

EFFECTS OF EXTERNAL SHADING DEVICES ON DAYLIGHTING AND NATURAL VENTILATION

Wong Nyuk Hien, Agustinus Djoko Istiadji
Department of Building, School of Design and Environment
National University of Singapore,
4 Architecture Drive, Singapore 117566

ABSTRACT

External shading devices have been utilized very extensively in residential buildings in the tropics to reduce the amount of solar radiation entering into the buildings. However, this will affect the availability of daylight for interior lighting as well as natural ventilation for passive cooling and thermal comfort. This paper discusses the impacts of six different types of external shading device on a residential building in Singapore. The investigation was carried out via the use of LIGHTSCAPE for daylighting simulations and PHOENICS CFD simulations for natural ventilation. From the series of parametric studies, the design of external shading devices to optimize daylighting and natural ventilation performance is developed. The interactions and the inter-relationship between daylighting and natural ventilation simulations that could affect the simulation results were also discussed. Lastly an actual field measurement was also conducted, which serves to provide data for the validation of simulation output.

INTRODUCTION

The most significant factor affecting the architectural environment in the tropical region is solar energy. Throughout the year, solar energy impinges on the building which influences either its inside or outside climate. To control the effect of solar energy on the indoor environment, it is usual to concentrate on the role played by the building skin and fenestration, which act as a filter between the outdoor conditions and those within the building. Focusing on the fenestration, which is the critical point of indoor heat gain, heat transfer can occur by radiation, ventilation (infiltration), conduction, and convection. Fenestration can contribute to 22% of energy consumption in residential buildings (Al-Mofeez 1991). Uncontrolled fenestration heat gain causes overheating, thereby causing poor thermal performance.

External shading devices can be utilized to block the solar radiation before it reaches the indoor environment, and are hence more effective than internal shading devices. However, external shading devices can affect daylighting and natural ventilation

performance of the building. In term of daylighting, there are two effects i.e. avoiding glare problem and reduction of light intensity. The former will improve visual comfort and the latter will cause a decrease in indoor lighting performance that is likely to increase energy consumption by utilizing artificial lighting. From the natural ventilation aspect, the shading device can be used as wind catcher. However, it must be designed and located in the right place, which otherwise can become a barrier to wind flow (wind breaker).

Thus, the design and construction of external shading devices require careful study and proper design to provide their effective functions.

METHODOLOGY

For the purpose of investigating the effects of external shading devices on daylighting and natural ventilation performance, this study used two stand-alone building performance simulations. They were LIGHTSCAPE for daylighting and PHOENICS Computational CFD package for natural ventilation performance.

The simulation process has been pursued by two phases. The first one was verification and validation process which included the field measurement of velocity, temperature, and illuminance. Then, a model with the external shading device similar to the real one in a residential flat was simulated for four different time period. The results of the field measurement were then compared with those of the simulations. The second stage involved simulating seven proposed models in two selected time period. The simulation process and boundary conditions of these simulations were based on the earlier simulation parameters, except the boundary condition for the solid wall for CFD simulations. This specific boundary condition was defined by heat balance calculation and the simulation results from LIGHTSCAPE.

The object of the case study was a unit of Housing Development Board (HDB) flat which was located in a densely populated urban housing area. The selected flat was a three-room flat where was situated on the eleventh floor at the corner as shows in Figure 1. The

study only focused on rooms A, B and C. All windows and only the doors at room A and D were fully opened (90°) for performing cross ventilation. Moreover, selected rooms were assumed unfurnished. All indoor equipments were turned off to simulate the natural environment. Seven models were considered in this study. The seven models include a model similar to the actual model of HDB flat (Shad.Or) and a model without shading device (Shad.Wo) as shown in Figure 2.



Figure 1 Floor Plans and Perspective of the Flat

For the validation exercise, the measurement was conducted in 2 days each day from 9 am to 4 pm. The instrumentation used were DANTEC multi-channel flow analyzer type 54N10 with 6 omni-directional hot wire anemometers, Yokogawa - DAQ STATION – DX230 Data Logger combined with thermo couple wires and two digital HAGNER lux-meters.

