Impact of solar insulation film on the cooling load of an office building in Singapore - A simulation study

Priya Pawar¹, Aaron Boranian² and Werner Lang¹

¹ Technical University of Munich, Institute of Energy Efficient and Sustainable Design and Building, Arcisstrasse 21, 80333 Munich, Germany.
² Big Ladder Software, Denver, United States of America.
E-mail: priya.pawar@tum.de, aaron.boranian@bigladdersoftware.com, w.lang@tum.de

Abstract. This study investigates the properties of a pre-existing high-performance Low-E Double Glazed Unit (DGU) commonly used for fenestration in buildings in Singapore through simulation. Lawrence Berkeley National Laboratory window series software Optics 6 and Window 7 were used to determine the thermal properties of the glazing systems. The window series software based calculations revealed that upon application of the film, Solar Heat Gain Coefficient (SHGC) and the Thermal Transmittance (U-Value) were reduced by 13% and 1%, respectively. Trimble SketchUp Pro was used to develop the geometry of the medium-rise office building, and the OpenStudio interface for EnergyPlus was used to simulate each scenario. Five studies were undertaken to holistically understand the impact of solar insulation film including the reduction in the cooling load and energy usage. The energy study consists of simulating two scenarios so that ACMV component capacities and flow rates are automatically calculated by EnergyPlus. These simulations quantified that after applying the window film, the cooling load reduction on a design day was 8%, and the annual cooling energy savings was approximately 9%. Higher cooling load reduction and cooling energy savings occurred for the shallow floor plan. The numerical calculations of Envelope Thermal Transfer Value (ETTV) suggest a comparative improvement of 14% with the application of a window film.

1. Introduction

In Singapore, high-performance, non-residential buildings are expected to have an Envelope Thermal Transfer Value (ETTV) value of 50 W/m² and lower [1]. Chua et al. [2] developed the ETTV formula shown in Section 2.1. The three variables as seen in Equation 1 that highly influence the ETTV value are the window-to-wall ratio (WWR), the wall and fenestration Thermal Transmittance (U), and the Solar Heat Gain Coefficient (SHGC). Since the WWR of contemporary non-residential buildings in Singapore is high, it is imperative to have lower U value and SHGC values. It indicates that the building envelope material must possess better insulation properties. It is a known fact that insulated walls and windows decelerate the heat transfer through the building envelopes, creating a lag between internal and external temperatures, thereby reducing the cooling and heating demands within the built space [3].

Although most existing buildings in Singapore use Low-Emissivity (Low-E), Double Glazed Units (DGU) there are few proven methods to increase their performance without replacing the existing fenestration units. According to the findings of Yin et al. [4], more improvements in cooling load reduction can be achieved when a solar insulation film is applied to the outer surface of the inner pane of the DGU as seen in Figure 2. Although there is enough literature
talking about the impact of solar insulation films worldwide there exists a gap in the knowledge regarding the impact of such films on Low-E DGU systems on the cooling loads and energy saving brought about in tropical buildings. This paper aims to fill in the knowledge gap using computer simulations to holistically quantify the impact of a solar insulation film on existing Low-E, DGU glazing systems in the tropical climatic conditions of Singapore.

2. Methodology
The work flow of various studies undertaken for this paper are explained in Figure 1. Study 1 & Study 3 follow the same methodology used by Yin et al. [4]. However, the building design and climatic conditions are different.

### 2.1. ETTV Calculation
Equation 1 was used to compute the ETTV improvements achieved by the application of the solar insulation film.

\[
ETTV = 12 \times (1 - WWR) \times U_w + 3.4 \times WWR \times U_f + 211 \times WWR \times CF \times SC
\]

where,
- \(U_w\): the thermal transmittance of the opaque wall (W/m²*K)
- \(U_f\): thermal transmittance of fenestration (W/m²*K)
- \(CF\): correction factor for solar heat gain through fenestration
- \(SC\): shading coefficient of fenestration
- \(WWR\): window-to-wall ratio (fenestration area / gross area of exterior wall)

