Study of the Effectiveness of Solar Heat Gain and Daylight Factors on Minimizing Electricity Use in High-rise Buildings

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Abstract—Over half of the total electricity consumption is used in buildings. Air-conditioning and electric lighting are the two main resources of electricity consumption in high-rise buildings. One way to reduce electricity consumption would be to limit heat gain into buildings, therefore reducing the demand for air-conditioning during hot summer months especially in hot regions. On the other hand, natural daylight can be used to reduce the use of electricity for artificial lighting. In this paper, effective factors of minimizing heat gain and achieving required daylight were reviewed. As daylight always accompanied by solar heat gain. Also interactions between heat gain and daylight were discussed through previous studies and equations which are related to heat gain and daylight especially in high-rise buildings. As a result, importance of building’s form and its component on energy consumption in buildings were clarified.

Keywords—High-rise buildings, Energy demand, Daylighting, Heat gain

I. INTRODUCTION

The overall thermal transfer value (OTTV) and daylighting are two main parameters for controlling building energy use [1].

Air-conditioning and electric lighting are the two main factors for electric use in cooling-dominated office buildings [2]. Recent studies revealed that air-conditioning and artificial lighting represent 50-60 percent and 20-30 percent, respectively, of total electricity use in buildings [3].

The OTTV is basically a measure of the heat transfer from outside to the indoor environment through the external envelope of a building. Solar heat gain through fenestration is considered as the largest provider of building envelope cooling load and the most important parameter for OTTV determinations [4].

In recent years, there has been an increasing interest in using daylight to save energy in buildings [1]. It has been pointed out that in tropical and subtropical regions, daylighting is always an energy saver [5].

Energy savings resulting from daylighting mean not only low electric lighting and reduced peak electrical demands, but also reduced cooling requirements and potential for smaller heating, ventilating and air-conditioning (HVAC) equipment size. Daylight, however, is always accompanied by solar heat gain. An increase in the OTTV and hence cooling requirement due to a bigger glazing area could be compensated from daylight-induced energy savings. However, daylight is always accompanied by solar heat gain. When the illuminance level exceeds the design requirement, the benefits from daylight will be penalized by the increased solar heat gains which will increase the cooling load [6].

Performance of the building envelopes was investigated in terms of the overall thermal transfer value (OTTV) [7].

The OTTV concept was introduced in the ASHRAE Standard 90A-1980. OTTV shows the average heat gain through the building envelope. Smaller OTTV cause less energy consumption for cooling. Three components of the heat gain are considered, namely conduction through an opaque surface, conduction through glass window and solar radiation through glass window. The general OTTV equation can be expressed as [8].

\[ OTTV = \frac{(Q_w + Q_d + Q_s)}{A_i} = \left(\frac{(A_w \times U_w \times TD_q + (A_f \times U_f \times DT) + (A_f \times SC \times SF)}/A_i\right) \]

\( A_f \) is the area of fenestration (\( m^2 \));

\( A_i \), the gross area of the walls (\( m^2 \) = \( A_w \) + \( A_f \);

\( A_w \), the area of opaque wall (\( m^2 \));

\( DT \), the temperature difference between exterior and interior design conditions (\( C \));

\( Q_d \), the heat conduction through glass windows (\( W \));

\( Q_s \), the solar radiation through glass windows (\( W \));

\( Q_w \), the heat conduction through opaque walls (\( W \));
SC, the shading coefficient (dimensionless);
SF, the solar factor (W/m2);
$TD_\epsilon q$, the equivalent temperature difference (C);
$U_f$, the U-value of fenestration (W/m2K);
$U_w$, the U-value of opaque wall (W/m2K).

This equation can be expressed in terms of window-to-wall ratio, WWR. Thus

$$OTTV = [(1 - WWR) \times TD_\epsilon q \times U_w] + [(WWR) \times DT \times (U_f)] + [(WWR) \times SC \times SF]$$

Where, WWR is the ratio of window area to gross wall area = $A_w/A_f$.