MODELING APPROACH

Daylighting Simulation

In this study, LIGHTSCAPE package software, developed by Autodesk, INC., USA was used. LIGHTSCAPE is an advanced lighting and visualization application (Autodesk 1999). The modeling strategies include the following:

- The geometry model consisted a unit of HDB block that was placed at a level of 27.75 m and the surrounding buildings as shown in Figure 3.
- The sky condition was assumed to be partly cloudy.
- Based on Singapore’s geographical location and four selected time period of the field measurement, suitable boundary conditions for the validation study were defined (see Table 1).
- The simulations used the number of iterations in the range of 15,000 to 20,000. With this number, light energy was distributed until 99.995 %.
- For the purpose of examining light distribution, horizontally work-plane (75 cm) was developed, as showed in Figure 4.

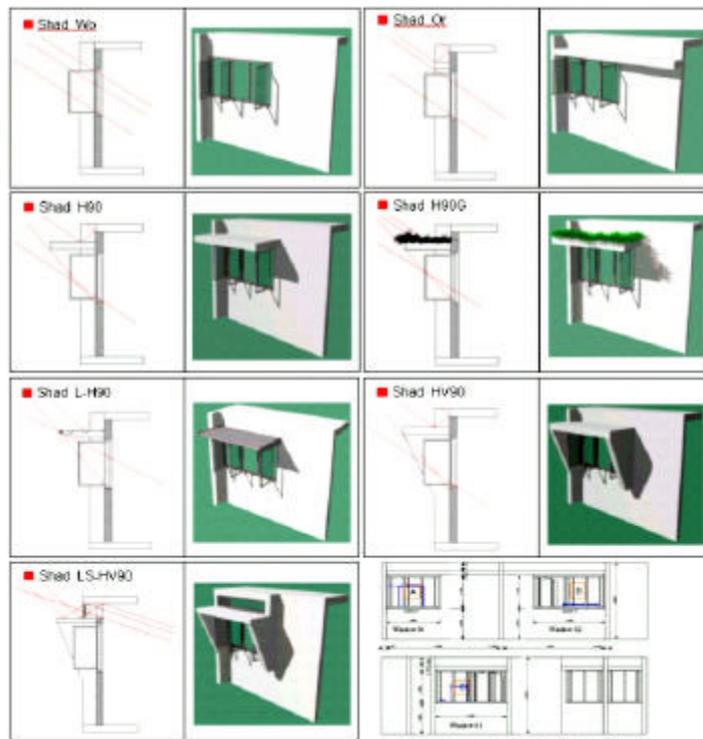


Figure 2 Seven Proposed Shading Devices and Elevations

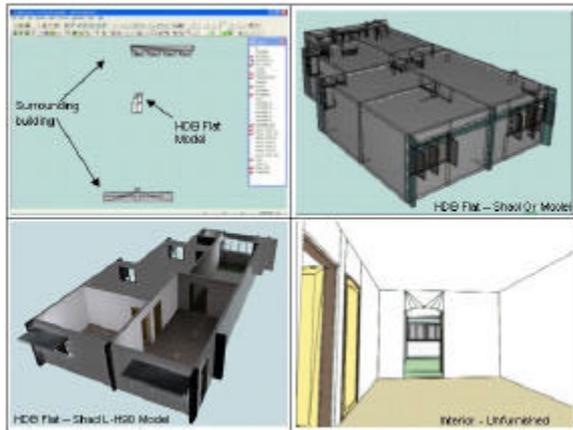


Figure 3 Geometry Models in LIGHTSCAPE

Table 1 Four Sets of the Boundary Condition for LIGHTSCAPE Simulations

Item	Case 1	Case 2	Case 3	Case 4
Time	11.00am	11.00am	1.30 pm	3.00 pm
Date	10-Jul-02	11-Jul-02	11-Jul-02	11-Jul-02
Azimuth	47°	30°	68°	56°
Altitude	52°	39°	68°	56°
Material	Com3	Com3	Com3	Com3
Sun illuminance	50318 lx	100637 lx	75478 lx	35223 lx
Sky condition	uniform	uniform	uniform	uniform

- The simulations used the number of iterations in the range of 15,000 to 20,000. With this number, light energy was distributed until 99.995 %.
- For the purpose of examining light distribution, horizontally work-plane (75 cm) was developed, as showed in Figure 4.

