Chapter 238
Steps in Designing an Indicator for Assessing Window's Effect on Indoor Thermal Comfort

Nan Wang, Neda Ghaeili, and Julian Wang

Abstract The effects of solar radiation play an important role in human thermal comfort, especially within the near-window zones. In the incorporation of the solar effect into the thermal comfort model, the comprehensive solar-optical characteristics of windows have to be taken into account, especially when it came to a largely variant or unbalanced spectral distribution of a building window. In this work, we examined the thermal effects varying with different spectral characteristics of glazing systems and also preliminarily proposed a new indicator "thermal effect index (TEI)" that can be used to estimate the impact levels of window systems on indoor users' thermal comfort in near-window zones. TEI could be used as a benchmark for assessing a window system's potential impacts on indoor users' thermal comfort, especially when direct sunlight is enabled in a space.

Keywords Spectrally-resolved method · Thermal comfort · Solar radiation · Glazing optical characteristics · Thermal effect index

238.1 Introduction

The indoor thermal comfort of human beings is a critical factor in maintaining desired indoor environments. Indoor thermal comfort could be kept by the active strategy like air conditioning system and passive strategy like solar thermal energy (Rashad et al. 2021). Compared to the active strategies, the adoption of solar thermal energy in controlling thermal comfort has less energy consumption and thus should be utilized properly. One of the major pathways for utilizing solar thermal effect is through specific window and glazing system design in which the optical and thermal properties of window systems need to be considered. To evaluate the role of solar irradiance passing through the windows and working on human skins to alter human thermal comfort, Arens et al. (2015) proposed a method flow to evaluate thermal comfort based on the predicted mean vote (PMV) model, which is used to predict

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thermal comfort by seven predictors including mean radiant temperature (MRT) and an equivalent conversion from shortwave radiation to longwave radiation to generate an additional MRT delta to incorporate into the PMV model. Thus, the MRT delta could be used to indicate the role of shortwave solar irradiance on indoor thermal comfort.

Window performance plays an important role in human thermal comfort. For instance, Duan and Wang (2019) studied the impacts of different window properties and associated air conditioning systems on indoor thermal comfort in private offices. Zhang et al. (2020) qualified the window performance's effects on indoor thermal sensation by taking the solar irradiance through the windows and the ankle draft effects by the convective heat transfer between the window and the interior. The existing window indicators provided on window labels, typically defined by the National Fenestration Rating Council (NFRC) and Canadian Standards Association (CSA), including the solar heat gain coefficient (SHGC), the U-factor, visible transmittance, air leakage, and condensation resistance (Gereffi et al. 2008), which have the potential to describe window properties from various aspects (Kim et al. 2014). Nonetheless, these indicators are not developed specifically for the thermal effects of windows on humans. In this context, several prior studies developed potential indicators. Huizenga et al. (2006) established seasonal ratings or comfort indexes for windows in the summer and winter. The winter comfort index is defined by using the U-factor of the window and the assumption of specific boundary conditions, while the summer ratings are determined by direct sun transmittance and indirect SHGC. Based on this study, the effects of windows on comfort in the summer and winter are fundamentally different. While winter comfort is determined by the temperature of the inner surface of the window, which is affected by the window's U-factor and outside temperature; summer comfort is determined by the combination of inner surface temperature and transmitted solar irradiance, which is affected by the optical properties of the window. Chaiyapinunt et al. (2005) utilized the predicted percentage of dissatisfaction (PPD) as a thermal comfort indicator to assess the various types of glazing systems in their research. This study was conducted while the following assumptions about the outside environment were adopted: direct normal solar irradiance on glass is 658 W/m^2, diffuse solar irradiance on the window is 111 W/m^2, outside air dry bulb temperature is 35 °C, and outside wind velocity is 3.8 m/s. The person is sitting one meter away from the window, which is facing west. Inside boundary conditions include an indoor air dry-bulb temperature of 25 °C, an inside air velocity of 0.15 m/s, relative humidity of 50%, clothing insulation of 0.5 clo, and a metabolic rate of activity of 1.2 met.

