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School of Mechanical Engineering

2014

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Effects of Fixed and Motorized Window Louvers on the Daylighting and Thermal Performance of Open-Plan Office Buildings

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ABSTRACT

This study investigates the daylighting and thermal performance of open-plan office buildings with two scenarios of daylight louvers – fixed and motorized ones. Both types are for facade window applications. They redirect transmitted daylight to eliminate glare on occupants and increase daylight levels deeper in the interior space, but have significantly different daylight transmitting characteristics. In addition to daylighting, these louvers also affect solar heat gain. The tilt angle of slats in motorized louvers can be adjusted to control solar heat gain and daylight. In this study, an existing energy-efficient office building with fixed louvers is used. A combined thermal and daylighting model for a typical section of the building is developed using a simplified approach, and validated with measured data. The option of motorized louvers is then added to this model. The daylighting and thermal performance for different designs and seasons are assessed using the model. Results show that motorized louvers can effectively enhance useful solar heat gain and/or daylighting. The effect of building depth is also investigated.

1. INTRODUCTION

Daylighting has significantly higher luminous efficacy than electric lighting (Murdoch 2003). This means less heat will be produced for the same illuminance level. Daylighting also enhances lighting quality and productivity of office occupants (Heschong 2002). Daylight utilization has attracted significant research and development interest.

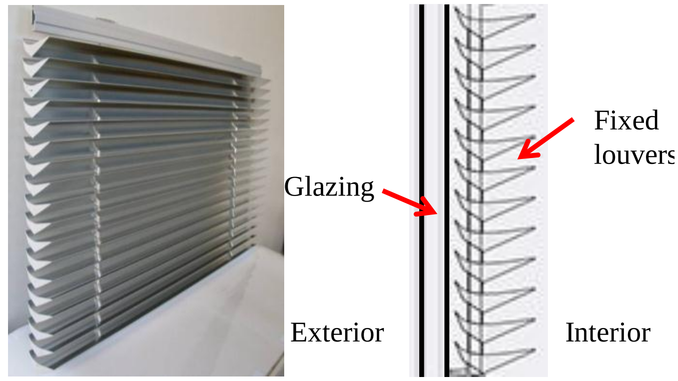
Daylight louvers are commonly used solar control devices. They have highly reflective slats that are meant to enhance daylighting in addition to the usual function of shading. Transmitted solar radiation can be reflected by louvers (typically towards the ceiling) and then diffusely reflected again deeper into interior space, onto the workplane. Important benefits of using daylight louvers include reduction of glare, particularly for occupants adjacent to daylighting windows, and increased daylight level on work surfaces further from the windows (Torcellini et al. 2010). These louvers can be installed on the exterior or interior of a window or inside a sealed glazing unit. Their positions and tilt angles can be fixed or movable (either manually or automatically).

In addition to enhancing daylighting, daylight louvers also affect passive solar heat gain. Motorized (i.e. automatically controlled) louvers can control incoming solar radiation. In a space heating period, useful solar heat gain can be maximized without causing glare. In a cooling period, excessive solar heat gain can be avoided while maximizing daylight level. Many studies have considered total energy consumption (including heating, cooling, and electric lighting), indoor environmental quality (indoor air quality, daylight availability, visual comfort) across different daylight louver types and control strategies. (Chan and Tzempelikos 2013, Nielsen et al. 2011, Oh et al. 2012). When considering occupant behavior, automatically controlled and fixed louvers are better than manually controlled ones in maximizing daylight (Cole and Brown 2009, Inkarojrit 2005).

