Energy-Efficient Window Concept 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 main parameter is classroom's cooling load or heat transfer through the building skins (< 10 watt/m^2) incorporated with secondary parameters, i.e. indoor illuminance level (200-400 lux) or daylight factor (2-3%), and horizontal illuminance distribution. Relationship among window to wall ratio, window to floor ratio, height of clerestory, clerestory to wall height ratio, and classroom's orientation, width and length are examined using Ecotect simulation program to establish a concept for energy-efficient classroom's window. Window with projected clerestory is the most energy efficient. It transfers minimum solar radiation and creates the most even horizontal illuminance distribution with sufficient level. Small difference in energy performance but lower cost can be achieved by window with glass-block clerestory or with lightshelf. Three kinds of clerestory should be applied on classroom with considering the window to wall ratio (20%), the clerestory head height to room height ratio (11%), the head height clerestory to room width ratio (around 5%).

Keywords: *clerestory, cooling load, daylight factor, illuminance distribution, window.*

1. 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 affects the building energy consumption for lamps and air conditioning [1]. 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). Proper shading devices and/or replacing the window glazing property with the lower solar admittance can modify WWR in order to achieve low thermal transmission and sufficient indoor illuminance. 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 proved the advantages of lightshelf in creating even daylight distribution and reduce penetration of solar heat gain [10][8][3].

Special glass for the clerestory can replace the internal shelf to avoid glare and creates uniform indoor illuminance [9]. The glass should have low thermal 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 concept of energy-efficient window, that can be applied on classrooms with varied dimension in Yogyakarta.

This paper reports results of two experiments. The first experiment examined 48 models of classroom with 3 variations in window design. These models have similar (not the same) window to wall ratio (WWR) and window to floor ratio (WFR). Fifty six models with the same WWR and WFR were constructed in the second experiment to improve the first experiment results. As the results of models with projected clerestory in the second experiment seem unreasonable, disscussion will combine results of the two experiments.

2. METHOD

Energy-efficient window will be designed on classroom models with variation 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 in relative short time without reconstruction of the model. The same procedure was applied in the first and the second experiments.

2.1 Define Classrooms with Variation in Capacity

Classroom models with three variations in capacity were designed by following principles of classroom design requirements. Calculation of the classroom area was based on National Standard of classroom area, i.e. 2 m^2/person [7]. 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 ceiling height is 3.05 m' [4].

Table 1: *Area of classroom models*

CAPACITY (p)	MIN. CLASSROOM AREA (m^2)	CLASSROOM AREA (m' x m')
The first experiment		
25	50	6.1 x 8.4
50	100	8.5 x 12
75	150	9.5 x 16.5
The second experiment		
25	60.2	7.0 x 8.6
40	82.0	9.3 x 9.0
60	123.0	11.7 x 10.5
75	154.0	11.0 x 14.0

2.2 Define Classrooms and the Height of Clerestory

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 [2]. In order to illuminate the deepest side of the classroom, clerestory head height 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 [12]. Considering net (occupancy) area of classroom, in the the second experiment clerestory head height became 1/3 times of the classroom width.

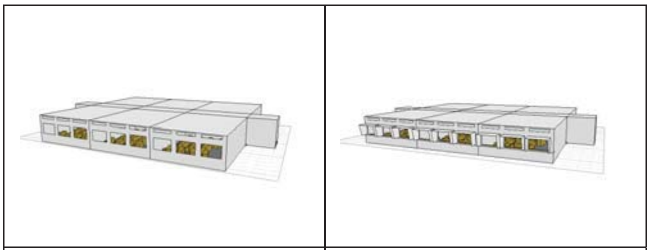
Table 2: *Height of classroom models*

CAPACITY (p)	CLASSROOM AREA (m' x m')	CLASSROOM HEIGHT (m')	CLERESTORY HEAD HEIGHT (m')
The first experiment			
25	6.1 x 8.4	3.2	$6.1/2.5 \leq 3.1$
50	8.5 x 12	3.5	$8.5/2.5 \leq 3.4$
75	9.5 x 16.5	4	$9.5/2.5 \leq 3.9$
The second experiment			
25	7.0 x 8.6	3.0	$8.6/3 \leq 2.9$
40	9.3 x 9.0	3.2	$9.0/3 \leq 3.0$
60	11.7 x 10.5	3.6	$10.5/3 \leq 3.5$
75	11.0 x 14.0	3.8	$14.0/3 \leq 3.7$