Nevertheless, these prior window's related comfort or indicator-development studies focused on conventional thermal transfer, either ignoring or only adopting simple "transmitted solar radiation". However, in our most recent study (Wang and Wang 2021), we have indicated that the ignorance of the spectra nature of solar irradiance, window transmittance, and human skin absorptance may cause an inaccurate or false understanding of thermal comfort influences. As such, a new spectrally-resolved method has been proposed and used to explore the influence of the variation of solar spectra on thermal comfort calculation results. With the development of a more complex fenestration system for building energy efficiency and indoor visual comfort, especially for those wavelength-dominated spectral characteristics, spectral variations and details need to be considered for determining the potential thermal effect. However, there are no existing indicators or metrics for users to assess the window properties in terms of the complexity of spectral characteristics. It is therefore in this paper that we aim to explore the influence of spectral variations of windows on user thermal comfort (i.e., MRT delta) under constant boundary conditions and move steps forward to designing a new indicator for quantifying the thermal comfort effect of window and glazing systems. Based on the analysis results, this paper also preliminarily proposes a new indicator "thermal effect index (TEI)" that can be used to indicate the impact levels of window systems on indoor users' thermal comfort in near-window zones.

238.2 Methods

238.2.1 Spectrally-Resolved Method Introduction

The key parameter that determines MRT delta in the spectrally-resolved method is the spectrum of the solar irradiance which includes direct, diffuse, and reflected indoor irradiances, and the solar irradiance that could work on human skin. The amount of solar irradiance outdoors that could enter indoors and work on human skin depends on multiple factors: First is the penetration of outdoor solar irradiance into indoors and reaching the occupant that is confined by the dimensions and orientations of the windows and the distance of the occupant from the window; Second is the transmittance properties of the windows that select certain amounts of solar energy at different wavelengths; Third is the posture of the occupant (seated or standing) which determines the fraction of the human body that could be irradiated (f_{eff}), named effective body surface; Fourth is the relative relationship between the direction of solar irradiance and human facing direction; Fifth is the absorptance properties of human skins, which are the absorptance spectra of skins.

In all, the spectrally-resolved method multiplies solar spectra outdoor, window transmittance spectra, and skin absorptance spectra wavelengths and considers the values of the above five factors.

238.2.2 Simulation Settings and Boundary Conditions

Outdoor solar spectra at 13:00 on day 18 of the year in Florida (27.6° N, 81.5° W) was used in the simulation which leads to the solar zenith angle of 48° and azimuth angle of 185°, and the SPCTRL2 excel-based software was used to make the simulation.

The integral direct irradiance for the wavelengths from 300 to 2500 nm is 775 W/m^2, and the solar spectra are depicted in Fig. 238.1a.

The window in the room faced south and was assumed to be 2.8 × 2.8 m, the sill height of the window was 0.5 m, and the effective height of the occupant was 0.9 m. The occupant was assumed to face the window and 0.5 m from the window. Based on the dimension of the window, the position of the occupant, the effective height of the occupant, and the solar zenith angle, the proportion of the sky exposed to the human body were 0.61 and the fraction of the body exposed to the sun viewed from the vertical direction was 0.94. Horizontally, direct irradiance could be introduced into the indoors according to solar azimuth angle, window dimension, occupant position, and the angle between the occupant's front and direct sunlight (*SHARP*) which is 5°. The occupant was assumed seated and thus the f_{eff} value was 0.696. The projected area factor to determine the fourth factor is 0.30 according to the occupant's posture, solar altitude angle (90°-solar zenith angle), and *SHARP*. The skin of the occupant was assumed to be white, and the reflectance spectrum of which (Fig. 238.1b) was provided by the Reference Data Set of Human Skin Reflectance with a skin absorptance of 0.570 (Cooksey et al. 2017).

For the calculation of the PMV values, the MRT and room temperature were both set at 25 °C, the air speed was 0.1 m/s, relative humidity was 50%, metabolic rate was 1 met, and clothing level was 0.5 clo.

