ENERGY-EFFICIENT WINDOW FOR CLASSROOM IN WARM TROPICAL AREA

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ABSTRACT

Shading device, window to wall ratio, window height, and glazing are important factors in determining building energy consumption in the tropics. This study employed the four factors in designing energy-efficient window for classroom to reduce the energy consumption for supplemented lighting and mechanical ventilation. The method was based on Ecotect simulations under some parameters, i.e. heat gains through the building fabrics, illuminance level, and daylight factor. This study concluded that projected clerestory is the most energy-efficient window design. It should be applied on classroom with considering the Window to Wall Ratio, the clerestory height to room height ratio, the window to floor area ratio, and using low visible transmittance of the view window glazing to achieve even horizontal daylight distribution.

INTRODUCTION

Three main issues in window design for warm tropical area are uneven horizontal illuminance distribution, glare and high solar heat gain. Window design is one of the factors, which affect the building energy consumption for lamps and air conditioning (ASHRAE, 2003). An energy-efficient window, then, should be able to distribute horizontal illuminance more evenly, avoid glare and reduce solar heat gain.

A determinant factor of window design in the transmission of solar radiation into indoor space is window to wall ratio (WWR). It can be reduced by installing proper shading devices and/or replacing the window glazing with lower solar admittance. Shading devices function as effective shields for solar radiation, but in some cases they cannot create even horizontal illumination distribution and even block occupant's view to outside.

To maintain the view through the window, while at the same time let daylight penetrate into the deepest side of the room, side window is divided into two parts. The lower window functions as view window with shading device surrounding the window to shade the indoor space from direct sunlight, rainfall, and glare. The upper window which called as clerestory allows daylight to penetrate into the deepest side of the room.

Lightshelf introduces internal shelf upper the view window to bounce daylight more deeply by reflecting the light up to the ceiling and to avoid direct glare to occupants. Many studies (Muniz, 1985; Floyd et al., 1998; Laar, 2001; Binarti, 2005) proved the advantages of lightshelf in creating even daylight distribution and reduce penetration of solar heat gain.

Special glass for the clerestory can replace the internal shelf to avoid glare and creates uniform indoor illuminance (Laar, 2001). The glass should have low heat transmission, but high or medium visible transmittance.

Projected clerestory is another idea to allow daylight coming into the deeper side of the room and functions as solar shading for the lower window.

In this study the three possibilities would be examined by using Ecotect simulations to find optimum model/form, dimension, and position with suitable glazing properties. The aim is to generate a rule of energy-efficient window, which then it can be applied on classrooms with varied dimension in Yogyakarta.

METHODOLOGY

Energy-efficient window will be design on three classroom models, which varied in capacity. It was assumed that classrooms rely on mechanical ventilation to achieve the indoor thermal comfort. Models are located in Yogyakarta, which is renowned as a student city with many educational buildings. Located on 8^0 south latitude and 110^0 east longitude, the city belongs to a tropical region with very bright sky and abundant solar radiation.

Ecotect simulation program were used to examine their thermal and visual performances. Comprehensive facilities provided by Ecotect offer possibility to analyze the solar, thermal and daylight aspects on relative short time without reconstruction of the model. With such facilities and the designer friendly method building designer enables to explore it as a design tool and helps to make right decision to achieve high energy-performance building design. Window designs on classrooms were defined by the following procedure.

Define classroom area for various capacity

Classroom models with three variations in capacity were designed by following principles of classroom design requirements. National Standard of classroom area, i.e. 2 m^2/person (Keputusan Menteri PU no.

441/kpts/1998) was used to calculate the classroom area. Classroom length must be no more than six times of screen height to maintain its visual comfort for learning. The width should be more than the screen width. The screen sill height is between 1.22-1.83 m’. The minimum height of ceiling is 3.05 m’ (Burnett, 2003).