2.3 Designing Energy-efficient Windows

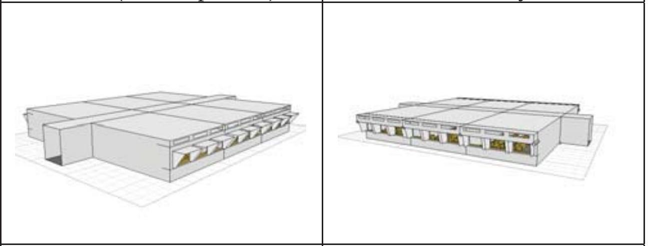
Window affects the building energy consumption in two ways.

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 [1]. 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.



Window without shading device (for comparison)

Window with glass block-clerestory



Window with lightshelf

Window with projected clerestory

Figure 1: Window models

The second, daylight incoming through the window can reduce electrical energy demand for artificial lighting during sunshine. 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.

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. Material properties of each model remain constant except glass-block clerestory.

2.4 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 be 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.

2.5 Illuminance Level and Daylight Factor

Ecotect analyzes illuminance level and daylight factor based on Building Research Establishment (BRE) Split-Flux method. Standard overcast sky illuminance distribution is used to calculate the illuminance level and daylight factor in order to represent a worst-case scenario to be designed for. Therefore, values 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.

3. RESULTS AND DISCUSSIONS

3.1 Projected Clerestory for Low Heat Transfer

At the first time total glass area had 34-39% of the exposed wall area and 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 45 W/m^2.

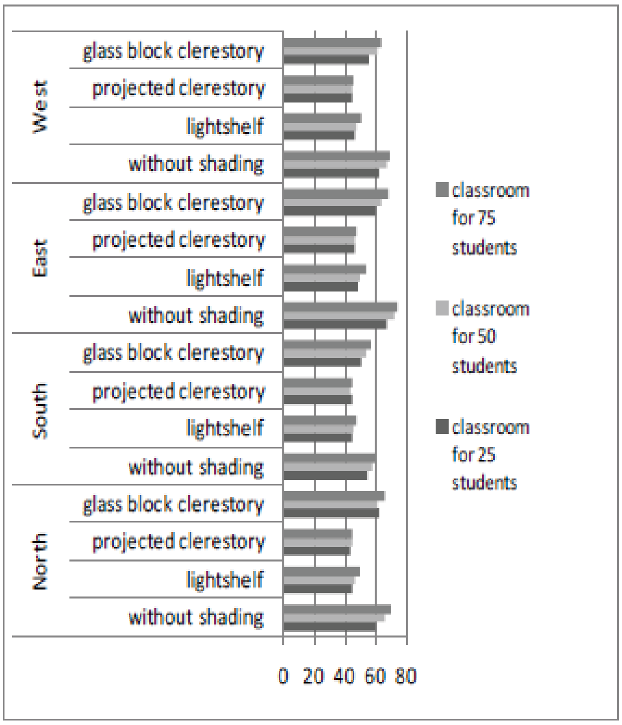


Figure 2: Hourly thermal transfer value (W/m^2) of window with 34-39% WWR (the first experiment)

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% [5]. Low daylight factor is considered as more comfortable, because the calculation of daylight factor is under the worst-case (overcast sky condition).

