DEVELOPMENT OF APPROACH TO OPTIMIZATION OF BUILDING ENVELOPE DESIGN IN ASPECT OF THERMAL COMFORT AND ENERGY USE

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ABSTRACT

This study examined the effect of building envelope on thermal comfort. The effects of key energy conservation measures, such as window/wall ratio, transmittance of fenestration glass and shading devices, were studied. The output from EnergyPlus was use to predict their influence on thermal comfort. Standard energy conserving measures proposed by ENVLOAD to reduce indoor thermal discomfort and cooling energy consumption were examined. This study proposes an approach which simultaneously optimizes both energy savings and thermal comfort. Employing this approach to optimize cooling set-point can optimize energy savings.

KEYWORDS

Building envelope, thermal comfort, energy saving.

INTRODUCTION

Lightweight construction designs have gained popularity in Taiwan, particularly the use of glass curtain walls or large windows. In summer, the interior surface of windows may increase dramatically due to absorption of incidental solar energy even though room air temperature may remain at a comfortable temperature. The indoor thermal environment, normally a major concern of occupants, is degraded by the large, hot surfaces of windows. Therefore, lowering indoor air temperature set-point, which gives the penalty of increasing energy consumption, is guaranteed to the comfort of occupants.. Conversely, the green building initiatives aim to achieve thermal comfort by minimizing energy consumption. A well-designed building envelope is considered the best approach to achieving this goal.

As in most other industrialized countries, the building envelope is defined in Taiwan by ENVLOAD [CPA 2003], an energy conservation index which is calculated by the following expression:

$$ENVLOAD = a \times \left[\frac{\sum_{i=1}^{k} (A_i \times \eta_i \times K_i \times IH_i)}{Aen} \right] + b \qquad (1)$$

where

η is the transmittance of glass;
K is the correction factor for a shading device;
IH is the insolation hours, in WH/m^2-yr;
A is the area of window, in m^2;
Aen is the area of building envelope, in m^2;
a, b are constant.

As equation (1) shows, the three key factors in ENVLOAD are window-wall-ratio, transmittance of fenestration glass and effect of shading device.

Unfortunately, most studies involving ENVLOAD focus on designing a building envelope to save energy rather than improve the indoor thermal environment. This study therefore examines the effect of building envelope on thermal comfort. The role of ENVLOAD in promoting thermal comfort is also examined.

SIMULATION

Methodology

A typical space was examined as a reference. Features of envelope design affecting cooling energy requirements and thermal comfort were identified. The EnergyPlus [Crawley *et al.* 2001] computer program was then run for parametric simulations by varying the values of chosen parameters over their specified range. The indoor climate data produced by each building envelope design were used as input to the Fanger comfort equation [ISO 1994] to measure thermal comfort.

The Fanger comfort equation was programmed into an EXCEL spreadsheet. Hourly EnergyPlus output was imported into the same spreadsheet to calculate hourly comfort indices . In order of better analysising this aspect of the problem, two index are here introduced: overheated hours and seasonal mean predicted percentage of dissatisfied(PPD). The overheated hours is simply the total hours of predicted mean votes (PMV) values over 0.5. The total overheated hours and seasonal mean PPD are evaluated as follows:

$$Overheated\ hours = \sum_{i=1}^{N} \Delta t_i \quad for\ PMV_i \geq 0.5 \qquad (2)$$

$$mean\ PPD = \sum_{i=1}^{N} \frac{PPD_i}{\Delta t_i} \qquad (3)$$

where PMV*i* and PPD*i* are the PMV and PPD values in the *i*th time period Δt_i. The examined time period was the hours of occupation during weekdays between April 1 and October 31.

Reference Space Description

The reference space is 5.0 m by 5.0 m square with walls 3.0 m high. One wall is exterior and facing west, and three walls are interior. A window is installed on the west façade. The construction characteristics of the floor, ceiling, exterior wall and interior walls are identical to those for a medium-weight construction shown in the ASHRAE Handbook of Fundamentals [ASHRAE 2001]. Internal heat gains from occupants, lighting and equipment were included in all calculations.