Table 1
Area of classroom models

CAPA-CITY (p)	MIN. CLASS-ROOM AREA (m^2)	SCREEN DIMEN-SION (m’ x m’)	CLASS-ROOM AREA (m’ x m’)
25	50	3.66 x 1.22	6.1 x 8.4
50	100	6.1 x 1.52	8.5 x 12
75	150	6.4 x 2.13	9.5 x 16.5

Define classroom and clerestory height

The classroom height was determined by the minimum standard of air flow rate for classroom and the minimum height of clerestory. A classroom should have 4-12 times of Air Change per Hour and provide 15 cfm per person of air-flow rate (ASHRAE, 2001). In order to illuminate the deepest side of the classroom, clerestory must have 1.5 times in height of the classroom width for window without internal shelf and 2.5 times for window with internal shelf (Stein, 1986).

Table 2
Height of classroom models

CAPA-CITY (p)	CLASS-ROOM AREA (m’ x m’)	CLASS-ROOM HEIGHT (m’)	CLERES-TORY HEIGHT (m’)
25	6.1 x 8.4	3.2	6.1/2.5 ≤ 3.1
50	8.5 x 12	3.5	8.5/2.5 ≤ 3.4
75	9.5 x 16.5	4	9.5/2.5 ≤ 3.9

Designing an energy-efficient window

Window affects the building energy consumption in two ways.

First, it can transfer heat energy into the building. Energy flows through window in a building by three physical effects, i.e. (1) conductive and convective heat transfer between the outer window surface and the adjacent air due to temperature difference, (2) net long-wave radiative heat exchange between outer window surface and the sky, ground, or adjacent objects; and (3) short-wave radiative heat exchange incident on the window (ASHRAE, 1993). Window to wall ratio (WWR) can determine the rate of conductive, convective and radiative heat transfer through the window and the wall. Design of the shading device (width, form, and thermal properties) can reduce radiative heat transfer rate. Whilst, glazing properties affect conductive and radiative heat transfer rate through the window.

The second, daylight incoming through the window can reduce electrical energy demand for artificial lighting during the sun shines. Window area, form (including shading device), position, and the optical properties of window materials (visible transmittance) are important factors in creating proper illuminance level and even horizontal distribution.

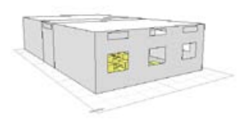
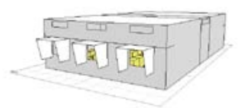
	
Window without shading device (for comparison)	Window with glass block-clerestory
	
Window with lightshelf	Window with projected clerectory

Figure 1 Window models

This study proposed three window models. First model is window with 1 m’-lightshelf. Second model is view window with clerestory made of glass block. This kind of glass is considered as affordable material with low thermal transmitance (U_v = 2.9 $W/m^2.K$) and medium visible transmitance (0.55). The third is view window with projected clerestory. Shading devices on view windows were designed by “shading design wizard” tool in Ecotect. The calculation was based on the sun path diagram.

Table 3
Material properties

MATERIAL	PROPERTY	VALUE
WALL		
Brick plaster	U_v ($W/m^2.K$)	2.62
	reflectance	0.85
CEILING AND ROOF		
Suspended concrete ceiling	U_v ($W/m^2.K$)	2.56
	reflectance	0.95
FLOOR		
Concrete tile suspended	U_v ($W/m^2.K$)	2.9
	reflectance	0.7
PANEL/SHADING DEVICE/SHELF		
GRC	U_v ($W/m^2.K$)	2.2
	reflectance	1
DESK/CHAIR		
Solid core oak timber	U_v ($W/m^2.K$)	2.26
	reflectance	0.85

MATERIAL	PROPERTY	VALUE
GLAZING		
Single glazing	U_v (W/m^2.K)	6
	Vis. transmittance	0.92
Glass block	U_v (W/m^2.K)	2.99
	Vis. transmittance	0.55
Low-e double glazing	U_v (W/m^2.K)	2.9
	Vis. transmittance	0.92
Tinted glass	U_v (W/m^2.K)	6
	Vis. transmittance	0.6

On the first step simulation three glazing models were made of clear glass. On the second step glazing properties were modified to reduce the classroom heat load. All materials of classroom models have properties as written on Table 3.