Table 3: Dimension of Windows

CLASSROOM CAPACITY (persons)	VIEW WINDOW (m' x m')	CLERESTORY HEIGHT (m')
The first experiment		
25	3 @ 1.3x1.0	0.35
50	3 @ 2.0x1.0	0.40
75	3 @ 3.0x1.0	0.45
The second experiment		
25	3 @ 1.75 x1.10	0.250
40	4 @ 1.75 x1.10	0.305
60	5 @ 1.75 x1.10	0.410
75	6 @ 1.75 x1.10	0.465

In order to reduce thermal transfer value and daylight factor, window areas are decreased into 20% of exposed wall areas. This value was also applied in the the second experiment. All models in the the second experiment have 20% WWR and 20% WFR. The height of view window remain constant in 1.10 m' with 1'm sill height.

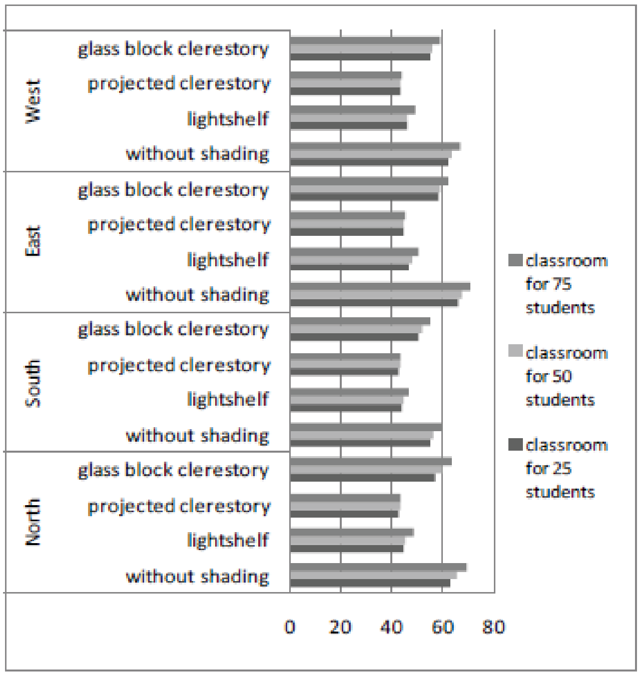


Figure 3: Hourly thermal transfer value (W/m^2) of window with 20% WWR (the first experiment)

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.

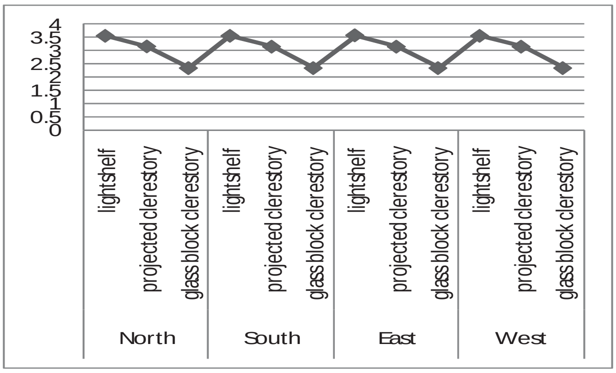


Figure 4: Average daylight factor (%) of windows for 25-students classroom (the first experiment)

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% [11]. 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.

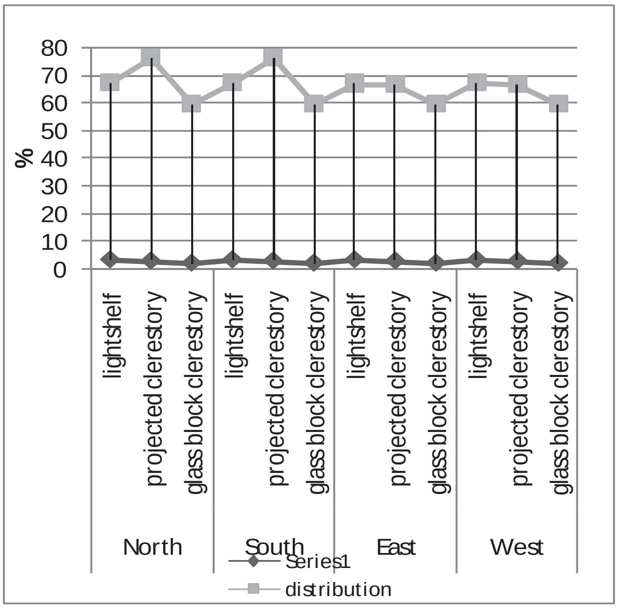


Figure 5: Distribution of daylight factor of window for 25-students classroom (the first experiment)

