Roller Shades and Automatic Lighting Control with Solar Radiation Control Strategies

Pimonmart Wankanapon[a, *] **and Richard G. Mistrick**[b]
[a]*Faculty of Architecture and Planning, Thammasat University, Pathumthani 12121, Thailand*
[b]*Department of Architectural Engineering, The Pennsylvania State University, University Park, PA 16802*

Abstract

This paper presents the methodology and energy saving results from a study on the use of roller shades in commercial buildings using different solar radiation control strategies and automatic lighting control. This study applies standard energy code-compliant double-pane windows across a variety of test parameters. A test private-office space was simulated using the EnergyPlus energy simulation program in two different U.S. cities, one heating- and one cooling-dominated climate, with the windows facing each of the four standard compass directions. The roller shades were operated with different solar radiation setpoint control strategies in an attempt to minimize total energy consumption. Impacts on lighting, heating and cooling energy are separately reported. A guideline for effective use of roller shades and automatic lighting control using solar radiation control strategies in architectural applications is also provided.

* Corresponding author.
E-mail: pimonmart@ap.tu.ac.th

Keywords: Roller shades, Lighting control, Solar radiation, Daylighting, Energy simulation

1. Introduction

Roller shades provide an opportunity for building occupants to control sunlight penetration for heat reduction as well as visual comfort. Roller shades directly impact solar heat gain as well as both daylight quality and quantity within a space. Their use can result in higher or lower energy usage for heating, cooling and lighting along with the potential for optimizing energy consumption.

Studies on translucent shades applied to windows have shown this energy savings potential (Farber, Smith, Pennington, & Reed, 1963; Moore & Pennington, 1967; Ozisik & Schutrum, 1959, 1960; Pennington, Smith, Farber, & Reed, 1964; Yellott, 1965). Translucent shade fabrics and window glazings nowadays are very different than in those studies. Within a space, occupants generally adjust their shades infrequently (Rea, 1984; Rubin, Collins, & Tibbott, 1978) resulting in poor daylight admission and less than optimum control of the building's mechanical system loads. Automated control of shades and lighting provides a solution to these infrequent adjustments of shades.

Research on automatic control of shading devices, glazing and lighting control systems has shown significant cooling and lighting energy savings, when compared with no shade or lighting control system (Lee & Selkowitz, 1995, 2006). A simple action such as closing the shades at night can help achieve energy savings compared to a window without shades (Luecke & Slaughter, 1995). These energy savings help to reduce CO_2 emissions by around 3% compared with manually controlled internal shading (Littlefair, Ortiz, & Bhaumik, 2010).

The combination of automatic shading control and automatic lighting control are often not fully addressed or understood. Typically, the energy impact of shades on a building's energy consumption is not considered during the design of a building, or in a green building rating system such as LEED (Haselbach, 2008). One reason is that shade settings are generally under control of the occupants. Hence, most energy simulation modelers do not include shading systems in their analysis. A study on the impact of translucent shades can provide a better understanding of how much energy can be saved, to what degree the size of building mechanical equipment is affected, and how shades can be automatically controlled to optimize energy savings.

2. Methodology & simulation parameters

This study focused on a private office space in a commercial building considering different control parameters for automatic shade control, coupled with automatic lighting control. The analysis addressed the savings on heating, cooling and lighting energy in the perimeter spaces of a case study building across a variety of parameters.

EnergyPlus (DOE, 2007) was used to determined the energy savings for both lighting and HVAC loads. The base-case represents performance with no shading or automatic lighting control as is commonly considered during the building design stage. Both a heating-dominated and cooling-dominated climate was considered. The study addressed performance in two private offices in a typical one story building that are 3m (10 ft) wide at the center of each orientation. The floor to floor height was 3.6 m (12 ft), and all four orientations were simulated (Figure 1).

Figure 1. Case study spaces and the simulation model.

