WINDOW ENERGY PERFORMANCE COMPARISON PROGRAM FOR NON-RESIDENTIAL BUILDINGS

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ABSTRACT

A new computer program has been written for comparing the annual energy and economic performances of different window systems in non-residential buildings. The program, called CSHADE, performs a sideby-side hourly energy performance simulation of a test window system compared to a reference one. A comprehensive report is printed out at the completion of each simulation. The program is much simpler and easier to use than large building simulation programs such as DOE-2 or BLAST, and has relatively more modest computer requirements. Results are reported on the use of the new program to compare the performances of seven different window systems installed in buildings in Miami and Chicago.

INTRODUCTION

In the last several years there has been a major expansion in the variety of building fenestration systems offered for sale world-wide[1-5]. Windows are now available with multiple glazings, various treatments for solar and illumination control, gas-fills, and low-emissivity coatings. Interior and exterior shading devices are also available in great varieties, including mini-blinds, verticals, pleated blinds, roller shades, shade screens, and shutters and awnings of many kinds.

This situation provides opportunities for designing more energy-efficient buildings, since most of these features offer improved energy efficiency.

The variety of products available also produces problems for building designers, since choosing between the many claims of manufacturers and properly evaluating the expected energy performances of the various options can be a very time-consuming task. Thus, designers presently seem to base their choices mostly on aesthetics, durability, and installation costs. The result of this can be missed opportunities for better building energy and economic performance.

Sullivan and others at the Lawrence Berkeley Laboratory of the University of California and this author[6] have begun work on a simplified method for comparing the various different kinds of fenestration performances of interest in non-residential buildings. I shall call this approach the LBL method. It is based upon the one-time execution of a number of repeated runs of the building energy performance simulation program DOE-2 and the application of multiple linear regression analysis to these results.

The result will be a very comprehensive approach to the evaluation of fenestration system performance at the preliminary design stage. However, it requires a variety of different measurements of fenestration system component performance and a large number of runs of the DOE-2 program, for each climatic condition and building type of interest. This approach is basically a pre-solution of the problem over a variety of expected application areas and a parameterization of the results so that they can be extrapolated and interpolated to specific but similar situations.

The advantage of the method is that it includes several energy performance indices, including peak electrical power consumption, and such additional performances as thermal and visual comfort and illumination performance. It therefore covers nearly all aspects of fenestration performance. The disadvantage is that a great deal of advance work must be done to make the approach available for a variety of fenestration systems, building types, and climatic zones.

This paper reports on an alternative method, one that looks just at the thermal aspects of fenestration energy performance. The approach concentrates on the comparative thermal performances of two different window systems (toplighting systems are to be added later). It is therefore not as generally useful as the LBL method, and it is limited to only the thermal aspects of performance, but it focuses on the principal driving force contributing to overall economic performance, energy, and it offers flexibility and relative ease of use.

The method is incorporated in an IBM PC-compatible hourly energy performance simulation program (called CSHADE because the program was originally written mainly to evaluate shading devices for commercial building applications) that offers user-friendly input screens and produces a comprehensive report of many aspects of fenestration energy performance.

The output values include the number of heating and cooling hours in the simulation, the heating and cooling period conductive gains and losses through the window systems, the direct beam and total solar radiant and luminous flux gains, and a variety of indicators of economic performance.

All of the performance indicators are calculated separately for windows facing each of the eight major points of the compass, from north through east and south to northwest.

ASSUMPTIONS

Two assumptions lie at the heart of the calculational procedure. First is that the building is non-residential, that it is occupied for most of the daylight hours of the day and that it employs a commercial-building-like heating, ventilating, and cooling (HVAC) system. Second is that the building is internally load-dominated, i.e. that the internal heat sources and losses are much greater than the conductive transfers through the foundation, floors, and roof. From this assumption all envelope heat transfers are neglected, except those through the fenestration systems. As a further simplification, the building is assumed to be massless, so that no time-delay effects are encountered.

For the purposes of fenestration system performance comparison analysis, these assumptions are thought to be reasonable for non-residential buildings. They greatly simplify the thermal performance calculational procedure and allow us to avoid any need to input the details of building design geometry and thermal conductances and capacitances of building materials. The resulting model, in effect, attempts to isolate the fenestration-related impacts on building energy performance.

We still have to model the operation of the HVAC system, at least to the extent of determining whether it is in heating, cooling, or ventilating mode for each simulation hour. If the building and HVAC system operations are too over-simplified, then these decisions will be in error and the thermal performances of the fenestration systems will be imprecisely estimated.

