INVESTIGATION INTO THE THERMAL IMPACT OF WINDOW-TO-WALL RATIO, BUILDING ORIENTATION AND GLAZING MATERIAL ON OFFICE SPACES

Prof. Dr. Ossama A. Abdou
Dr. Tarek S. Elhinnawy
Center for Building Environmental Studies and Testing
Cairo, Egypt

ABSTRACT

This paper examines the influence of the building envelope on the annual hourly heating and cooling loads of office spaces in hot dry climates. Particular focus is on the glazed part of the envelope. A number of fenestration parameters are discussed and their effect on the thermal performance are investigated. Special consideration is given to the effect of orientation on building performance. A computer simulation was performed that employed real weather data representative of hot, dry climatic zones. The impacts of window-to-wall ratios, building orientation and individual fenestration parameters are described. It was determined that, from a thermal point of view, a windowless building façade is the optimum design for office spaces with single exposure to the elements regardless of building orientation. However, when windows are incorporated in the external building envelope, the orientation of buildings strongly affects thermal performance and, hence, energy requirements of office buildings. Based on combined annual heating and cooling loads, the preferred orientation is north, with the smallest possible window-to-wall ratio. Further, glazing material strongly influences thermal performance of the envelope ensemble.

INTRODUCTION

In order to maintain a comfortable state within a building, the building fabric must deal with the energy gains from both external and internal environments. A major component of these gains is imposed by a multitude of climatic elements, the most significant of which are temperature, humidity, solar radiation, and wind speed and direction. The impact of these elements on the interior is modified by the filtration effects of the building envelope. The indoor thermal environment is further affected by the thermal inertia of the building structure and the low-temperature radiation exchange between the building surfaces.

Fenestration systems have always played a role in shaping the building envelope. Fenestration is a term that refers to the arrangement, proportion, and design of window, skylight and door systems within a building. Fenestration components include glazing material, either glass or plastic; framing, mullions, dividers; external and internal shading devices; and integral shading systems. Fenestration can serve as a physical and/or visual connection to the outdoors, as well as a means to admit solar radiation. The solar radiation provides natural lighting and heat gain to the building space. Fenestration can be fixed or operable, and operable units can allow natural ventilation to a space and egress in low-rise buildings.

BUILDING'S THERMAL RESPONSE AND ENERGY REQUIREMENTS

To predict accurately the energy requirements for heating and cooling a building, it is necessary to evaluate the internal sensible heat and simulate the building and the operation of system components at small time increments. The main sensible heat source is the incoming solar radiation through windows. Therefore, an accurate estimation of incoming solar radiation is necessary for the prediction of annual energy consumption. Some of the incident solar energy is absorbed by the building envelope, and some passes through the windows and is absorbed by the inside surface. The parameters that affect the transmitted solar radiation are the orientation of the building surfaces, the environment of the building, the time of the year, the number of glass sheets, the physical properties of the glazing material, the extinction characteristics of the atmosphere, and the position and size of the window in the wall.

The transparent and non-transparent parts of the building façade have different thermal and optical behavior. These components allow interaction between the indoor climate and the environment through the façade in a way in which a maximum of indoor comfort and a minimum of energy is obtained. Therefore, it is particularly necessary to establish a procedure by which such an assessment can be made.

Solar heat gain to a room is one of the largest single components of the exterior room cooling load. Due to hourly, daily, and seasonal variations in the intensity of this load, careful investigation is necessary. Due to the nature of solar radiant heat, all solar gain does not become an instantaneous load on the heating, ventilating, and air-conditioning (HVAC) equipment because it must strike a solid surface before becoming a load on the equipment. Depending on the heat storage capacity of the space-enclosing components, individual maximum cooling loads for each exposure may or may not occur at or near the time of peak solar heat gain to the space. As the radiant heat strikes a solid surface, it is absorbed, raising the temperature of the surface above that inside the material and the air adjacent to the surface. This temperature difference causes heat flow into the material by conduction and into the air by convection. The heat conducted away from the surface is stored, and the heat convected from the surface becomes an instantaneous cooling load. However, as this process of absorbing radiant heat continues, the material becomes warmer and less capable of storing more heat. Thus, the highly varying and relatively sharp peak of the instantaneous solar heat gain results in large part of it being stored at the time of peak solar gain.