The cooling capacity of the HVAC system was automatically determined by the program EnergyPlus. Cooling capacity was the peak load of the space under ASHRAE summer design conditions for Taipei [ASHRAE 2001]. Typical Taipei weather was assumed for annual simulation.

Parameters Analyzed

Building envelope factors influencing cooling energy requirements and thermal comfort, including window-wall-ratio, transmittance and absorbance of fenestration glass, shading devices, glass conductance, thermal insulation and thermal mass of walls, floor and roof. For simplicity, the three ENVLOAD parameters, window/wall-ratio, transmittance of glass and shading device, were identified in the following parametric simulations.

Three curtains were selected to analyze the effect of shading devices on indoor thermal environment: light color curtain with η=0.7, medium color curtain with η=0.5 and dark color curtain with η=0.1. The two selected window sizes were 4.0mx3.0m and 4.0mx1.5m with corresponding window/wall ratios of 0.9 and 0.45, respectively. Table 1 shows thermal characteristic of seven generic windows .

Calculating PMV and PPD

As formulated by ISO 7730[ISO 1991], the Fanger equation is expressed in two comfort variables (*i.e.*, PMV and PPD). The PPD is given in terms of the PMV as

$$PPD = 100 - 95\exp[-(0.03353PMV^4 + 0.2179PMV^2)] \qquad (4)$$

The PMV is then related to six parameters by

$$PMV = f(Ta, \phi, v, Tmrt, Mw, Icl) \qquad (5)$$

The following summarizes the treatment or extraction of each parameter from the EnergyPlus hourly output.

Table 1 Thermal characteristic of seven generic windows

No	Description	Code	η^+	α^+
1	6mm clear	S-Clr	0.80	0.13
2	6mm green	S-Tin	0.49	0.46
3	6mm reflective	S-Ref	0.16	0.57
4	6mm Low-E	S-LoE	0.34	0.46
5	6mm clear, 6mm air gap, 6mm clear	D-Clr	0.65	0.24
6	6mm clear, 6mm air gap, 6mm green	D-Tin	0.39	0.51
7	6mm clear, 6mm air gap, 6mm Low-E	D-LoE	0.28	0.50

- Air temperature, *Ta*: This variable is determined by EnergyPlus output data.
- Relative humidity, ϕ: The zone relative humidity, also extracted from the EnergyPlus data..
- Relative air Speed, *v*: Since EnergyPlus cannot calculate zone air speed, *v* is treated as a constant 0.25 m/s; that is, the ASHRAE acceptable summer air speed.
- Metabolic rate, *Mw*: Specified as a constant 1.2 met, the metabolic rate for general office activity.
- Clothing index, *Icl*: Held constant at 0.6 clo, which is the insulation value of typical summer clothing.
- Mean radiant temperature, *Tmrt*: The mean radiant temperature is derived from the absolute surface temperature of the surrounding surfaces, *Ti*, and the angle factors between the person and the surrounding surfaces, F_{p-i}

$$T_{mrt}^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots + T_n^4 F_{p-n} \qquad (6)$$

In equation (6) the temperature of surrounding surfaces are extracted from the EnergyPlus output data. The angle factor can be computed as a function of width *a*, and height *b*, of the surface and as a function of the distance *c*, between the person and the surface, by the following equation: [Rizzo 1991]

$$F_{P-i} = F_{\max}[1 - e^{(a/c)/\tau}][1 - e^{(b/c)/r}] \qquad (7)$$

where

$$\begin{aligned} \tau &= A + B(a/c) \\ \gamma &= C + D(b/c) + E(a/c) \end{aligned} \qquad (8)$$

The coefficients *Fmax, A, B, C, D* and *E* are calculated for an occupant sitting along the centerline of the window. The occupant is seated 1.5 m away from the window.

DISCUSSION AND RESULTS

Environmental discomfort is usually due to solar radiation and outdoor temperature. Both factors affect the surface temperature of windows and surrounding, which significantly affect mean radiant temperature and thus comfort. Figure 1 shows the transmitted sun radiation and surface temperatures of seven generic windows with different curtains under ASHRAE's 1% cooling design condition of Taipei.

