Parametric Energy Simulation Methods for Solar-NIR Selective Glazing Systems

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Abstract. Solar near-infrared (NIR) selective glazing systems have been proposed by incorporating photothermal effects (PTE) of a nanoparticle film into building windows. From an energy efficiency perspective, the nanoscale PTE forms unique inward-flowing heat by heating up the window interior surface temperature under solar near-infrared, significantly improving the window thermal performance. Also, the PTE-driven solar heat gains are dynamic upon solar radiation and weather conditions. However, the PTE on annual building energy use has not been investigated thoroughly, due to the lack of an accurate and appropriate energy simulation method. In this study, we used the EnergyPlus energy management system to develop a parametric energy model and simulation approach in which a solar-temperature-dependent thermal model was embedded into the parametric energy simulation workflow. Applying this method, we examined the solar near-infrared-dependent PTE-induced thermal performances of glazing systems and their effects on annual heating energy use in representative cold climates (i.e., Zones 4, 5, and 6). The results show that the dynamic model considering the PTE demonstrated more heating energy savings, up to 11.64% in cold climates, as opposed to the baseline model that ignored the PTE. This work presents a method to model and simulate the dynamic thermal performance of windows with PTE.

1. Introduction
The photothermal effect (PTE) has been studied in biomedical applications for decades, and in recent years, a few studies have explored it in relation to building window systems [1–4]. PTE is directly correlated to plasmonic properties of nanoparticles, namely localized surface plasmon resonance (LSPR) in particular. LSPR occurs when a metallic nanoparticle is illuminated by light, and the excited free electron from the metallic surface forms a plasmon oscillation with the positive nuclei. When this LSPR oscillation matches a particular incident frequency of light, it induces strong absorption of light to obtain energy, and then other light scatters. Their ratio of absorption and scattering abilities can be tuned by the wavelength of the light, size, composition, and shape of the nanoparticles [2]. After the excitation, the thermal energy stored in the surface plasmon releases to the surroundings and produces...
local heating [5]. The continuous oscillation is caused by electrons accelerating with enough energy to overshoot equilibrium configuration and effectively switching the local electric field with maintained illumination. In recent years, there have been studies trying to simulate this PTE for window applications. For instance, Zhang et al. have developed a thermodynamic analytical model for nanoparticles Fe₃O₄@Cu₂₋ₓS on a single pane window to help understand the thermal behaviors of nanoparticles with PTE [4].

There are many challenges associated with simulating PTE thermal dynamic envelope materials, as they depend on both indoor and outdoor conditions. Parametric energy simulation is required to leverage this information and demonstrate control strategies. However, most parametric environments are limited to either geometric-focused changes or physical-related changes but low-resolution. In order to access the necessary variables at an appropriate resolution, standalone energy software is required. Although this limits building geometry, it allows for a detailed analysis necessary for selective glazing systems. EnergyPlus energy management system (EMS) enables parametric energy simulations for such dynamic glazing applications.

Based on a solar- and temperature-dependent solar heat gain coefficient (SHGC₅₇) regression model derived in a previous study [6], this paper presents a parametric energy simulation approach with the SHGC₅₇ applied to a whole building energy analysis. This approach incorporated the PTE thermal dynamics into a parametric energy simulation workflow using EnergyPlus EMS.

2. Methodology

2.1. Introduction and previous applications of parametric energy simulation

In recent years, the simulation-driven design has become an integral part of the building design process. Researchers are able to predict building behavior before construction and test energy-saving strategies. As the availability of simulation engines increased, many began to integrate simulation and parametric design in order to quickly evaluate design options or simulate dynamic building technologies. More broadly, access to energy simulation in parametric design environments has helped inform the early design decision-making process [7–9]. Parametric energy simulation paired with optimization techniques has been used to develop effective HVAC control schemes [10,11] and lighting control strategies [12,13]. Similarly, previous studies on dynamic facade systems [14,15] relied on parametric energy simulation to incorporate environmental conditions and occupant comfort. While existing literature shows promising possibilities for parametric energy simulation, there is also an opportunity for dynamic building envelope material applications.