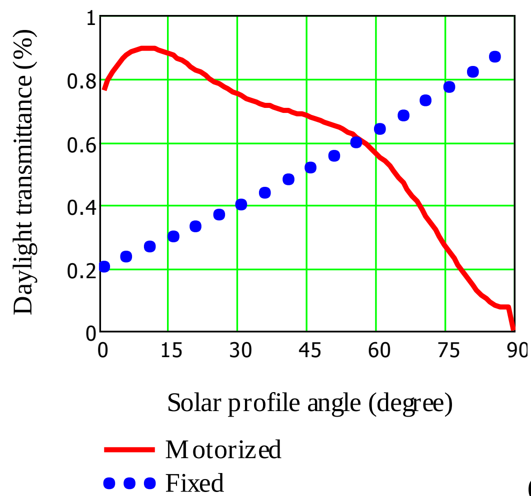
Different daylight louvers may have significantly different solar radiation transmittance characteristics. Peng (2009) conducted an experimental study on motorized louvers between glass panes. The author measured the maximum daylight transmittance (**Figure 1**) when direct penetration of beam component was not permitted (i.e. reflected at least once). **Figure 1** also shows the transmittance of a fixed daylight louver as a function of the solar profile angle.

The fixed daylight louvers have higher transmittance in low latitude areas since it has higher transmittance for larger profile angles. On the other hand, the motorized daylight louvers are better for passive solar heating applications in high latitude areas (e.g. higher than 40-45 degrees).

(a)



(b)



(c)

Figure 1: Two types of daylight louvers. (a) Motorized daylight louvers between glass panes (www.unicelarchitectural.com); (b) Fixed daylight louvers on the interior side of the window (www.lightlouver.com); (c) Daylight transmittance (data source for fixed type is www.lightlouver.com).

Other than the optical properties of daylight louvers, the window-to-wall ratio is also an important design parameter as it determines passive solar gains and useful daylight throughout the year. The optimum window area as a percentage of façade area depends on climate, function, selected shading/daylighting device, control strategy and importance of views to the exterior (Tzempelikos et al. 2007). The design and operation of daylight louvers has to be an integral part of the whole building design (Tzempelikos and Athienitis 2007).

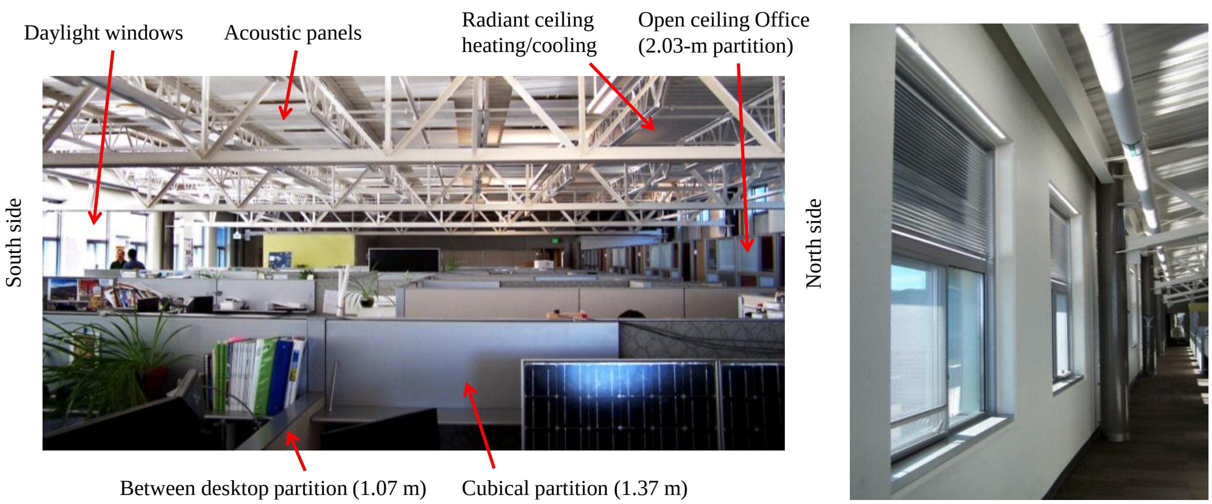
In this study, the effects of the two above mentioned daylight louvers on the overall daylighting and thermal performance are presented, in the context of an energy-efficient office building in heating and cooling periods. Both daylight louvers are for facade window applications. The approach is as follows:

1. With available as-built information, a combined daylighting and thermal custom model is created for a typical section of an existing office building. The model is validated, and calibrated with monitored data;
2. Evaluate the daylighting and thermal performance of the typical section with two types of daylight louvers, after integrating active daylighting and solar heating control;

