NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
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1

IMPACT OF SOLAR SHADING GEOMETRY ON BUILDING ENERGY USE IN HOT HUMID CLIMATES WITH SPECIAL REFERENCE TO MALAYSIA

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ABSTRACT

External solar shading devices can substantially reduce the cooling load of buildings and large energy savings can be achieved. Hence, intercepting the radiant heat wave before penetrating to the internal environment through envelope openings is the main criterion in designing solar shading. In hot and humid climate, one draw back of using shading devices is the risk to reduce daylight level thus increases in use of artificial lighting. Therefore it is important to understand the magnitude of energy consumption for cooling and lighting when shading devices are adapted in order to analyze optimum shading as energy conservation option in high-rise office buildings. In other words, little is known about the relationship between energy use and external horizontal shading device geometry. In an attempt to elucidate these complex relationships, a simple experiment of an office room is carried out using dynamic computer simulation program eQUEST-3 (DOE 2.2). The study indicated depth of the external horizontal overhang can be manipulated to obtain an optimum energy use in high-rise buildings. The results showed that correlation between overhang depth and energy is an important aspect compared to correlation between overhang depth with building cooling loads and daylight level, especially in tropical climate conditions.

Keywords: tropical climate, external horizontal solar shading, natural-lighting, cooling load, energy consumption.

1.0 INTRODUCTION

The intensity of solar radiation in hot humid climates such as Malaysia is generally high and uniform throughout the year. Records of hourly solar radiation data for Altitude 3.7 North and Latitude 101.3 East (Subang Jaya Meteorological Station), received a maximum of 1055 W/m^2 for the year 2001. This is about 75-80% of the solar radiation intensity outside the earth's atmosphere. Further, annual maximum intensity of solar radiation falling on horizontal surface is about 1000 W/m^2 and on vertical surface is about 850 W/m^2 for east and west facing surfaces. Therefore in tropical hot humid climate, solar radiation prevention is the crucial factor in climate design criteria.

In hot and humid climate, one draw back of using shading devices is the risk to reduce natural-light (direct sunlight & daylight) level and as a consequence increases in use of artificial lighting. What makes natural-light utilization so interesting is that in terms of building energy use it reduces the electricity consumption for lighting and indirectly reduces the cooling demand through reduction of internal heat load from lights. However, there is abundance of natural-light in the tropics has not been utilized to the optimum or either it has not been considered as design criteria [1, 2, 3]. The main drawback is maximum natural-light availability is usually concurrent with solar heat gain, especially in hot humid climate like in Malaysia.

Previous studies on solar shading had been focused mainly on five issues: impact on solar radiation [4, 5, and 6], daylight quantity and distribution [7, 8, 9 and 10] impact on energy use [11, 12 and 13], shading design methods [14, 15 and 16] and impact on human comfort and perception [17]. The above review suggest that effect of solar shading on solar heat gain, internal daylight level and on energy consumptions have been dealt as separate issues. However there is room for further research on relationship between external shading device geometry, natural light penetration and on the electric consumption for cooling and lighting. Further the previous studies do not indicate an optimal shading strategy for any particular climate. This paper attempts to elucidate

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
Holiday Villa, Subang Jaya, 10-11 May 2005

2

these complex relationships and propose optimum external horizontal shading device strategies as design solutions in hot humid tropical climate.

One way to take into consideration both cooling load and natural-light utilization in the design of shading devices is to study their impact on energy use or natural-light levels using an energy simulation program [18]. The advantage of using a dynamic energy simulation is that most complex thermal and radiative processes between the building, shading device and the external environment are considered in the calculations. Based on above assumptions the analysis was carried out using eQUEST-3 (DOE 2.2) energy simulation program.

2.0 OBJECTIVE

Specific objectives of the study are as follows:
1. To determine the work plane illuminances for the proposed horizontal shading devices.
2. To determine the energy performance of proposed horizontal shading devices
3. To compare the energy performances of proposed horizontal shading devices with a base-case model (without shading device) and results obtained from (1) and (2) for determining the optimum overhang depth to achieve optimum energy consumption.