The surface temperature of windows is relatively higher than the outside air temperature. High absorbance glass such as single pane tinted glass and single pane reflective glass have inside surface temperatures of 42ºC or more while clear glass has an inside surface temperature of 35ºC due to low absorptance. The curtain also dramatically affects the inside surface temperature of the glass. However, the increased transmittance of the curtain limits temperature reduction.

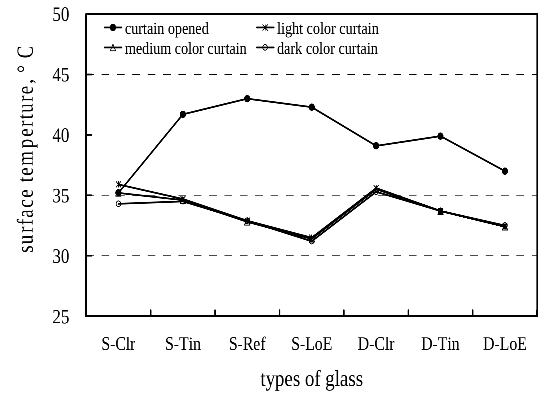

Figure 1 Variation in inside surface temperature for seven generic glass windows

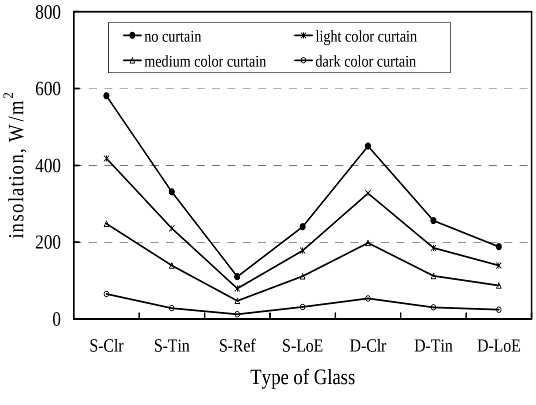

Figure 2 Variation in radiation transmission for seven generic glass windows

The significant variation in transmitted sun radiation in seven generic glass windows is due mostly to the effect of transmittance . Figue 2 shows that the increased transmittance of the curtain significantly dilutes solar radiation.

Figures 3-5 show the impact of varying values for identified parameters on thermal comfort.

As Fig. 3 shows, window/wall ratio clearly reduces overheated hours. As no curtain is used, the overheated hours eliminated in the seven generic windows are similar. The large window (WWR=0.9) has an average of 250 more overheated hours than the small window (WWR=0.45). The higher average is due to differences in solar radiation passing through the windows and somewhat to difference of the angle factors between large window and small window. Conversely, the patterns of overheated hours for both window sizes is different as medium color curtain is used. Window/wall ratio produces a difference of 250 overheated hours in clear glass cases, 150 hours in tinted glass cases and as few as 20 hours in low-E glass and reflective glass cases. Reduction in overheated hours is less dramatic in small windows with glass transmittance lower than 0.34 because the difference in sun radiation is less significant.

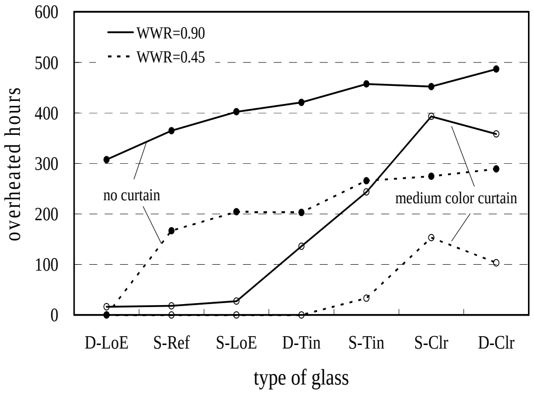

Figure 3 Effect of window/wall ratio on thermal comfort

As Fig. 4 shows, glass type affects oveheated hours . Figure 4 lists glass types in order of transmittance. The double loe-e glass had minimum transmittance, but it did not exhibit minimum oveheated hours due to the absorbtance affecting the inside surface temperature of the glass. As Fig. 1 shows, the inside surface temperature of double low-e glass is 37ºC, which is 6ºC less than that of single reflective glass. The decreased inside surface temperture tends to diminish the discomfort effect of radiation through the window. Figure 4 also shows that overheated hours increase with increasing transmittance of glass. Excluding double low-e glass, the change in