3. Abstract the key elements in design and operation, and suggest potential design options for better performance.

2. DESCRIPTION OF THE CASE STUDY BUILDING

The Research Support Facility (RSF) building of the National Renewable Energy Laboratory (NREL) is the case for study. The RSF is located in Golden, Colorado, U.S.A. The latitude is 39.7°N, and the altitude is 1829 meters above sea level. The local climate is space heating dominated with large daily temperature fluctuations of about 8°C in the winter and 12°C in the summer. Most days of the year are sunny and the air is dry. The RSF building is a 20 440 m^2 (220 000 ft^2) office building designed to hold 822 occupants. With its roof-mounted photovoltaic system, the RSF was designed to produce about as much renewable energy as it consumes on an annual basis. The monitored energy consumption for the first year of building occupation is 111.7 $kWh/m^2/yr$ (Hootman 2012).



(a) (b)

Figure 2: (a) Interior space of the typical section, and (b) fixed daylight louvers installed on the interior side of south windows (measured illuminance levels are shown later in Figure 4, for 12:00 P.M.)

The window areas as a percentage of the façade areas are as follows: South: 30%, North: 21%. The RSF has no separate interior zone and has an open plan in order to maximize daylight penetration and natural ventilation (Figure 2). The floor plate depth was chosen to be 18.3 m (60 ft) as a compromise between the ratio of exposed exterior wall area to volume and daylight availability.

The south facing window aperture is divided into two sections (Figure 2b). The lower *vision window* is triple-glazed. Its low-e glazing has a RSI-value of 1.04. Insulated framing decreases the assembly RSI-value to 0.52 – half of the glazing value. The upper *daylighting window* is double-glazed. Its low-e glazing has a RSI-value of 0.65. Insulated framing decreases the assembly RSI-value to 0.4. The vision window is used for all of the north facing windows. Their optical characteristics are tabulated in Table 1.

Table 1: Window optical characteristics (SHGC: solar heat gain coefficient; transmittance for diffuse component is taken from fenestration database (ASHRAE 2009). Windows types not used in the RSF are for later analysis).

Glazing type		**SHGC**		**Daylight transmittance**	
		Normal incidence	Diffuse	Normal incidence	Diffuse
Triple-glazed	Low SHGC (RSF vision window)	0.23	0.15	0.43	0.28

	High SHGC	0.62	0.52	0.68	0.57
Double-glazed	Low SHGC (RSF daylighting window)	0.38	0.32	0.7	0.59
	High SHGC	0.70	0.61	0.76	0.66

The daylighting windows are equipped with interior daylight louvers. Incoming transmitted solar radiation is reflected towards the ceiling, and then diffusely reflected again deeper into the space, onto the workplane (as shown in Figure 2). The view window section is equipped with exterior shading, which is designed to block low-altitude beam radiation from entering through the window. The north facade glazing is not shaded and permits indirect natural light to enter.

The space conditioning of the office area is provided through a hydronic ceiling slab radiant conditioning system with 0.125 m thick concrete. A displacement ventilation strategy was adopted, partially in order to fully expose the ceiling to the office space below. A raised floor creates a 0.3 m high space for under floor air distribution. The 100% fresh air is supplied at a neutral temperature of about 19.5°C.

3. MODEL DEVELOPMENT

A combined daylighting and thermal model is created for a typical cross section of an intermediate floor (Figure 2). The width of the typical section in the numerical model is 3.05 m, equal to the building's modular width and windows' spacing. The interior space, along with its associated ceiling and floor slabs, is divided into three thermal zones – south, interior, and north, corresponding to surfaces "3", "4", and "5" as indicated in Figure 3. The surrounding surfaces of these three zones (i.e. surfaces "1" to "15" in Figure 3) are used for longwave radiation, solar radiation, and daylight distribution calculations with a radiosity method. The workplane (0.9 m above raised floor) is used for calculations, instead of the floor.