3.0 METHODOLOGY

3.1 Energy Simulation Program

The energy simulation program eQUEST-3 (DOE 2.2) was used to carry out the parametric study and to determine the hourly values of internal work plane illuminance and energy consumptions for the tested overhang depths. The simulation "engine" within eQUEST-3 is derived from the latest official version of DOE-2.2 which is the extension of previous version of DOE-2. Developments and updates of the DOE-2 program have continued since the first version. Each new version of the program is denoted by appending numbers and letters for major and minor changes, respectively [19]. Since its first release in late 1970's DOE-2 has been widely reviewed and validated in the public domain [20]. Further, Shank [21] and Brown et al [22] reported that eQUEST-3 software is proven reliable and validated for evaluation of energy efficiency measures of typical building forms.

3.2 Preparation of Models

Energy performance of high-rise building is influenced by several design variables. The best option to optimize the total building energy consumption is to test the number of design alternatives, which is time consuming and laborious approach. The other way of dealing with the problem is by varying one variable at a time and keeping the others fixed at reasonable practical values in order to determine the effect of the particular variable on the energy performance of the building.

A single glazing perimeter zone primary unit office room is selected for the experiment. The geometry and characteristics of the typical office room model is developed based on the analysis of the high-rise office buildings in Malaysia. The base-case office room geometrical configuration for the present study is taken as; height from floor to ceiling to be 9 feet (2.8m) and width and depth of the room as 20 feet (6m) (figure 1). These measurements are taken as to comply with gross internal area (GIA) of 36m^2 and ratio between height, width and depth almost to be 1:2:2.
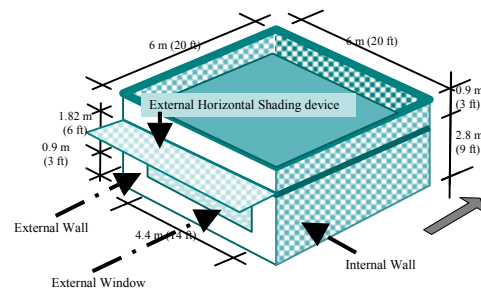

Figure 1. Office room model with external overhang

In this study, maximum limit of window area is assumed as 50percent (50%) of the internal wall area of window. The aperture above the height of the work plane is assumed to be effective in daylight distribution and below the window sill have no effect on light distribution on work plane. Therefore the window sill height and the work plane height are assumed to be equal. The window extends from one side wall to the other side wall and upward to the ceiling line. Hence, the size of the window is 1.82m (6ft) height (above the sill up to ceiling line) and 4.4m (14.4ft) in width.

The external overhang is the primary independent variable in this study. Geometry of external horizontal shading device depends on three dimensions namely; depth, width and

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
Holiday Villa, Subang Jaya, 10-11 May 2005

3

the angle of the shading device [23]. Each of these parameters depends on the amount of solar radiation incident on the fenestration, angle of incident, on how much shade is required on the fenestration and also on size of the fenestration. The depth of the over hang is considered as the main variable in this study. The depth of the device is often described as a dimensionless proportional relationship to the fenestration height (from sill to top plate), which is defined as 'projection factor' (PF). Critical over heated period during the day time is considered as from morning 9.00 am to evening 17.00 pm in order to determine the overhang depths. The overhang is extended on either side of the window. Therefore solar radiation and natural-light entering from the side of window is neglected. Table 1 presents the tested cases in the experiment and their overhang depths with the correspondent overhang ratio (OHR) or projection factors, (PF).

$$\text{Projection Factor (PF)} = \frac{\text{Overhang Depth (D)}}{\text{Fenestration Height (H)}}$$

Table 1. Description of tested cases for independent variable

PF = D/ H	Overhang Depth	
	In Meters	In Feet
0 (Base Case)	0	0
0.4	0.73	2.4
0.6	1.09	3.6
0.8	1.46	4.8
1	1.82	6
1.4	2.55	8.4
1.6	2.92	9.6

The Exterior surface constructions, insulation choices, material properties, internal load schedules, HVAC system types, system schedules and system control input data were selected from the default library materials and values. These values are based on previous studies of ASEAN office buildings [24] and Malaysian Standards (MS 1525:2001) [25] which were considered as to be typical of Malaysian office building characteristics. The operating conditions as well as some basic characteristics of the prototype building have been kept constant for all the data base simulations.