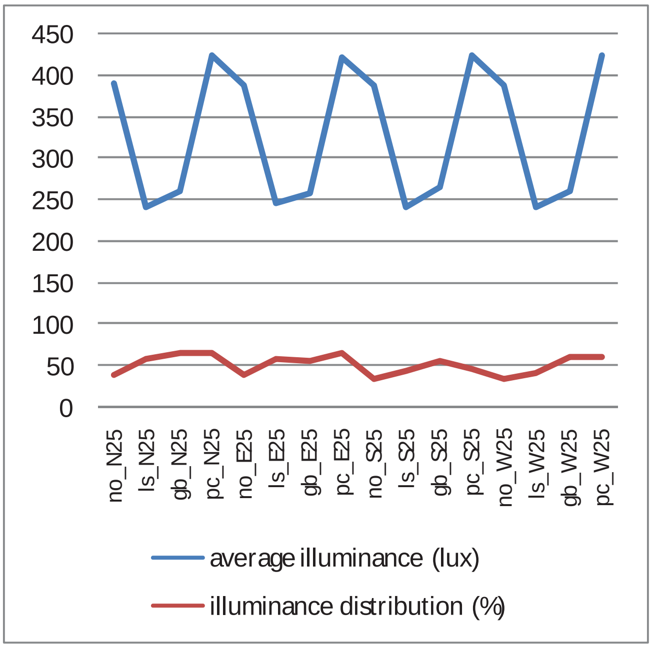


Figure 6: Average illuminance and illuminance distribution of windows for 25-students classroom (the second experiment)

Daylight performances of windows simulated in the second experiment show regular patterns. Windows with lightshelf create the most comfortable illuminance level. The average illuminance levels of windows with glass-block clerestory are still acceptable/comfortable. Similar patterns in illuminance distribution indicate there is insignificant improvement in classrooms with shading device. The best improvement occurs in small-capacity classrooms. Results of window with projected clerestory, however, seem unreasonable. Window with any shading device should have lower average illuminance level than window without shading device. There may be an error in the model construction.

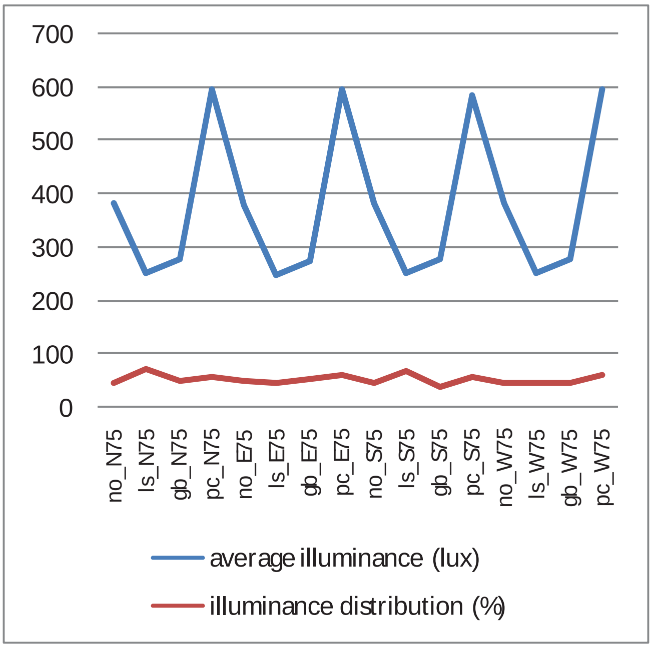


Figure 7: Average illuminance and illuminance distribution of windows for 75 students classroom (the second experiment).