The spectral data of eleven different glazing systems were modeled and calculated using LBNL WINDOW and OPTICS. The glazing systems under consideration are all double windows with a 13 mm gap, and the spectrum data was obtained utilizing

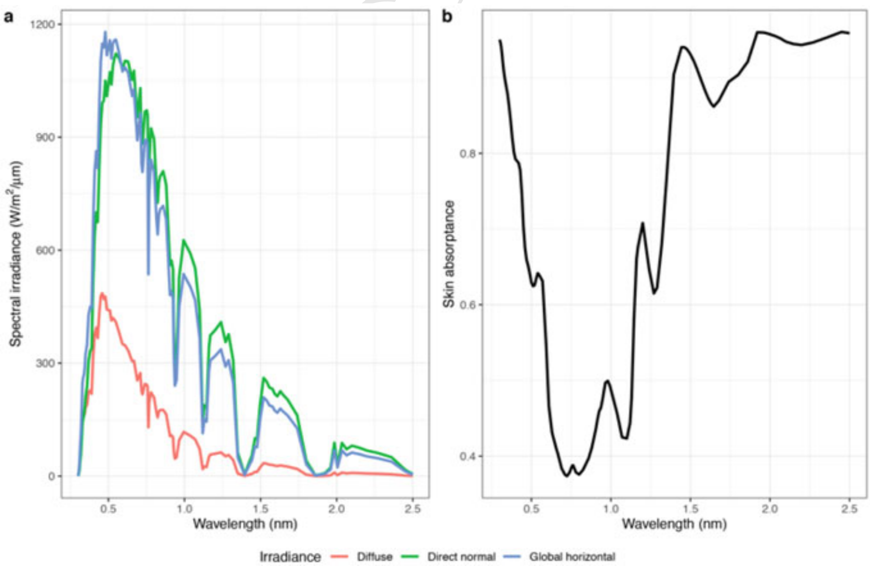

Fig. 238.1 The spectra of **a** solar, and **b** skin absorptance

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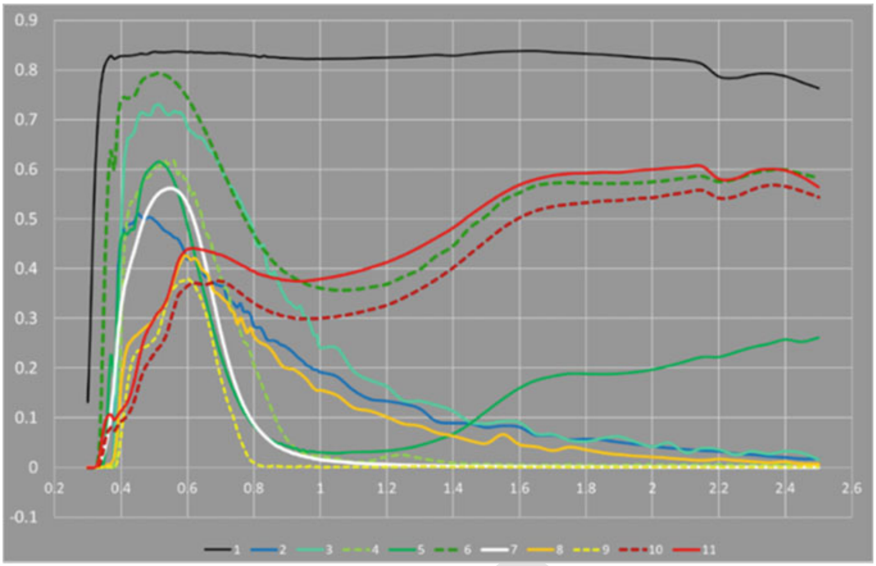

Fig. 238.2 Spectral transmittance curves of the selected glazing systems

a combination of monolithic, coated, and applied film layers. The obtained spectral range of glazing systems was within 0.38–2.5 μm. The primary goal of the glazing system modeling and simulation was to cover representative glazing types and associated spectral variations. These samples include clear double-pane glazing, double-pane glazing with high SHGC or low SHGC low-e coatings, double-pane glazing with different tinted coatings, etc. Figure 238.2 presents the spectral transmittance of these 11 selected glazing systems. Furthermore, the spectral properties of glazing—solar transmittance, NIR transmittance, and thermal properties—emissivity, SHGC, and U-factor, were also output from the program. Table 238.1 lists the key properties of the chosen glazing systems.