The building external wall construction is 200mm thick medium weight concrete blocks with 50mm cement plaster. The total U value

is about 0.5 W/m^2 K. The internal walls and ceiling were considered as adiabatic, which means there is no heat transfer. Inside visible reflectance from wall surface is 0.5. The ceiling and the floor U values are about 2.0 W/m^{2}K (0.361 Btu/Hr-sqft-F) and 0.5 W/m2K (0.085 Btu/Hr-sqft-F) respectively. Reflectance values for ceiling and floor are taken as 0.7 and 0.2 respectively. Single clear glazing 3mm thick was used for the window. The glazing properties of the existing glazing are as follows: 0.89 visible transmittance, 0.83 solar transmittance, 1.0 shading coefficient and U value is 0.5 W/m^{2}K (0.084 Btu/Hr-sqft-F).

The indoor design conditions were set as follows. In this study the desired internal illuminance is considered as 500lux. The daylight photo sensors were limited to two and their locations were determined by two input data; height above floor and percentage depth of the zone from external vertical window wall. The height is selected as work plane height of 0.84m (2'-9"). Location for reference points were selected as 50% and 90% of zone depth. Thus reference points were positioned at 3.04 m (10'-0") from the window pane and at 5.7 m (19'-0") from the window pane. The two positions were selected to represent the mid zone value and back edge value of the considered room. Also, the sensor points are aligned in the center of the length of the window pane.

The maximum light power requirement is set as 20 W/m^2 (1.8 W/ft^2), the equipment load installed capacity is, 14 W/m^2 (1.3 W/ft^2) and the indoor design temperature were set to 24^{0}C (75.2 ^{0}F) as recommended by Malaysian Standard MS 1525:2001 for office buildings. The experimental office room is assumed to be used by a single person, thus, minimize the occupants load in energy calculations.

Hourly weather data from DOE-2 weather file was used for the location, 3.7 N latitude, and 101.6 East longitudes. The sunlight and sky illuminance were calculated for clear sky conditions. Assumptions were made as this data represents tropical climate conditions.

3.3 Experiment Analysis Criteria

The analysis of the experiment is based on the output data obtained from the simulation for the tested overhang options. The output results were obtained in two forms: hourly values for the designated year and annual energy consumption by end use.

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
Holiday Villa, Subang Jaya, 10-11 May 2005

4

The annual results were obtained for mean work plane illuminance. The annual energy consumptions by endues were analyzed for the following performance variables: building cooling loads, electricity consumption for cooling, lighting and total electricity.

The suggested energy standard for non-residential buildings was 135 kWh/m^2 (Malaysian Standard) and this will be used as a bench mark in describing the energy consumption of the correspondent tested overhang models. The analysis of the each tested overhang models will be evaluated with the correspondent performance variables values for base-case model (without overhang). Also, all the performance variables were correlated with overhang ratio (OHR) of the tested overhang models. This gives the designer more flexibility in determining a shading strategy than a fixed depth of an overhang.

The impacts of natural-lighting on building cooling loads were determined as a function of differential cooling energy use in identical rooms with and without natural-lighting. The differential energy use (DEU) for cooling with daylight and non-daylight room (or building) would be [26]:

$$\Delta DEU_{CL} = EU_{cl,\ daylight} - EU_{cl,\ non\text{-}daylight} \qquad (1)$$

If ΔDEU_{CL} is a positive vale, an increase in cooling energy use occurs because of the use of daylight as an interior illuminant. Vis-à-vis a negative value indicates decrease in total cooling energy use.

Also, for better understanding of the optimum energy consumption due to solar heat gains and natural-light utilization, the incremental energy use (IEU) was correlated with shading overhang ratio. The incremental energy use (IEU) is the difference between electricity consumption (EC) for base-case model with the correspondent tested overhang model.

$$\Delta IEU = EC_{base\text{-}case} - EC_{with\ shade} \qquad (2)$$

If ΔIEU is a positive value, an increase in energy consumption occurs due to the use of shading strategy. If ΔIEU is a negative value, a decrease in energy consumption occurs due to the use of shading strategy.