The rate at which heat flows through the structure and the time delay before a change on the outside affects the inside surface of a building space are functions of the thermal characteristics of each envelope layer. In opaque envelope surfaces, the resistance to heat flow per unit area is proportional to the thickness of the layer divided by the thermal conductivity. The heat stored per unit area is proportional to the density and the thickness

(i. e, mass per unit area) and the specific heat of each layer. The heat transferred through transparent surfaces such as glass is more a function of the thermal radiation characteristics of the glass and less dependent on the thermal storage capacity of such materials.

APPROACH

In order to obtain fundamental information on the thermal performance of transparent and non-transparent envelope components of office buildings, an office space exhibiting variant fenestration patterns was thermally modeled under hot, dry climatic conditions. A computer simulation analysis was performed to examine the impact of various combinations of transparent and opaque envelope components on the annual energy requirements of the building space. These were measured in terms of heating and cooling loads for the hot, dry climate of Phoenix, Arizona, USA.

A number of previous studies (Selkowitz and Bazjanac, 1979; Sullivan et al., 1988) investigated window performance in the context of overall building energy performance. The major innovations in the approach taken here are the realistic representation of the fenestration systems in a building façade and the systematic management of the window-to-wall ratio and exterior wall orientation.

Office Space Model

A typical 5m x 5m x 3.6m office space was thermally modeled. It was assumed that the space occupied an intermediate location having a single exposure along the periphery of a multi-story building. No heat transfer is assumed across internal partitions, the floor, and the roof. The model was thus set up so that the only energy transfer occurred across the exterior wall. The exterior wall consisted of 6-inch medium weight concrete masonry units (CMU) with no exterior finish (gray color). No exterior insulation was used. The ceiling/roof system consisted of 6-inch concrete with interior finish consisting of ceramic tiles for the floor, and cement plaster was used for inside ceiling finish, with no suspended ceiling.

The initial window type and arrangement representing the base case fenestration system is a single glass window with aluminum frame (0.434 BTU/(h.ft^2) conductance, and 0.7 absorptance. No accommodations were made for shading devices. All internal heat gains due to people, the lighting system, and the office equipment were accounted for. A typical hourly office schedule for all internal heat gain loads was used in this study.

Physical Characteristics and Thermal Description of Building Components

Table 1 outlines the thermal and physical characteristics of all building materials used in the office space model. As seen, the walls and roof possess high thermal masses. Note that the thermo-physical characteristics of the exterior wall are fixed throughout the study, however, thermal performance of the wall changes according to the ratio of glazing to opaque parts. Table 2 outlines the thermal and physical properties of glazing materials used for simulation.

Table 1: Thermal Properties of the Modeled Building Materials

Description	Thickness (cm)	Conductivity W/(m°K)	Density (kg/m^3)	Specific Heat kJ/(kg°K)	Resistance (°Km^2)/W
Concrete	15	1.73	2243	837	0.088
Concrete Block	20	0.67	849	837	0.303
Built-up Roof	1	0.162	1121	1464	0.026
Polystyrene	5	0.035	29	1213	1.468

Table 2: Thermal Properties of Window Glazing Materials

Glazing Type	Thickness mm	U W/m^2	SC	SHGC	T_{sol}	Ref_{sol}
Clear	3	6.31	1.00	0.86	0.84	0.08
Tinted	6	6.17	0.71	0.61	0.48	0.05
Low-e	6	4.27	0.84	0.72	0.68	0.09
Reflective	6	4.9	0.23	0.19	0.07	0.34

where SHGC = Solar Heat Gain Coefficient
SC = Shading Coefficient for the total window system representing the ratio of the solar heat gain through the window system relative to that of a 3-mm clear glass
U = Total Heat Transfer Coefficient for the window system
T_{sol} = Solar Transmittance
Ref_{sol} = Solar Reflectance

The investigation proceeded according to the following process. Hourly thermal loads were calculated for the model space using typical weather data for Phoenix, Arizona, a location representative of hot, climatic regions of the world. Figure 1 outlines major characteristics of the climate.