OTTV Analysis

Overall Thermal Transfer Value (OTTV) method is used to control building energy contributed by the envelope design. The measurement of average heat gain into a building through the building envelope is based on the calculation of conduction through opaque walls and window glass and solar radiation through window glass. The following formulae can be used to calculate the OTTV:

$$\mathbf{OTTV = (WWR \times SC \times SF) + (U_f \times WWR \times \Delta T) + \alpha \{(1-WWR) \times U_w \times T_{deg})\}} \quad (1)$$

Standard Nasional Indonesia established a standard of thermal transfer value of wall surface that should not raise more than 45 W/m^2 (Dept. PU, 2002).

Latest version of Ecotect does not provide OTTV analysis. Heat transfer through the building envelope, however, can be analyzed in a similar way. Solar access analysis is a facility in Ecotect to calculate absorbed/transmitted solar radiation into the building as one of five options. This facility calculates the average amount of solar radiation absorbed/transmitted by the building envelope hourly for each m^2 of planar surface.

For windows (transparent surfaces):

$$\mathbf{W_{transmitted} = W_{incident} \times F_{trans} \times SC \times F_{refract}} \quad (2)$$

For walls, floors, roofs, etc.:

$$\mathbf{W_{transmitted} = W_{incident} \times F_{trans}} \quad (3)$$

To obtain the OTTV of an external room surface, the results must be multiplied with material transmittance and temperature difference between the indoor and the outdoor. The method seems rather complicated, because there is no facility in Ecotect to find the temperature difference (ΔT) and the equivalent temperature differential (T_{deg}). Simulation results of heat gains through the building fabrics of the classroom models can be compared to examine energy-efficiency of the window designs. Heat gains through the building fabrics (other facility in Ecotect) can be more realistic and simple parameter to measure the energy-efficiency of a design than OTTV.

Heat flows through the building fabrics

Ecotect's "Thermal Analysis" provides "Losses and Gains" as a facility to simulate relative contribution of different heat flow paths. Actual hourly fabric gains distribution can show the amount of heat flows through the external surface of each zone. The calculation is based on Admittance method. This method is based on the concept of cyclic variation. It is not as physically accurate as the response factor or finite difference methods. However, it can very helpful in desicion making of building design process in conditions where the temperature swing and energy inputs are changing steadily. This method is suitable to the models condition, where mechanical cooling is applied to achieve indoor thermal comfort. Simulation of fabric gains can describe relative accurate results, because the simulation calculates incident solar radiation passing through an aperture as part of space load and fabric load based on internal admittance values.

Validation

Heat flows through the building fabrics consist of Q_c and Q_s. Q_c denotes heat flow rate through building fabrics/skins determined by the skin surface area, transmittance value and temperature difference. It can be described by the equation:

$$\mathbf{Q_c = A_w \times U_w \times \Delta T} \quad (4)$$

Q_s denotes the solar heat flow, which be determined by the window area, the radiation heat flow density, and the solar gain factor of window glass. The equation can be established as:

$$\mathbf{Q_s = A_g \times I \times \theta} \quad (5)$$

Daylight Factor

Ecotect analyzes daylight factor based on Building Research Establishment (BRE) Split-Flux method. Standard overcast sky illuminance distribution is used to calculate the daylight factor in order to represent a worst-case scenario to be designed for. Therefore, daylight factor value will not change with different dates or times and not be affected by changing model orientation. Ecotect also provides link to Radiance for physically accurate and comprehensive lighting analysis.