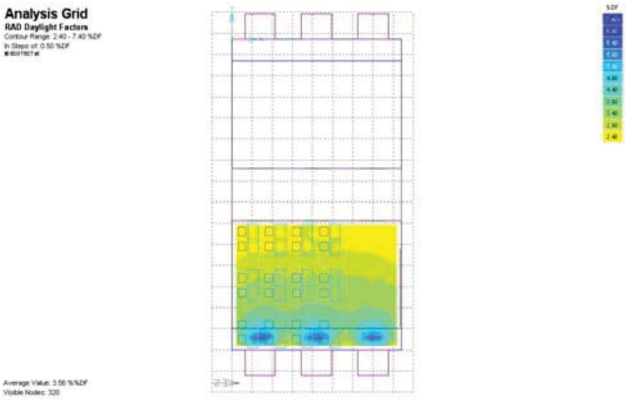


Figure 8: Daylight Factor in a classroom for 25 students with lightshelf facing to East (the first experiment)

Figure 8 and figure 9 show that high daylight factors (> 7%) or illuminance level (> 600 lux) 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.

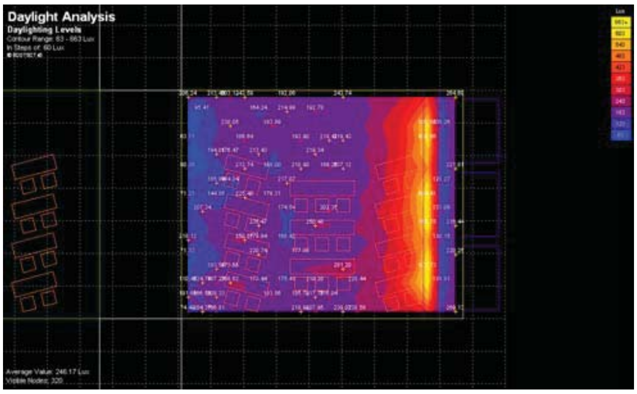


Figure 9: Illuminance level in a classroom for 25 students with lightshelf facing to East (the second experiment)

3.2 Heat gains through the building fabrics

Simulation results of hourly heat flowing through the building fabrics (figure 10) 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.

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 [5].

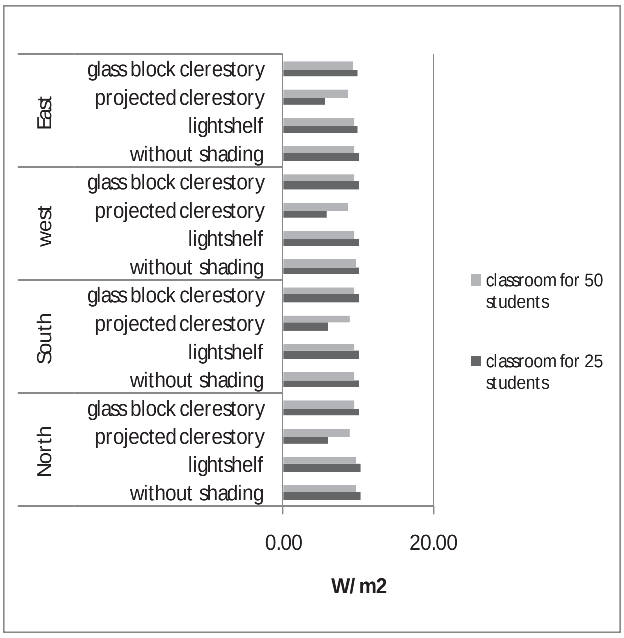


Figure 10: Hourly heat flows through the building fabrics (the first experiment)