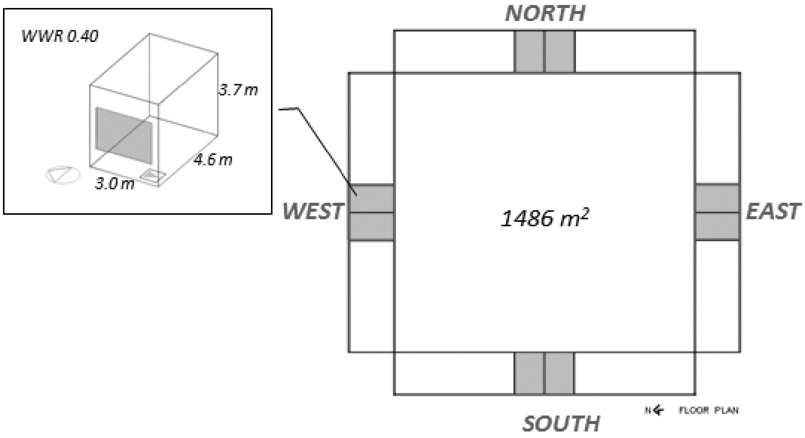


Table 1. Climate thermal and daylighting characteristics for the two test cases.

Region	Heating Degree Days	Cooling Degree Days	Heating Design tempera-ture, °C (°F)	Cooling Design temperature, °C (°F)		Annual Cloudiness (number of days)		
	HDD65	CDD50	99.5%	Dry-Bulb 1%	Wet-Bulb 1%	Clear	Partly Cloudy	Cloudy
Houston	1599	6876	-2.8 (27)	34.4 (94)	25 (77)	90	114	161
Minne-apolis	7981	2680	-26.7 (-16)	31 (88)	21.7 (71)	95	101	169

Figure 2. Roller shades and two shade fabrics, white (denoted: ws) and dark grey shade (denoted: ds).

Table 2. Window and roller shade solar, optical and thermal properties used in this study.

Window / shade	SHGC	Tvis	ρ (rho)	U-factor Btu/h-ft2-F (W/m2-K)
Window A - Insulating double pane Low-E glass (for cold climate)	0.38	0.70	0.11	1.55 (0.29)
Window B – Insulating double pane Low-E glass (for hot climate)	0.24	0.48	0.33	1.52 (0.29)
White shade	*	0.14	0.71	*
Dark grey shade	*	0.04	0.05	*

The locations used in this study are Minneapolis, MN and Houston, TX (see Table 1). The proportion of heating, cooling, and lighting energy use for a test space in Minneapolis is about 70%, 15%, 15% and 10%, 60%, 30% for Houston.

The independent variables considered include location, orientation, shade material properties and control strategy. The windows used were standard insulating double-pane low-E glass that is regularly used in commercial applications. An exterior window-to-wall ratio of 0.4 was considered. All building configurations comply with ASHRAE Standard 90.1-2007 (AHSRAE, 2007).

The shade control strategies at which shades are lowered consider different incident solar radiation setpoints. Savings were calculated based on differences from the base-case with no shading or lighting control (NS). The results do not address visual comfort.

Roller shades can be classified by their optical properties, which represent their ability to deliver light into a room. White and dark grey shades (Figure 2) with different optical properties were used in this study. Different glazings that complied with ASHRAE 90.1 in solar heat gain coefficient (SHGC) and thermal transmission (U-Factor) were used in the two cities (Table 2).

EnergyPlus models translucent shades using window heat balance and daylighting calculations. For the window heat balance calculation, it applies basic heat transfer using glazing data and considers the natural convective airflow between the shading device and the glass. This flow affects the temperature of the shading device and glazing and, for interior shading, is a determinant of the convective heat gain from the shading layer and glazing to the perimeter zone. The airflow model is based on ISO standard 15099 (ISO, 2003). The heat balance calculation for a window and shade does not use the U-factor directly. EnergyPlus calculates nominal U-factors for reporting, but the simulation computes

U-factors for current conditions and time steps using the physical properties of the glass and shade.

The daylighting calculation uses solar and visible transmittance and reflectance data at normal incidence with an assumption that the shades are flat, perfectly diffuse, and cover all parts of the window, excluding the frames. Shades are controlled by the control strategies that are described in a later section. Lighting energy is based on how much electric lighting energy is needed to satisfy an illuminance of 538 lux (50 fc) at a reference work plane point mounted at a height of 0.762 m (2.5ft). Daylighting calculations within EnergyPlus apply the split flux method. The performance of this approach was compared to results from AGI32 and was found to be acceptable.

3. Solar radiation shade control strategies

Different roller shade control strategies were applied in evaluating the energy savings for heating, cooling and lighting across the different parameters. The shades were dropped when solar radiation on the window reached one of three setpoints, as shown in Figure 3.

(1) Low solar setpoint 95 W/m^2 (30 Btu/h-ft^2),
(2) Medium solar setpoint 189 W/m^2 (60 Btu/h-ft^2), and
(3) High solar setpoint 400 W/m^2 (127 Btu/h-ft^2).