RESULTS AND DISCUSSIONS

Projected clerestory for OTTV < 45 W/m^2

At the first experiment total glass area had 34-39% of the exposed wall area and the height of clerestories are between 25% and 34% of the classroom height. Only window with projected clerestory can reach the standard of thermal transfer. Windows with lightshelf transfer solar radiation relative low, but still above the standard.

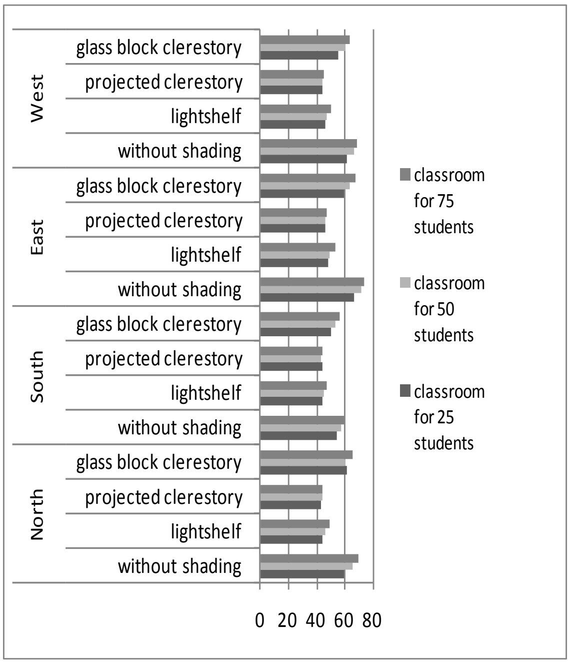


Figure 2 Hourly Thermal Transfer Value (W/m^2) of Window with 34-39% WWR

Results of daylight factor simulations show very high value. Windows with projected clerestory create daylight factor above 5%. Windows with lightshelf have higher value (more than 6.5%). These results are too high for classroom which the standard of DF is 2-3.5% (Dept. PU, 2001). Low daylight factor is considered as more comfortable, because the calculation of daylight factor is under the worst-case (overcast sky condition).

20% WWR for 3% of average DF value

In order to reduce thermal transfer value and daylight factor, window areas are decrease into 20% of exposed wall areas. The height of view window remain constant in 1 m' with 1'm sill height. Clerestory heights offset into 11% of classroom heights. Table 4 shows dimension of modified windows.

Table 4
Dimension of modified windows

CLASSROOM CAPACITY (persons)	VIEW WINDOW (m' x m')	CLERESTORY HEIGHT (m')
25	3 @ 1.3x1.0	0.35
50	3 @ 2.0x1.0	0.40
75	3 @ 3.0x1.0	0.45

Important ratios that should be considered in energy-efficient window design are presented in Table 5.

Table 5
Window ratios

RATIOS	CLASSROOM MODELS		
	FOR 25 Students	**FOR 50 Students**	**FOR 75 Students**
CLERESTORY HEIGHT/ROOM HEIGHT	0.11	0.11	0.13
CLERESTORY HEIGHT/ ROOM WIDTH	0.06	0.05	0.05
WWR	0.21	0.20	0.20
WINDOW AREA/ FLOOR AREA	0.11	0.08	0.08
ROOM HEIGHT/ WINDOW HEIGHT	1.97	2.5	2.44