COMPUTER SIMULATION

A public domain energy simulation program eQUEST (James J. Hirsch, 2003) was used to determine the effect of fenestration patterns and orientation on the thermal performance and energy requirements of the building. The computer program consists of an enhanced, interactive, simulation engine, an advanced derivation of DOE-2 (LBNL, 1982) to perform an hourly simulation of the described building for a user-selected one-year time period. For each hour of the simulation, heating and/or cooling loads are calculated based on contributions from walls, windows, people, plug loads, and ventilation air.

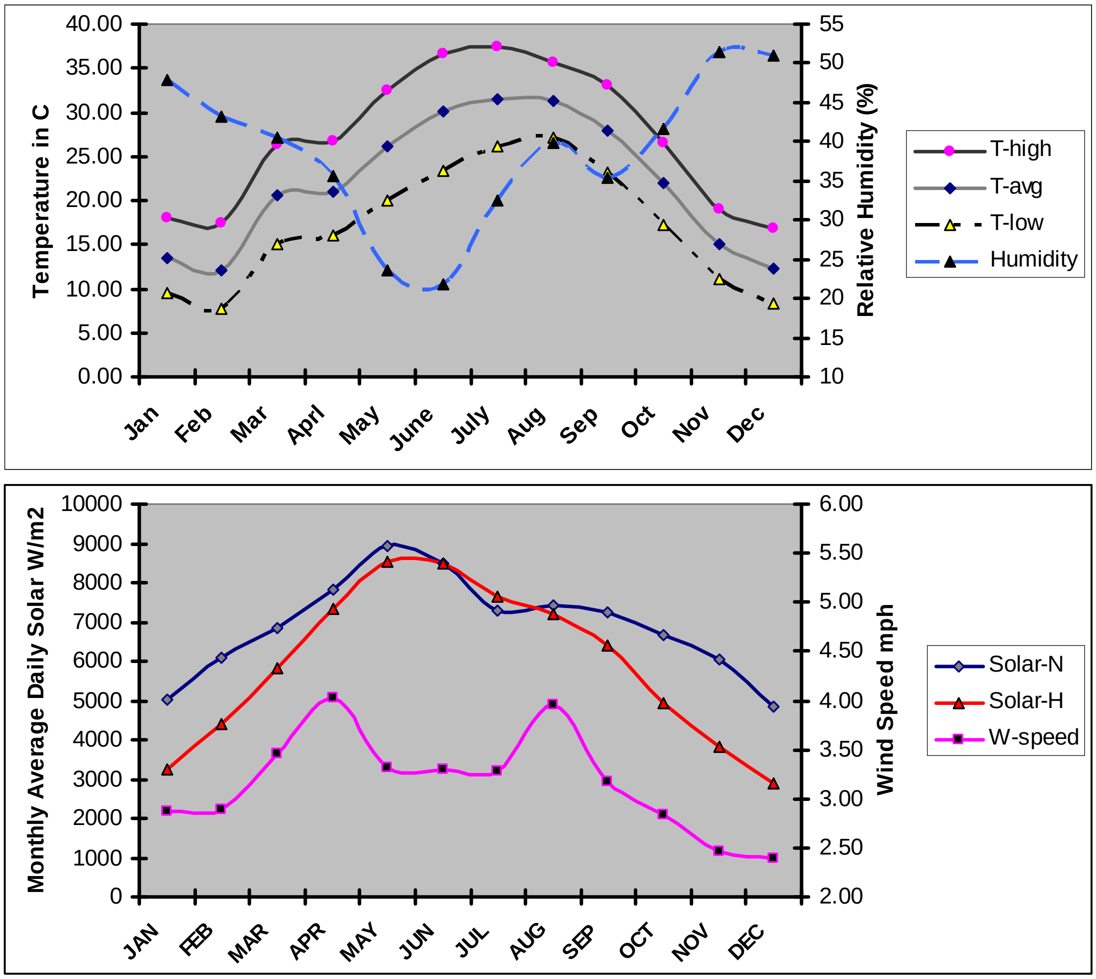

Fig. 1. Climatic Data of Phoenix, AZ, USA

Analysis Method

Heat transmission through opaque exterior surfaces was modeled using "delayed" method via conduction transform functions (accounting for mass effects in delayed envelope heat transfer). For heat transmission through transparent surfaces: the shading coefficient method was used.

The program's solar heat gain calculations provide detailed treatment of solar distribution on interior surfaces (i.e., it does project "sun patches" into a space's interior). Space Loads information relies on DOE-2's standard and/or custom weighting factors methods.

As indicated earlier, eQUEST calculates hour by hour building energy consumption over the entire year (8760 hours) using hourly weather data for the location under consideration. Input to the program consists of a detailed description of the building being analyzed, including hourly scheduling of occupants, lighting, equipment, and thermostat setting.

For each hour simulated, a complete radiant, convective, and conductive heat balance for each building surface and a heat balance on the room air were performed. This includes all envelope as well as internal heat gain loads, in addition to infiltration loads and the temperature control strategy used to maintain the space temperature. In this simulation, no integration of daylighting was made.

Input Data

The type of building can be selected from a number of building types that are listed to choose the appropriate building type. Building location also will be assigned by choosing weather file from a wide range of listed locations around the world. Building number of floors is assigned. The user will be allowed to choose or select the preferred building footprint to describe generic shape of building footprint, and then the user can edit the footprint dimensions or select custom or draw custom footprint from scratch. A completely custom building footprint shape can be created by importing DWG file and then tracing around it.