The magnitudes of these errors will be assessed in the next phase of this project by comparing the results of CSHADE's predictions with those of some DOE-2 runs for the same building. In the latter, we will vary the thermal mass and wall envelope conductances to see how sensitive the results are to such variations. The results of this analysis will be reported separately.

ROOM GEOMETRY

The model simultaneously simulates eight identical, totally isolated rooms, with identical windows in only one wall of each room. For each of the eight rooms, the window wall faces a different direction (NO, NE, EA, SE, SO, SW, WE, and NW).

This configuration is intended for preliminary assessments of different fenestration systems, without reference to a particular building. A later modification will simulate one room with windows of arbitrary sizes and facing any of the eight directions.

The floor area of the rooms being simulated is input, along with the lighting power density in Watts per unit floor area, in order to determine the heat gain from the lighting system.

HVAC OPERATION STRATEGY

The number of persons occupying each room is input, to determine the heat gain from this source. A sensible heat gain of 66 Watts per person is assumed. The latent gain is not included since the HVAC system thermostat is assumed to sense only air temperature.

Lighting heat gain is calculated by multiplying the lighting power density (W/m^2) by the room area in square meters.

Solar radiant heat gain is calculated as described in the next section.

HVAC heating and cooling modes are considered separately. Let T_i and T_o be the inside and outside air temperatures in degrees Celsius, respectively. Let U_h and U_c be the heating and cooling season values, respectively, of the window overall heat transfer coefficient, in Watts per square meter and per degree C. Let A be the total area of all the windows in the room.

We choose a ventilation rate of 15 cfm per person, a ventilation minimum for maintaining air quality. This is converted to the number of Kilojoules of heat gain per degree Celsius temperature difference.

With these definitions, the HVAC operating mode test (season test) is performed as follows.

Set the conductive heat gain QUG and the conductive heat loss QUL equal to zero.

If $T_o > T_i$ then $QUG = 3.6 \cdot U_c \cdot A \cdot (T_o - T_i)$ [KJ]

If $T_o < T_i$ then $QUL = 3.6 \cdot U_c \cdot A \cdot (T_i - T_o)$ [KJ]

Next calculate the total net heat gain for the room in Kilojoules:

$$QG = QS \cdot A + 3.6 \cdot PWR \cdot AF + 3.6 \cdot 66 \cdot N + QUG - QUL$$

where QS is the solar radiant heat gain per square meter window area, PWR is the lighting power density in W/m^2, AF is the floor area of the room in m^2, N is the number of persons in the room, QUG is the conductive gain, if any, and QUL is the conductive loss, if any, through the windows. If the room is not occupied by people at the time of this evaluation the second and third terms are dropped from the above equation.

Next the cooling- and heating-mode heat losses from the room are calculated:

$$QLC = (U_c \cdot 3.6 \cdot A + 50.9 \cdot N) \cdot (T_{ic} - T_o)$$

$$QLH = (U_h \cdot 3.6 \cdot A + 50.9 \cdot N) \cdot (T_{ih} - T_o)$$

where T_{ic} is the inside set point temperature for cooling and T_{ih} is the inside set point for heating.

Now the season test can be performed:

If QG>QLC then the HVAC system is in cooling mode.

If QG<QLH then it is in heating mode.

If neither of these conditions is satisfied, then the system is in ventilating-only mode.

SOLAR RADIANT HEAT GAIN

The method used for calculating the solar radiant heat gain through the fenestration systems is described in a previous paper[7]. It involves use of the angle-dependent solar optical properties of single- and multiple-pane windows with and without gas fills and with coatings applied to the outer glazing. It employs the Perez model for the angular distribution of radiation from the sky[8,9]. Circumsolar, isotropic sky, and horizon band components are included, as well as the direct beam and ground-reflected radiation components incident on the window.

SHADING DEVICES

The model performs calculations for both shade-present and shade-absent modes, and for both the test and reference window systems, throughout each simulation. Only diffusely reflecting interior shades are presently included in the model. These shades are assumed to be either totally open or totally closed. Exterior awnings and overhangs will be added in the future. The calculations will be based upon a revised version of a previously published awning and overhang shading algorithm[10].

The model includes the possibility that the closure of the interior shade will be accompanied by a reduction in the overall U-value of the window/shade system. Thus, additional energy savings are accounted for in such cases.

The computer program outputs the results for both shade-present and shade-absent cases with every run and for each of the eight orientations. Any combination of shade and window strategy can be used for either the test or the reference case fenestration system. This permits great flexibility in comparing different window and/or shade systems.

ENERGY CREDITS AND DEBITS

For each hour that the HVAC system is in cooling mode the program sums the net heat gain to the room attributable to the windows. If it happens to be colder outside than inside during a cooling hour, then the conductive heat losses are subtracted from the heat gains as a credit for the fenestration system.