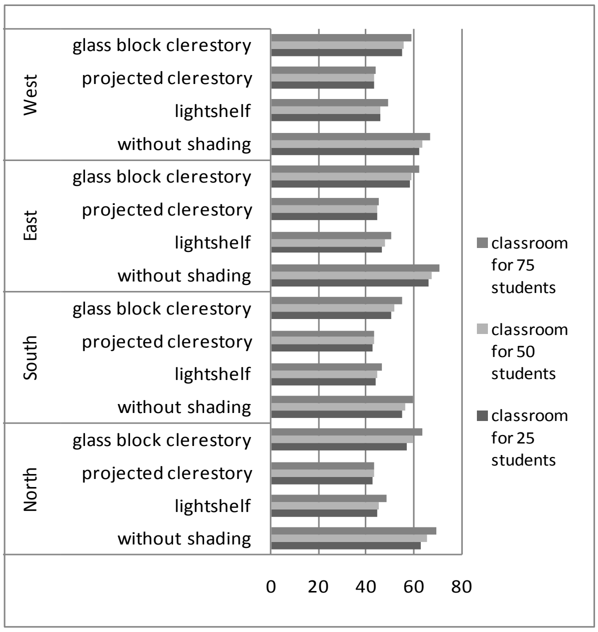


Figure 3 Hourly Thermal Transfer Value (W/m^2) of Window with 20% WWR

New dimensions reduce the rate of heat transfer insignificantly (< 10%), but can create acceptable daylight factors. Only windows with projected clerestory transfer solar heat below the standard. Some windows with lightshelf facing to North or South can raise the standard of thermal transfer value. Others are still above 45 W/m^2.

Uneven daylight distribution potentially creates glare in area with high level illuminance or needs more electrical lighting to supplement daylighting in area with low illuminance level. Daylight distribution can be considered as uniform if the distribution value is not less than 80% (Pritchard, 1986). Some windows with projected clerestory facing to north and south have more uniform daylight distribution (76%). Daylight factor distributions of windows facing to west and east are still difficult to handle.

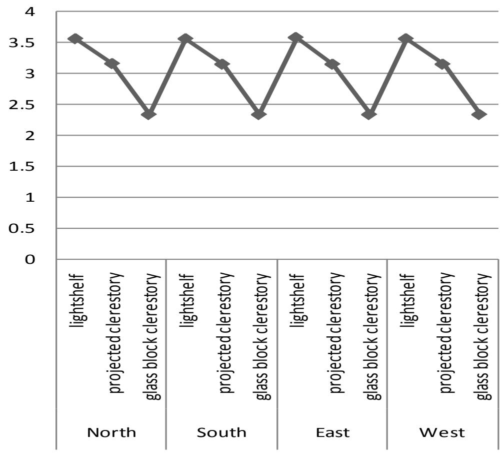


Figure 4 Average Daylight Factor (%) of windows for 25 students classroom

Figure 5 shows that high daylight factors (> 7%) are located on the area near the windows, because large amount sunlight passed through view windows directly. Two alternatives to improve daylight distribution without reducing window area in order to maintain comfortable view angles:

- Enlarge the shading device. This alternative seems to be unrealistic, as the recent shading devices are large enough.
- Change glass of view window with low visible transmittance glass, such as: tinted glass.

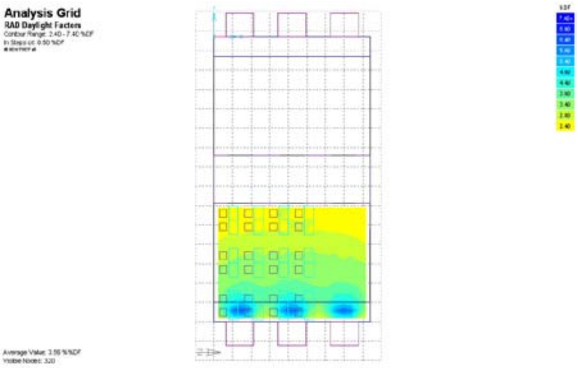


Figure 5 Daylight Factor in a classroom for 25 students with lightshelf facing to East

Figure 6 Three dimensional picture of a classroom for 25 students with projected clerestory is resulted by Radiance (link to Ecotect) simulation.

