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ENERGY CONSUMPTION RATES DUE TO WINDOWS, ON LIGHTING AND COOLING

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Abstract - This paper reports on an experimental study dealing with the effects of an automatic shading device on the energetic performance of a dimmable lighting system and on a cooling system. Some equations related to fenestration thermal properties are reformulated under a theoretical approach. In order to collect field data, energy demands and other variables were measured at the "Test Tower" on two distinct floors with identical fenestration features. New data were gathered after adding an automatic shading device to the window of one of the floors. The energetic performance evaluation of the shading device is made possible by comparing the collected data.

1. INTRODUCTION

Among final uses of energy in buildings in general, lighting and air conditioning are those that present the highest levels of consumption. Windows have been traditionally held as one of the most influential factors in high-energy consumption rates due to air conditioning systems. After the appearance of dimmable lighting systems, windows have increasingly been seen as a source of conservation, provided advantage of natural lighting is taken. This is bringing about a change in the very concept of windows, and the equation of energy flows becomes more complex if other final uses are taken into consideration.

Lynes [1] poses the question in terms of "effects" of the windows, namely: admission of sunlight, admission of daylight, heat loss, solar gain, evenness of natural light indoors, view, sky glare, privacy, natural ventilation and composition of facades.

Of the effects listed above, this paper deals with those which are energetic. Their significance is supported by Bevington; Rosenfeld [2]: "Most windows do not insulate well: they lose heat to the outdoors during the winter and admit excessive solar radiation into a building during the summer and thus account for 25 percent of all heating and cooling requirements in the U.S."

As the role of windows in relation to energy consumption has been duly emphasized, the next items briefly describe a research executed in the Building Systems Laboratory of the Escola Politécnica at the University of São Paulo

(EPUSP), and also the theoretical formulation, the experiment arrangements and the results obtained with a reference window and a shading device. The principal objective of the project was the integration of building systems for total energy performance analysis.

2. THEORETICAL BASES: EQUATIONING OF LIGHT AND HEAT IN WINDOWS.

The equationing of the interaction between natural light and electric power of artificial lighting as a function of fenestration refers to a single optical phenomena, whereas the formulation of thermal gains involves two components: the portion that refers to the conduction, convection and radiation of window glass and that which refers to the direct transfer of heat by solar radiation.

2.1. Lighting

One of the first graphic formulations about the electric power behavior of dimmable lighting systems is found in Gillette [3], although there is no quantitative proposal. The figure below includes some of the variables for an estimate of this power.

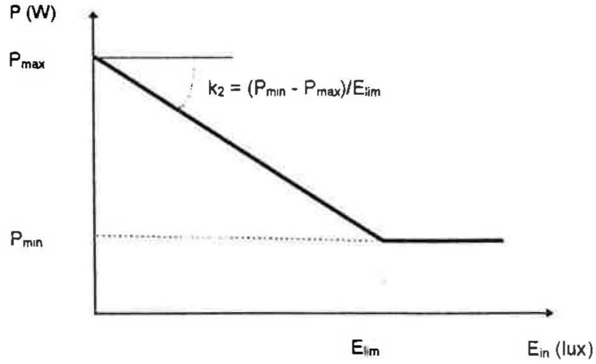

Fig. 1 - Electric power and natural lighting

In the figure above, the electric power of the system (P), which varies between a maximum corresponding value of the user setting at night and a minimum value (inferior limit of the technology), appears as a function of natural illuminance (E_{in}). For the largest usable natural contribution (E_{lim}) power will be at a minimum.

To this effect, the equation hereby proposed to represent the curve above is:

$$P = P_{max} + k \times I_t \qquad (1)$$

where

P instantaneous electric power, W;

P_{max} maximum electric power, W;

k angular coefficient;

I_t total solar radiation, W/m^2.

The angular coefficient, k, can be put as a function of the daylight factor and the luminous efficacy of the solar radiation. But today the daylight factor has several approaches and is very questionable. As regards the luminous efficacy, databases are required, no matter how rare.