The net heat gains are also calculated and accumulated for each heating hour. Any conductive heat losses to the cold outside are considered a debit while solar radiant heat gains are credits during heating mode.

The purchased energy costs in dollars associated with the resulting heating and cooling loads are calculated using the heating and cooling coefficients of performance (COP's). Although the values used are fixed and not variable, they are input by the operator and different values from the default ones can be used.

The heating and cooling season energy savings are computed separately, for both test and reference windows and are output for both the shade-present and shade-absent cases and for each of the eight window orientations. The dollar values of these savings are calculated using the appropriate prices for the energy forms involved (electricity, natural gas, and oil).

OTHER FEATURES

The model incorporates a number of additional features of interest. These include:

- The program can be run using hourly weather data for 233 cities in North America and several Pacific and Caribbean islands.
- The program presently employs a library of 21 different 1-, 2-, and 3-pane windows with six different coatings, including grey and green tint,

reflective, pyrolytic low-e, sputtered low-e, and bronze coatings. The library is expandable and other window types will be added in the future.

- The building operating schedule includes options for starting- and ending-hours each day and days per week for both occupancy and HVAC system operation.

- Peak electrical demand is calculated and a simple demand charge is used to assess peak demand impacts of the competing strategies.

- Sloped glazings are included by specifying an angle of window tilt other than zero.

- Maintenance costs are input and any differences in these costs between test and reference systems are used in the economic performance calculations.

- Simple payback time and its reciprocal, first-year return on investment (ROI) are used instead of escalated or discounted versions of these quantities because: 1)most users are interested in the short-term economic performance of fenestration systems, 2)it is difficult to predict long-term future economic trends or system lifetimes with much accuracy and precision, and 3)experience has shown that within normal ranges of economic growth rates, these simple measures are not greatly different from their escalated or long-term counterparts.

- For the cash flow analysis, in which money is borrowed to pay the extra costs of installing the test system, tax credits are included to reduce the net yearly payments on the loan and the difference between the yearly energy dollar savings and the net yearly loan payments are calculated as a fraction of the initial investment (the amount of the loan). Whenever this net cash flow can be shown to be positive, a powerful argument exists to support the use of the test case system instead of the reference system.

- Four operating strategies are implemented for the interior shades:
  1. Closed during day cooling and night heating hours.
  2. Closed all the time.
  3. Closed during night heating and daytime unoccupied hours.
  4. Closed during night heating hours and whenever the direct sun enters the window.

PROGRAM CHARACTERISTICS

The program is written in Microsoft's QuickBASIC. It is divided into three parts, which may be chained together by the operator or run separately. First is the input program. This one loads a set of default values for all inputs and displays these on three screens. The default values can be input either from a standard pre-set file or from the input file of any previous run of the program that has been stored. The program displays a list of all such case files available to choose from.

The operator need only change those input values that are different from the default case.

In some cases the program runs through a procedure to help the user calculate the values needed.

Once all the correct input data is shown on the screens, the program stores it in a case file whose name is user supplied and prompts whether to run this case or to build another case input file. If the decision is to run the present case, the input program is exited and the hourly simulation program is automatically started.

The hourly simulation program takes the name of the input case file from a small file reserved for this purpose and performs the simulation, displaying the case name, the day of the year presently being run, and some other information. When the simulation is completed, the

Table 1. Characteristics of windows simulated

Window	Solar Transmittance	Shading Coefficient	Winter U-value W/m^2C	Summer U-value W/m^2C	Extra Installation $Cost/ft^2$
1 pane clear	.6983	.8662	6.4414	6.0610	$0.00
1 pane tinted	.2185	.4087	5.0781	5.0422	$6.10
1 pane shaded	.0279	.5025	3.0041	2.9187	$3.80
2 panes clear	.5006	.7093	2.8483	3.2708	$2.25
2 panes tinted	.1555	.2952	2.3426	2.6876	$8.35
2 panes low-e	.4560	.6453	2.3426	2.6309	$7.60
2 panes shaded	.0200	.4788	1.8914	2.0688	$6.05

hourly program stores all the relevant input and output data in an output data file and automatically executes the third program which prints out the results.

The printout program reads the data file and writes a five-page formatted report to a print file and then exits. A special DOS batch file can be used to perform multiple case runs automatically, storing each run in its own output file. The output report is put on a file rather than sent to the printer in order to obtain a permanent record of the results and to avoid an interruption of the sequence if the printer runs out of paper or otherwise malfunctions.