2.2. General EMS parametric energy simulation workflow

Energy Management System (EMS) enables parametric energy simulation within EnergyPlus [16]. It requires user-defined conditional statements in Energy Runtime Language (erl), a simplified programming language. An EMS program includes sensors, actuators, internal variables, global variables, and a calling point. The available sensors and actuators are dependent on the model itself and can be found in the RDD and EDD output files, respectively. Typically, sensor data is leveraged to modify a component of the model, which is called the actuator. There are many available sensors pertinent to window control, including surface inside face temperature, indoor air temperature, indoor relative humidity, among others. Similarly, there are several types of building envelope actuators such as window shading control, surface construction state, surface boundary conditions, and surface convection heat transfer coefficient. Users can also define internal variables or declare global variables. The calling point determines when the EMS program is called with respect to the energy simulation; for example, the program can be called before or after zone loads are calculated. Erl only permits IF statement structures and WHILE loops. Although erl is a simplified programming language, there are many possibilities for simulating dynamic glazing materials like solar-NIR selective glazing.
2.3. Solar- and temperature-dependent thermal dynamics of glazing systems

In the photothermal windows [3], the photothermal film layer was placed on the inner surface for improving window interior surface temperature and inward-flowing heat. Figure 1 provides the structure diagram of the Low-E and photothermal windows.

![Diagram of Low-E and Photothermal Windows](image)

Figure 1. Window structures of the Low-E and photothermal windows.

It is known that the solar heat gain coefficient (SHGC) values are the same for low-e windows regardless of outdoor climate changes. However, for photothermal windows, the SHGC values are dynamic according to the outdoor solar irradiance and temperature. This is because the photothermal film is sensitive to solar NIR and absorbs more solar NIR than the low-e coating, subsequently inducing a nanoscale PTE temperature increase. Therefore, solar irradiance and outdoor temperature are two major factors that affect the nanoscale PTE on photothermal windows, specifically the inward heat flow that occurs from the inner surface.

Based on the thermodynamic analytical model proposed in our research group, a series of calculations were performed in 49 different boundary combinations, in which the outdoor temperature ranged from -15°C to 15°C and solar irradiance levels between 50 and 600 W/m²[4]. Then, the SHGC values of the photothermal windows were obtained by calculating the fraction of net solar heat gain over the incident solar irradiance. Thus, this solar- and temperature-dependent heat gain coefficient of the photothermal windows was named $SHGC_{ST}$, which is different from the traditional SHGC concept. Meanwhile, a $SHGC_{ST}$ regression model has been proposed in terms of statistical analysis:

$$SHGC_{ST} = 1 - (1 + e^{(\alpha G + \beta T_{out} + 0.236)^{-2}})^{-1} \tag{1}$$

where $G$ is the incident solar irradiance level in W/m² and $T_{out}$ is the outdoor temperature in K. The coefficients $\alpha$ and $\beta$ are 9.182E-4 and 1.521E-7, respectively.