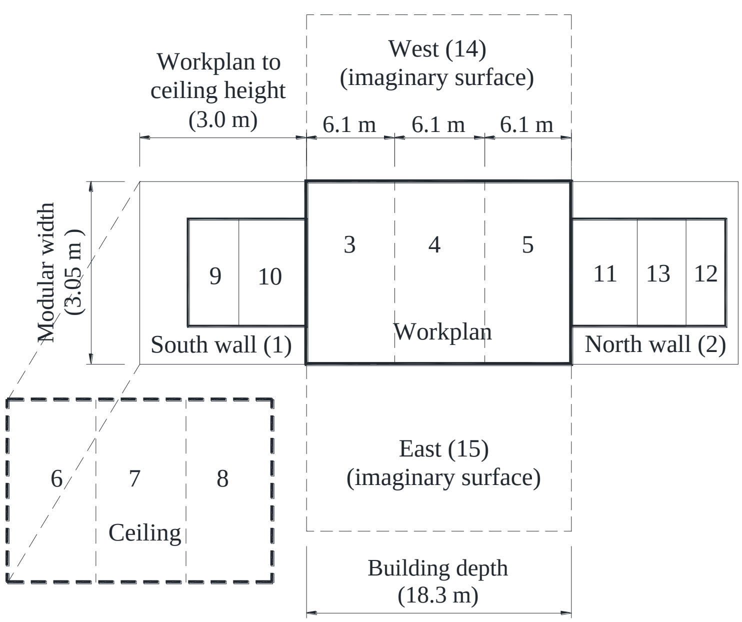


Figure 3: Surface division for radiosity calculation.

Perez's model (Perez et al. 1990) is used to estimate the exterior illuminance on facades based on beam and horizontal diffuse radiation. Transmittance for beam radiation of all windows is a function of incidence angle. For daylighting windows, it is assumed that 90% of the transmitted solar radiation is reflected evenly to the ceiling surface “6” of the south zone. The remaining 10% becomes diffuse radiation. All transmitted solar radiation through the other windows is assumed to be perfectly diffuse since the windows are designed to avoid direct beam radiation. All surfaces are assumed to have diffuse reflection. Hence, the solar radiation leaving from surface “6” after reflection is considered perfectly diffuse. The reflectance of each surface is tabulated in Table 2. These are deduced values from the properties of the surface material, taking into account influencing factors, mainly the ceiling acoustic panels, structural trusses, corrugated surface of the steel decking, and cavity effects of the workstations. Using the radiosity method, the radiant heat and illuminance of each surface are calculated.

Table 2: Surface reflectance (see Figure 3 for surface numbering)

Type of radiation	**Surface number**														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Daylight	0.6	0.6	0.2	0.2	0.2	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.6	1	1
Solar	0.3	0.3	0.2	0.2	0.2	0.4	0.4	0.4	0.6	0.4	0.4	0.4	0.3	1	1
Longwave	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	1	1

Thermal network with explicit finite differencing techniques are applied in the thermal modeling. One-dimension heat conduction is assumed for the exterior walls; two-dimensional conduction for the ceiling/floor concrete slabs. Eq. (1) (Barakat 1987) is used for calculating inter-zonal heat transfer due to air convection.

$$U_{zn}(T_{z1},T_{z2}) = \frac{0.3 \cdot Gr(T_{z1},T_{z2},H_{zn})^{0.5} \cdot Pr_{air} \cdot k_{air}}{H_{zn}} \cdot A_{open} \quad (1)$$

where H_{zn} is the effective height of the zone (3.0 m, from the top of workplane to ceiling). It is also used as the characteristic height in the calculation of the Grashof number, Gr. T_{z1} and T_{z2} are the air temperatures of the two adjacent zones. k_{air} is the air conductivity. Pr_{air} is the Prandtl number of air (0.71). A_{open} is the area of an opening between two thermal zones, 3.0 m x 3.05 m in this case.