The DOS PRINT command can be used to print out the results of several runs in batch mode, freeing the computer for other use during the printing operation.

The simulation takes about 20 minutes for a 7-days-per-week schedule and 10-hours-per-day-of HVAC operation and occupancy on an IBM-compatible AT type computer with a clock speed of 10 MHz and a math co-processor installed. For a 5-days-per-week schedule this is shortened to about fifteen minutes.

The development of this program was funded by Verosol USA, which owns it. Inquiries should be directed to Mr. Paul Stark, Director of Marketing, P. O. Box 517, Pittsburgh, PA 15230.

SAMPLE RESULTS

Judging from comments received from building designers, there is much confusion about the relative effectiveness of insulated window units, window tinting, low-e coatings, and interior shading devices. In an attempt to assess these different options, CSHADE was run repeatedly using several different window strategies, for Miami to represent a hot climate and Chicago for a cold one.

The room simulated was 50 feet wide and 120 feet long (6000 square feet or 557.6 m^2 of floor area), with 40 windows in one of the long walls, each being .91 m (36 inches) wide and 1.46 m (57.6 inches) high, for a total window area of 53.5 m^2 or 576 ft^2. The window-to-wall area ratio is therefore .6 for this case.

We assume that this space is occupied by 30 people, each accounting for 200 sq. ft. on the average, and that the building is occupied between the hours of 8 and 18 five days per week.

The assumed HVAC operating schedule for the simulations was between hours 7 and 20 five days per week. Heating and cooling mode set point temperatures were 22.2 and 25.6 C (78 and 72 F), respectively.
A lighting power density of 28 W/m^2 (2.6 W/ft^2) was used. For all the runs natural gas was used as the heating type, with a COP of .8 and a purchased energy cost of

$.0136 per KWh. A cooling COP of 3.0 was used along with an electricity cost of $.0581/KWh.

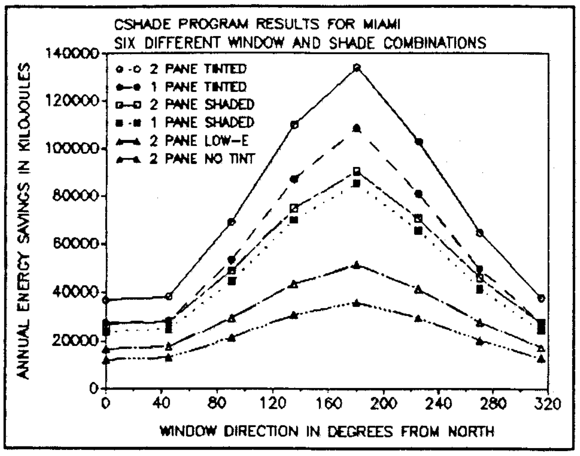

Figure 1. Relative energy savings for six different window types in Miami.

The performances of six different (test case) window systems were compared with those of a clear, single-pane window of 6mm (.25 in.) thick ordinary soda-lime window glass (the reference case). The diffuse solar transmittances, effective shading coefficient for normal incident radiation, and the ASHRAE winter and summer U-values of the reference and test case windows are given in Table 1 along with their extra installation costs over the single-pane clear case. These costs were based on a pricing procedure and cost information supplied by James I. Fox of Fox Glass Company in Uniontown, Pennsylvania.

Further descriptions of these cases are given below:

- o <u>Single-pane, tinted</u>. 6 mm thick reflective glass.
- o <u>Single-pane, shaded</u>. 6 mm thick clear glass with a nearly opaque interior shade with a reflective aluminum coating facing toward the window. Shade diffuse reflectance is 52% and solar transmittance is 4%.
- o <u>Double-pane, clear</u>. 6 mm thick clear glass with 12 mm (1/2 in. air gap) and no other shading.
- o <u>Double-pane, tinted</u>. Same as double-pane clear, but with a reflective coating on the cuter pane.

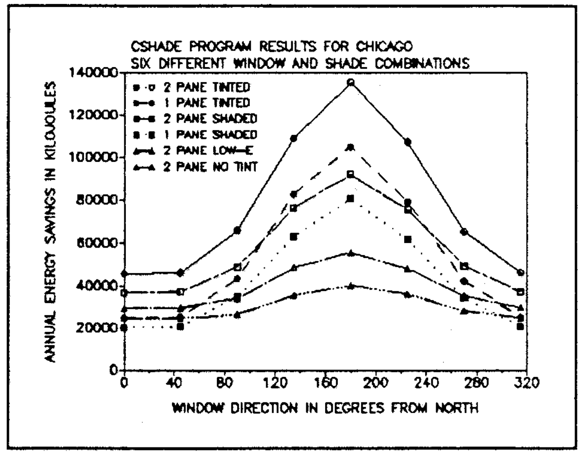

Figure 2. Relative energy savings of six different window types in Chicago.

