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SUMMARY

Johnson, Arasteh, Selkowitz: Energy Reduction Implications with Fenestration. In this paper we discuss results from a number of parametric analyses of the energy and cost influences of fenestration in a prototypical office building. The energy important parameters of fenestration, daylighting, and electric lighting were systematically varied in several climates using the DOE-2.1 energy simulation program to determine net annual results. Results are presented for two climate extremes; one heating-load dominated and the other cooling-load dominated. The increase or decrease of net annual energy consumption and peak electrical demand due to fenestration is demonstrated. Daylighting, is shown to be the single most important strategy to reduce energy use, but can be an energy and cost liability. Conditions under which these liabilities occur are discussed, and optimal design solutions for minimizing energy costs are suggested.

RESUME

Johnson, Arasteh, Selkowitz: Influences des fenêtres sur la consommation d'énergie. Ce rapport présente les résultants de plusieurs analyses paramétrieques sur l'influence des fenêtres dans un batiment tertiaire, en termes de consommation et coût d'énergie. L'utilisation du programme de simulation DOE-2.1 a permis d'étudier la sensibilité des résultats énergétiques annuels, aux paramètres importants liés aux fenêtres, à l' éclairage naturel et électrique. Des résultats sont présentés pour deux climats extrêmes: prédominance soit du chauffage, soit de la climatisation. On observe une variation (positive ou négative) de la cosommation annuelle et de la demande d'énergie, dûe aux paramètres des fenêtres. L'éclairage naturel semble la stratégie la plus adaptée pour réduire la consommation d'énergie mais son usage peut être délicat et coûteux: à cet effet, différentes configurations sont présentées et des solutions visant à un coût minimum sont suggérées.

KURZFASSUNG

Johnson, Arasteh, Selkowitz: Parameterstudie ueber die Energieeinfluesse von Fenstern. In diesem Artikel werden die Ergebnisse einer Anzahl von Analysen ueber die Energie-und Kosteneinfluesse von Fenstern in einem standardisiertem Buerogebaeude diskutiert. Die fuer die Fensterstudie wichtigsten Parameter, Tageslicht und kuenstliche Beleuchtung, wurden fuer unterschiedliche Klimata systematisch variiert. Fuer die Simulationen wurde das Gebaeudesimulationsprogramm DOE-2.1 zur Bestimmung der jaehrlichen Energieverbraeuche herangezogen. Die Ergebnisse wurden fuer zwei extreme Klimata durchgefuehrt; eines mit vorherrschendem Heizenergieverbraeuch, das andere mit beherrschendem Kuehlenergieverbrauch. Die Unterschiede des jaehrlichen Netto-Energieverbrauchs und der Spitzenlast infolge unterschiedlicher Fensterauslegungskriterien werden dargestellt. Tageslicht ist der wichtigste Einflussfaktor fuer Energieeinsparung, wenn auch unter Umstaenden nicht der kostenguenstigste. Die Bedingungen, unter denen diese Faelle eintreten koennen, werden erlaeutert und optimale Auslegungsanleitungen fuer die Minimierung der Energiekosten werden vorgeschlagen.

ENERGY REDUCTION IMPLICATIONS WITH FENESTRATION

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This paper discusses results from a number of office building parametric studies in which we systematically varied fenestration and electric lighting variables in specific climates. Results demonstrate that properly designed and managed fenestration in office buildings can reduce costs for energy consumption and electrical peak demand and may reduce chiller requirements.

Methodology

Our office building model consists of four identical perimeter zones, each 4.8 m deep, surrounding a common core. The ceiling and floor were modeled as adiabatic surfaces (no net heat transfer), limiting envelope thermal transfer to the walls and fenestration. Overall thermal conductance was held constant as glass area was varied, isolating solar gain and daylighting effects. Fenestration thermal conductance, glazing area, visible transmittance, and shading coefficient were varied. Use of shades for visual or thermal comfort was assumed. Electric lighting was varied from 7.5 to 29.1 W/m^2, based on a design illuminance of 538 lux. For daylighted cases, electric lighting output was reduced uniformly in response to daylight. The DOE-2.1B building energy analysis program [1] was the modeling tool. A detailed description of the building model appears elsewhere [2,3]. To better understand the influence of fenestration on results, we define a lumped parameter which we call effective aperture. This parameter is the product of the ratio of glass area to wall area times the visible transmittance of the glass.