238.2.3 Thermal Effect Calculations by the Spectrally-Resolved Method

The MRT delta values of the 11 selected glazing systems were calculated by using the spectrally-resolved method in which the skin absorption spectra and the other boundary conditions were set based on the method in the above section. Subsequently, the MRT delta values obtained for these chosen glazing systems were analyzed. Meanwhile, the correlations of the MRT delta values and existing window parameters (e.g., SHGC, U-factor, visible transmittance) were tested, in order to examine whether certain existing indicators can be used to describe the window thermal effects.

Table 238.1 Properties of chosen glazing systems

GS #	Color appearance	Visible trans	Solar trans	NIR trans	SHGC	U-factor	Emissivity feature
1	Clear	0.836	0.829	0.821	0.837	2.728	N/A
2	Blue	0.39	0.176	0.024	0.278	1.88	Layer 2-0.153
3	Clear	0.708	0.433	0.121	0.583	2.425	N/A
4	Gray	0.593	0.267	0.019	0.381	2.664	N/A
5	Green	0.556	0.250	0.104	0.391	2.716	N/A
6	Green	0.769	0.568	0.467	0.726	2.735	N/A
7	Clear	0.541	0.220	0.015	0.27	1.602	Layer 3-0.013
8	Silver	0.366	0.231	0.073	0.375	1.813	Layer 2-0.112
9	Bronze	0.336	0.124	0.002	0.409	1.804	Layer 2-0.112
10	Bronze	0.304	0.327	0.416	0.422	2.715	N/A
11	Bronze	0.372	0.391	0.517	0.509	2.699	N/A

238.3 Results

238.3.1 MRT Delta Values Across Different Glazing Systems

The calculated MRT delta values across 11 representative glazing systems are listed in Table 238.2.

The calculated MRT delta values across the glazing systems ranged from 5.11 to 33.08, which led to the variations of PMV values, ranging from 0.52 to 6.06. This highlights the significant difference among the influences on thermal comfort by the different glazing structures. In particular, as shown in Table 238.1, several glazing systems have quite similar visual appearance (i.e., visible transmittance and color), such as GS9, GS10, and GS11, while the thermal effects on user comfort are greatly different.

Table 238.2 Calculated MRT delta and PMV values

	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9	GS10	GS11
MRT Δ	33.08	11.54	16.76	10.95	11.20	23.48	9.33	8.57	5.11	12.64	15.12
PMV	6.06	1.70	2.69	1.59	1.64	4.03	1.29	1.15	0.52	1.91	2.38

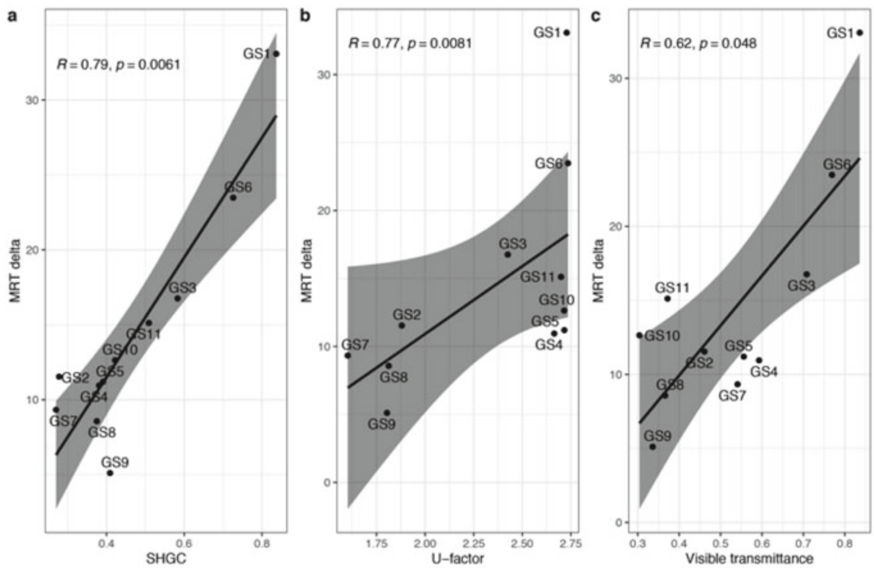

Fig. 238.3 MRT delta values by **a** SHGC, **b** U-factor, and **c** visible transmittance

