
		SWFG/WFG	20 %	13 %
Tokyo	Cfa	Base_EC4st /WFG	23 %	16 %
		SWFG	22 %	15 %
New York	Cfa	SWFG/WFG	22 %	15 %
		Base_EC4st	21 %	14 %
London	Cfb	WFG	22 %	15 %
		SWFG	21 %	14 %
Rome	Csa	SWFG	26 %	19 %
		Base_EC4st /WFG	25 %	18 %
Canberra	Cfb	WFG	23 %	14 %
		SWFG	22 %	13 %
Beijing	Dwa	WFG	24 %	18 %
		Base_EC4st /SWFG	23 %	17 %

Overall, this study highlights the significance of accounting for such radiative fluxes on the occupant during thermal comfort assessments, as without such considerations the comfort can be overestimated. The greatest impact of shortwave radiation for this study is observed in Canberra (Cfb), Rome (Csa), and Tokyo (Cfa) for both buildings. This is an expected result, due to the temperature nature of the climates and their geographical positions.

4.3. Turning discomfort into comfort: Hourly and seasonal evaluation

Whilst assessing the relative comfort performance of each technique and climate is important, this must be supplemented by a contextual analysis. Here, by assessing the hourly and seasonal thermal comfort that is achieved through the year using each glazing technique, this comes with several unique advantages that may not be apparent when solely viewing an annual evaluation. These include i) how the thermal inertia developed by each window technique responds throughout the day, ii) the ability to assess if comfort can be managed by some form of adaptive or responsive control, iii) if there is a potential for capturing energy during occupied hours, and iv) whether thermally neutral periods coincide with occupied periods. For example, climates that present considerable seasonality such as temperate and cold ones (represented by cities such as Rome, Tokyo, New York, and London), the overheating discomfort periods during heating and transitory seasons (Spring, Autumn, and Winter) could represent an advantage rather than a liability. To examine this concept, Fig. 8 below displays an example carpet plot for Beijing, which shows the distribution of longwave PMV results for each hour of the year. For this comparison, SWFG has been assumed to have an adaptive control, that enables the shading condition to cycle between the three states (unshaded, 20 %, 40 %), depending on the illuminance control in Table 1). This reflects the optimized operation of the technique.

In terms of the base case, overheating is mainly experienced between March and September throughout the entire day, with very little cold sensation experienced. Between November and February, overheating is mainly reduced to occupied hours, with cold experienced early and late during the day. Overall, due to the insulative nature of double glazing, periods with warmer air temperature will result in the internal comfort also being warm and hot. For Base_EC4st, Base_SHGC0.2, and Base_2G+AS, a higher degree of comfort is experienced in the spring and summer months, due to less overheating experienced (May-August). Cold sensations are majorly experienced during the rest of the year, for almost the entire day. With regards to WFG and SWFG, these exhibit different behaviour to that described above. During occupied hours, there is a significant amount of comfort experienced throughout the year, with overheating occurring during February, March and October. For such climates, the outside temperatures in these months are characterized by low values; to this effect, there are two strategies in which this overheating sensation could be made advantageous and/or mitigated.

The first strategy to lower this excess heat is by deploying passive measures, such as increasing natural ventilation to reduce the indoor air temperature. However, the excess heat is not utilized further, and is wasted to the outside environment. A second strategy that may permit more efficient utilisation of this heat discomfort is through sharing the heat among different thermal zones of the building, if technological solutions permit this redistribution. This task could be performed by utilising SWFG and WFG, which can uniquely take advantage of the fluid dynamic mass (water flow) inside the window to shift excessive solar gain from one thermal zone to another through the connected hydronic system of the building. This will result in either maximizing comfort (higher than the presented data), or providing additional energy savings within the building.

These savings, denoted as 'q_useful' within this paper, would enable captured solar energy to be readily used e.g., for solar water heaters, and for a domestic hot water supply. The authors recognize that this benefit is dependent on the overall function of the building and its hot water demand profile, and as such has been calculated and presented separately below in Fig. 9 for WFG and SWFG. The sunroom scenario has been presented, as this would best indicate the potential for this strategy.

In climates with stronger solar irradiation, this concept would offer a more significant benefit. However, in recognition that the instantaneous use of captured heat depends on the function of the building, the heat energy was only quantified for heating periods. This is shown for climates such as Dubai and Singapore, which experience negligible savings in this study. With this being said, other subfunctions such as domestic hot water demand may provide opportunity for use outside of these periods (since no energy conversion is required), and as such the heat redistribution demand could be available throughout the year. Further research is required to assess whether this captured heat energy can be better optimized, by converting it into storable thermal energy.

As expected, the WFG-based technique that possesses the highest q_useful is SWFG, resulting in up to 72 % increased energy savings when compared to WFG (uncoloured). With only a small embodied carbon emission increase required to implement the adaptive controls of SWFG, the annual benefits strongly outweigh the resource cost in every location.

Overall, this study shows that evaluating the impact of thermal comfort solely based on annual PMV percentages can be misleading, as the discomfort periods of overheating during winter can be turned from a liability into an asset using either strategy above. For such strategies, MRT values and outdoor air temperatures become significant.