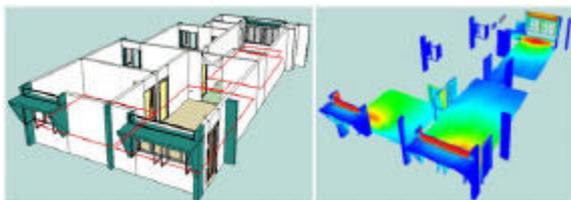


Figure 4 Horizontal Work-planes in LIGHTSCAPE

CFD Simulations

The effect of external shading device is to reduce solar radiation. Solar radiation from the sun and the sky would be blocked and it consequently influences radiant heat transfer inside the space. For simulating the phenomenon, one problem faced was to model

sun and sky radiation within the domain. Most of the CFD modeling cannot simulate solar radiation directly. The applicable model is a surface-to-surface radiation which occupies wall boundary condition. For this reason, it requires a converter which could express the effects of solar radiation within the domain. It converts the magnitude of solar radiation to surface temperature or radiant flux.

There were two kinds of wall boundary conditions that must be defined. The first one was indoor wall boundary condition. The calculation involved 3 steps. They include:

1. Obtain irradiance of the actual model by utilizing the wall conduction equation, mean radiant temperature equation, outside face heat balance equation and inside face heat balance equation (ASHRAE 2001).
2. Adopt LIGHTSCAPE ratios (Lsr) for determining irradiance values of the proposed models. Irradiance of the actual model was multiplied by those ratios. The new irradiance of each model was computed by this equation; $E_{irr,new} = E_{irr} - (E_{irr} \cdot Lsr)$ where Lsr could be positive that indicated irradiance increase or negative that indicated irradiance decrease.
3. Convert the irradiance value into new value of surface temperature by using the inside face heat balance equation.

The second assumption concerns the surface temperatures of the shading device. Their surfaces will affect ventilation heat gain in term of conductive-convective heat transfer. The process of determining the soffit temperature of the proposed shading devices was performed by an experimental set-up. The model was a scaled model that required assumptions and therefore was approximate. There were two assumptions which were included i.e. there was only one-dimension heat transfer which occurred from outside surface to inside surface (bottom) and surface temperature was a linear function of the ambient temperature near the shading device.

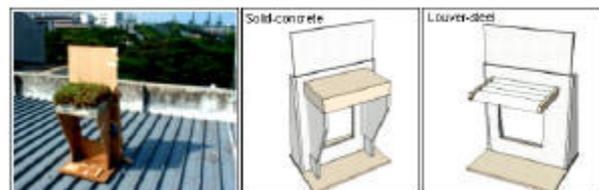


Figure 5 Models of Shading Device Experiment

To obtain the surface temperature, the surface temperatures of these models were measured by a data logger and thermo-couple wires. According to the proposed designs, there were three different

shading models i.e. solid-concrete, solid-concrete with grass (plants) and louver-steel as shows in Figure 5.

PHOENICS was utilized to study the effects on velocity and temperature. This Software is a package of CFD software developed by CHAM INC., UK which adopts three-dimensional partial derivative equation, finite volume method as numerical discretization technique and staggered grid. Its calculation is performed in a rectangular cuboids solution which is operated in Cartesian coordinates (CHAM 1999). Using Flair, which is a component of the PHOENICS CFD package, this study adopted the modeling strategies as follow:

- Approximation of the flow domain was developed by taking into account its proportion similar to the actual condition of HDB flat. The direction of airflow was assumed perpendicular on the openings that flowed from South to North similar to the result of field measurement (Figure 6).

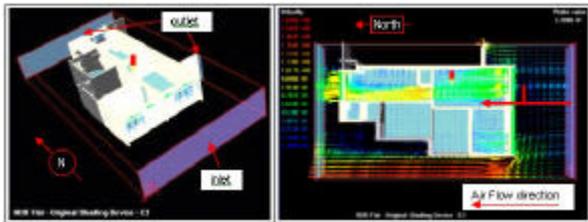


Figure 6 Geometry Models for CFD Simulations

- The grid was built by faces of quadrilateral and cells of hexahedron. The number of cells was 26,244.
- The fluid flow calculations were performed with the aid of the following physical models:
 - A high Reynolds number form of the k-ε turbulence model;
 - The total energy method for heat transfer;
 - The Boussinesq approximation for buoyancy effects;
 - A proprietary radiation heat transfer model (Immersion) based on the radiosity concept.