Measured data from a winter period are used to verify and calibrate the numerical model. Figure 4 compares the simulated and measured workstation illuminance on the first sunny day. All electric lights were off, except emergency lights. The main potential factors that cause the discrepancies between measurement and simulation values include:

- Partitions (Figure 2a): a desktop is 0.7 m in height. The partitions between desktops are 1.1 m high. The workplane is taken as 0.9 m high in the radiosity enclosure. The partitions between workstations are 1.0 m high. The open-ceiling offices in the north zone have walls 2.0 m high;
- The assumption that 90% of the transmitted solar radiation from window surface “9” is reflected to the ceiling of the south zone (surface “6” in Figure 3);
- Self-shading of adjacent wings.

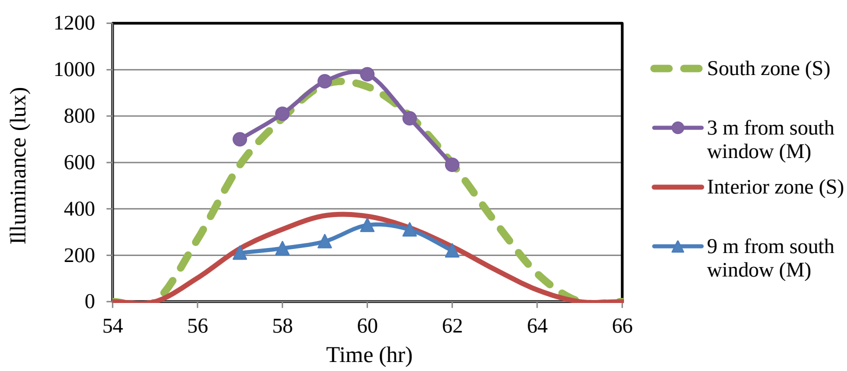


Figure 4: Measured (M) and simulated (S) daylight levels on a winter sunny day, Jan 16th, 2013 (3 m is at the common edge of the south zone and the interior zones, 9 m is at the center of the interior zone)

4. SIMULATION RESULTS

In this section, the daylighting and thermal performance under two daylight louver scenarios in two seasons is simulated using the calibrated model. Weather conditions of typical two-day design periods are used – August 1st and 2nd for the summer period and Feb. 12th and 13th for the winter period (Figure 5). Two-day periods allow better observations of the transient thermal response of buildings with significant thermal mass, which is the case in this study. The daylighting illuminance level of the interior zone needs to exceed 300 lux before dimming the transmittance of the motorized daylight louvers to avoid excessive solar heat gain. The room temperature set point for heating demand is 22°C between 6 A.M. and 6 P.M., 19°C for the rest of the time. It is 24°C and 27°C respectively, for the cooling demand. The existing window-to-wall- ratio (WWR) for the daylight window (surface "9") is about 13%, and 3.5% for window-to-floor ratio. Effects of different window-to-wall ratio on daylighting and thermal performance are investigated. Discussion of results is presented in the following section.

At each time interval (15 mins in this case), the room air temperature will be sensed and the current profile angle of sun will be calculated. If the room air temperature is not 2°C or more higher than the room heating setpoint (22°C), the slats of the motorized shades will be tilted to the maximum transmittance position. Otherwise, the tilt angle will be adjusted (increased from the tilt angle for maximum transmittance) to a value corresponding to a transmittance τ_{new}.

$$\tau_{new} = \frac{E_{spt}}{E_{zn.i}} \cdot \tau_{max} \tag{2}$$

where illuminance set point E_{spt} is set at 300 lux and $E_{zn.i}$ is the average illuminance level of the interior zone.