5. Recommendations for future research

There are a few avenues of future research that would complement the study undertaken in this paper.

First, in this study any captured heat (q_useful) has been assumed to be exclusively used for heating periods. If this heat could be used to match a consistent readily available demand, then the study could be changed to simulate the use of captured heat at all times.

Second, similar analyses could be undertaken for different building types and functions in each climate. This would help provide a bespoke

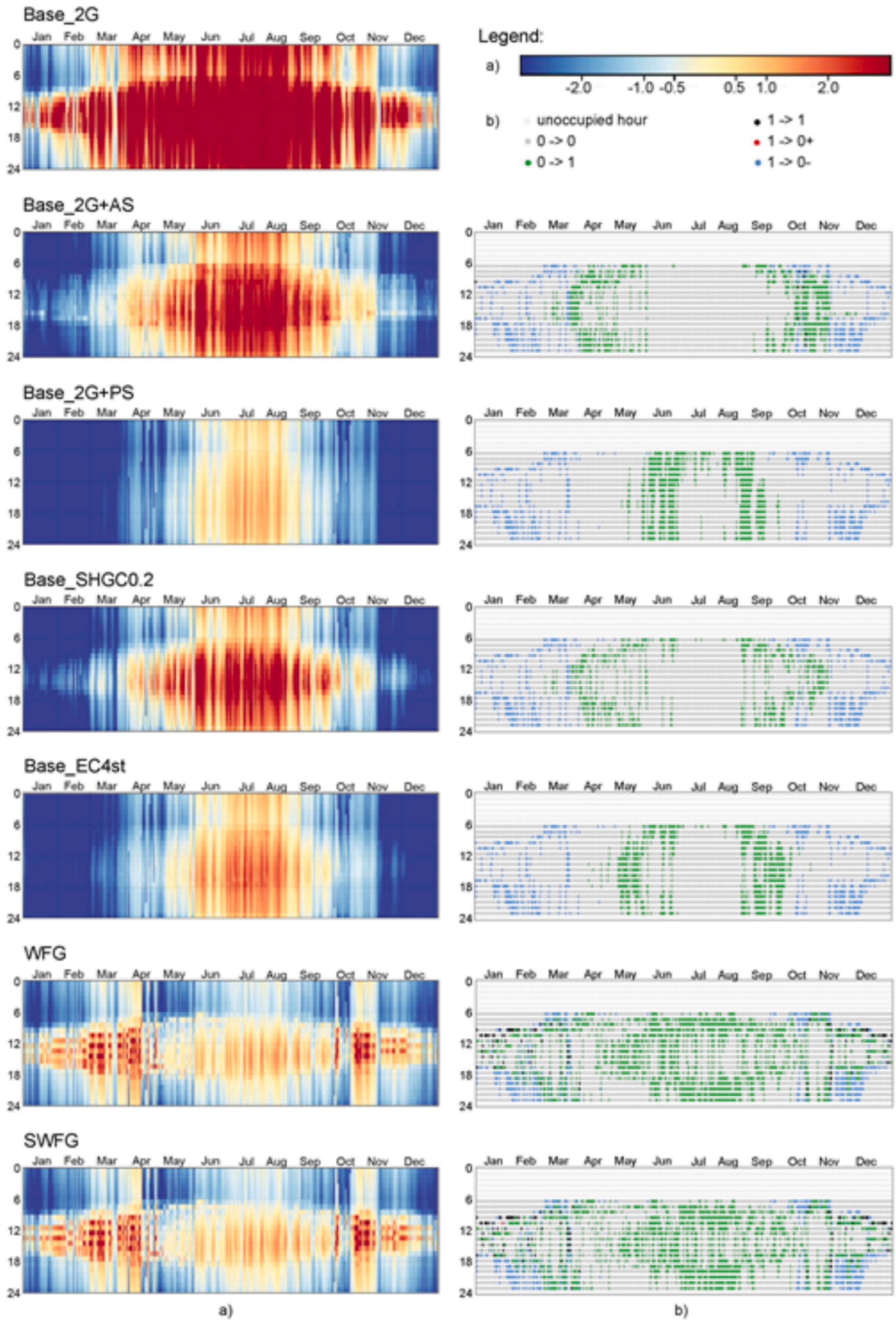


Fig. 8. Overall Hourly comfort, Beijing, showing thermal comfort over a year (left) and difference to double glass base case (right).

analysis and more deterministic judgement to which glazing is most suitable to every type of building and climate. This would provide a more sustainable outcome for building design in general, since glazing is a large contributor to thermal discomfort and operational energy usage within a building.

Third, visual glare should be considered in future studies, to assess visual comfort as well as thermal simultaneously. This would provide a more holistic understanding of the overall indoor comfort of the occupant, to quantify the impact of glazing on such parameters.