Building orientation is specified relative to true north. Floor height is specified as a distance from one floor to the next and also the floor to ceiling and applied to all building floors. Building envelope construction is assigned by choosing from the listed most common envelope construction types for roofs and exterior walls. The properties include exterior finish type exterior color and insulation. The choices for finish and color are used to define the exterior solar absorbance and exterior film resistance.

Building envelope infiltration reflects the envelope’s tightness and infiltration characteristics. The infiltration is specified in air changes per hour (ACH).

Interior wall constructions options were selected as well. For the case at hand, interior wall construction is used as adiabatic to represent no exterior exposure – a surface through which no heat will transfer to tell the program to ignore heat transfer through these walls.

Exterior doors are specified including number of doors and door type, orientation and construction. The opaque door type and frame type selection is per ASHARE Handbook of Fundamentals [2001]. Glass doors properties are using the DOE-2 glass library. Window area is indicated as a ratio of window-to-wall for floor-to-ceiling dimension. Glass type is selected from glass categories and types of DOE-2 library, which allows for wide range of selections, with detailed list of glass properties (SHGC, Shading Coefficient, U-Factor).

THERMAL BEHAVIOR OF WINDOWS

Decreasing or increasing the relative amount of glass area by changing the window-to-wall ratio from a base case changes the thermal characteristics of the exterior envelope in three ways. First, it changes the heat transmitted by conduction, since glass possesses a higher conductance than most opaque wall material. Second, since glass is relatively transparent to thermal radiation, it changes the amount of radiant heat that is passed through the building skin. Finally, with the increase in the number of window units the infiltration load increases through the increased length of cracks around the window frames (Yellott, 1979).