### 2.2. Modeling Inputs
The physical attributes of the building energy models are described in Table 1. Details regarding the fenestration properties obtained from window series software during Study 1 are described in Table 2. Figure 3.1b and Figure 3.2b show the core-perimeter layout of models 1 & 2 where the core dimensions are 10m x 10m and 40m x 40m, respectively. All the exterior envelope and internal partition material specifications are described in Table 3.
Figure 2. Position of solar insulation film

Table 1. Simulation Input: Building Parameters

| Building Parameters       | Details            |
|---------------------------|--------------------|
| Location                  | Singapore          |
| Orientation               | All directions     |
| External Shading          | None               |
| Space type                | Office             |
| Floor dimension (Model 1) | 30m x 30m          |
| Floor dimension (Model 2) | 60m x 60m          |
| Number of Floors          | 15                 |
| Fenestration Height       | 3.5 m              |
| Plenum Height             | 1.25 m             |
| WWR                       | 90%                |

Table 2. Simulation Input: Low-E DGU Properties

| Details                      | Without Film | With Film |
|------------------------------|--------------|-----------|
| Thickness (in mm)            | 26           | 26        |
| Assembly                     | 8+12A+6      | 8+12A+6   |
| Film Position                | NA           | 6mm glass |
| U Value (W/m² * K)           | 1.672        | 1.650     |
| Solar Heat Gain Coefficient  | 0.582        | 0.499     |
| Visible Transmittance        | 0.7          | 0.7       |
| Tint                         | clear        | clear     |

Table 3. Simulation Input: Building Envelope Material Properties

| Building Element       | Material Specification |
|------------------------|------------------------|
|                        | Thickness (m) | U Value (W/m² * K) | VT   | SHGC |
| Window Film            | 0.026         | 1.71               | 0.714| 0.47 |
| Internal Partition     | N/A           | 7                  | 0.99 | 0.99 |
| Exterior Wall          | 0.057         | 0.468              | 0.00 | N/A  |
| Floor                  | 0.250         | 0.589              | 0.00 | N/A  |
| Roof                   | 0.186         | 1.623              | 0.00 | N/A  |

The building energy models include lighting, receptacle and occupancy loads typical for offices in all conditioned zones (none of these internal loads occur in unconditioned plenum zones). To maintain the desired heating and cooling thermostat set-points in conditioned zones, an Air Conditioning and Mechanical Ventilation (ACMV) system was defined for all models. The ACMV system includes an Air Handling Unit (AHU) containing a chilled water coil, electric heating coil, and variable-volume fan. This AHU provides central supply air to variable-volume air terminals with an electric reheat coil connected to all conditioned zones on each floor. Each model has three AHU systems total (one for each floor modeled). Input values for these parameters are presented in Table 4.
Table 4. Simulation Input: Internal Loads and ACMV System

| Lighting (W/m²) | Receptacles (W/m²) | Occupancy (m²/pax) | Chiller COP | Cooling System (kW/RT) |
|-----------------|--------------------|--------------------|-------------|------------------------|
| 10.5            | 7.6                | 17.7               | 5.6         | 0.74                   |

3. Findings & Results
Singapore experiences consistently hot and humid weather conditions throughout the year. Hence, there are only cooling season considerations for this study.

3.1. Study 1: Fenestration Properties
From Study 1, the window series software was used to determine that there is 1.33% reduction in the U value and 13.9% reduction in the SHGC value of the glass brought about by the application of a solar insulation film.

3.2. Study 2: ETTV Calculation
ETTV values were computed using Equation 1, based on the thermal property values obtained from Study 1. Figure 4 shows the comparative values for all orientations of the facade as well as the whole building for the 30m x 30m floor plan of Model 1. On average, there is 14% ETTV reduction for the whole building when the solar insulation film was applied.

Figure 4. ETTV calculations.

Figure 5. Calculated peak cooling load on design day (21st June).