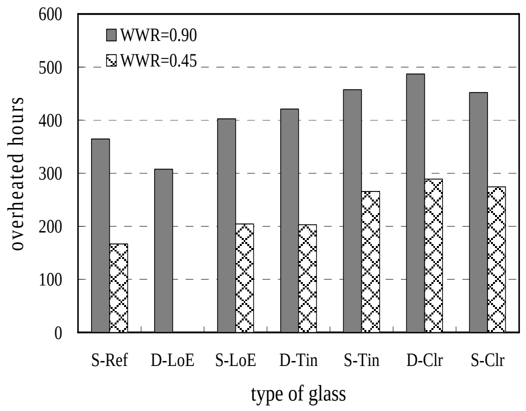

Figure 4 Effect of glass transmittance on comfort

overheated hours is approximately 180 hours for both large and small window areas.

Figure 5 shows that the overheated hours is very sensitive to specific combinations of glass type and curtain type. At WWR=0.90, the number of overheated hours in single reflective glass or double low-e glass was below 50 hours when curtains are used, even with transmittance as high as 0.7 (light color). Where overheated hours is zero, such as in the combination of double low-e glass and light colored curtain, further energy-saving is still possible by allowing increased air temperature without sacrificing thermal comfort. However, in single clear glass, the overheated hours are still approximately 100 hours even though a dark colored curtain (transmittance =0.1) is used. This indicates that the only way to reduce discomfort is by lowering air temperature in the space, which thus increases energy consumption of the air conditioning system. Therefore, choosing the appropriate combination of glass and curtain is important not only for thermal comfort but also for energy conservation.

Comfort trends versus energy savings measures were also examined, as Figs. 6-7 illustrate.

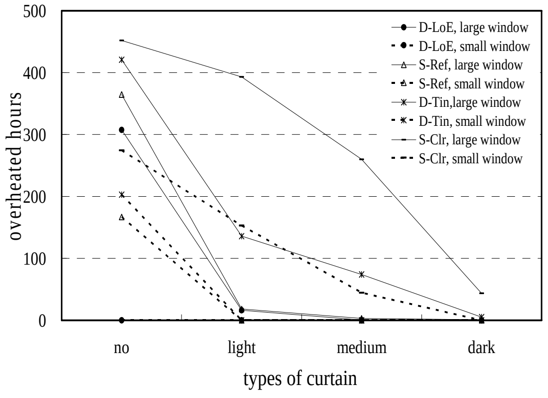

Figure 5 Effect of shading device on comfort

Figure 6 estimated overheated hours against seasonal mean PPD for entire cases consisting of fifty-six runs of the EnergyPlus programs. Figure 5 demonstrates that no overheated hours are observed when the seasonal mean PPD is lower than 13%. This means that occupant discomfort does not happen in the range of seasonal mean PPD<13%. When seasonal mean PPD>13%, the value of overheated hours increases linearly against seasonal mean PPD untilit reaches 20%. In the range of seasonal mean PPD>20%, the value of overheated hours also increases linearly but the increase is gradual over the period.

Figure 7 displays the linear relationship established between mean PPD and ENVLOAD. The R^2 value for the fitted line is 0.8889 and significant. The ENVLOAD benchmark is 80 KWH/m^2-yr. As Fig. 6 illustrates, the seasonal mean PPD at benchmark value is approximates13%, indicating no discomfort. This implies that a building envelope met the energy conservation benchmarks of ENVLOAD also ensure no discomfort occurrs in the cooling season.