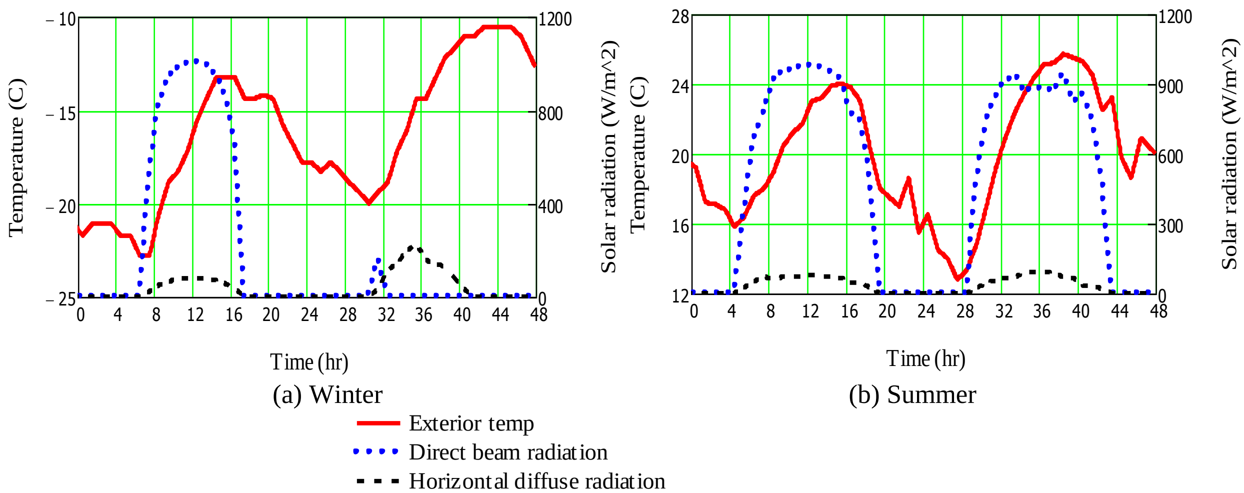


Figure 5: Weather conditions of two design periods

4.1 Winter design period

Windows with a high solar heat gain coefficient (SHGC) (Table 1) are used for the winter design period, double-glazing for the daylighting window and triple-glazing for all other windows. The selected typical weather conditions are shown in Figure 5a – a cold sunny day followed by an overcast day. The reason for this choice is that, in order to save purchasing energy for space heating, buildings should be able to collect and store significant solar heat from a sunny period to compensate for their heat loss for a significantly long period of time. Daylight performance of the south and interior zones is shown in Figure 6 (original WWR) and Figure 7 (40% WWR for the daylighting windows). The north zone has a similar but slightly higher daylighting illuminance level than the interior zone.

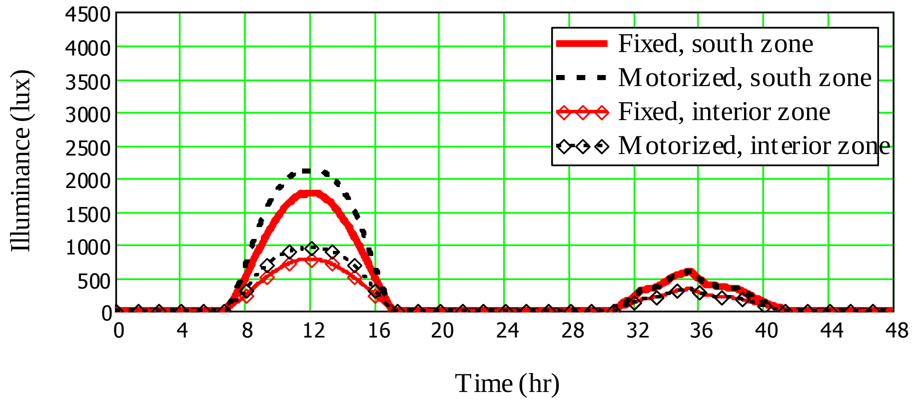


Figure 6: Daylight illuminance levels with original daylighting window area (13% WWR), winter