4.0 RESULTS AND DISCUSSION

4.1 Impact of overhang depth on work plane illuminance.

The absolute work plane illuminance (direct sunlight + sky light) were calculated for the correspondent horizontal overhangs. The results were obtained for four days (21 March, 22 June, 24 September and 21 December), at four times within general office working hours (9:00, 12:00, 15:00 and 17:00 hours) and for four main cardinal orientations (East, West, North and South). The two correspondent reference points were; reference point 01 (Ref.Pt 01) at 3.04m (10ft) and reference point 02 (Ref.Pt 02) at 5.7m (19ft), positioned along the center of the 6.08m (20ft) deep office room at a work plane height of 0.8m (2'-9"). The evaluation of daylight quantity is based on the target absolute work plane illuminance at 500lux. Mean work plane illuminance values were plotted against overhang ratio to determine a general distribution profile of illuminance level received at respective reference points for the tested overhang depths (figure 2, 3, 4 & 5).
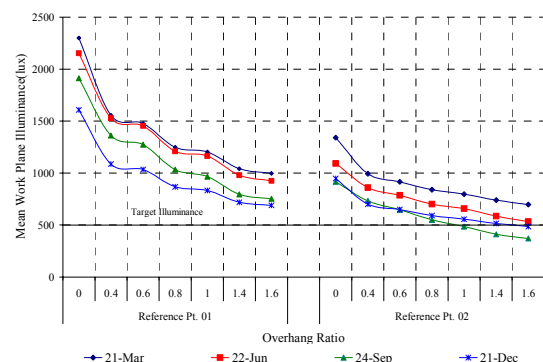

Figure 2. Mean work plane illuminance at ref.pt.01 & 02 East orientation.

Figure 2, 3, 4 and 5 illustrate that increase of overhang depth reduced the mean work plane illuminance at both reference points on all orientations considered. Reference point 01 received more than target illuminance level (500lux) for all overhang depth tested except on 21 December for the overhang ratio 1.4 on north orientation. The high illuminance levels at reference point 01 are mainly due to the amount of direct sunlight received. The mean work plane illuminance below the target level at reference point 02 were received for overhang ratio 1.0, 1.4, 0.4 and 1.0 on east, west, north and south orientations respectively.

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
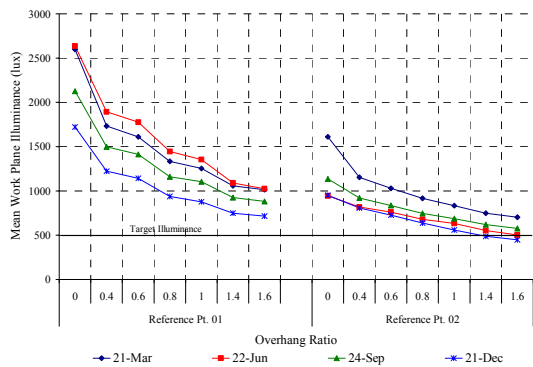Holiday Villa, Subang Jaya, 10-11 May 2005

5

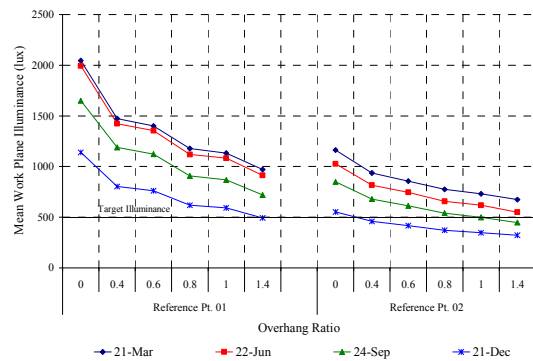Figure 3 Mean work plane illuminance at ref.pt. 01 & 02 West orientation

