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Preliminary Simulation Investigation of Building Energy Consumption of Solar PV Windows in Hot Summer and Cold Winter climate zone in China

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Abstract. Photovoltaic building integrated windows can provide electric energy, heat energy and lighting for buildings, which will change the way that buildings consume energy. Aiming at the influence of photovoltaic windows on building energy consumption in hot summer and cold winter conditions, a simplified energy consumption simulation model based on light-heat-electricity is studied. The building energy consumption model, daylighting model, and Sandia photovoltaic model are integrated. Based on the tested building thermal performance parameters, the window’s power generation performance and its optical performance parameters, the impact of double-layer crystalline silicon PV windows on building energy consumption is simulated. The test results were used to validated the simulation model. According to simulation results, PV window could take advantages of the positive of blocking solar radiation, and compensate the negative effect. Considered the whole year energy saving, the PV window could save 470.03kWh, and reduce 466.5 kg of CO2.

Keywords: hot summer and cold winter area; STPV; light-heat-electricity; annual energy consumption

1、Introduction
Building integrated photovoltaics, which uses photovoltaic power generation technology to convert solar energy into electrical energy to meet the building energy consumption, is the focus of research
and application in recent years\textsuperscript{1-3}. Photovoltaic windows, as a technical form of BIPV, can provide buildings with clean electric power while meeting the architectural aesthetic design, and reduce the energy consumption of buildings\textsuperscript{4,5}.

In the researches of light-heat-electricity performance of double-layer PV window, most research\textsuperscript{6-11} mainly established a heat transfer model to simulate the thermal and electrical performance of double-layer STPV. Jong-Hwa Song et al. \textsuperscript{6-7} established a numerical simulation model for double-layer STPV windows based on actual meteorological parameters in numerical simulation software TRNSYS. Simulation results showed that installation angle is an important factor affecting thermal and electrical performance, and 30° is the best installation angle. Tady Y.Y. Fung et al. \textsuperscript{11} simulated thermal conduction of double-layer PV windows using one-dimensional transient thermal equilibrium equation. The results showed that when the coverage of PV modules is close to 80\%, the heat gain can be reduced by 70\%. It can be seen that the factor that has the greatest impact on indoor heat is the coverage area of PV modules.

Double-layer PV window as semi-transparent enclosure, it’s light-electricity performance is another focus of research. Shen Xu et al. \textsuperscript{12} simulated the effects of different crystalline silicon component coverage on the photovoltaic performance. The results show that the higher photovoltaic coverage rate is suitable for buildings with large window and wall ratio and large-and-deep buildings, which increases the total power generation but reduces the photoelectric conversion efficiency. K. Kapsis et al. \textsuperscript{13} used Daysim to study the indoor lighting of different film transmittances. The results showed that the optical-electrical performance of the thin film photovoltaic window was optimal when the light transmittance was 30\%.

According to previous research, most of the simulations of photovoltaic double-layer windows are light-electrical studies or thermal-electrical performance studies. There are fewer light-thermal-electricity simulations of STPV windows.

In the hot summer and cold winter climate zone, the presence of solar windows will greatly affect the solar energy through the windows, and affects the load conditions at different times, which is mainly shown by decrease of the cooling load in summer and the increase of heating load in winter. At the same time, photovoltaic windows will also reduce the natural lighting in the room when they block solar radiation, which will increase the lighting load. STPV windows can also have effects on indoor loads due to self-heating, which affects the power generation efficiency. Taking into account the influence of double crystalline silicon photovoltaic windows on indoor load, daylighting, and power generation, the energy savings compared with conventional double-glazed windows are studied.

Therefore, in light of the coupling mechanism of light-heat-electricity, the simulation of double-layer crystalline silicon PV windows and outdoor measurements were conducted in hot summer and cold winter regions. A three-factor model was established, and the simulation model was verified using the test results. The simulation results for the room with double-layered crystalline silicon photovoltaic windows were compared with the simulation results for the room with ordinary double-glazed windows to study the energy saving potential of the STPV. The development of this research
is very important in theoretical research and has practical application value.

2. Methodology
The translucent double-layer crystalline silicon photovoltaic window was used as the research object. Its structure is shown in Fig. 1. The common double hollow window structure is similar to it, except that the photovoltaic glass layer is replaced with a 4mm ordinary glass layer. In order to simulate the overall performance of the double-layer crystalline silicon window in hot summer and cold winter regions, a light-heat-electricity three-factor model was established using the lighting model, heat transfer model and Sandia model in EnergyPlus, as shown in Fig.2. The room model is shown in Fig.3. The temperature of the glass panel, the indoor illumination, and the power generation performance of the photovoltaic window were tested. The test results were used as verification of the simulation model.

![Fig.1 structure of STPV](image1)

![Fig.2 Light-Heat-Electricity model in EnergyPlus](image2)

![Fig.3 Room Model](image3)

![Fig.4 Electricity Generation Power Comparison](image4)
3. Simulation results and test validation of double-layer crystalline silicon PV windows

The model is verified in three aspects, as shown in Fig.4, Fig.5 and Fig.6. It can be seen in Fig.4 that the power of simulated photovoltaic panel electricity generation and test value are within the acceptable range. After calculation, the average value of the power generated by the test data and the average of the simulation results are within 15%. From Fig.5, the measured value of the photovoltaic window outer surface temperature is close to the simulated value. This shows that the window heat transfer conditions in the simulation match the test. From Fig.6, the simulation results are similar to the test results. The calculation results show that the difference between the simulation results and the test results are within 15%. Through the above experimental verification, it can be shown that the simulation model can simulate the real operation of the room. Therefore, the validated simulation model is used for annual energy analysis.

4. Annual Energy Consumption

The validated simulation model above was used to study the overall performance of the two-layer crystalline silicon window and the lab's annual energy consumption. The simulation result of room with STPV window and room with ordinary window is shown in Fig.7 and Fig.8.
From the monthly energy consumption shown in Fig. 7, the energy required for lighting in winter is generally greater than that in summer, but the difference is not significant. Mainly due to the relatively large window-to-wall ratio, natural lighting can meet indoor lighting requirements during the day with the photovoltaic window in 20% transmittance.

Comparing the annual energy consumption of a room with a STPV window and a room with an ordinary double-layer window, it can be seen that the difference between the thermal loads is 30.14 kWh, the difference between the cooling loads is -244.9 kWh, and the difference in lighting power consumption is 88.23 kWh. The total energy consumption of a room with a STPV window and a room with an ordinary double-glazed window is compared. The former is 1125.6 kWh and the latter is 1252.13 kWh. In this case, the room with STPV window has a decrease of 126.53 kWh. The reduction of the cooling load caused by blocking the solar radiation can completely offset the increase of the heat load and the increase of the lighting load brought about by the same time.

5. Conclusion
According to the simulation results, the effects of STPV window in light-heat-electricity aspect in the hot summer and cold winter regions should be taken into account, especially on the cooling load. According to the results of the annual energy consumption simulation, the decrease of cooling load can offset the increase of lighting energy consumption and heating energy consumption. Subtracting PV power generation, the annual comprehensive energy consumption is 779.11 kWh. The annual energy consumption of a room with an ordinary window is 1252.13 kWh. The energy savings from photovoltaic windows is 476.03 kWh. The energy savings of the simulation results were converted into standard coal and carbon dioxide. The use of double-layer STPV windows can reduce 466.5 kg of carbon dioxide and save about 190.4 kg of standard coal, and the energy saving rate was 38%. Therefore, photovoltaic windows contribute a lot energy saving potential in hot summer and cold winter regions.
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