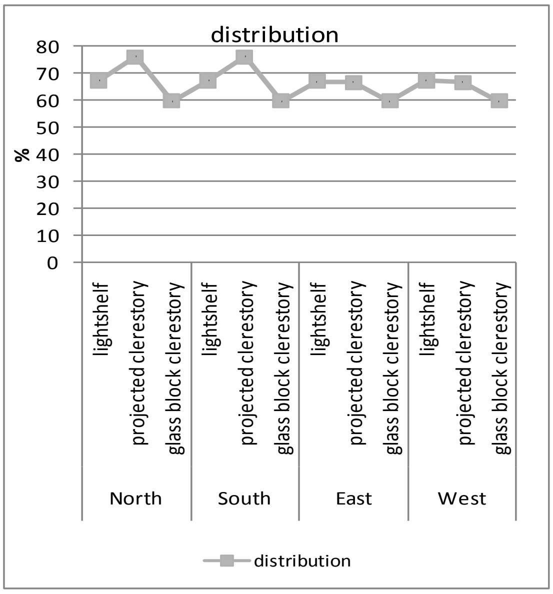


Figure 7 Distribution of daylight factor of window for 25 students classroom

Heat flows through the building fabrics

Simulation results of hourly heat flowing through the building fabrics (Figure 8) show similar conclusion. Window with projected clerestory is the most energy-efficient. Windows with glass block-clerestory perform better in heat gains comparing to windows with lightshelf. This is opposite to results produced by simulations of thermal transfer value through exposed wall surfaces. Higher values are potentially caused by higher transmission of visible wave radiation , which then converts from light energy into heat in classrooms with lightshelf. Figure 4 shows that average daylight factors of window with lightshelf are 0.4% higher than those of window with glass block-clerestory.

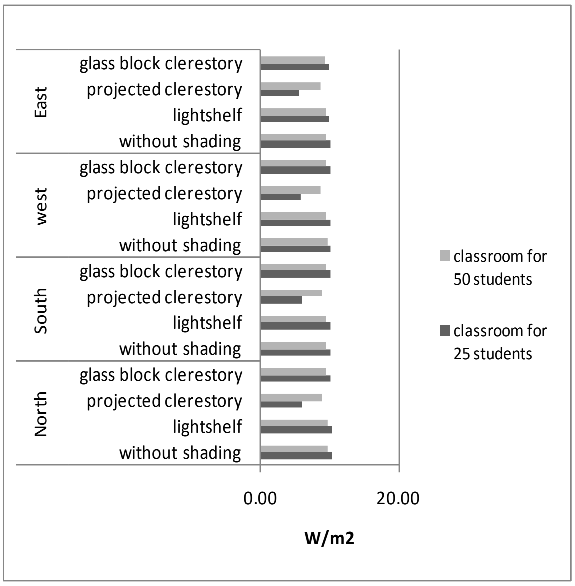


Figure 8 Hourly heat flows through the building fabrics

Interesting results were shown by comparing results of classroom for 50 students to those of classroom for 25 students. Three window models have the same pattern. Heat energy flowing through classroom models for 25 students has higher rate than those for 50 students if window models applied are glass block clerestory, lightshelf and without shading. These make sense, because classrooms for 25 students have bigger WWR, window to floor area ratio, window to wall height ratio, clerestory height to room width ratio, and smaller room width to window height ratio.

Classrooms with projected clerestory show opposite results. Higher value of classroom for 50 students than its classroom for 25 students may be related to the ratio of the room width to the room length. The ratio of classroom for 25 students is 0.73 (0.02 higher than the ratio of classroom for 50 students). Relative narrow space allows higher penetration of solar radiation. Ratio of room width to room height seems to work in a room with projected clerestory.

A classroom having 10 W/m^2 heat loads through the building fabrics with adequate daylight level can be considered as energy-efficient if it is compared with 15 W/m^2 for energy standard of lighting for classroom. (Dept. PU, 2002)

Validation

Manual calculations of heat gains through the building fabrics of classroom models without shading have been done to validate the simulation results. They were based on formulae 4 and 5. Table 6 presents the comparison between the results of manual calculations and the simulations.