Figure 4. Mean work plane illuminance at ref.pt. 01 & 02 North orientation
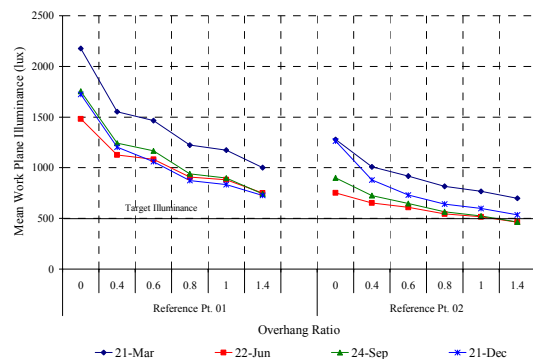

Figure 5. Mean work plane illuminance at ref.pt. 01 & 02 South orientation

4.2 Impact of overhang depth on building cooling loads.

4.2.1 Base-case cooling loads

Space cooling load is the rate at which heat must be removed by mechanical means from the space to maintain the space air temperature at the desired condition. Building cooling energy performance of the base case generic office rooms for the four main cardinal orientations (east, west, north & south) was investigated to understand the main sources of heat gains and the building parameters of the model. Heat gains into the building occur by two means: envelope heat gains and internal heat gains. Figure 6 shows the breakdown of the cooling load for the base case generic office space, with natural-light utilization and without natural-light utilization.
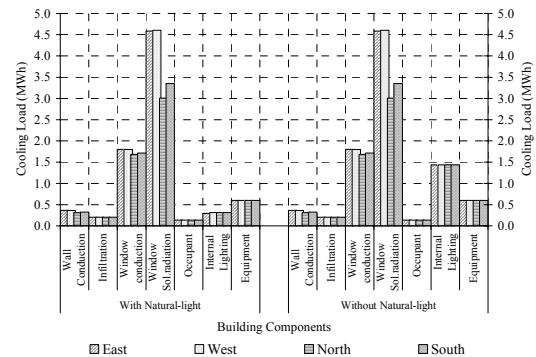

Figure 6. Annual cooling loads with and without natural-light for base-case model.

According to figure 6 about 80% of the building's total cooling loads are envelop loads and about 20% are internal loads for the base case generic office room with natural-light utilization on all orientations considered. Further, the west (8.02 MWh) and east (7.99 MWh) orientation had the maximum contribution and north (6.26 MWh) had the least contribution of cooling loads.

The solar heat gain and conduction heat gain through window are the largest components of the building envelope cooling loads. Base-case cooling loads due to window conduction and solar radiation had a similar contribution of 22% and 57%, on east and west orientations, while 27% and 48%, 26% and 50% on north and south orientations respectively compared to the base-case total building cooling loads.

The cooling loads from equipment had the maximum impact on the internal cooling loads. However, the equipments and number of occupants were kept constant in this experiment, therefore their contribution remains the same for all the orientations and for the tested overhang ratios.

The results indicated that utilization of natural-light minimize the internal lighting cooling loads. When natural-light is not utilized, annually 1.44 MWh cooling load is required to remove the heat gain from internal lighting in the office room considered. This increase the total building cooling and internal loads by 14% on east and west orientations, while 18% and 17% on north and south orientations compared to the base-case with natural-light

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
Holiday Villa, Subang Jaya, 10-11 May 2005

6

total cooling load respectively. However, the envelop loads remains the same for without natural-light scheme, hence, utilizing natural-light in the building reduced the internal loads considerably. Also heat gain from internal lighting is very low compared to solar heat gain as the office room considered is within the 6m deep perimeter zone. Therefore the use of artificial lighting is less due to natural-light availability. This indicates that limiting the excessive solar heat gain is the crucial factor while use of beneficial natural-light as an important energy saving potential.

4.2.2 Influence of overhang depth (given as ratio to window height) on cooling loads

The results indicated all orientations had a significant reduction on building envelop cooling loads when solar shadings are applied (figure 7). The building envelope cooling loads were reduced by 43%, 40% 28% & 31% on east, west, north and south orientations respectively for overhang ratio 1.4 (east/west) and 1.0 (north/south). The total cooling loads were reduced by 36%, 33%, 21% & 25% for the above correspondent overhang ratios on respective orientations. Also horizontal shading devices were effective on east and west orientations which reduced the cooling loads due to control of solar radiation through window more than half the load compared to base-case model without solar shading. Hence, eliminating the direct solar radiation before reaching the window pane is the crucial factor to reduce the cooling loads. Although introduction of external overhang had little impact on cooling loads due to internal lighting, increase of overhang ratio increase the amount of heat generated by artificial lighting that needed to be removed from the space to maintain a constant air temperature. Influence of heat gain through window conduction varies with the increase of overhang ratio. Although the impact of window conduction is less effective compared to solar radiation heat gains, this accumulate to the overall building envelope cooling load which may affect on large cooling load energy consumption.