2.2. Heat gains by conduction, convection and radiation through the window glass

This heat gain is calculated by means of the overall heat transfer coefficient (U-value) of the window glass area and the difference in temperatures of the exterior and interior air. The U-value is equated as follows:

$$U = 1 \Big/ \left(1/h_i + e/k + 1/h_o \right) \qquad (2)$$

where

U overall heat transfer coefficient (U-value), W/m^2 °C;

h_i inside glass surface combined radiation and convection effect, W/m^2 °C;

e glass thickness, m;

k thermal conductivity, W/m °C;

h_o outside glass surface combined radiation and convection effect, W/m^2 °C.

The estimates of the surface coefficients of the above equation have been improving. For the internal coefficient, ASHRAE [4] proposes:

$$h_i = h_{ci} + h_{ri} = A\left(T_g - T_i\right)^{0.25} + \left[e_g \times \sigma\left(T_g^4 - T_i^4\right)\right] \Big/ \left(T_g - T_i\right) \qquad (3)$$

where

h_{ci} inside glass surface convection coefficient, W/m^2 °C;

h_{ri} inside glass surface radiation coefficient, W/m^2 °C;

A = 1.77

T_g temperature of the glass, K;

T_i inside air temperature, K;

e_g hemispherical emittance of room side glass surface;
σ Stefan-Boltzmann constant.

For the outside coefficient, h_o, ISO, *apud* Curcija; Ambs; Goss [5], considers just the wind effect:

$$h_o = 10 + 4.1 \times v \tag{4}$$

where v is the wind speed (m/s).

Then the gains through windows by conduction, convection and radiation of glass is obtained as follows:

$$q_{ccr} = U \times A_g \times \Delta T \tag{5}$$

where
q_{ccr} thermal load due to conduction, convection and radiation, W;
U overall heat transfer coefficient (U-value), W/m^2 °C;
A_g glass area, m^2;
ΔT temperature difference between outdoor and indoor air, °C.

2.3. Heat gains by solar and total radiation through the glass

The heat gains by radiation is obtained by multiplying radiation, window glass area, energy fraction passing through the window glass (denominated Solar Heat Gain Coefficient, for example) and the Cooling Load Factor, the latter expressing the time gap in which the heat gain turns into thermal load. Then, the thermal load due to direct radiation through the glass area is obtained as follows:

$$q_r = SHGC \times A_g \times I_t \times CLF \tag{6}$$

where
q_r thermal load due to direct solar radiation, W;
$SHGC$ Solar Heat Gain Coefficient;
A_g glass area, m^2;
I_t solar total radiation, W/m^2;
CLF Cooling Load Factor.

Thus the total thermal load due to the glass q (W) will be:

$$q = q_{ccr} + q_r \tag{7}$$

Total energy consumption can be estimated when the thermal load due to the glass is divided by the cooling system coefficient of performance (*COP*).

3. RESEARCH METHODOLOGY

This experimental, comparative research took place on two distinct floors of the "Test Tower" in the Building Systems Laboratory of the Department of Civil Construction Engineering of EPUSP. Each floor contains two windows and both floors are 2.55 m high, 4.13 m wide, and 3.78 m deep. During this research, an automatic shading device (Fig. 2) was installed and the field data on lighting and cooling were collected.

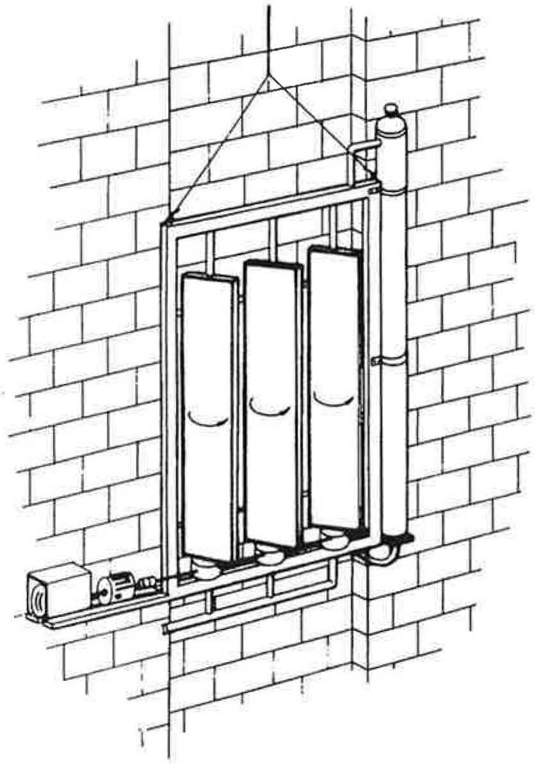

Fig. 2 - Automatic Shading Device in front of the Third-Floor window of the "Test Tower".