- o <u>Double-pane, low-e</u>. Same as double-pane clear, but with a pyrolytic low-emissivity coating on the inner surface of the outer pane. Emissivity = .15.
- o <u>Double-pane, shaded</u>. Same as double-pane clear, but with the same shade used previously for the single-pane shaded case added.

<u>RESULTS</u>

Comparisons of the energy savings of these six window types, relative to the single-pane, untinted reference case, for Miami and for Chicago are shown in Figures 1 and 2. The results are plotted versus window orientation direction, from zero degrees (north) through east (90 deg) to northwest (315 deg).

It is clear that the savings vary strongly with window direction, that reflective coatings perform better than shades and that these perform better than low-e coatings for hot climates like Miami. This is even true for Chicago's colder climate, when we look only at the southerly-facing directions.

Insulated glass units do not do well, in comparison with the other strategies, when they are the only strategy used.

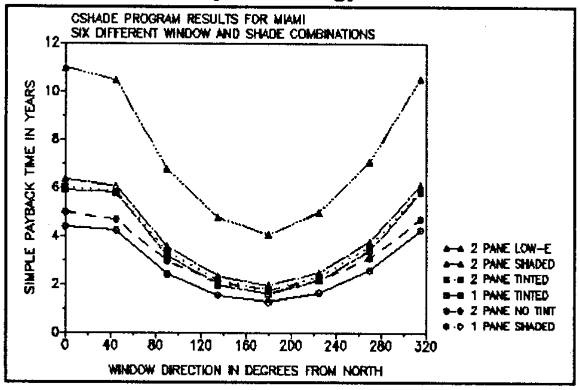

Figure 3. Payback times for six different window types in Miami.

This result and the similarity between these results for Chicago and Miami may at first seem surprising. However, the building simulated in both cases is internal load dominated and has very little connection with the outside air, other than through the windows and the small amount of ventilation needed to maintain air quality.

Such very well-insulated buildings require more cooling than heating year round, even in fairly cold climates like Chicago. Thus insulated glass units do not save signficant quantities of energy compared with the savings produced by heat gain rejection during cooling periods.

For example, in Chicago for the south-facing single clear glazing case, there were 1085 heating hours and 2147 cooling hours.

Energy savings are not the only indicators of performance. The current economic system in most of the world is based upon profit-oriented business enterprise. In this economic system energy-saving systems are valued not for their energy savings but for their marginal profit-enhancing abilities, either through reduced overall costs or through increased income.

A straightforward measure of the

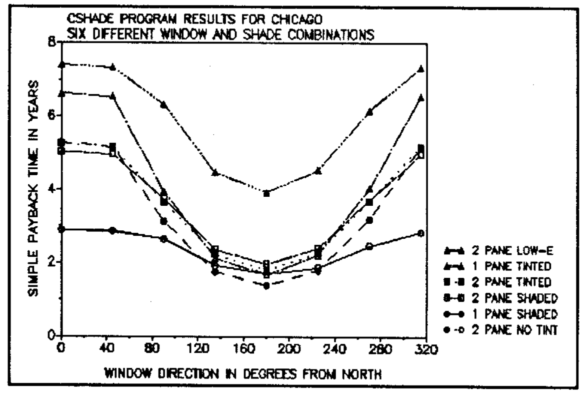

Figure 4. Payback times for six different window types in Chicago.

profitability of an energy-saving system is its payback time, the time required for the net monetary value of the energy savings to offset the extra initial costs to install the system.

Figures 3 and 4 show the simple or straight (uninflated or undiscounted) payback times of the six window systems studied as functions of window orientation in Miami and Chicago, respectively.

We can see that when the costs to install the various window options are considered, the relative values of the competing options changes. Some of the strategies are only marginally cost-effective, even for the south-facing glazing which receives the most radiation year-round due to the lack of an overhang or other exterior shading device.

There is a strong variation in cost-effectiveness with orientation, indicating that it makes no economic sense, from an energy perspective, to use the same window treatments for all window orientations on a building.

The surprising result here is that the low-e coated double-pane windows are the poorest performers in Chicago. This is attributed to the relatively high cost of these windows, coupled with the relatively modest non-residential building heating load in that city.

ACKNOWLEDGEMENTS

Subrato Chandra is gratefully acknowledged for his assistance in developing the HVAC operating strategy. This work was supported by Verosol, USA, with supplemental funding by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U. S. Department of Energy through grant DE-FG01-84CE22122.

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