2.4. Simulation method for PTE windows

The approach is an accurate and appropriate method that incorporates the dynamic $SHGC_{ST}$ parameter into the whole building energy simulation in the EMS program, which is also called the dynamic envelope simulation method [17,18]. The overall workflow of the method is provided in Figure 2. Considering solar irradiance $I_{solar}$ and outdoor temperature $T_{out}$, different types of photothermal windows with different $SHGC_{ST}$ were defined according to the $SHGC_{ST}$ regression model (Equation 1), and different construction states $W_i (i = 1, 2, 3, \cdots)$ of the building windows were determined accordingly. Comparing hourly outdoor solar irradiance and temperature to the values decided by Equation 1, if they lied in the corresponding range of the values decided by Equation 1, then the solar- and temperature-dependent heat gain coefficient belonged to number $i$ type of photothermal windows with construction state $W_i$, and then this $SHGC_{ST}$ would be assigned to the type $i$ photothermal window ($SHGC_{ST} \in W_i$). The PTE are used to trigger a change in the SHGC in the EMS program. Then, annual energy simulations in EMS were activated using this parametric relation.
In this specific simulation, “Zone Outdoor Air Dry Bulb Temperature” and “Surface Outside Face Incident Solar Radiation Rate per Area” were used as the sensor parameters. The actuator related to the window type, called “Construction State,” was also adopted. The selected calling point in this work was “Begin Timestep Before Predictor,” which occurred near the beginning of each timestep but before the zone loads were calculated. One challenge was encountered during the parametric simulation process. In the current version of EnergyPlus, SHGC cannot be written as a continuous function in the construction state of building windows, therefore the $SHGC_{ST}$ based on the regression model (Equation 1) was utilized as a discrete variable to represent different photothermal windows. The smaller interval of solar irradiance ($[I_{i-1}, I_i]$) or outdoor temperature ($[T_{i-1}, T_i]$), the more types of building windows should be constructed, and the more complex program should be written in the EMS program.

3. Results
Two models including a baseline model and dynamic model were employed for a series of whole-building annual energy simulation analyses in 3 climate locations (Zones 5, 6, 7). The baseline model was the DOE prototypical small office building model for the 2019 edition of ANSI/ASHRAE/IES Standard 90.1 and IECC, while the dynamic model is based on the baseline model considering the solar- and temperature-dependent dynamic solar heat gain coefficient of the window system. The $U$-factor used for the baseline and dynamic models were identical: 3.5 W/m²K. The visible transmittance of the baseline and dynamic models were 0.77 and 0.75, respectively. The SHGC value for the baseline model is 0.57, but for the dynamic model, it changed based on the regression model (Equation 1).

![Diagram](image)

**Figure 2.** Overall workflow of the annual energy use method that considers PTE.

![Diagram](image)

**Figure 3.** Annual heating loads and difference percentages.
In three representative cities, annual energy simulations were performed for two models with two types of windows. Annual heating energy use was compared because the major concern regarding photothermal effects on windows was in the winter season. Therefore, in this work, the annual heating energy and associated energy difference percentages for these three cities are reported in Figure 3, and the details are provided in Table 1.

**Table 1. Annual Heating Loads and Associated Difference Percentages With and Without PTE.**

| Zone | City          | Baseline model annual heating energy use (GJ) | Dynamic model annual heating energy use (GJ) | Heating load difference % (relative to the baseline model) |
|------|---------------|----------------------------------------------|---------------------------------------------|----------------------------------------------------------|
| 4    | Seattle, WA   | 12.64                                        | 11.67                                       | -7.70                                                    |
| 5    | Denver, CO    | 14.10                                        | 12.49                                       | -11.46                                                   |
| 6    | Missoula, MT  | 29.05                                        | 27.03                                       | -6.94                                                    |

The baseline model’s annual heating energy use values in winter for Zones 4, 5, and 6 were 12.64 GJ, 14.10 GJ, and 29.05 GJ, respectively, in which the photothermal effects were not considered during the simulations. On the contrary, when considering the PTE related to decreased heat loss, the dynamic model saved up to 11.46% annual heating energy use compared to the baseline without the PTE. That is to say, the conventional energy use predictions ignore the significant heat gain through the photothermal effect.

**4. Conclusion**

In this research, a new approach that couples the experimentally and numerically demonstrated thermodynamic analytical model of solar-NIR selective glazing system and EMS-based parametric energy simulation was proposed. This parametric simulation method incorporates solar- and temperature-induced thermal dynamics to compute whole-building energy use. Applying this method, we examined the solar NIR-driven plasmon-induced photothermal effects of glazing systems and their influences on annual heating energy use in cold climate zones. The results show that compared with the baseline model of Low-E windows, the photothermal windows led to greater heating energy savings in winter, ranging from 6.94% to 11.46%.

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