Starting up was done with a step motor controlled by a computer program, which has the following variables: latitude and longitude of the place, day of the year and direction of the building facade. Calculations are carried out in solar time.

Tracking the sun was intended to prevent direct solar radiation from penetrating in the ambient. On the one hand, the shading device keeps the users from seeing the sun through the window, which would cause discomfort due to the glare from the too high luminance. On the other hand, it avoids the greenhouse effect of direct radiation and prevents this radiation from being absorbed by elements of the building and furniture and later radiated in long wavelengths, such as infra-red, which does not cross the glass back. However, when in the rest position, the device allows maximum solar radiation if users wish so.

Installed on the 3rd floor of the "Test Tower" are 128 W of dimmable fluorescent lighting and a 10,000 Btu cooling system. The 5th floor, besides a similar cooling system, is provided with the very same type of window as that on the 3rd floor and has the same characteristics, except for their ballasts, which are not dimmable. All ballasts used were electronic.

Data were collected minute by minute with the aid of a building automation system, which made it possible to monitor the electric lighting and cooling powers with the existing reference window (4 mm thickness clear glass) before and after the automatic shading device was installed.

Using certain instruments it is possible to evaluate heat gains and visible light through windows. This study included the following instruments: radiometer, photovoltaic cells, temperature sensors, power transducers, voltage transducers, air speed sensor and a building automation system with operator workstation, network control unit and field controllers.

Voltage transducers are useful for conditioning signals from photovoltaic cells and radiometer. Radiation measurement with such cells is limited because they register wavelengths just a little beyond what is visible. However, regressions between the signals generated by these two types of instruments presented a correlation coefficient, R^2, of around 0.97. Direct measurement of the energy for air-conditioners and lighting systems was possible due to the electric power transducers.

4. EXPERIMENTAL RESULTS

A summary of tests results with and without the automatic shading device is presented below. The weather conditions under which the experiments occurred - cloudy and partly cloudy skies - did not allow the efficiency of the device to achieve optimal status, considering the two final uses under study.

4.1. Experiments with dimmable lighting

Before testing the automatic shading device was done, the performance of dimmable lighting was verified using just the reference glass of the windows. At the same time, some theoretical hypotheses were developed. The main one assumes the instantaneous electric power of the lighting system to be a function both of its own characteristics and solar radiation, such as in equation (1) above. Fig. 3 shows the results.

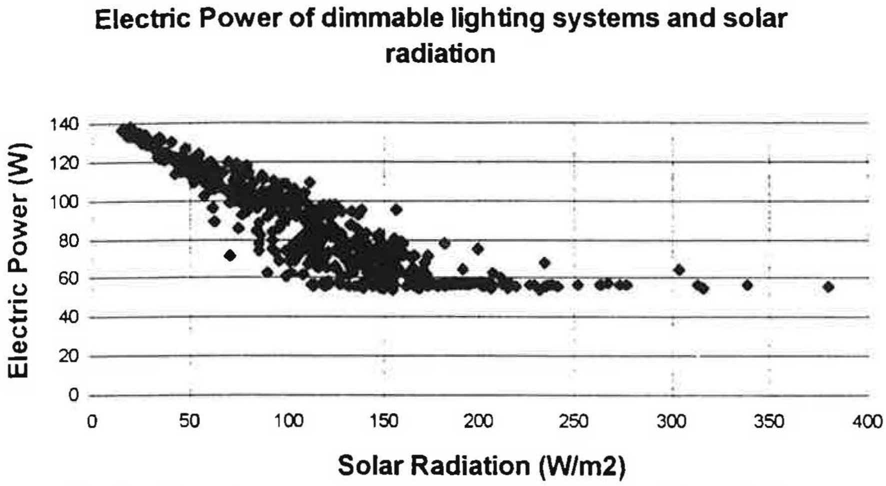

Fig. 3 - Electric power of dimmable lighting and solar radiation

Although the data in this figure show a dispersion, the system behavior falls approximately with what is presented in equation (1), which can be used to estimate energy consumption reductions, if there is a solar radiation database available. If luminous efficacy were added, the results would be better.