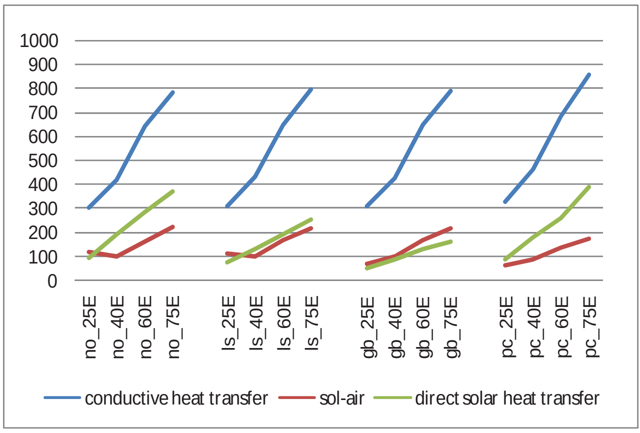


Figure 11: Heat Transfer Through The Building Skins of Classrooms Facing to East (in Watt)

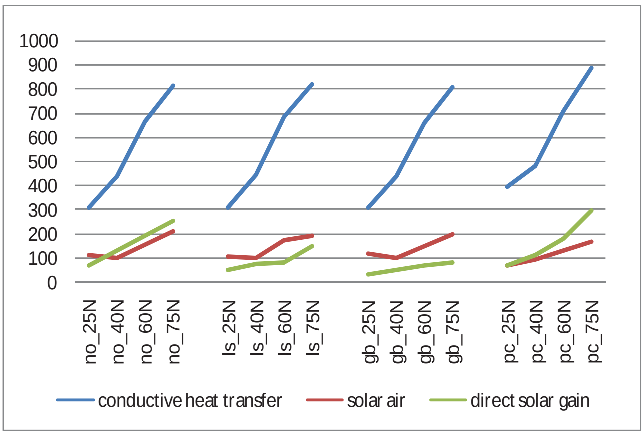


Figure 12: Heat Transfer Through The Building Skins of Classrooms Facing to North (in Watt)

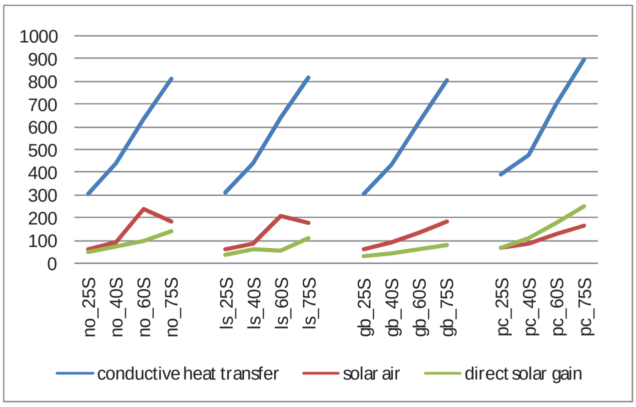


Figure 13: Heat Transfer Through The Building Skins of Classrooms Facing to South (in Watt)

Results of the second experiment show the effect of shading device on the heat transfer. The present of shading device reduces direct solar gain of the classrooms. Window with glass-block clerestory reduces the greatest direct solar gain. Lightshelf can decrease the direct solar gain. Window facing to south admits the lowest direct solar gain, but the greatest effect occurs on windows facing to east. Projected clerestory gives unreasonable results again. Its energy performance is worse than without shading device.