Table 2 Four Sets of the Inlet and Outlet Boundary Condition for CFD Simulations

Item	Case 1	Case 2	Case 3	Case 4
Time	11.00am	10.00am	1.30pm	3.00pm
Date	10-Jul-02	11-Jul-02	11-Jul-02	11-Jul-02
INLET PROPERTIES				
Velocity	0.27	0.5	0.37	0.48
Temp	33	32	35	36
Turb. Int.	25%	25%	25%	25%
Ext. Rad	67	0	0	87
OUTLET PROPERTIES				
Velocity	0	0	0	0
Temp	34.7	29	32.7	36.9

- There were two kinds of boundary conditions which were set up i.e. wall and inlet/outlet boundary conditions. Wall boundary condition was defined by a specific method that has been discussed before. Inlet/outlet boundary, which was obtained from field measurement, is presented in Table 2.
- Iterative convergence was defined by the global convergence criteria of 0.001 with the total number of iteration set at 2500.

RESULTS AND DISCUSSIONS

The Validation Exercise

The validation was carried out by comparing simulation results of the actual model to the results of the field measurement for four different time period (four cases). The entire cases were analyzed using statistical method of linear regression. In addition, the regression model developed was used for calibrating the result. The Pearson correlation coefficients obtained were high (0.707 – 0.984). These values indicate both data for each parameter are collinearly related or normally distributed. By observing the regression model, it can be seen that, generally, R^2 and F statistic of both parameters present significant coefficients. However, constant coefficients of velocity and daylighting models exceed 0.05. This exercise shows that Lighting and CFD simulation can predict significantly both parameters although it still has deviations. The prediction result of the simulations has a deviation around 25% for daylighting, 19% for velocity and 1.5% for temperature. The analysis of the developed regression model also indicates that the models are useful for calibrating the results. The calibration results of Case 1 and Case 3 appear better than the other cases so these two cases were selected for further simulations. The calibration results for both cases can reduce deviation around 21.3% for daylighting, 15% for ventilation, 0.83% for temperature respectively.

The Effects of Shading Devices on Daylighting and Ventilation Performance

The analysis of the effects of external shading devices on daylighting and ventilation performance is conducted by comparing a model without shading device and the models with shading device.

The Effects on Light Intensity

This study observed and measured the performance of daylighting by adopting IES code for residential building (300 lux for rough visual-task) [5]. The effects of each shading device on illuminance of the rooms are presented in Figure 7. Generally, most of the shading devices admit illuminance higher than the recommended level, except for Shad.HV90. It can be seen that Shad.H90 and Shad.L-H90 admit

illuminance higher than the recommended level, ranging between 370 lux and 444 lux. This shading device can prevent direct light of 100% and diffuse light of 65% with shading coefficient of 0.55. For Shad.HV90, the result shows that this shading device admit the threshold level of illuminance.

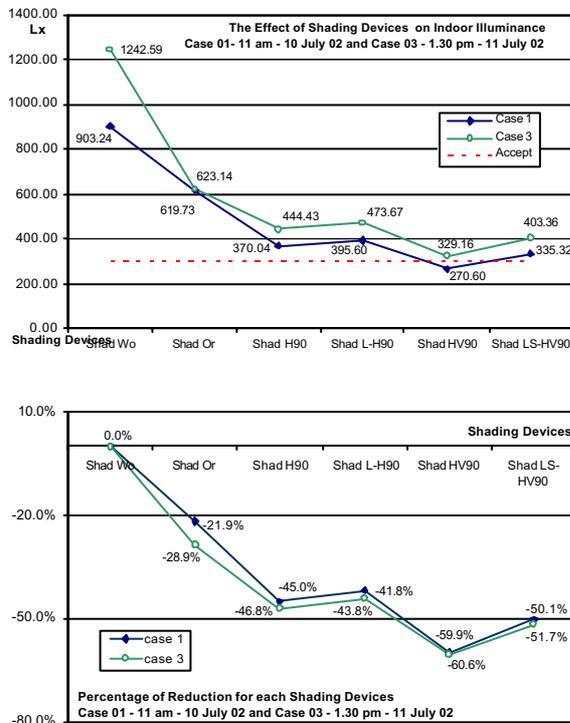


Figure 7 The Effects of Shading Devices on Indoor Illuminance

The louver model (Shad.L-H90) admits illuminance about 3% higher than that of solid overhang model (Shad.H90) although both shading models create the same shaded area. The reason for this condition could be due to the inter-reflection of light among fins that allows more light to penetrate into the space. Shad.LS-HV90 reduces illuminance by 50% but admits illuminance 10% higher than Shad.HV90. This model increases the window area by 30% from which the total un-shaded area becomes 44%. In comparison to Shad.H90 with un-shaded area of 35%, it can be seen that this window addition is less useful to admit illuminance.