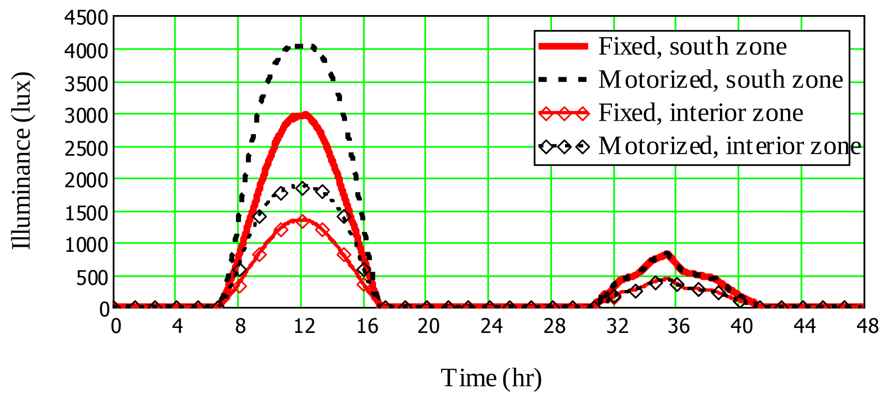


Figure 7: Daylight illuminance levels with 40% daylighting WWR, winter

4.2 Summer design period

Double-glazed windows with low SHGC but high daylight transmittance (Table 1) are used for all windows for the summer design period. The selected typical weather conditions are shown in Figure 5b. Daylight performance of the south and interior zones is shown in Figure 8. The north zone has a slightly higher daylighting illuminance level than the interior zone. For summer conditions, since the day 1 and day 2 daylighting conditions are similar, only the illuminance levels of the first 24 hours are plotted.

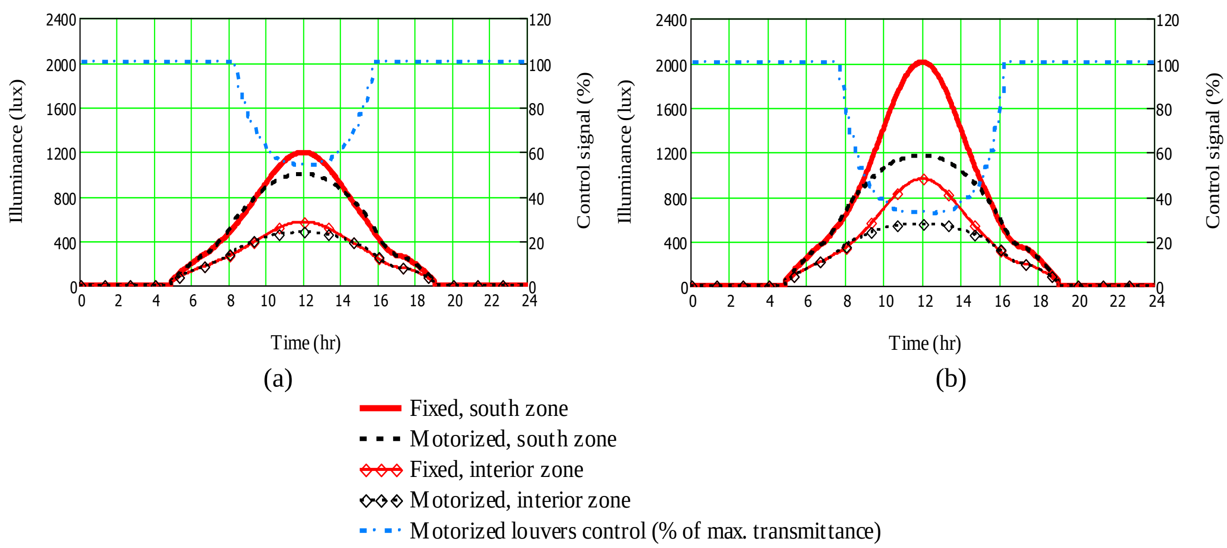


Figure 8: Daylight illuminance levels with (a) original daylighting window area (13% WWR) and (b) 40% daylighting WWR, summer

5. DISCUSSION

The space heating/cooling energy consumption per meter width of facade (excluding the ventilation portion) for different WWR and seasons are tabulated in Table 3. For the winter period, the simulated daylighting and thermal performance of the two types of daylight louvers with 13% WWR are similar, especially for the interior zone. Motorized daylight louvers have better thermal performance, mainly because the solar altitude is low in the winter period. As the WWR increases, using motorized louvers allows more and more daylight penetration into the building as compared to the fixed case, and consequently more solar heat gain and hence less space heating energy consumption (Table 3).