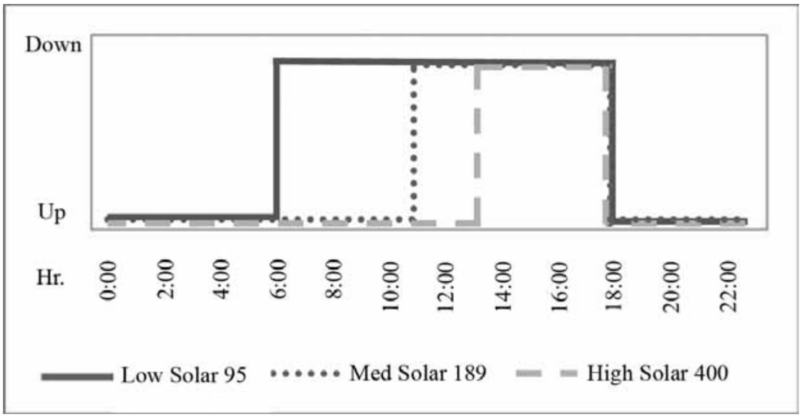


Figure 3. Period of time that shading device is lowered when used with the three solar radiation control strategies (in a west-facing perimeter office on July 15 under clear sky conditions).

Electric lighting control with continuous dimming and shut off was considered in the space to achieve 538 lux (50 FC) at the reference point with a lighting power density of 9.89 W/m^4 (0.9 W/ft^2).

4. Results

1) Heating-dominated region (Minneapolis, MN).

Annual energy consumption due to heating, cooling and lighting and total consumption for perimeter offices in Minneapolis, MN are shown in Figures 4, 6 and Table 3 for a window-to-wall area ratio of 0.4. Both shade types (ws=white, ds= dark grey) were simulated with the three shading control strategies.

For heating energy, which is the largest portion of the energy required in this climate, energy use increased by 8-14% compared to the base-case when shading and automatic lighting control were applied. Due to higher solar loads, the dark grey shade required less annual heating energy than the white shade. The cooling energy savings benefited from a white shade with the medium solar setpoint (189 W/m^2), with savings ranging from 21-27%% across all orientations. This savings is about 5% of the total energy. The highest lighting energy savings resulted from the high solar setpoint control (400 W/m^2) with a white shade yielding a 76-83% savings in lighting energy compared to the base case, which is about 14% of the total energy. The lighting savings provide a net reduction in total building energy over all six cases. A maximum total energy savings of about 11% relative to the base-case occurred with a white shade at the high solar setpoint control 400 W/m^2), which lowered the shades the least amount of time.

2) Cooling-dominated region (Houston, TX).

Annual energy consumption due to heating, cooling and lighting and total energy consumption for the perimeter offices for the Houston, TX site are shown in Figures 5,7 and Table 4.

Heating dominated region – Minneapolis, Minnesota

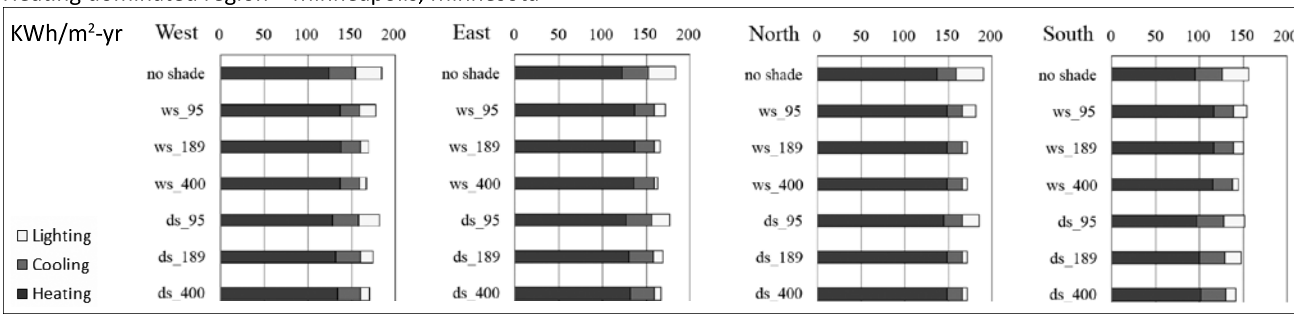


Figure 4. Results for perimeter offices with roller shades on insulated low-E glazing (window A) using different solar control strategies and daylight dimming control.