The Effects on Light Distribution

The analysis of light distribution is conducted by plotting horizontal contour profiles. Figure 8 shows contour profile for only Case 1 with illuminance generally lower than Case 3. The results indicates that direct light and high intensity of diffuse light only illuminate the area near the window and external shading devices have little impact on the distribution of daylight. The average light distribution of

Shad.Wo is 74%. The presence of external shading reduces the light distribution ranging from 5% to 25%. It indicates that all the external shading devices still allow light distribution higher than the recommended level (50% of room depth) except for Shad.HV90 which is slightly lower.

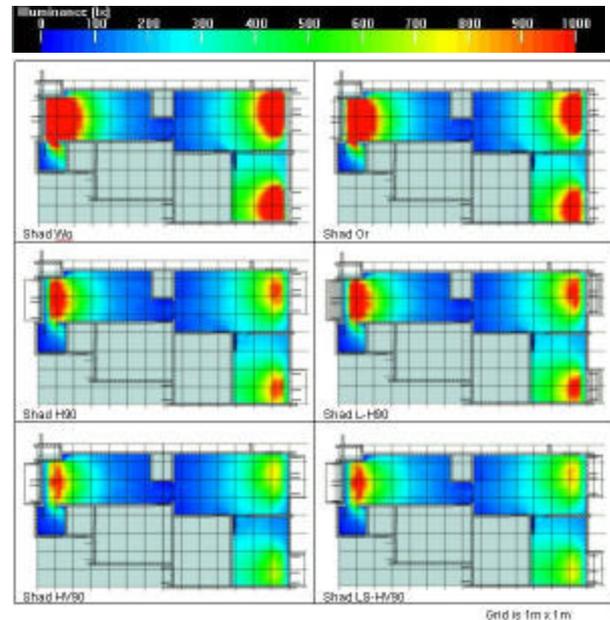


Figure 8 Illuminance Contour on Horizontal Work Planes

The Effects on Glare

Glare problem is analyzed by taking into consideration glare index for each model which focuses on the glare from the sky. The point of observer is placed in the center of the room (1m height). Sky luminance is defined as 5000 cd/m² by taking into consideration the calculation results that produce glare indexes which reach the critical level. This study adopts IES code for rough visual-task (25 to 28) (Lighting Handbook 1993). Figure 9 shows the calculation results.

This figure shows that the glare indexes for each room are different. Glare indexes in room B are the lowest. This could be due to the observer position which produces difference value of visual angle and sky luminance. The observer position in room B which is furthest from the window, causes the observer to see smaller exposed area of the window so that it produces low glare indexes. The effects of shading devices on glare also show different values for each room. The shading devices do not always reduce glare index. It may even increase the glare indexes like in room C. This could be due to the indoor luminance that decreases as a result of the effects of shading devices. In room C, these effects can cause the reduction of indoor luminance to be quite high, ranging between 27% and 61% while the

other room ranges from 7% to 20%. Decreasing of indoor luminance sufficiently high can increase glare index

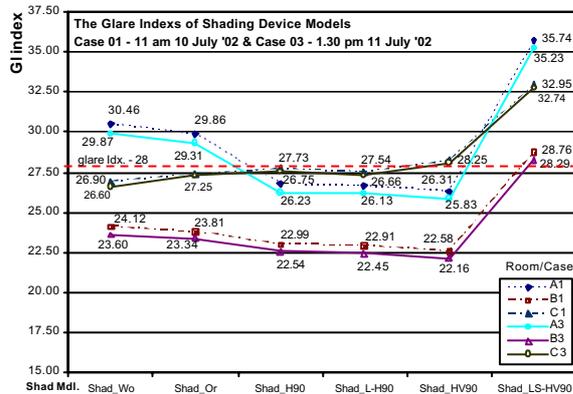


Figure 9 The Glare Indexes for each Shading Devices

The Effects of Shading Devices on Ventilation Performance

In this section, the effects of external shading devices on velocity and temperature are analyzed. The comparison of magnitude is based on the average value.

The Effects on Velocity

The effects of each shading devices on velocity of the entire rooms are presented in Figure 10.