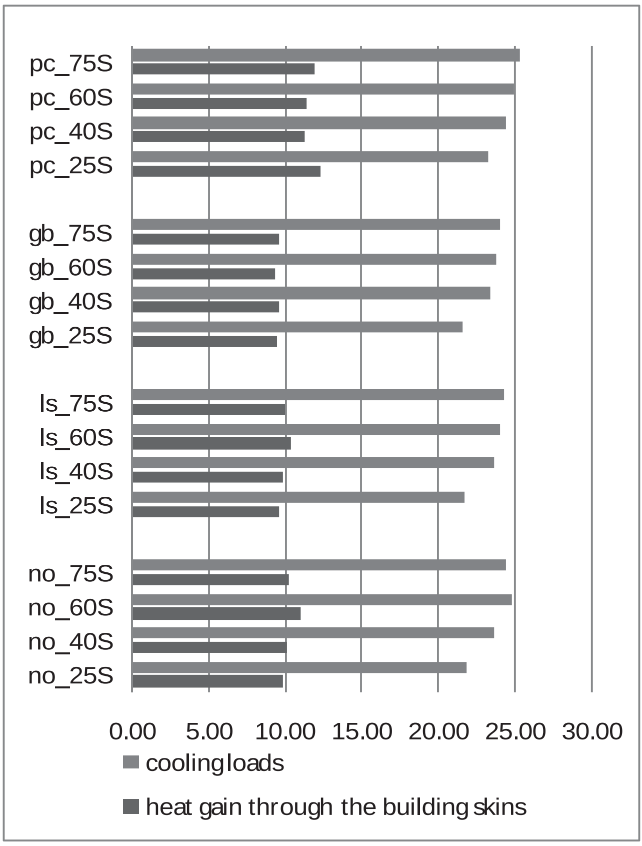


Figure 14: Energy profile of classrooms facing to South (W/m2)

Calculations of classrooms cooling load in the the second experiment show similar pattern. Window with glass-block clerestory or lightshelf has the best energy performance.

Glass-block clerestory can reduce solar heat gain until below 10 W/m^2 for the window facing to south. Relative high energy performance of classroom can be reached by applying lightshelf on its windows. Lightshelf can reduce cooling load a little bit lower than glass-block clerestory. However, it can distribute daylight more evenly, especially in classrooms with big capacity. Application of glass block on clerestory has an advantage in construction cost. Lightshelf and more even projected clerestory are still much more expensive. However, the internal shading device which presents on lightshelf and projected clerestory can prevent annoying glare that may appear on its clerestory.

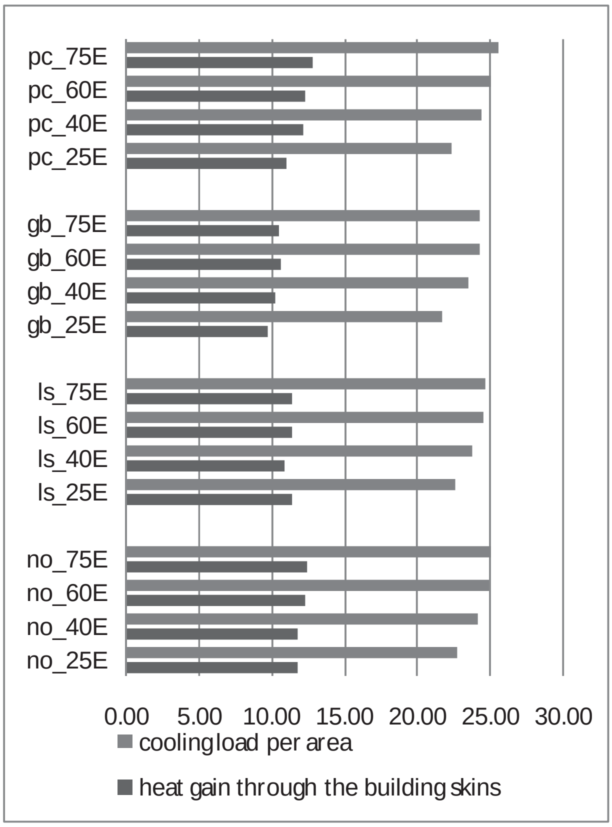


Figure 15: Energy profile of classrooms facing to East (W/m2)

3.3 Window glazing

Low-e double glass replaced clear glass on view windows in order to achieve the most energy efficient window. However, low-e double glass on view windows cannot improve their thermal performances. The 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 (naturally ventilated room), but it work effectively in mechanically ventilated room.