Measuring the power supplied to the dimmable lighting system, it was possible to create Fig. 4, with the fixed electric power of the system of the 5th floor and the dimmable system of the 3rd floor both with and without the automatic shading device.

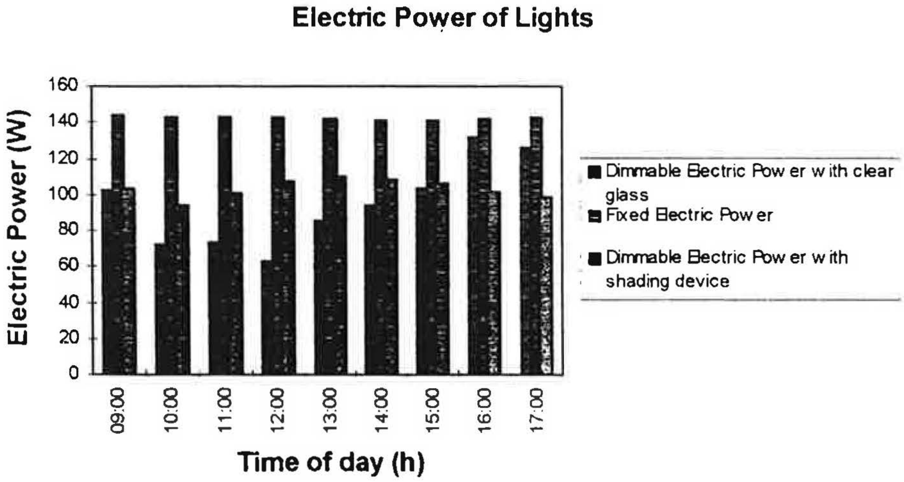

Fig. 4 - Electric power of fixed and dimmable lighting with clear glass and shading de ice

For clear glass, the reduction in electric power consumption made possible by the dimmable lighting was 39 percent, as shown in Fig. 4. Taking into account that all shading is detrimental to natural illumination, the reduction in electric power consumption with the automatic shading device, shown in the figure above, was 29 percent. However, the area of the window under study was only $0.36m^2$. With larger windows, the lighting system would tend to function with minimal power and the energy consumption would be even lower for this end use.

4.2. Cooling experiments

A reduction of energy consumption for cooling is achieved mainly by reducing the Solar Heat Gain Coefficient, which is measured with photovoltaic cells. This effect of the automatic shading, as compared with the reference glass, can be verified in Fig. 5.

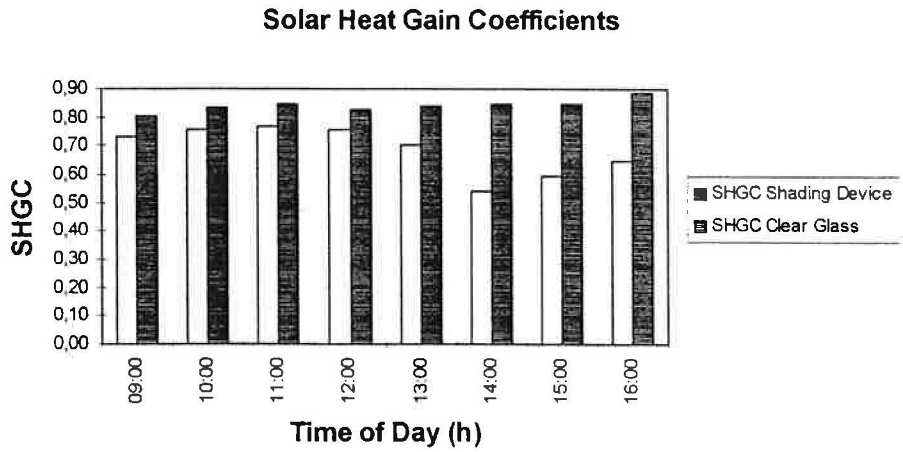

Fig. 5 - Solar Heat Gain Coefficients with and without the shading device

The average Solar Heat Gain Coefficient was 0.85 for clear glass against 0.69 for clear glass with shading device. The latter presented a minimum value of 0.48, which corresponded to the interval at which the blades were practically closed. The Solar Heat Gain Coefficient did not drop to zero because the radiation from the east window, which has a glass area of $0.20\ m^2$ was not obstructed.