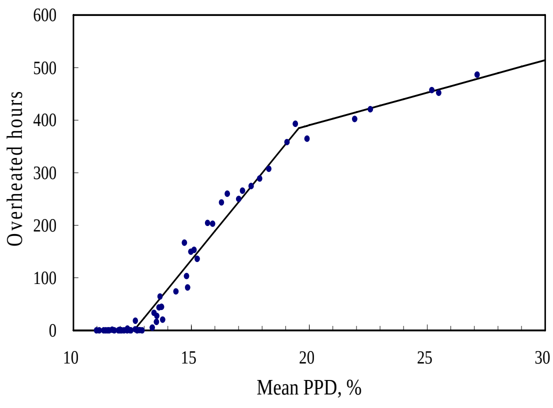

Figure 6 Overheated hours against seasonal mean PPD

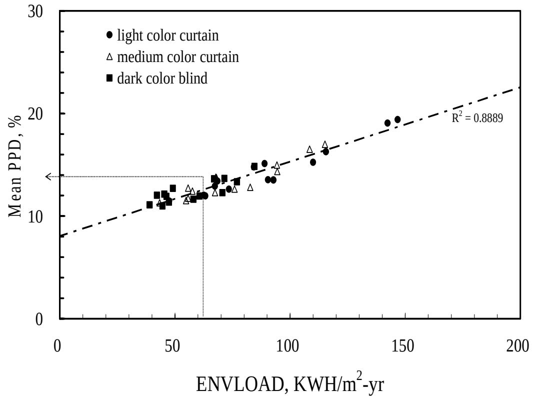

Figure 7 Relationship between energy conservation measures and seasonal mean PPD

The above discussion and simulation results assume a 24ºC cooling set-point.However, a more practical solution is setting a cooling set-point limit above which air temperature adjustment for energy savings is inadvisable . If the actual cooling set-point for a built environment is below the specified limit, then additional energy conservation measures may be implemented, but indoor thermal comfort attained would remain at the same level, i.e., no overheated hours are observed. Table 2 displays the additional energy saving models examined in RUN #1 and RUN #2 .

Table 2 Energy and comfort comparison of two cases

item	RUN #1	RUN #2
ENVLOAD	70	90
Cooling set-point temperature=24ºC		
Cooling energy	65.8	71.7
Mean PPD	5.9%	7.4%
Cooling set-point temperature=25ºC		
Cooling energy	58.8	67.3
Mean PPD	9.9%	12.8%
Cooling set-point temperature=26ºC		
Cooling energy	54.5	62.7
Mean PPD	12.9%	21.1%

Unit: ENVLOAD in KWH/m^2-yr; Cooling energy in KWH/m^2-yr

The RUN#1 model had an ENVLOAD value of 70 KWH/m^2-yr while the RUN#2 had a value of 90 KWH/m^2-yr. The cooling set-point temperatures were increased from a base of 24ºC to 26ºC. Although seasonal mean PPD increased progressively over the period, Run #1 exhibited an opportinuty of energy savings until 26ºC. Additional savings of 11.3 KWH/m^2-yr (about 17%) cooling energy were observed. In RUN#2, the only energy savings, 4.4 KWH/m^2-yr (about 4%) cooling energy, occurred 25ºC. However, with a well-designed building envelope, total savings of 12.8 KWH/m^2-yr cooling energy was achievable.

CONCLUSION

In this study, the concept of PMV-PPD was employed to assess the performance of building envelopes. Among the envelope parameters, those affecting solar transmission were also found to significantly affect indoor thermal comfort. These parameters, window wall ratio, transmittance of fenestration glass and shading device, are also the key features of the ENVLOAD standard energy conserving measures in Taiwan.

This study also examined whether ENVLOAD energy conserving measures can be applied for optimizing thermal comfort. To explore this inference, hourly EnergyPlus output were correlated with thermal comfort indications .A significant linear correlation between ENVLOAD and mean PPD was observed. Thus, ENVLOAD can be employed for both energy conservation as well as thermal comfort.

The two example runs verified that additional energy conservation can be achieved if building envelope and cooling set-point of air temperature are considered in building design.

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