All windows, regardless of their orientation, lose heat by conduction when the indoor temperature is higher that the outside temperature., and the situation is reversed when the outdoor temperature becomes warmer than the indoor air. As radiant energy passes through glass, some of it is absorbed, raising the glass temperature enough to allow the absorbed energy to be dissipated by radiation and convection from the inner surface of the glass to the outdoor environment.

The amount of incident solar energy a window transmits during any given day depends on the angle at which sunlight strikes the window and how long it does so. The angle of sunlight affects the amount of solar energy transmitted by determining the proportion of light reflected, absorbed, and transmitted, and by establishing the projected width of the window measured perpendicular to the rays of light. Less light is transmitted as less area is exposed.

Fenestration Patterns

To analyze the effect of varying window size on the energy performance of the office space, a strategy was developed in which window area (and, hence, fenestration pattern) was changed in a systematic way. The office space façade was divided into equal units. Window-to-wall ratio was changed in an incremental way such that it takes up a certain percentage of the overall exterior wall are. The base case represents a full opaque wall, i.e., window-to-wall ratio being 0%. A gradual increase in window area followed. First to 20% then 40%, followed by equal increments of 20%, until the window took up the entire façade reaching 100% of its entire area. This way, six different window-to-wall ratios have been simulated for each computer run performed. Heating load and cooling load for each case was then calculated to measure the impact of varying window-to-wall ratios.

Building Orientation

From an energy conservation point of view, southern exposure of building facades has been shown to be superior in many locations (Olgyay, 1963; Givoni, 1976; Abdou, 1990). However, most buildings have facades facing other directions. Hence, it is important to assess the impact of fenestration orientation in order to predict the thermal performance of buildings.

There is substantial variation between the amounts of solar radiation reaching different surfaces of a building. Of prime concern here is the impact of vertical wall orientation on incident solar radiation. Of particular relevance is the energy transmitted through glazing versus the angle of incidence. This angle determines the amount of direct sunshine intercepted by the surface. In the case of ordinary glass, at low angles of incidence (i.e, 30 degrees), 86% to 87% is transmitted and 8% to 9% is reflected, with the remainder absorbed by the glazing material itself. As the angle of incidence increases, more solar energy is reflected and less is transmitted. For example, at an incidence angle of 80 degrees for the same ordinary glass, approximately 52% is reflected and only 42% is transmitted. In the case of a fenestration system consisting of two 6-mm plate glass panes with white Venetian blinds in between, energy transmitted through the system amounts to only 26% of the total energy incident on the outer surface of the glazing system at a 30 degree incidence angle (Carrier, 1972).

Simulations were conducted for the four cardinal orientations representing due north, east, south, and west. This was accomplished for each fenestration pattern and glazing type investigated.

RESULTS OF SIMULATION

Comparison of one window scheme with another requires a benchmark or baseline to rank their thermal potential. Two benchmarks were established; one relates to the fenestration pattern and the other to building orientation.

Presented in this section are the simulation results for each fenestration pattern and building orientation considered. Figure 2 gives a summary of results of all conditions simulated.

Base Case

A base case consisting of a windowless office space model was used to facilitate comparison among fenestration patterns (in terms of window-to-wall ratio), glazing material, and orientation. As expected, the windowless pattern, representing a window-to-wall ratio of 0% was optimum in terms of energy conservation. In general, the increased cooling load and resulting increased electrical energy consumption associated with any window area, as well as the decreased thermal integrity of the envelope, negated any solar heat gain benefits.

Figure 2 shows that, in the absence of windows, space heating and cooling are at their minima. In the hot, dry climate of Phoenix, the respective heating and cooling loads for this case were 35 W/m2 and 68 W/m2, respectively, with the annual cooling loads being roughly 94% higher than the annual heating loads at north orientation. This particular case applies to the 3-mm thick glazing system. In the absence of windows, it seems that the magnitude of the heating load at all orientations is not affected. In contrast, there exists variation in cooling load depending on orientation with highest load occurring in the east orientation and the lowest at north orientation with a relative difference of 10%.