Results

Cold climate energy use

Total annual energy consumption for a south zone in Madison, WI is plotted against effective aperture in Fig. 1. The solid lines represent an electric lighting schedule that follows an occupancy schedule without regard to daylight levels. The dashed lines represent operation with the same schedule but with electric light dimming in response to daylight. This cold (Lat. 43.1^{o}N) climate heating season (4176^{o}C HDD at base 18^{o}C) can use solar gain to offset heating loads, but during summer months solar gain is a cooling load.

With thermal conduction losses held constant (U = 0.97 $W/m^{2o}C$) and without daylighting controls, even at the highest lighting power density studied (29.1 W/m^2), fenestration up to an effective aperture of about 0.10 produces net energy benefits in the south zone. At larger effective apertures the added solar gain plus the high internal load produces an energy penalty. As electric lighting's internal load diminishes, more solar gain offsets heating load, and minimum energy consumption occurs at larger effective apertures.

When daylighting is integrated into the system, annual energy consumption falls off as effective aperture increases up to a limit beyond which it levels off. Daylighting diminishes the internal load from electric lighting, and solar gain offsets more of the heating load. The negative impact of summer solar gain is mitigated by lowered internal gains from electric lighting.

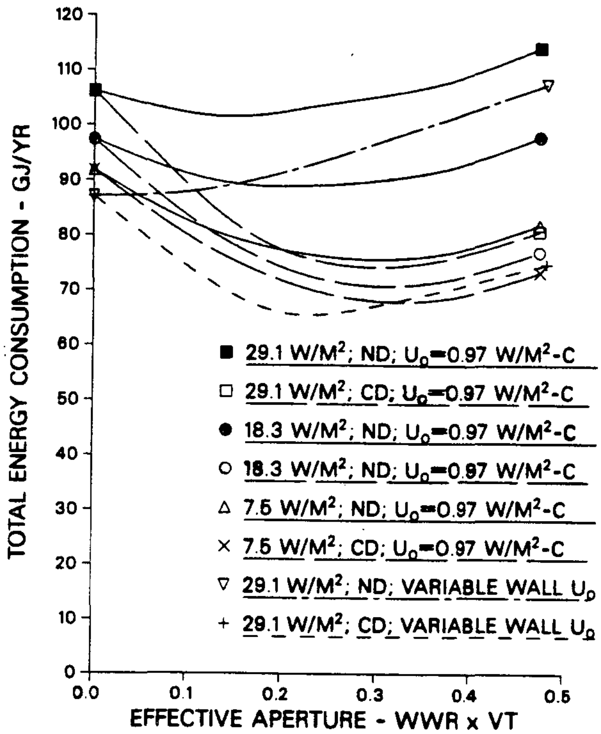

Figure 1 Total annual energy consumption for south zone (139.4 m^2) in Madison WI.

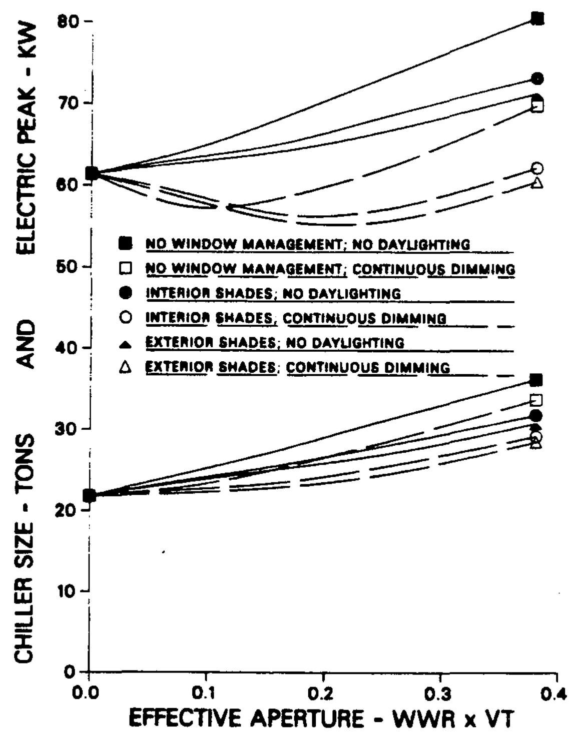

Figure 2 Chiller size and peak demand for entire module (1,486 m^2) in Madison WI.