As walls at different orientations receive different amounts of solar radiation, the general procedure is to calculate the OTTV of individual walls with the same orientation and construction first [8].

$$OTTV_{wall} = [A_1 \times OTTV_1 + A_2 \times OTTV_2 + \ldots + A_n \times OTTV_n]/A_{ww}$$

Where,

$$OTTV_{wall}$$

is the OTTV of the whole exterior wall (W/m2) and

$$A_{ww} = S(A_i) = \text{total gross exterior wall area} \ (m^2)$$

[8].

It has been shown that among the three components of heat gain in the OTTV equation, solar radiation through the fenestration is the most significant [4].

The building variables controlling solar heat gain are SC and window-to-wall ratio (WWR), which are two parameters in the OTTV calculation. Large WWR means high $Q_g$ and low $Q_w$, and vice-versa.

It should be pointed out that excluding $Q_g$ in OTTV determination may lead to an underestimation of total building envelope heat gain, particularly for curtain-walled buildings with full floor-to-ceiling height glazing. More solar heat gain contributes to more cooling requirements and hence larger air-conditioning plants [9].

Higher solar heat gain, however, could also mean more daylight available for a day lighting scheme. There is a scope for integrating daylight with electric light to save building energy use. It is argued that the increased cooling load and electricity expenditures caused from larger window areas could be offset by daylight-induced savings.

II. METHODOLOGY

In this paper all parameters that can effect on energy consumption especially heat gain through envelope were investigated with using Overall Thermal transfer value equations based on previous research then several suggestion for reduction heat gain were represented. In addition each parameter of OTTV equation were clarified and correlation between energy consumption, heat gain and daylight were contemplated to appear the effect of heat gain, day light and interaction between them on minimizing energy consumption.

III. FINDING AND DISCUSSION

It’s clear for reduction energy consumption in buildings especially in high rise buildings that have much area against solar radiation, the amount of OTTV (Overall Thermal Transfer Value) should be reduced.

Lam (1994) revealed that The OTTV is basically a measure of the heat transfer from outside to the indoor environment through the external envelope of a building [4].

To reduce the amount of OTTV, Three component of OTTV were investigated. Conduction through an opaque wall is one of component of OTTV equation and it is considered as $Q_w$.

$$Q_w = A_W \times U_W \times TD_\epsilon q$$

A. Wall Area ($A_W$) and Fenestration Area ($A_f$)

The area of each envelope in each orientation is one of important parameters that can influence on the amount of heat conduction through opaque wall. However the area of wall depend on designing envelope and it’s obvious that if the amount of $A_W$ become less, the heat conduction through opaque wall decreases but with respect to

$$A_2 = A_w + A_f$$

and $A_1$ is a fix number. Reduction area of opaque wall means increasing the area of fenestration.

Also U-values of different types of glass such as clear, tinted and reflected glass are 6, 6.2 and 5.6 respectively, with compare to U-value of common opaque wall (30mm Concrcrete) with 2.4 the U-value of glass is more than U-value wall thus despite of reduction the amount of heat conduction through opaque wall with decreasing area of wall, the amount of heat conduction through fenestration and also solar radiation through glass increase.

It means decreasing the area of wall that causes increasing window area, not only does not reduction overall thermal transfer but also it causes increasing overall thermal transfer value.

In addition according to OTTV equation and definition of WWR That is the ratio of window area to gross wall. It’s clear that with increasing WWR the amount of OTTV increase.

B. U-value of Opaque Wall ($U_W$) and U-value of Fenestration ($U_f$)

U-value of opaque wall also can effect on the amount of OTTV. Less U-value means less heat conduction through opaque wall hence it cause the less amount of OTTV. External walls usually had 125 – 250mm thick concrete, mostly with mosaic/ceramic tiles applied to cement render and without any thermal insulation.
U-value ranged typically from 2.2 to 2.9 W/m².K, depending on the thickness of concrete and the type of surface finish. If insulation materials attach to the external walls the amount of U-value decrease significantly as well.