The maximum total cooling load reductions on east and west orientation were obtained for overhang ratio 1.4 and overhang ratio 1.0 for north and south orientations (figure 8). The results thus suggest that overhang ratios of 1.4 on east & west and 1.0 on north & south orientations can be recommended for maximum reduction of total heat gain from

transmitted and re-conducted solar radiation into the building.
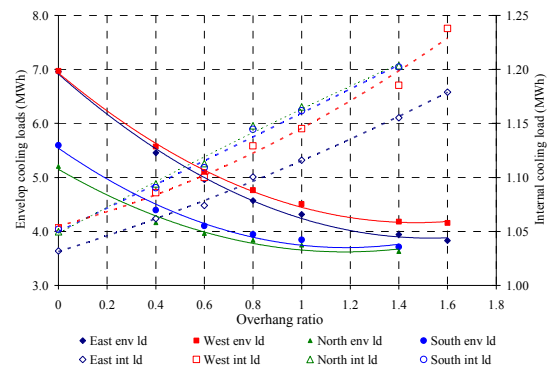

Figure 7 Total envelop and internal component cooling load (MWh) for tested external overhang ratio on east, west, north and south orientations
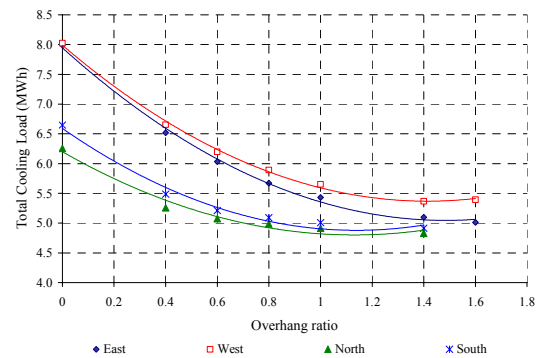

Figure 8. Total building space cooling load (MWh) for tested external overhang ratio on east, west, north and south orientations
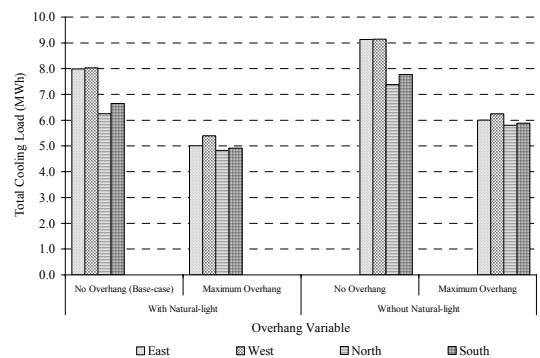

Figure 9. Total cooling load (MWh) with and without natural-light utilization for a base-case and maximum overhang option for east, west, north and south orientations

Figure 9 indicates that shading with natural-light utilization obtained lowest cooling loads, while without both natural-light and shading device obtained the maximum cooling load, for all orientations. Cooling load reduction percentages were calculated compared to the no overhang-with natural-light base-case office room option. Maximum cooling load

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
Holiday Villa, Subang Jaya, 10-11 May 2005

7

savings were obtained with natural-light and maximum shading options for all orientations. Total climate rejection building option, with no natural-light and no shading had more energy consumed than the base-case option.