As expected, even with 40% WWR, electric lighting is still needed in the morning and afternoon on an overcast day in order to have an illuminance level higher than 300 lux. The two daylight louvers in this study have the same daylight level on the overcast day. This is because they are assumed to have the same transmittance for diffuse light. Increasing the WWR from 13% to 40% increases the illuminance level of the interior zone by about 20%. Another alternative for increasing daylighting performance is to reduce the depth of the building. By reducing the depth from 18.3 m (60 ft) to 15.2 m (50 ft) while keeping the 40% WWR, the interior daylight level increases about another 10% for the winter overcast day – the daylight illuminance level reaches 200 lux at 8 am.

Table 3: Space heating/cooling energy consumption (kWh per meter façade width; energy consumption for ventilation is not included; negative signs indicate space cooling; no heating for summer and no cooling for winter)

Season	Daylighting WWR	Type of daylight louvers	
		Fixed	Motorized
Winter	13% (original)	10.5	9.7
	25%	10.3	8.7
	40%	10.1	7.1
Summer	13% (original)	-1.9	-1.8
	25%	-2.2	-1.9
	40%	-2.6	-2.0

In the summer period, less daylight is able to penetrate at noontime on a sunny day than that in the winter period, for the respective types of daylight louvers. Furthermore, the fixed daylight louvers do not admit significantly more daylight than the motorized one, contrary to what is suggested by its higher transmittance at larger solar altitudes. This is mainly because the high solar altitude results in less solar radiation on the facades and smaller transmittance of the glazing. For an overcast day, the daylight levels are similar to those of the winter period. Therefore, the results are not plotted. The motorized slats were operated to reduce the transmittance to avoid unnecessary daylight penetration.

Judging from the two analysis periods, the motorized daylight louvers have better overall daylighting and thermal performance. With 13% WWR, switching from fixed to motorized daylight louvers will not result in significant energy savings in space heating/cooling. However, the space heating/cooling energy savings are above 15% for 25% WWR, and above 30% for 40% WWR. The motorized louvers have higher transmittance for smaller solar altitudes (Figure 1c), and simulation results show that the fixed louvers also have higher transmittance in the winter period. Therefore, buildings in higher latitude will have a better summer daylighting performance than those shown above since they have smaller solar altitudes, and buildings in lower latitude will have a better winter performance than those shown above, respectively.

However, evaluating louvers is more than just an issue of energy efficiency. Automatic controls have relatively low acceptance by occupants due to disturbance and by facility managers from a building maintenance point of view (Bordass et al. 1993, Galasiu and Veitch 2006). Additional time and effort is required in the initial installation to properly commission the automatic control systems (Lee et al. 1998). One important characteristic of fixed daylight louvers is that they have no moving parts. This means lower costs in control commissioning and operation and maintenance. For an average size window (about 1 m by 1 m), the material cost of fixed louvers is about $500 per square meter, and it is about $550 for motorized louvers excluding the glazing. These prices are sensitive to louver and window size. Further study of economic aspects is worthwhile.

6. CONCLUSIONS

The effects of fixed and motorized daylight louvers on buildings' daylighting and thermal performance were investigated in this study. A combined daylighting and thermal model for open-plan office buildings with interior fixed and motorized interior daylight louvers was developed using a simplified approach. Using this model, the daylighting and thermal performance for different daylighting design and operation options for different climates are assessed. Results show that motorized daylight louvers can effectively optimize useful solar heat gain and daylight both in heating and cooling seasons. They generally give better daylighting and thermal performance over fixed daylight louvers.

NOMENCLATURE

RSF	Research Support Facility
SHGC	Solar heat gain coefficient
WWR	Window to wall ratio

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ACKNOWLEDGEMENT

This case study was completed with financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC) Smart Net-zero Energy Buildings strategic Research Network (SNEBRN) and in-kind support from the National Renewable Energy Laboratory (NREL) of the U.S.A. NREL's Adam Hirsch and Shanti Pless provided significant input and information that made this study possible, particularly during a visit by Yuxiang Chen to the RSF.