Table 6
Comparison between manual calculations and simulations

CLASS-ROOM MODELS	HEAT GAINS THROUGH THE BUILDING FABRICS (W/m^2)		DISCRE-PANCIES	
	Manual calcula-tions	Simu-lations	W/m^2	%
For 25 students without shading and oriented to North	17.2	20.5	-3.3	20
For 25 students without shading and oriented to South	28.5	23.5	4.9	20
For 25 students without shading and oriented to East	17.3	19.5	-2.3	10
For 25 students without shading and oriented to West	28.2	26.2	2.1	10

Simulation results of classroom oriented to North and East tend to exagerate the matimatical/manual calculation results. Whilst, simulation results of classroom models oriented to South and West are smaller than the manual calculation results. Average discrepancy is 0.35 W/m^2 (10-20%).

Window glazing

At the third experiment, low-e double glass replaced clear glass on view windows. However, low-e double glass on view windows cannot improve their thermal performances. Amount of solar radiation transmitted through building envelope remains the same as those of view windows with clear glass. Low emittance glass cannot work effectively if there is only small temperature difference between the indoor and the outdoor.

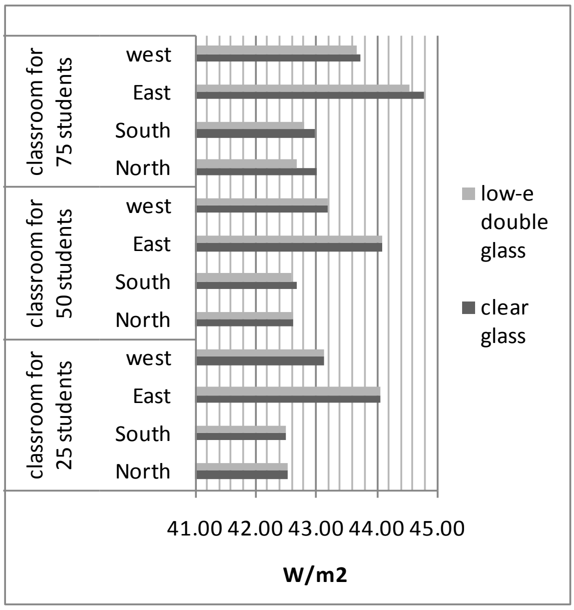


Figure 9 Comparison of Hourly Thermal Transfer Value (W/m^2) between projected clerestory with single glazing and with double glazing low-e

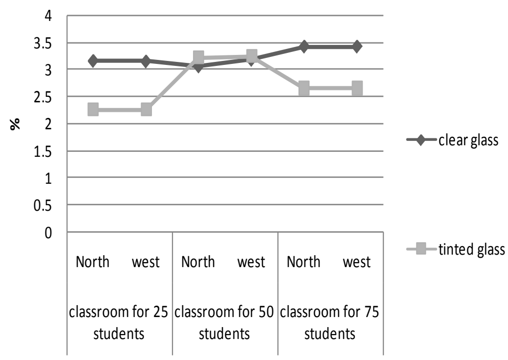


Figure 10 Comparison of average daylight factor between projected clerestory window with clear glass and with tinted glass

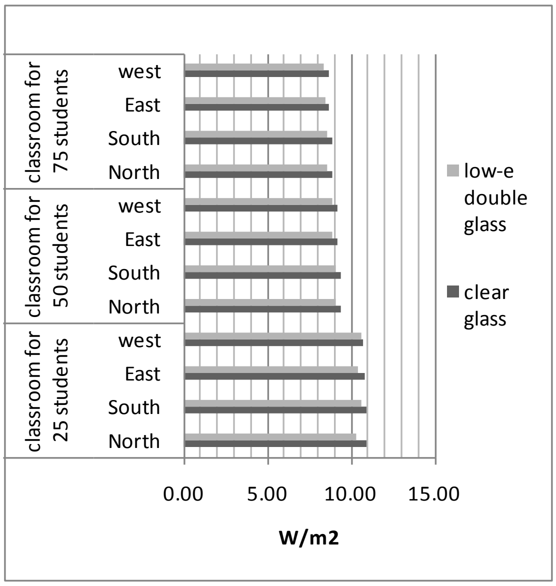


Figure 11 Comparison of Hourly heat gains through the building fabrics between projected clerestory with single glazing and with low-e double glazing