Fig. 6 applies equations (5) and (6) to estimate heat gains. In reality, gains by conduction, convection and radiation absorbed by the glass were admitted equally on the 3rd and 5th floors, which favors security, since the automatic shading device constitutes, among other effects, a barrier against the wind.

Conduction, convection and glass radiation gains

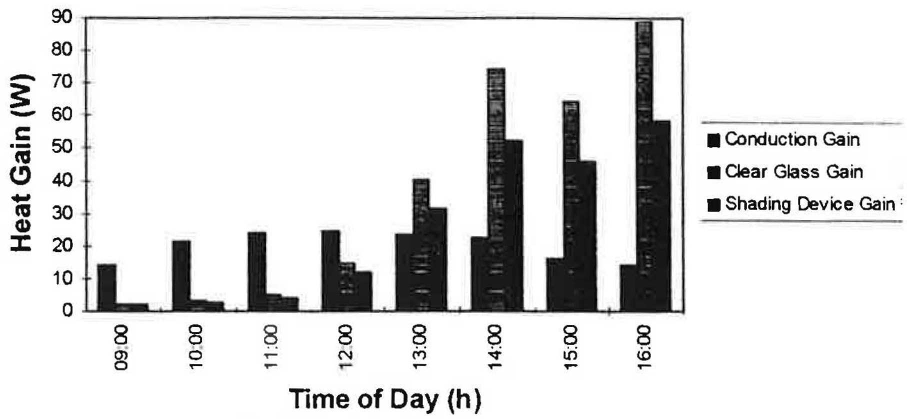

Fig. 6 - Gains by conduction, convection and radiation absorbed by clear glass and shading device

After installation of the automatic shading device, a reduction of 6 percent in energy consumption was verified. On a typical test day, with measurements of temperatures, radiation, coefficients and electrical powers of air conditioners, the error between direct power measurement and that estimated with the aid of instruments was 3.1 percent. As the "Test Tower" possesses a very high thermal inertia (structural brickwork), this error tends to decrease in lighter buildings. In cases of expeditious estimates of measures to conserve energy through changes in fenestration, the methodology with the aid of instruments should be considered valid.

The 6 percent reduction in energy consumption for cooling is intrinsically related to the dimensions of the west window chosen for testing. So, if the area of this window complied with the recommendations stated, for instance, in the research results mentioned by Tregenza [6], as regards the relation between total glass area/total facades area, there would be a need of more than 2.0 m^2 of glass on the floor studied, which would bring about a much higher percentage of energy consumption reduction.

While the shading device was still under testing, the effect of dimmable lighting on the consumption of energy for cooling was verified: there has been a reduction of 26 percent concerning heat gains from lighting.

5. CONCLUSIONS

The experiments were carried out on two floors of the "Test Tower", which are not comparable to modern test cells, mainly due to the vertical effects of heat transfer through the building structure.

Regardless of the very small size of the window tested in the present research, the automatic shading device allowed a reasonably good use of natural light indoors.

The average Solar Heat Gain Coefficient of the device, which amounted to 0.69, seems high if compared to other kinds of fenestration. However, this result stems from the conception of the shading movement itself: while there was no direct solar radiation incident to the west face wall during the morning, the device allowed maximum radiation to penetrate.

Then, more important than establishing a fixed Solar Heat Gain Coefficient for a window is using a flexible automatic shading device - one that can be programmed either daily or at short intervals to perform any movement required or commanded by the user or by radiation and temperature sensors. It all happens as though the window glass area were variable.

Finally, the research results make it possible to say that the partials tests of the past, which pointed exclusively to lighting or cooling effects of fenestration, do not constitute a final answer in terms of the devices that enhance energetic performance. The sum of the effects should be measured.

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