C. Temperature Difference Between Exterior and Interior Design Conditions (DT)

As DT is the temperature difference between exterior and interior design conditions (C) and in door average temperature is around 22°C thus the amount of DT is depend on average of outdoor temperature. If the differences between outdoor and indoor temperature become less hence the heat conduction through opaque wall become less.

D. Equivalent Temperature Difference (TD_eq)

If the the amount of TD_eq decreases, the heat conduction through opaque wall deceases as well. TD_eq Equivalent temperature difference considers both the conduction heat gain due to the temperature difference between the indoor and the outdoor environment and the effect of solar radiation on opaque surfaces (e.g. external walls). TD_eq is determined as follows: [10]

\[ TD_{eq} = DT + [a \times R_{so} \times \text{avg}(I_t)] \]

where \( a \) is absorption coefficient of the opaque wall surface and \( R_{so} \) is defined as outside surface resistance (m²K/W) [10]. In addition these parameters depends on characteristics and way of finishing of external wall. The less a and \( R_{so} \) means less \( TD_{eq} \) hence it cause less heat conduction through opaque wall and finally less OTTV. 

\( I_t \) is defined solar intensity falling on the surface and \( I_t \) also can effect on energy use in buildings for cooling. For reduction the amount of heat conduction through fenestration, the amount of area of fenestration, U-value of fenestration and DT have significant role. with reduction the amount of each factor of these factors, the amount of OTTV decreases and vice-versa.

E. Shading Coefficient (SC) and Solar Heat Gain Coefficient (SHGC)

Among the three components of heat gain in the OTTV equation, solar radiation through the fenestration is the most significant [4].

The building variables controlling solar heat gain are SC and window-to-wall ratio (WWR), which are two parameters in the OTTV calculation. Large WWR means high \( Q_s \) and low \( Q_w \), and vice-versa. It should be pointed out that excluding \( Q_w \) in OTTV determination may lead to an underestimation of total building envelope heat gain, particularly for curtain-walled buildings with full floor-to-ceiling height glazing. More solar heat gain contributes to more cooling requirements and hence larger air-conditioning plants [11].

Solar radiation through fenestration depends on \( A_f, SC \) and \( CF \).

The shading coefficient (SC) was the primary term used to characterize the solar control properties of the glass in windows. Although it is being replaced by the solar heat gain coefficient (SHGC). It is still referenced in books and product literature.

The shading coefficient (SC) is only defined for the glazing portion of the window and does not include frame effect. It represents the ratio of solar heat gain through the system relative to that through 3mm clear glass at normal incidence. The shading coefficient is expressed as a dimensionless number from 0 to 1. A high shading coefficient means high solar gain, while a low shading coefficient means low solar gain.

For any glazing, the SHGC is always lower than the SC. To perform an approximate conversion from SC to SHGC, Multiplying the SC value by 0.87.

Window standards are now moving away from use of shading coefficient to solar heat gain coefficient, which is defined as that fraction of incident solar radiation that actually enters a building through the window assembly as heat gain. The SHGC is influenced by all the same factors as the SC, but since it can be applied to the entire window assembly, the SHGC is also affected by shading from the frame as well as the ratio of glazing and frame. The solar heat gain coefficient is expressed as dimensionless number from 0 to 1.

A high coefficient signifies high heat gain, while a low coefficient means low heat gain.

According to ASHRAE (2007) Fenestration solar heat gain has two components. First is the directly transmitted solar radiation. The quantity of radiation entering the fenestration directly is governed by the solar transmittance of the glazing system. Multiplying the incident irradiance by the glazing area and its solar transmittance yields the solar heat entering the fenestration directly. The second component is the inward-flowing portion of the absorbed solar radiation, radiation that is absorbed in the glazing and framing materials of the window and is subsequently conducted, convected, and radiated to the interior of the building [12].