Finally, it should be noted that that whilst PMV is an efficient tool for addressing thermal comfort in general, a simple comparison of annual percentages can be misleading. For example, whilst WFG and SWFG

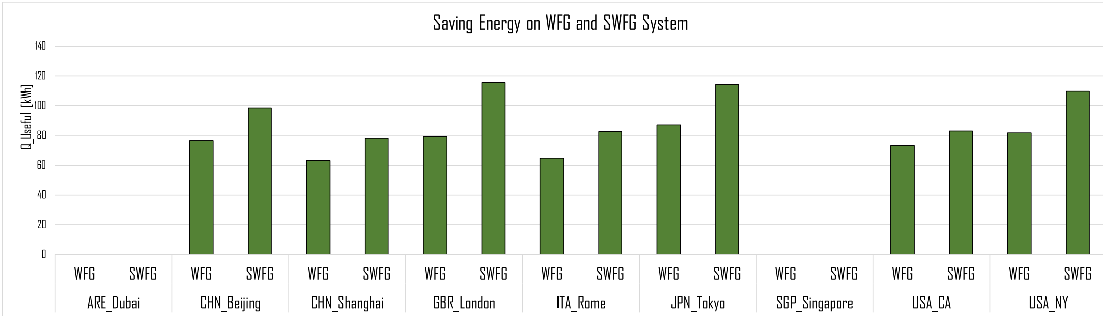


Fig. 9. Captured (absorbed) energy with WFG System.

shows more overheating in a year than electrochromic for example, much of WFG and SWFG overheating occurs during Spring and Fall. For colder climate conditions, this outcome is actually desirable and easy to mitigate. Hence, our recommendation is that windows should not simply be compared only by using PMV numbers, and instead supplemented with annual, seasonal, and hourly plots (as is the case with this paper).

6. Conclusion

In this paper, various glass options have been analysed in two free-floating scenarios (office and sunroom extension) in different climates, to establish which glazing technique provides the best thermal comfort throughout the year. Seven techniques across nine cities (all major inhabited Koppen Geiger climates represented) have been simulated, with the output of PMV and MRT based data. The Analytical Comfort Zone PMV Method has been used, as proposed by ANSI ASHRAE 55.

Results show that WFG and SWFG are suited to a variety of climates, and can achieve the highest level of thermal comfort experienced in up to eight out of nine climates, (represented as 26 % of annual occupied periods). The findings also suggest the importance of thermal mass within glass structures, and demonstrate how dynamic fluid mass systems can provide better inertia and control over the indoor microclimate, when compared to solid-state conventional glazing solutions. In addition to this, the paper proposes how WFG and SWFG have the unique ability to provide additional energy savings through heat redistribution and solar absorption within the water layer, either by equilibrating the thermal comfort elsewhere in the building, or readily using the heat energy within hot water systems.

The study also indicates that solely relying on just annual PMV data to determine thermal comfort can be misleading, as overheating can actually occur at times of the year where it is beneficial for user and building. As such, this paper also presents the hourly and seasonal distributions of discomfort and comfort, to enable the identification of 'zones' that may offer beneficial opportunities. This paper also highlights the significant opportunity for passive systems; across all climates and typical glazing solutions, thermal comfort cannot be guaranteed for typically more than 74 % of the year (considering free floating conditions). Finally, the substantial discrepancy of comfort/discomfort provided by different glazing techniques also highlights the significance of glazing within the built environment when achieving indoor environmental quality, and the importance of choosing the correct technique for each scenario.

7. Validation

For LBNL WINDOW, each individual glazing technique produced was cross-referenced against real parameter values (found in various academic studies and manufacturer product portfolios). Such parameters checked include spectral, thermal, and physical dimensioning. It is noteworthy that the software has an extensive library of gaps, glass, frames, and shading that are verified and updated often to reflect offerings from the industry. The WINDOW software is compliant to many current design standards, including ASHRAE SPC142, ISO15099, ISO/EN 10077, and the National Fenestration Rating Council.

For TRNSYS, the construction and materiality of each building model was based on the typical construction detailing for that typology. Whilst the specifics of the building (e.g., urban form) may vary geographically, an individual office space was modelled instead of the entire building. This way, the differences can be minimised since offices are largely modularised across the building stock. Whilst parameters such as heating and cooling setpoints and internal gains (electrical equipment, occupants, lighting) will invariably be heterogenous, it was deemed suitable to use the values recommended by ASHRAE for all locations. This would also enable the effect of the glazing to be isolated, without interdependence on such variables. Thermal comfort factors were based on DIN ISO 7730, ANSI ASHRAE 55, and Building Regulations Approved Document F (for the office case) [440]. TRNSYS has also been cross verified through various validation procedures, and is compliant with several standards, such as ANSI/ASHRAE 140 (BESTEST) [432].

CRediT authorship contribution statement

Abolfazl Ganji Kheybari: Writing – original draft, Visualization, Supervision, Software, Methodology, Data curation, Conceptualization. **Matyas Gutai:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Brandon Mok:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Giulio Cavana:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Matyas Gutai reports a relationship with Water-filled Glass Ltd that includes: equity or stocks. Abolfazl Ganji Kheybari reports a relationship with Water-filled Glass Ltd that includes: equity or stocks. Matyas Gutai has patent issued to Matyas Gutai. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper].

Data availability

Data will be made available on request.

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