4.3 Impact of overhang depth on building energy consumption.

4.3.1 Base-Case energy consumption

Figure 10 shows the annual electricity consumption for base-case generic office room obtained on east, west, north and south orientations under tropical climate conditions. Four components, namely, space cooling, area lighting, miscellaneous equipments and ventilation fans contribute to the total office room electricity consumption. In this study miscellaneous equipments and ventilation fans were set to a constant value for all shading devices tested. However, it can be seen that energy use related to HVAC system (for space cooling and ventilation fans) dominated the electricity consumption on all four orientations. East and west orientations had the highest effect (55% & 54%) while north and south (50% & 51%) had the least effect on electricity consumption for space cooling of total energy use. As expected for tropical climate with ample daylight, relatively electricity consumed for area lighting is insignificant, which accounted for 7.5%, 8%, 8.8% and 8.6% of total energy use on east, west, north and south orientations respectively.
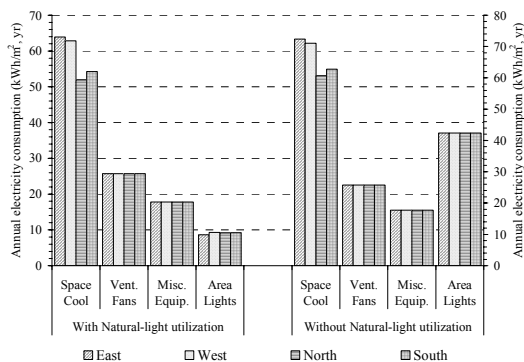

Figure 10. Base case energy consumption with and without natural-light.

The computed results without natural-light utilization showed significant increase in electricity consumption for area lighting accounting to 27% and 29% of the total energy use obtained for east/west and north/south orientations respectively. Hence, the results indicate the importance of daylight

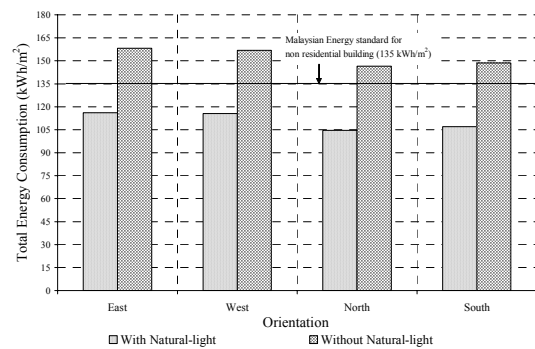utilization and impact of solar heat gains in cooling dominated office room.

Figure 11. Total energy consumption with & without natural-light schemes for base case model on east, west, north and south orientations

As illustrated in figure 11, total energy consumption with daylight scheme yielded, below the Malaysian energy standard (135 kWh/m^2) for non-residential buildings. The results indicated 14% reduction on east and west, 22% reduction on north and 21% reduction on south oriented office rooms. But total climate rejecting design option with no shading and no natural-light utilization, yielded 17%, 16%, 8.5% and 10% more than the energy standards, for east, west, north and south orientations respectively.

4.3.2 Influence of overhang depth (given as ratio to window height) on energy consumption

In order to better understand the optimum energy consumption due to solar heat gains and natural-light utilization, the incremental energy use (IEU) was correlated with tested overhang ratios. In this case the IEU is calculated compared to the electricity consumed by base-case generic office room without external shading device for space cooling, area lighting and total energy consumptions. Energy saving for cooling, lighting and total electricity use was calculated as a percentage compared to base case generic office room energy consumptions (figure 12 & 13)

As shown in figure 12 with increase of overhang ratio, energy saving for cooling progressively increased and optimum energy saving of 31%, 26%, 19% and 22% were indicated at overhang ratio between 1.4, 1.3, and 1.2 on east, west and north/ south orientations respectively. However, the cooling energy saving starts degrading when further increases of overhang ratio.

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
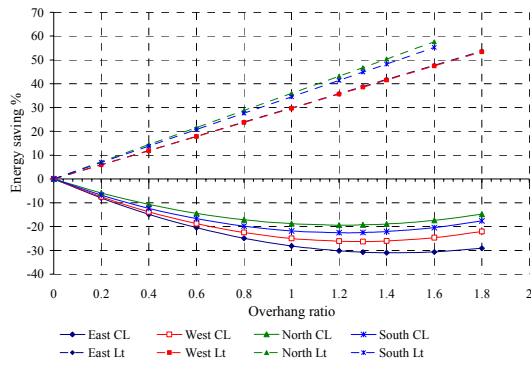Holiday Villa, Subang Jaya, 10-11 May 2005