238.3.2 Correlations Between MRT Delta and Glazing Properties

A few correlational analyses were conducted between the calculated MRT delta and the existing glazing properties—SHGC (Fig. 238.3a), U-factor (Fig. 238.3b), and visible transmittance (Fig. 238.3c) that are typically labeled by the NFRC and CSA in North America and shared with homeowners by manufacturers. Comparatively, SHGC has slightly better performance with a spearman correlation of 0.79; however, such correlations may still not sufficiently and accurately indicate the thermal effects.

238.3.3 Correlations Between MRT Delta and Glazing Optical Properties

In addition to the above typical window or glazing properties, a few optical properties can be extracted from the LBNL WINDOW and OPTICS programs, such as solar transmittance and NIR transmittance (780–2500 nm). Notably, such properties still need full spectral information and are not typically accessible to users. Similar to the above correlational analyses, as shown in Fig. 238.4, two correlations between the MRT delta values and solar transmittance and NIR transmittance were obtained. In general, both spearman correlation values, 0.98 and 0.92 for solar and NIR transmittance, respectively, are much higher than the values when using the conventional

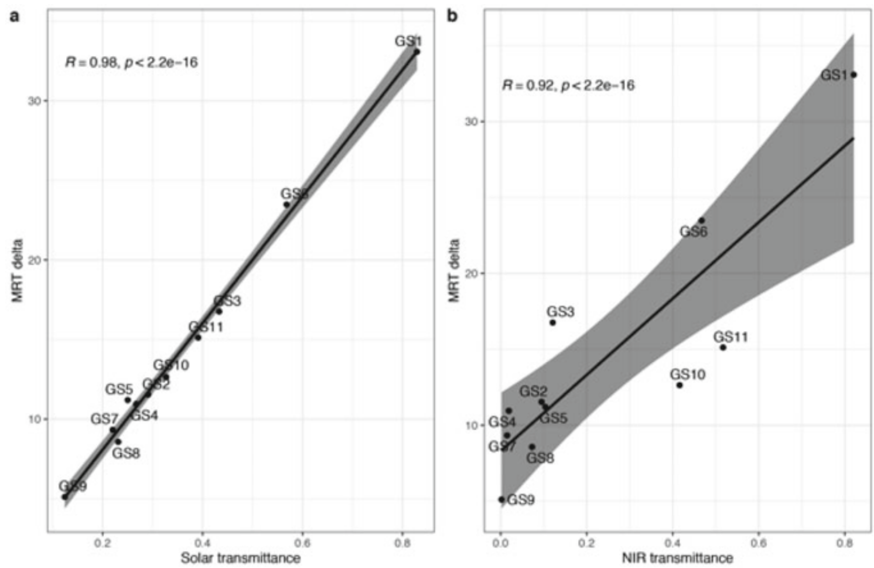

Fig. 238.4 MRT delta values by **a** solar transmittance, **b** NIR transmittance

window labeled properties. So, from the statistical perspective, both glazing optical properties, especially the solar transmittance, do help a rapid appraisal of window's thermal influences on users when it comes to a large number of glazing products. Higher solar transmittance of glazing systems tends to produce relatively higher thermal effects on indoor users. AQ1

However, when it comes to the indication, each glazing product should be accurately assessed and clearly labeled. Unfortunately, some erroneous labels have been observed in this analysis with very small samples. For instance, it can be seen from Fig. 238.4a that GS8 has a slightly higher solar transmittance than GS7, while it shows a lower MRT delta value than GS7. This also applies to the relationship between GS4 and GS5.

Furthermore, to examine the use of the solar or NIR transmittance as the thermal effect indicator, we normalized all the selected glazing systems to the same solar or NIR transmittance and in turn compared the normalized MRT delta values across the glazing systems. Supposedly, a similar level of the MRT delta should be obtained. However, as shown in Fig. 238.5, the normalized MRT delta values for solar and NIR transmittance are varying with different glazing systems. Comparatively, the normalized MRT delta when using the NIR transmittance have relatively better performance, falling in a similar range, although there are still three glazing systems staying at much-different levels.