3.3. Study 3: Impact on Peak Cooling Load and Annual Cooling Energy Use
Windows account for two types of building loads: conduction from the windows and solar radiation transmitted through the windows [1]. This study will focus on the reduction of solar radiation through the glazing system since radiation through windows can account for 30-40% of the total annual sensible cooling load as seen in Figure 8 and Figure 9. Figure 4 shows the simulation results of the monthly cooling energy requirements for the entire building throughout the year for both the glazing systems (with and without the solar insulation film). It is evident from the results that on an average, annually, there can be 6.7% reduction in the cooling energy requirement. Narrowing the investigation from the building to floor levels, Figure 5 illustrates the simulation results of the peak cooling load of three representative floors (L1, L8, and L15).
on the design day. Within the perimeter zones of each floor, the highest reductions in cooling load due to film installation were observed on L1 (8.8%) while the lowest reduction was on L15 (7.1%). Within the core zones of each floor, the results show a higher reduction on the intermediate floor L8 (7.8%) compared to a similar reduction in both top and bottom floors (6.2%).

Moving to the annual simulation, the window film resulted in 6.5% reduction in total building energy use as seen in Figure 6. The internal loads were not altered, so this energy reduction happened solely in the ACMV system which achieved 8.1% reduction in energy use from 2,889 MWh/year to 2,654 MWh/year, which aligns with the peak cooling load reduction. The cooling energy use of the chiller was the primary driver of ACMV energy use (67.3%).

![Figure 6. Total building energy use.](image)

![Figure 7. Floor depth impact on cooling load on design day (21st June).](image)

### 3.4. Study 4: Impact of the Floor Plan Depth

Study 4 focused on the impact of applying the window film to both Model 1 (30m x 30m) and Model 2 (60m x 60m) to determine the impact of the depth of the floor plan on peak cooling loads and annual cooling energy use. Figure 7 shows the comparative data obtained from the peak cooling load for level L8 over the summer design day. In Model 1, it was found that the cooling load per floor area is 1.8 times higher as compared to the deeper floor plan.

### 3.5. Study 5: Quantification of Sensible & Latent Cooling Energy & Impact on ACMV Equipment Capacity

Study 5 was divided into two phases. Phase 1 simulated Model 1 without the window film in a cooling design day in order to calculate ACMV equipment capacities. These capacities were then preserved for annual simulations with and without the window film. This represents a building retrofit where only the window film is applied. Phase 2 then simulated Model 1 with the window film in a cooling design day to calculate updated ACMV equipment capacities, which were then used for an annual simulation with the window film. This represents a building retrofit where both the window film is applied and the original ACMV equipment is replaced. Phase 1 results are shown in Figure 8, where it can be concluded that only applying the window film has a minimal energy savings impact. Phase 2 results are shown in Figure 9, where the average cooling energy use reduction of 9.3% shows that right-sizing the ACMV equipment for the reduced cooling loads allows the ACMV system to operate at better efficiencies. In both phases, sensible cooling energy constituted approximately 40% of the total cooling energy.
4. Conclusion
From this study, it is evident that by adding a solar insulation film the U-Values and the SHGC value can be lowered by 1.33% and 13.69% respectively as suggested by the software based computations. These reductions are specific to the the weather conditions and solar geometry of Singapore. For buildings that may undergo performance evaluation and certification in Singapore, a solar insulation film may help to improve the ETTV values by up to 14% which is one of the most crucial evaluation criteria [5]. From Study 4, it can be inferred that high-performance glazing systems would be more beneficial for buildings with shallower floor plans. The cooling load per m$^2$ increases by a ratio of approximately 2:1 when the floor area decreases by the ratio of 1:4 as is seen from the results. Inferences from Study 5 indicate that there are no significant energy savings possible solely by the application of solar insulation film. Right-sizing of ACMV system cannot be disregarded to ensure energy savings can be harnessed from implementation of passive technology.

W.I. Wan Mohd Nazi et al. conclude that the two aspects of de-carbonization of tropical buildings are reducing the cooling load and improving the energy efficiency of the ACMV equipment [6]. It is important to reiterate the relevance of integrated passive strategies within the building envelope to reduce the cooling demands in the future sustainable building stock. This study quantifies the impact of applying a solar insulation film on Low-E DGU in the tropical climate of Singapore. It also furthered the research by understanding the implications of changing building geometry and importance of right-sizing the ACMV equipment to reap maximum benefits from such simple retrofitting solutions.

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