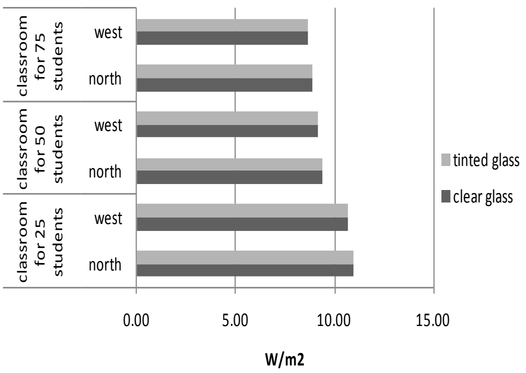


Figure 12 Comparison of hourly heat gains through the building fabrics between projected clerestory window with clear glass and with tinted glass

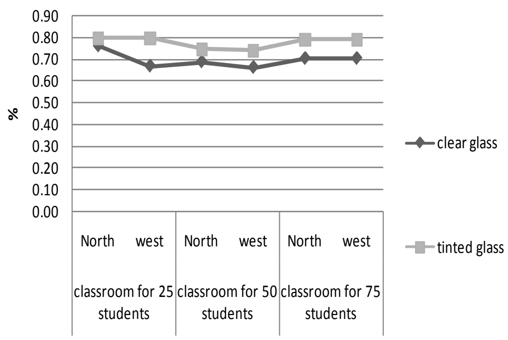


Figure 13 Comparison of daylight distribution between projected clerestory window with clear glass and with tinted glass

Replacing clear glass with tinted glass on view window can improve the average and the distribution of daylight factor. All windows with projected clerestory and tinted glass on their view windows produce uniform daylight distribution (> 75%) and suitable daylight factors for learning activity (reading and writing). However, different interior illumination levels created by placing clear and tinted glass on the same wall plane cause a feeling of gloom.

CONCLUSION

Projected clerestory can protect the indoor area from direct solar radiation. Its horizontal surface reflects sunlight into the deep side of the room depending on the ratio of clerestory height to room width. For classroom's window without obstruction from adjacent wall or building, the clerestory height should be around 0.4 of the room width to achieve low energy classroom. Horizontal surface of the projected clerestory also functions as horizontal shading for view window below the clerestory. It is suggested that clerestory height is not more than 11% of the room height. A window with 20% WWR and around 11% window to floor area can be considered as an optimal window area for classroom with reflectances 0.95 for the ceiling, 0.85 for the internal wall, 0.7 for the floor, 0.85 for the desks and 1.0 for the shading device; both for energy-efficiency and to maintain proper view to outside. Lower average classroom reflectance needs higher WWR, clerestory height, and window to floor area.

Proper shading device is more effective in achieving high energy performance of the window than special glass especially for naturally ventilated rooms. Using glass with low visible tranmittance on the view window can improve the horizontal illuminance distribution.

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NOMENCLATURE

A_w : wall surface area

A_f : fenestration area

α : solar absorptance

F_{refrac}: refractive index (no units)

F_{trans} : material transparency (no units)

I : radiation heat flow density (W/m^2)

SF : solar factor (W/m^2)

SC : shading coefficient (no units)

OTTV : Overall Thermal Transfer Value (W/m^2)

U_f : transmittance of fenestration ($W/m^2.K$)

U_W : transmittance of wall ($W/m^2.K$)

ΔT : temperature difference between indoor and outdoor

T_{deg} : equivalent temperature differential (K)

θ : solar gain factor of window glass

$W_{transmitted}$: transmitted solar radiation (W)

$W_{incident}$: incident solar radiation (W)