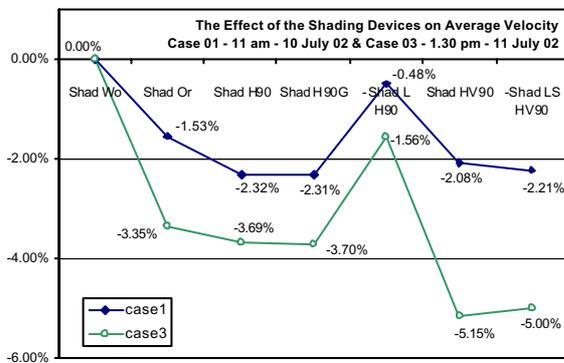


Figure 10 The Effects of Shading Devices on Indoor Velocity

Generally, all of the shading devices cause reduction of indoor velocity. Yet, their reduction is small. It ranges from 1.5% to 5% or 0.009 m/s to 0.024 m/s for both cases. Figure 11 shows the comparison between inlet velocity and indoor velocity of room A and B for Case 1 and Case 3. It can be seen that the average indoor velocity of both rooms is generally higher than inlet velocity. It indicates that the current design of the windows can accelerate indoor velocity, ranging between 20% and 30%. The shading devices reduce the increase and each shading device causes different reduction.

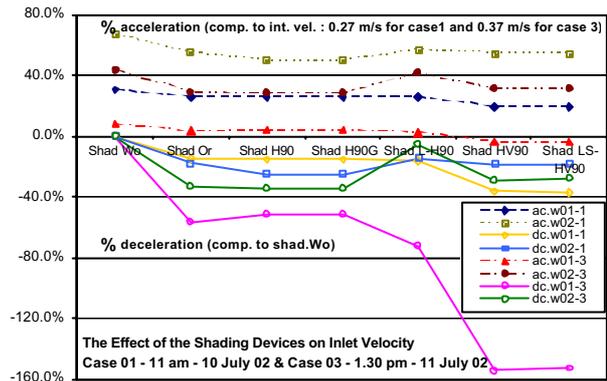


Figure 11 The Effects of Shading Devices on Inlet Velocity

The Effects on Airflow Distribution

Airflow distributions for only Case 1 are presented in Figure 12. It can be seen from the contour profile (Shad. Wo) that the window leaves which are opened fully (90°) perform as vertical shading device. It generates venturi effect that accelerates the incoming air stream. The shading devices reduce the air velocity by modifying the shape of the incoming air stream. The incoming airflow is divided and deflected by window leaves and the shading device. For window leaf that is placed at the side of the window, it causes the air stream to strike the wall and divert into the space with some air stream diverted outside. Vertical shading device that is placed close to the side-end of windows will break the air stream (Shad HV90). This reduces the acceleration of the incoming air stream. To improve the current design, window leaves located in the middle of the frame should be removed and the shading device can be placed far from the side-end of the window. This will allow and give more opportunity for the airflow to enter into the space (Figure 13)

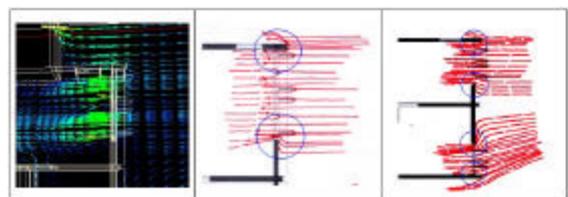


Figure 13 Characteristic of Horizontal Airflow

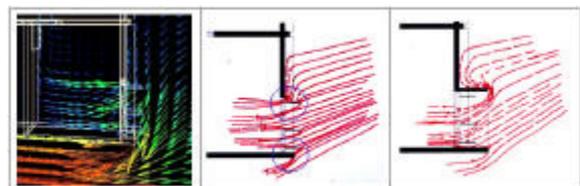


Figure 14 Effect of Vertical Shading Device on Incoming Airflow

For wind flowing in an oblique angle, it causes the air stream to strike the window leaves and retard it before entering into the space. This decreases the performance of the window to accelerate the incoming air stream. Constructing vertical shading device (shad.HV90) will create similar effect especially for shading device that is placed on the windward side. It will break the wind (Figure 14).

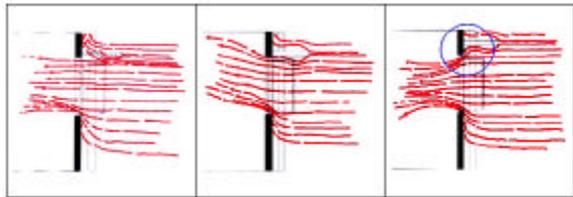


Figure 15 Effect of Horizontal Shading Devices on Vertical Airflow

The lowest reduction is shown by shad.L-H90 for wind flowing perpendicularly to the windows. It is observed that its louver fins can equalize the high pressure and subsequently controls air flow in the middle level of the windows to allow wind to enter the space smoothly. Different airflow pattern will occur for the solid shading device which causes high pressure of air under the shading device and allow the airflow to divert towards the ceiling. It causes indoor air velocity at the upper level to be high, with lower velocities at the middle and lower level. This can be improved by placing the shading device far from the head of the window. It will divert the airflow towards the floor (Figure 15).