Absorbed solar radiation, including ultraviolet, visible, and infrared radiation from the sun and sky, is turned into heat inside the absorbing material. In a window, the glazing system temperature rises as a result to some approximately equilibrium value at which the energy gains from absorbed radiation are balanced by equal losses. The absorbed solar radiation is dissipated through conduction, convection, and radiation [12].

Some heat goes outside the building, and the remainder goes inside, adding to the directly transmitted solar radiation. The magnitude of what is called the inward-flowing fraction \( N_i \) of the absorbed radiation depends on the nature of the air boundary layers adjacent to both sides of the glazing, including any gas between the panes of a multiple-pane glazing system [12].

\( N_i \) is often used to distinguish the inward-flowing fraction from the outward flowing fraction, \( N_o \). However, because only the inward-flowing fraction is used here, the subscript \( i \) is dropped for simplicity [12].

The concept of the solar heat gain coefficient is best
illustrated for the case of a single glass pane in direct sunlight. Let 
\[ E_D \] be the direct solar irradiance incident upon a single pane 
of glass,

\[ T \] be its solar transmittance, 
\[ A \] be the solar absorptance and 
\[ N \] be the inward-flowing fraction of the absorbed radiation. 
In this case, the total solar gain (heat flow per unit area) \( q_b \) 
that enters the space due to the incident solar radiation is 
\[ q_b = E_D \times (T + N \times A) \]
in units of energy flux per unit area, \( W/m^2 \). The quantity in 
parenthesis in Equation is called the solar heat gain coefficient 
\( (SHGC) \).

It is the fraction of incident irradiance that enters through 
the glazing and becomes heat gain. It includes both 
the directly transmitted portion and the absorbed and reemitted 
portion:

\[ SHGC = T + NA \]

The \( SHGC \) is needed to determine the solar radiant heat 
gain through a window’s glazing system. The \( SHGC \) for cer-
tain defined conditions of spectrum and incident angle should 
be included along with U-factor and other instantaneous 
performance properties in any manufacturer’s description of a 
window’s energy performance. Because the optical properties 
\( A \) and \( T \) vary with the angle of incidence [defined as the 
angle between the rays incident on the glazing and the normal 
(perpendicular) to the glazing], according to Equations, the 
solar heat gain coefficient is also a function of angle of 
inidence. [12].

Besides all parameters, \( WWR \) and \( SC \) have magnitude 
effect on value of \( OTTV \). They are the more dominant design 
variables as solar radiation accounts for most of the building 
envelope [13].

The shading coefficient \( (SC) \) dominates solar gains and thus 
affects the peak cooling demand and energy consumption of 
a building. 

It means if the amount of \( SHGC \) can be reduced if the 
proper strategy like external shading device or self shading 
strategy used for obstacle incident irradiance.

\section*{G. Light Transmittance (LT)}

Light transmittance also referred to as visible light trans-
mittance, is the visible portion of the spectrum that passes 
through a glazing material.

A higher \( LT \) means there is more day light in a space which, 
if designed properly, can offset electric lighting and cooling 
loads due to lighting. Visible transmittance is influenced by 
the glazing type, the number of layers, and any coating that 
might be applied to the glazing ranges from above 90 percent 
to less than 10 percent for highly reflective coating on tinted 
glass.

The light transmittance \( (LT) \) of the fenestration controls the 
indoor daylight availability, and offsets the electric lighting 
energy and cooling requirements due to sensible heat gain 
from the artificial lighting system. [14].

\section*{H. Solar Aperture (SA) and Day Light Aperture (DA)}

Solar aperture is defined as the \( WWR \) times \( SC \). Solar 
aperture indicates the proportion of incident solar that enters 
the zone as heat gain.

Day lighting aperture is the product of \( WWR \) and \( LT \) of 
the window glass and equal to \( WWR \) times \( LT \) [5].

Day lighting aperture determines the amount of daylight 
entering a building and it directly affects the performance of 
A day lighting design. [14].