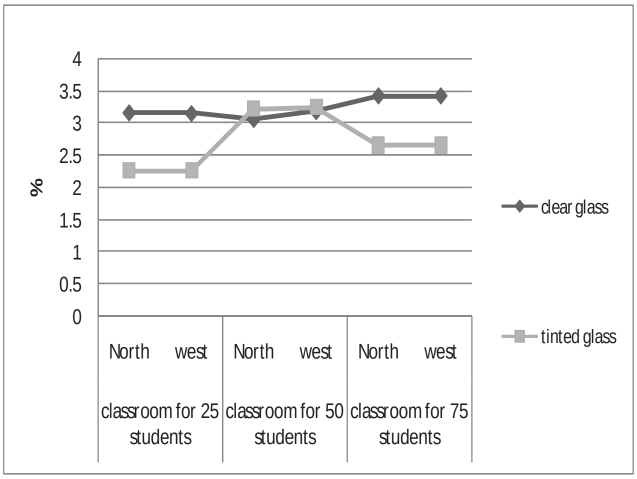


Figure 16: Comparison of average daylight factor between projected clerestory window with clear glass and with tinted glass (the first experiment)

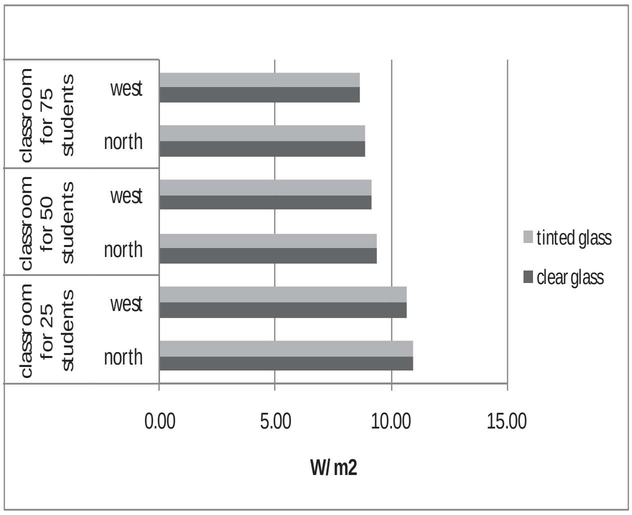


Figure 17: Comparison of hourly heat gains through the building fabrics between projected clerestory window with clear glass and with tinted glass (the first experiment)

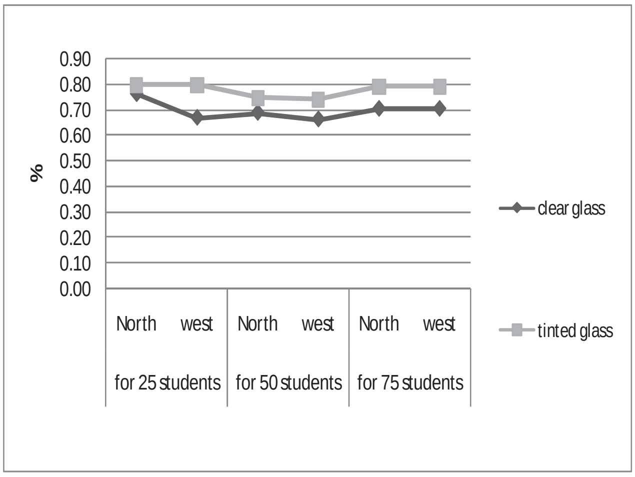


Figure 18: Comparison of daylight distribution between projected clerestory window with clear glass and with tinted glass (the first experiment).

Figure 19: Three dimensional picture of a classroom for 25 students with projected clerestory is resulted by Radiance (link to Ecotect) simulation.

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.

4. CONCLUSION

Projected clerestory can protect the indoor area from direct solar radiation. Horizontal surface of the projected clerestory also functions as horizontal shading for view window below the clerestory. Its horizontal surface reflects sunlight into the deep side of the room depending on the ratio of clerestory height to room width. Less expensive alternatives are lightshelf and glass-block clerestory.

A window with 20% WWR 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.

Comparing the results of the first and the second experiment, for classroom's window without obstruction from adjacent wall or building, the clerestory head height should be around 0.4 of the room width to achieve low energy classroom. One meter height view window with around 11% of clerestory head height to room height and 5% of clerestory head height to room width can distribute daylight evenly. Higher view window creates hotspot on area near the window. View window glazing with low visible tranmittance can improve the horizontal illuminance distribution.

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