The high heating loads in this climate impose the need to control thermal losses. The low insulating value of glass typically reduces the overall thermal resistance and compromises the benefits just demonstrated. Figure 1 shows the effect of reducing the conductance of a well-insulated wall (U = 0.57 W/m^2 ^{o}C) by increasing glass (U = 2.2 W/m^2 ^{o}C) area. Without daylighting adding glass lowers energy performance by increasing winter thermal losses and summer solar gains. Using daylighting, however, provides minimum energy consumption. The minimum occurs at a smaller effective aperture because with better control of thermal loss less solar gain is beneficial.

For the north zone with fixed overall conductance in Madison, annual energy consumption in the nondaylighted case steadily decreases with increasing aperture; with daylighting it decreases more rapidly. When thermal losses are controlled, north fenestration can provide net energy benefits. These results suggest the importance of glazing materials having low thermal conductivity and high visible transmittance. When overall thermal resistance declines with increasing glass area, net annual energy consumption without daylighting goes up, but with daylighting performs better than an opaque wall.

Cold climate peak electrical demand

With our model's gas-fired boiler and electric chiller, peak electrical demand is a summer phenomenon. In Fig. 2 coincident peak demand for the entire module is plotted as a function of effective aperture for a lighting power of 18.3 W/m^2. Daylighted and nondaylighted conditions with and without window shade management are shown. The solar gain admitted by fenestration imposes cooling load and peak demand increases with effective aperture. Daylighting, by reducing electric lighting, reduces peak demand to below that for an opaque wall. Compared to the nondaylighted case with identical glazing, this reduction reaches approximately 20% with 37.5% of the floor space daylighted. The reduction would increase with more daylighted space. Peak demand in the unmanaged window case is substantially higher, indicating the importance of solar control.

Hot climate energy use

In Fig. 3 results for a north zone in Lake Charles, LA are shown. In this cooling-load dominated climate (Lat. 30.1°N, 1051°C HDD at base 18°C) fenestration, without daylighting, imposes an energy penalty. With daylighting, windows provide net energy benefits, and energy consumption is minimized within the effective aperture range 0.15 to 0.20. Larger effective apertures provide more daylighting but increases net energy consumption.

Hot climate peak electrical demand

Since peak electrical demand in both climates occurs during the summer peak cooling season the implications discussed above for Madison also apply to Lake Charles with solar gain control being an even more critical concern.

Daylighting efficacy

It is generally assumed that because the luminous efficacy of daylight (100 - 120 lumens/watt) is greater than that of typical fluorescent systems (60-90 lumens/watt), daylighting will reduce cooling loads relative to electric lighting. This assumption ignores the details of light distribution within a room and the difference between total admitted flux and the fraction received at the work surface. When these factors are accounted for, the advantage of daylight as a cooler source of light is compromised by the nonuniform daylight distribution typical of a sidelighted office space. Figure 4 compares annual cooling loads from skylights and vertical fenestration. The more uniform flux distribution with the skylight system reduces cooling load as daylight displaces electric light up to a daylight saturation level. Daylight is delivering light with higher luminous efficacy than the electric lighting. In the case of vertical fenestration, cooling load decreases only at high lighting power density. At lower power densities the cooling load of daylighting increases relative to electric lighting, indicating a lower effective luminous efficacy for daylight.

Cooling equipment

While fenestration can provide the benefits of reductions in energy requirements and peak electrical demand it may impose penalties on cooling equipment sizes. Peak cooling load, occurring during summer conditions of coincident high ambient temperature and solar gain, is the usual criterion for sizing chillers and associated cooling equipment. Chiller size (Fig. 2) increases continuously with effective aperture, but daylighting reduces chiller size compared to the same fenestration without daylighting. These results are consistent with Fig. 4, which shows cooling energy increasing with effective aperture for an installed power density of 18.3 W/m^2.