Effect of Window Size

As indicated earlier, six simulation runs were conducted representing the following window-to wall ratios: 0%, 10%, 20%, 40%, 60%, 80%, 100%. Simulation results indicated general trends. Heating loads, with no exceptions, generally increased with the increase in window size, indicating that solar gains exceeded conduction and convection losses. However, the increase was a very modest one, with the rate increasing only slightly as the number of window units increased. A somewhat different trend can be seen in the cooling loads. Figure 2 illustrates the fenestration schemes and corresponding energy loads for all orientations.

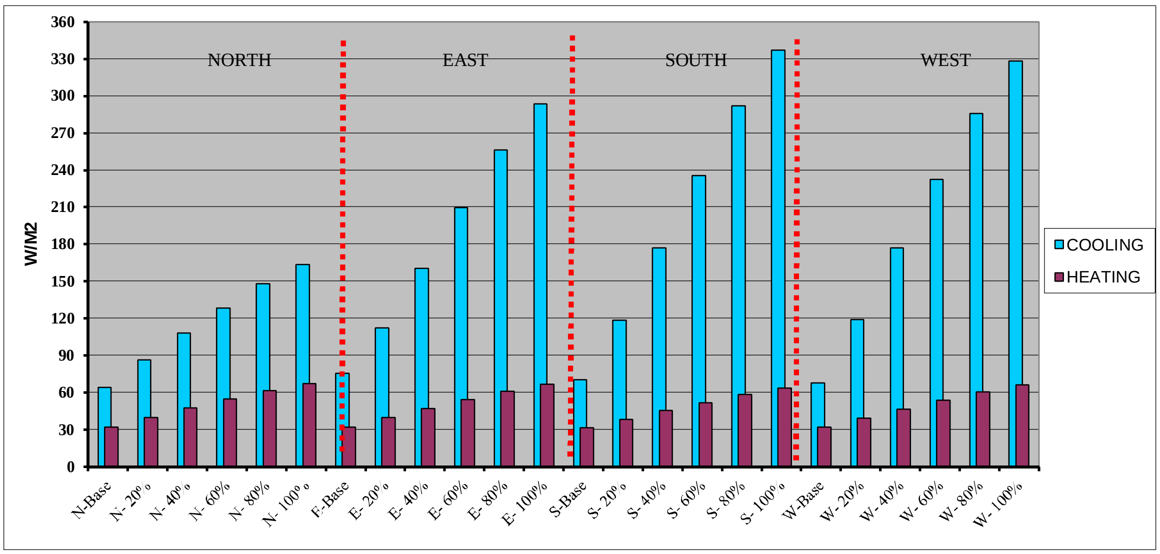

Fig. 2: Effect of Building Orientation and Window-to-Wall Ratio on Building Cooling and Heating Loads

It is indicated that for all orientations, a slight increase of roughly 15% to 20% in the heating load can be expected with each increase in window unit size in increments of 20%. However, since the heating component is relatively small compared to the cooling component, final assessment has to be made based on total energy loads. At all four cardinal orientations, the more glass area, the more energy loads will be required for both heating and cooling purposes. It is noted, that for any given orientation, the rate of change in energy load is higher for cooling than that for heating, indicating that the relative effect of window size is more pronounced when cooling is called for. This is of particular consequence in this type of climate, due to the relatively large magnitude of cooling needs compared to heating needs. For example, when ordinary 3-mm glass is used at a 20% window-to-wall ratio, the cooling load represents circa 75% of the annual energy load for the building. In the case of an all glass façade (i.e., 100% window-to-wall ratio), the cooling load jumps to approximately 83% of the entire annual energy load.