Table 3. Total energy savings percentage (heating+cooling+lighting savings) compare to the base case of no shade for Minneapolis, MN.

% Savings compare to total energy of base case	no shade	ws_95	ws_189	ws_400	ds_95	ds_189	ds_400
North		4.2%	9.6%	9.7%	2.5%	9.5%	9.7%
South		1.3%	3.9%	7.2%	3.2%	5.5%	9.2%
East		5.9%	9.5%	10.7%	3.3%	7.5%	9.0%
West		3.8%	7.6%	9.4%	1.4%	5.4%	7.3%

Cooling dominated region – Houston, Texas

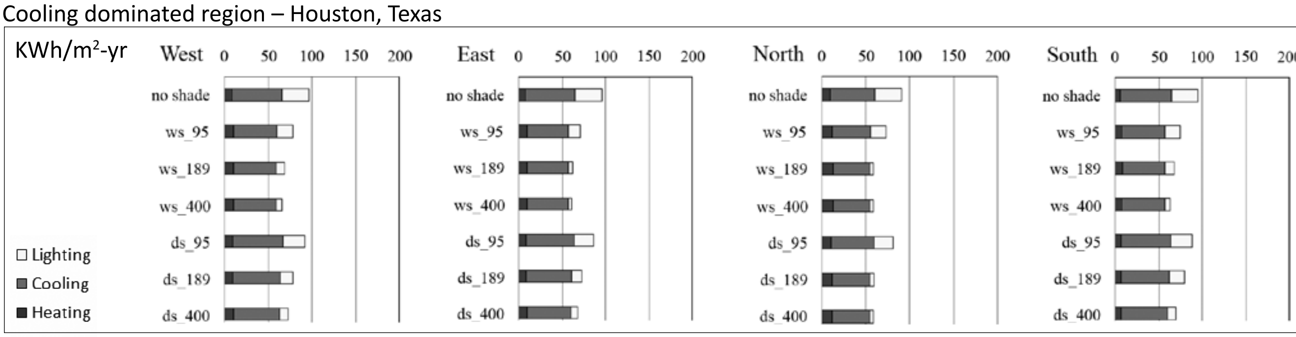


Figure 5. Results for perimeter offices with roller shades on insulated low-E glazing (window B) using different solar control strategies and daylight dimming control.

Table 4. Total energy savings percentage (heating+cooling+lighting savings) compare to the base case of no shade for Houston, TX.

% Savings compare to total energy of base case	no shade	ws_95	ws_189	ws_400	ds_95	ds_189	ds_400
North		19.7%	34.8%	35.2%	10.8%	34.4%	35.1%
South		21.5%	28.2%	33.5%	6.8%	16.2%	26.2%
East		25.6%	34.7%	36.2%	10.2%	24.4%	29.3%
West		18.7%	28.7%	31.5%	4.9%	18.5%	24.1%

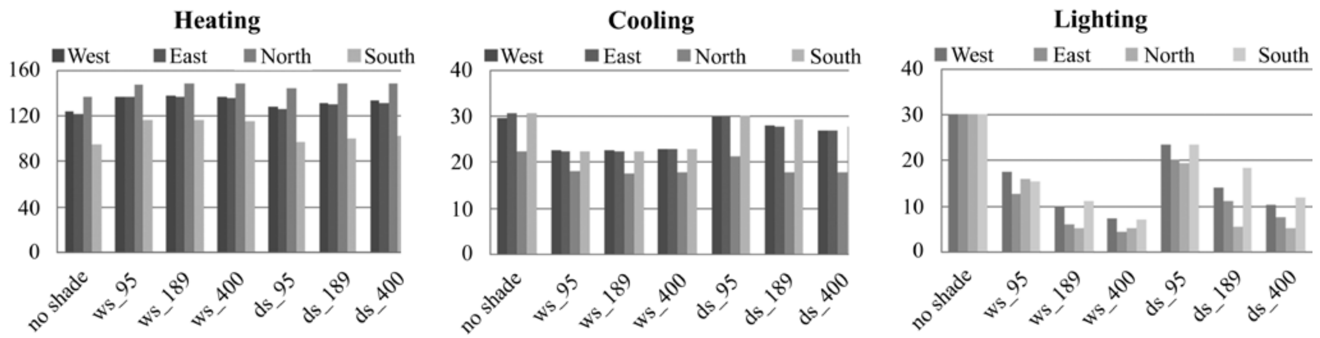


Figure 6. Comparison of heating, cooling and lighting energy in Minnesota, MN.