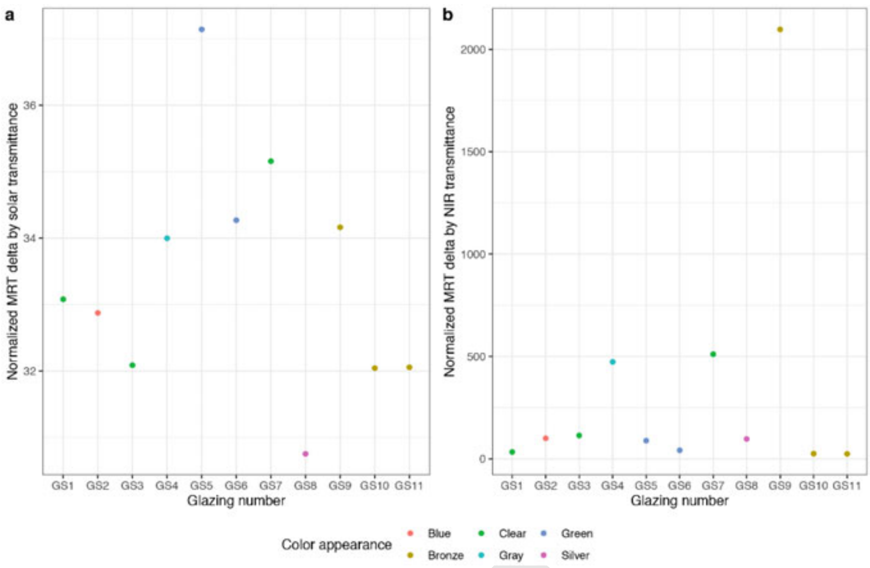

Fig. 238.5 Normalized MRT delta values by **a** solar transmittance, **b** NIR transmittance

238.4 Discussion

The above analyses showed that the thermal effects can be substantially different even for some windows that are with similar properties (SHGC, visible transmittance, U-factor, solar transmittance, and NIR transmittance). This manifests a need for methods of determining the thermal effects of solar radiation through a complex variety of fenestrations and associated film or coating systems. The calculation of thermal effects for different locations, climates, sky conditions, window orientations, and window designs can yield an accurate amount and associated PMV variations; however, it will be a time-consuming process. To ease these computations and conveniently compare different window or glazing products, a single-number TEI and its calculating or simulation procedure need to be developed and standardized.

It is also worth mentioning that, as indicated in previous studies (Duan and Wang 2019; Zhang et al. 2020), the thermal properties (e.g., U-factor and emissivity) of glazing systems can also strongly affect the thermal environment in near-window zones. In particular, with weak solar radiation, such thermal property-induced influences can be pronounced. Therefore, both thermal and spectral information of glazing systems should be considered in an indication development process. By following the typical ASHRAE and NFRC procedure on fenestration properties, a series of boundary conditions should be standardized, such as direct and diffuse solar radiation, incident angle, outdoor temperature, wind speed, window orientation, occupant position and posture, indoor air conditions, etc. Meanwhile, the output of TEI can be normalized into the range of 1–10, in which a standardized neutral glazing product for thermal effects needs to be defined. Accordingly, different windows or glazing products with their detailed spectral information can be used to compute the TEI and compared it with the neutral glazing product. As such, a lower rating of TEI can refer to certain cooling effects for use in a hot climate, and a higher TEI can indicate the potential warming effect on indoor users for use in a cold climate.

238.5 Conclusion

In this work, we explored the potential thermal effects of spectral variations of different glazing systems by using a previously-developed computation method. As the glazing systems become more sophisticated, existing methods of characterizing the thermal effect of glazing systems are becoming inadequate, and a new thermal effect indicator needs to be developed. This is not to replace the existing window or glazing properties but rather to provide more interpretable information for users or homeowners when they make selections in terms of different thermal comfort needs. With indoor comfort and well-being concerns becoming more prominent, such indications can be also helpful for architects or building engineers to perform a rapid assessment of indoor comfort.

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