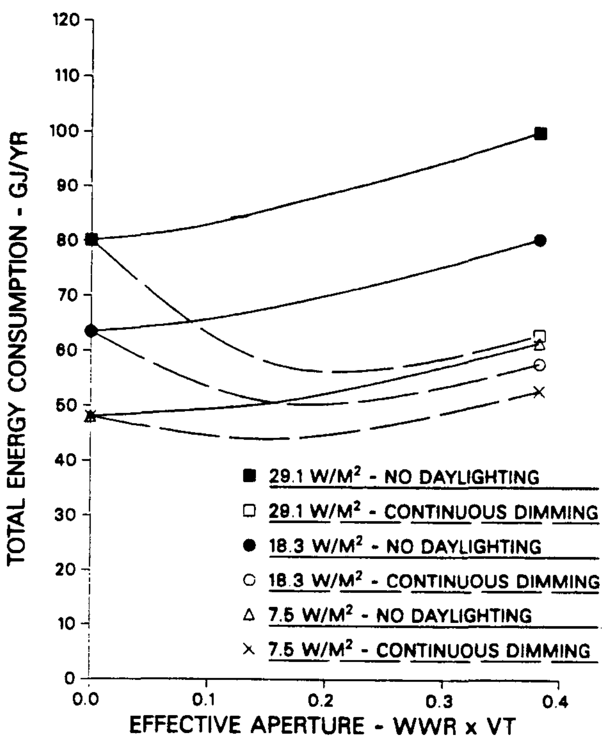

Figure 3 Total annual energy consumption for north zone (139.4 m^2) in Lake Charles LA.

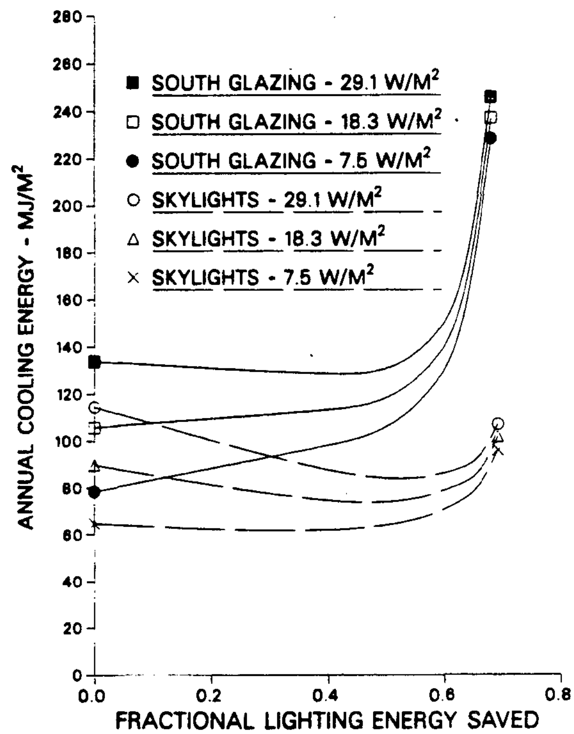

Figure 4 Cooling energy per unit floor area of daylighted space as a function of electric lighting savings in Lake Charles LA.

Cost implications

The integrated design of fenestration and lighting systems in which solar gain is controlled, daylight is admitted, and electric lights are dimmed in response to daylight levels will reduce net annual energy consumption and peak electrical demand. These reductions lower operating costs over the life of the building. The magnitude of the savings will depend on the specifics of building design, climate, heating fuel costs, and utility rate structure. To realize these savings typically requires added first cost for electric lighting dimming control systems. In the United States these systems presently cost about $12/$m^2$ of floor area. These first costs may, however, be offset by reductions in chiller and cooling equipment costs. In Madison with 18.3 W/m^2 lighting power density, an effective aperture of 0.2 and managed shades, daylighting reduces chiller requirements by about 3 tons. At $2000/ton for cooling equipment, this is a cost reduction of $11/$m^2$ of floor area, which is about equal to the cost of the lighting control system.

Summary and Conclusions

With proper design and operation, daylighting and solar control, fenestration can provide energy and cost benefits. Extensive parametric simulation results suggest the following generalizations:

1. For each climate, orientation, and lighting power density there is an optimum effective aperture for minimum net annual energy consumption. Larger effective apertures diminish the benefits because of increasing cooling load.

2. Daylighting strategies can reduce peak electrical demand by substantially reducing the electric lighting component of peak demand.

3. Solar gains must be controlled to mitigate potential negative influences of fenestration on energy consumption and chiller size. The benefits of daylighting strategies can be negated if solar gain is not controlled.

4. The luminous efficacy of daylight is greater than that of fluorescent light, but it may not be a "cooler" light source. Daylight's efficacy will depend on solar controls, luminous flux distribution in the space, and electric lighting control system response to that distribution.

These conclusions are sensitive to variations in climate, orientation, and modeling assumptions. Results may differ for building configurations, operating systems, and operating schedules other than those modeled.

Acknowledgements

This paper presents selected results from a series of parametric modeling studies. Results of these studies are discussed in greater detail in the referenced papers and others available from the authors. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Portions of this work were supported by Battelle Pacific Northwest Laboratory.

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