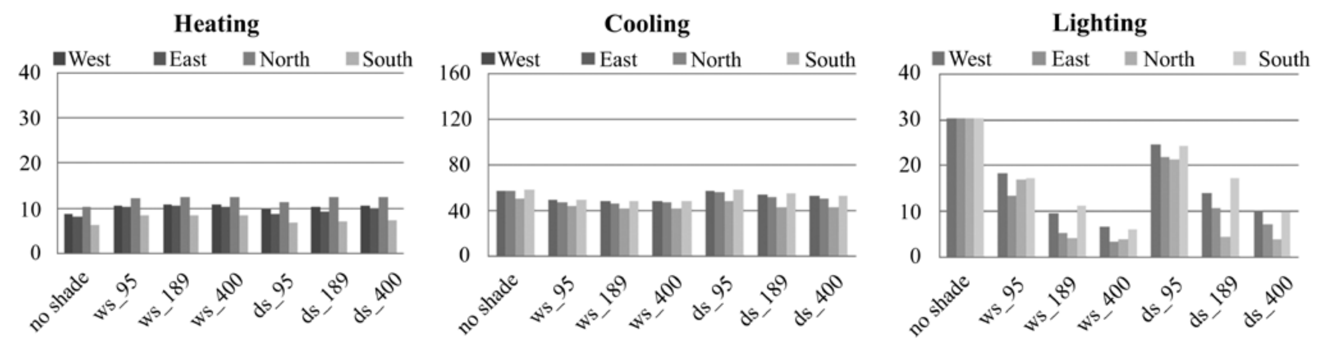


Figure 7. Comparison of heating, cooling and lighting energy in Houston, TX.

Again, the heating savings do not benefit from the use of shades, but for this region, the heating energy portion is very small compared to the cooling energy. Cooling savings of 13-16% is achieved from the white shade with a medium solar setting (189 W/m^2). Lighting yielded 81% in lighting energy savings which is about 26% of the total energy for the white shade with high solar setting (400 W/m^2). The maximum savings is clearly from the lighting control system. A maximum total energy savings yield of 36% from the base-case occurs with a white shade and high solar setpoint control (400 W/m^2).

5. Conclusion

From Figures 6 and 7, the savings are mainly driven by the daylight benefit that offsets the electric lighting load. The incident radiation at which the shade is lowered should be set as high as possible, while still providing occupant comfort, to receive the maximum benefit from these savings.

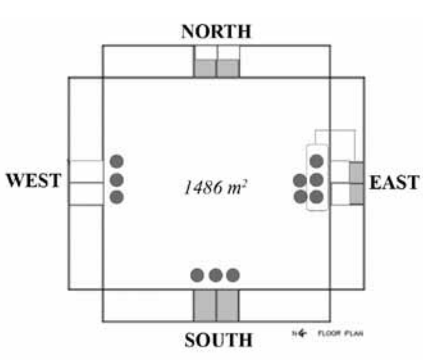
The high solar control setpoint with white shades provided maximum energy savings with the most significant savings in the Houston climate. However, white shades required similar total energy compared to dark shades in all cases. White shades had only about 1% greater total energy savings than the dark shades in cold climate but the different can be seen in hot climate especially on the south, east and west. The control combination provides maximum daylight to a private office space while shading direct sunlight, although closing the shades when sunlight was present increased the heating load over one that did not consider shading devices. The benefits of using the integrated roller shades for solar control in warmer months, coupled with automatic dimming of electric lighting, can offset the heating energy loss and still save up to 11% of the total space energy required in a cold climate and up to 36% in a hot climate when applied in perimeter offices. There is a significant difference in lighting energy savings between different solar control strategies across orientations due to their different incident radiation profiles. Still, dimming of electric lighting and a simple solar radiation control strategy for shade control provide a significant reduction in energy consumption in perimeter private offices, especially in hot climates.

6. Architectural application guidelines

The potential energy benefits of roller shades and automatic lighting control with solar radiation control strategies were shown in this study for the two different climates, a heating-dominated and cooling-dominate region. Architects and designers should consider including the use of these systems as one potential strategy in building energy conservation. Given the wide variety of glazing and shadings, it is difficult to make generalizations about the design for all buildings. However, the application guidelines provided in Figure 8 should result in energy savings in similar climates and with similar glazing conditions.