The Effects on Temperature

The effects of shading devices on temperature can be observed in Figure 16. Generally, the shading devices reduce indoor temperature. The reduction ranges between 0.5 deg C to 1 deg C or 1.3% to 2.8%. Horizontal shading devices (Shad.H90 or Shad.L-H90) have reduction in a range of 0.61 deg C to 0.88 deg C. The vertical shading device (Shad.HV90) reduces the temperature by 0.98 deg C. However, Shad.LS-HV90 has lower temperature reduction ranging between 0.08% and 0.26% in comparison with shad.HV90 since this model allows more daylight to enter into the space. The study also showed that presence of plants has very small effect on the indoor temperature. In this case, the reduction is 0.003 deg C. This could be due to the small area of plants that covers the shading device. For getting better effects, this can be improved by the combination with other methods like landscaping, sky gardening, wall gardening, etc (Chen Yu 2002) that can reduce the outdoor and surface temperatures.

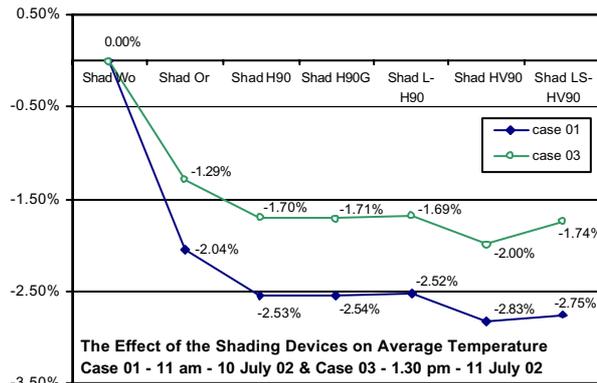
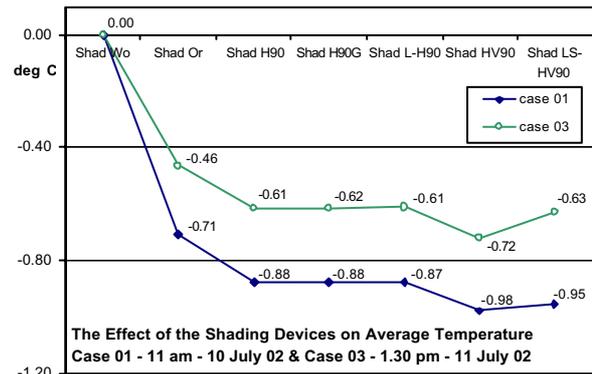


Figure 16 Effects of Shading Devices on Indoor Temperature

CONCLUSIONS

This study examined the effects of seven proposed shading devices on three parameters i.e. daylight, velocity and temperature for a residential building in Singapore. The study has come to the following conclusions:

- The shading device with shading coefficient of 0.55 can admit daylight with illuminance exceeding the recommended level. It also allows provision of light to penetrate deep into space, even to maintain light distribution slightly higher than the acceptable level. For the tropical region where the average luminance of the sky is often high (more than 7000 cd/m²), glare from the sky could be a critical problem. The shading devices can reduce glare but it is not always successful, since glare index is not only a function of the exposed area of the window but also of the outdoor and indoor luminance and the view angle of the observer. It demands a comprehensive solution which includes admitting more daylight into space, reducing more direct view to the sky patch and providing suitable interior design.
- This study also revealed that when the window leaves are opened fully; the current configuration of windows could accelerate the incoming airflow significantly. However, the shading devices

reduce the incoming air velocity though insignificantly.

- The study also concluded that vertical shading devices are not effective in enhancing daylighting and natural ventilation.

REFERENCES

Al-Mofeez, Ibraheem Abdul., 1991, *Insulation in the Opaque Envelope: Effects on Thermal Performance of Residential Building in Hot-arid Climates*, Dissertation for degree of Doctor of Philosophy in The Texas A&M University, UMI dissertation information service, Michigan.

Autodesk, Inc., 1999, *Lightscape User's Guide*, USA.