8

Figure 12. Energy saving percentage for space cooling and area lighting incremental energy use as a function of overhang ratio, on east, west, north and south orientations

Simultaneously, when cooling energy saving reach the optimum range, the lighting energy use increased significantly at respective overhang ratios by 42%, 39%, 43% and 41%, compared to lighting energy use for base case generic office room. As discussed in section 4.1, at overhang ratio 1.4 (405lux), 1.3 (390lux), 1.2 (350lux) and 1.2 (360lux), the mean work plane illuminance indicated bellow 500lux for respective orientations. Thus, it suggests the need for electric lighting. Hence, an optimum cooling and lighting energy balance has to be determined by analyzing the total energy consumption.
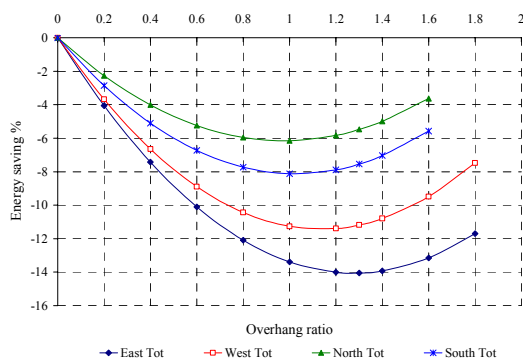

Figure 13. Energy saving percentage for total incremental energy use as a function of overhang ratio, on east, west, north and south orientations

As illustrated in figure 13 when overhang ratio increases, total energy saving curve progressively degrades up to overhang ratio 1.0 (east and west), 0.6 (north) and 0.8 (south) and show a very small additional energy saving beyond this point. Further, when overhang ratio is 1.4 (east and west), 1.2 (north) and 1.3 (south) the energy saving curve starts increasing. Hence, the optimum energy saving were indicated at overhang

ratios 1.3 on east, 1.2 on west, 1.0 on north and 1.0 on south orientations respectively. As shown in figure 13, about 14%, 11%, 6% and 8% of total energy saving were obtained compared to base case generic office room total energy consumption on east, west, north and south orientations respectively. Increasing the overhang ratio to the maximum limit, 2.0 ohr (east and west) and 1.6 ohr (north and south) reduce the total energy saving by 10% (east) 4.4% (west), 3.6% (north) and 5.6% (south) compared to base case total energy consumption, respectively. Therefore energy saving values of 14%, 11%, 6% and 8% were determined as optimum savings. The resulted mean work plane illuminances for optimum overhang ratio for total energy consumption were as follows: east (425lux), west (530lux), north (345lux) and south (525lux). This indicated west and south received above the target illuminance level while east and north obtained below the target level. However, the mean illuminance was adequate for general illuminance of office space (above 300lux) on all orientations.

5.0 CONCLUSIONS

A parametric study of natural-lighting, cooling load and energy consumption of an office room equipped with external overhang was presented. Optimum overhang ratios for following performance variables were experimented; work plane illuminance, building cooling load, electric consumption for space cooling and total energy consumption. The study indicated that the depth of simple horizontal overhang can be manipulated to control the internal thermal and lighting conditions in order to determine the building energy use. The finding suggested several optimum solutions for respective performance variables under tropical climate conditions as illustrated in table 2.

Table 2. Summary of optimum overhang ratio for various performance variables

Orientation	Optimum OHR for target mean work plane illumin. (500lux)	Optimum OHR for building cooling load	Optimum OHR for energy cons. for space cooling	Optimum OHR for total energy cons.
East	1.0	1.4	1.4	1.3
West	1.4	1.4	1.3	1.2
North	0.4	1.0	1.2	1.0
South	1.0	1.0	1.2	1.0

Further, total energy consumption for the designated generic office room was well

NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM
Holiday Villa, Subang Jaya, 10-11 May 2005

9

below the Malaysian Standard (135 kWh/m^2) for all orientations. This implies that application of Malaysian Standard (MS1525: 2001) generally resulted in energy consumption within the energy efficient range with natural-light utilization.

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