\section*{I. Electricity Use}

Peak electricity demand determines the maximum loads and 
and is useful for plant and equipment sizing. Initial costs and op-
erating strategies are affected by the maximum demands, even 
though building energy consumption may not be significantly 
affected.

Incremental electricity use is defined as the difference 
between the consumption with windows and the consumption 
without windows.

According to Li(2002) There is a correlation between 
total electricity use (IEU) and \( OTTV \). 
This correlation shows the effect of heat gain on energy 
consumption in buildings. \( IEU_0 \) for all perimeter zones can 
be expressed in term of \( OTTV \) as follow: [14]

\[ IEU_0(\text{inMWh}) = 30.7(OTTV - 30) \]

The critical variable determining the solar heat gains and 
the amount of daylight entering a building is the glazing area. 
A large window area means more cooling requirements due 
to an increase in solar radiation and also less electricity for 
lighting 
two parameters, namely solar aperture \( (SA) \) and day lighting 
aperture \( (DA) \), were used for interaction between heat gain 
and day light.

There is a correlation between \( PED \) (Peak Electricity Use) 
and \( SA \).

The \( PED \) (Peak Electricity Use) can be expressed in term of 
\( SA \) as follow:

\[ PED = 2562.9SA + 4101.3(KW) \]
There is a correlation between $IEU$ (Incremental Electricity Use) and $SA$.

The $IEU$ (Incremental Electricity Use) can be expressed in terms of $SA$ as follow:

$$IEU = 4713SA (KWh)$$

There is also another correlation between $PED$ (Peak Electricity Use) and $DA$.

$PED$ (Peak Electricity Use) can be expressed as a cubic function of $DA$ as follow:

$$PED = -15.023DA^3 + 17.488DA^2 - 3880DA + 4162 (KW)$$

Also there is another correlation between $IEU$ (Incremental Electricity Use) and $DA$.

$IEU$ (Incremental Electricity Use) can be expressed as a cubic function of $DA$ as follow:

$$IEU = 1676(e^{-7.3DA} - 1)$$

The ratio of light transmittance to shading coefficient, is a measure of the energy efficiency of a particular glass type in terms of the day lighting potential and likely impact on cooling load [15].

Nevertheless, $K_e$ provide an indication of the likely energy efficiency and the optimum solar and day lighting apertures [14].

The ratio of $OTTV$ to $DA$ ($OTTV/DA$), which modifies the ratio of $LT$ to $SC$, can be used to measure the energy efficiency of a particular building envelope design in terms of day lighting potential and the likely impact on cooling energy.

The same $OTTV/DA$ can be obtained with different combinations of $DA$ and $OTTV$. For a fixed $OTTV/DA$ value, the energy performance can vary a great deal.

This indicates that $OTTV/DA$ in itself is not a sufficient parameter to determine energy performance. Nevertheless, $OTTV/DA$ can provide an indication of the likely energy efficiency and the optimum $OTTV$ and $DA$ [1].

IV. Conclusion

Among a lot of parameters that can effect on energy consumption in buildings especially high rise buildings, $WWR$, $SHGC$ and $LT$ have important role in amount of heat and day light enter in to space of building and they have significant effect on electricity use in buildings.

There is a correlation between the annual incremental electricity use and $OTTV$, also there are correlations between $IEU$ (Incremental Electricity Use) and $PED$ (Peak Electricity Use) with day lighting aperture ($DA$) and $SA$ Solar aperture.

Also $SA$ and $DA$ indicate the amount of heat gain and day light respectively and the correlation between them and $IEU$ and $PED$ shows the interaction between them.

In addition preventing solar incidence with using external shading devices or self shading strategy can intervene on $SHGC$ hence $OTTV$, so these strategies play fundamental role in minimizing energy consumption in buildings especially high rise buildings. Energy savings mean not only low electric for cooling and lighting but also it causes the potential for smaller heating, ventilating and air-conditioning plants.

REFERENCES