ASHRAE HANDBOOK., 2001, *Fundamentals Handbook*, ASHRAE Inc, Atlanta

CHAM Ltd., 1999, *User Guide of Phoenix*, London
Lighting Handbook., 1993, Illuminating Engineering Society of North America, New York.

Chen Yu., 2002, *An investigation of the effect of shading with vertical landscaping in Singapore*, Proceedings of the IFPRA Asia-Pacific Congress, 21-24 October, 2002, Singapore, paper S4A2.

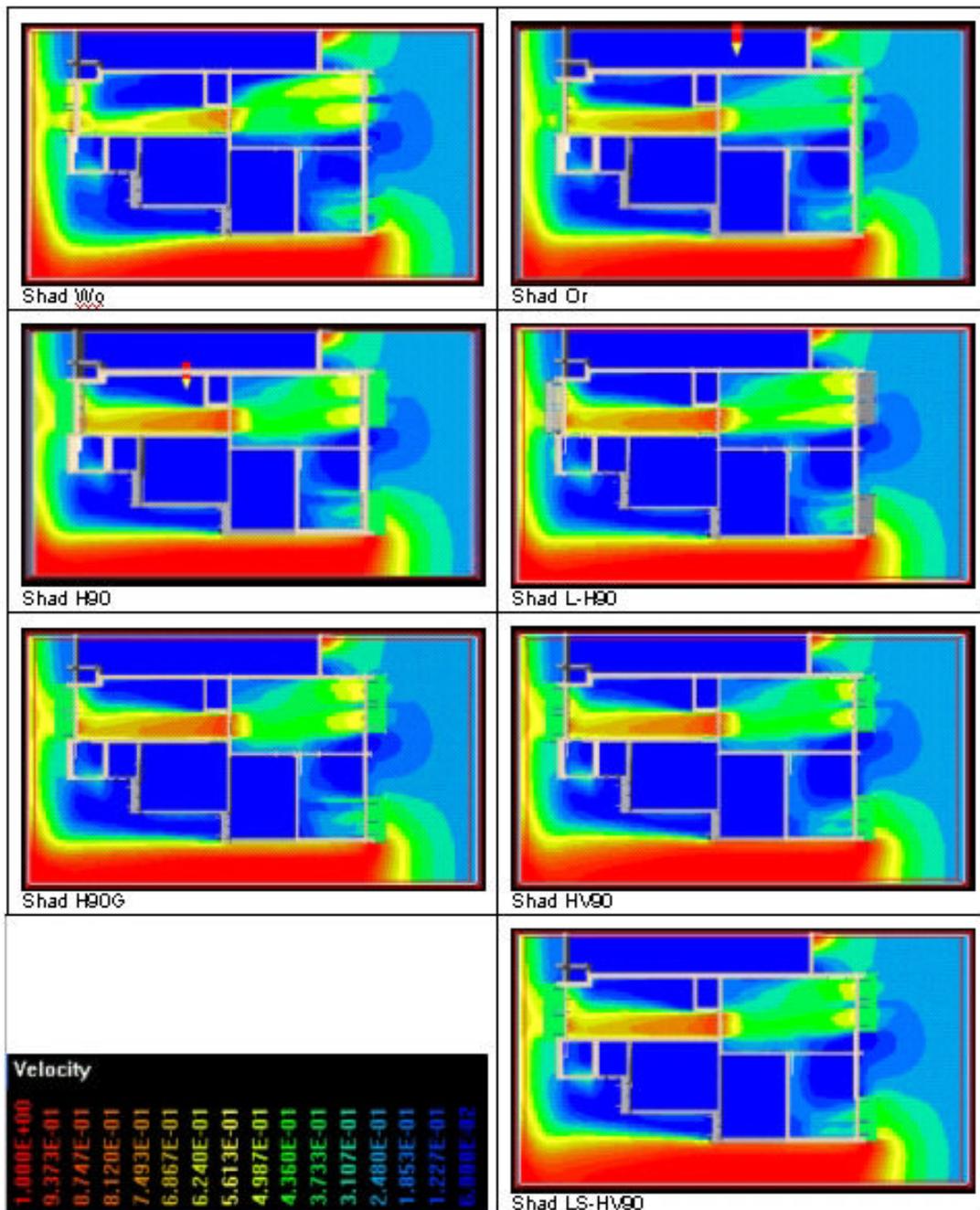


Figure 12: Velocity Contour on Horizontal Plane