This study considered windows that are flush with the façade. It is important to note that exterior shading devices can be used to further reduce the cooling load that results from sunlight entering vertical glazing, particularly in warmer climates. Exterior shading will also help to maintain the view out a window for longer periods of times, since shading devices can be applied less often.

Guidelines for heating-dominated region (ex. Minneapolis, MN)



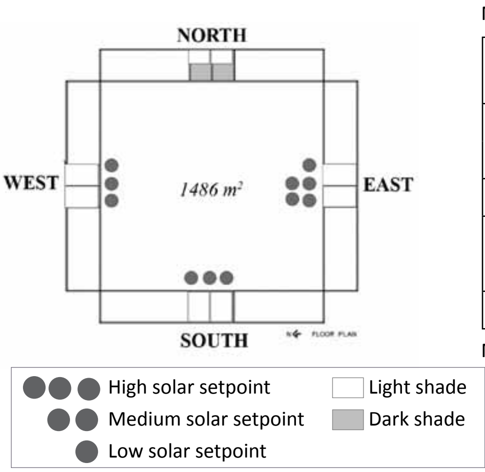
Maximum annual energy savings yielded:

Orientations	Shade properties	Solar Setpoint
North	Light	High or Medium
	Dark	High or Medium
South	Dark	High
East	Light	High or Medium
	Dark*	High
West	Light	High

Maximum Savings potential: about 11%

* only High solar settings yielded the maximum savings on East

Guidelines for cooling-dominated region (ex. Houston, TX)



Maximum annual energy savings yielded:

Orientations	Shade properties	Solar Setpoint
North	Light	High or Medium
	Dark	High or Medium
South	Light	High or Medium
East	Light	High or Medium
	Dark	High
West	Light	High

Maximum Savings potential: 36%

Figure 8. Guidelines on the use of interior fabric roller shades that are triggered by incident solar radiation levels for different façade orientations.

References

AHSRAE. (2007). *ANSI/ASHRAE/IESNA standard 90.1-2007.* Atlanta, GA: ASHRAE.

DOE. (2007). *EnergyPlus engineering reference.* The Reference to EnergyPlus Calculations.

Farber, E. A., Smith, W. A., Pennington, C. W., & Reed, J. C. (1963). Theoretical analysis of solar heat gain through insulating glass with inside shading. *ASHRAE -- Transactions, 69,* 392-405.

Haselbach, L. (2008). *The engineering guide to LEED-new construction: Sustainable construction for engineers*. New York: McGraw-Hill.

ISO. (2003). *ISO 15099:2003 Thermal performance of windows, doors and shading devices - detailed calculations* (Vol. 15099:2003): International Organization for Standardization.

Lee, E. S., & Selkowitz, S. E. (1995). *Design and evaluation of integrated envelope and lighting control strategies for commercial buildings.* Chicago, IL, USA.

Lee, E. S., & Selkowitz, S. E. (2006). The New York Times Headquarters daylighting mockup: Monitored performance of the daylighting control system. *Energy and Buildings, 38*(7), 914-929.

Littlefair, P., Ortiz, J., & Bhaumik, C. D. (2010). A simulation of solar shading control on UK office energy use. *Building Research & Information, 38*(6), 638 - 646.

Luecke, G. R., & Slaughter, J. (1995). Design, development, and testing of an automated window shade controller. *Journal of Solar Energy Engineering, 117*(4), 326-332.

Moore, G. L., & Pennington, C. W. (1967). Measurement and application of solar properties of drapery shading materials. *ASHRAE -- Transactions, 73*(Part 1), 15.

Ozisik, N., & Schutrum, L. F. (1959). Heat flow through glass, with roller shades. *ASHRAE Journal, 1*(4), 49-53.

Ozisik, N., & Schutrum, L. F. (1960). How drapes affect heat gain as tested with regular and heat absorbing glass. *ASHRAE Journal, 2*(6), 53-56.

Pennington, C. W., Smith, W. A., Farber, E. A., & Reed, J. C. (1964). Experimental analysis of solar heat gain through insulating glass with indoor shading. *ASHRAE Journal, 6*(2), 27-39.

Rea, M. S. (1984). Window blind occlusion: A pilot study. *Building and Environment, 19*(2), 133-137.

Rubin, A. I., Collins, B. L., & Tibbott, R. L. (1978). Window blinds as a potential energy saver-a case study. *NBS Building Science Series, 112.*

Yellott, J. I. (1965). Drapery fabrics and their effectiveness in solar heat control. *ASHRAE -- Transactions, 71*(Part 1), 260-272.