Effect of Glazing Material

As shown in (Fig. 3), glazing types affect the amount of heating and cooling loads with different rates. A general observation can be made: Low-emissivity glass, regardless of orientation and window size has a positive effect during the heating season of the hot, dry climate. In other words, an office space with low-E glass consumes less heating energy than other types of glazing systems. In the overheated period (cooling season), however, reflective glass takes over and provides a more energy efficient solution for office spaces, regardless of window size and orientation. Clear 3-mm glass provides the worst thermal condition. This is specially pronounced in the south orientation, followed by west, east, then north.

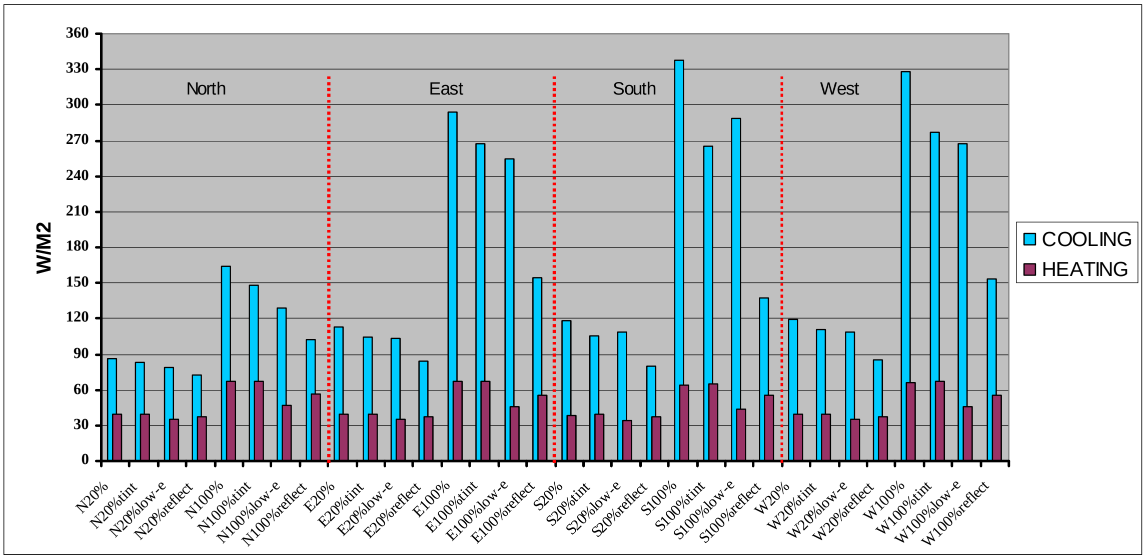

Fig. 3. Effect of Glazing Materials on Building Cooling and Heating Loads

On south orientation, reflective glass reduces loads by approximately 26% in lower window size units (20% window-to-wall ratio) to 52% for full wall (100% window-to-wall ratio). Where for other types of glazing materials (tinted, low-e), loads were reduced by only 8% to 18%. West wall also has almost the same amount of loads saving. Reflective glass reduces loads by 22% to 47%, and for other types ranging from 5% to 21%. For east orientation, loads reduced by 20% to 42% for reflective glass type and from 5% to 17% for other types. North orientation experienced the least amount of reduction ranging from 13% to 31% for reflective glass and 3% to 24% for tinted and low-e glass types.

Effect of Orientation

The dependence of building energy performance on fenestration orientation was established by rotating the office space so that its exterior wall faced all four cardinal points in four consecutive runs. A rather inconsistent load pattern existed as a function of glazing material.

From a cooling load point of view, Figures 2 and 3 indicate a preference for the north window orientation followed by east, west, and finally south, in the case of windowless office space. With a 20% window-to-wall ratio, this sequential preference has not changed. An increase in window-to-wall ratio to 40% exhibits a similar cooling load pattern. This pattern seems to remain for any additional increases in window-to-wall ratio. When using reflective glass at the 20% window-to-wall ratio, the north orientation is still preferable, followed by south, east, then west. Increasing the window-t-wall ratio to 100% did not exhibit any pattern change.

CONCLUSIONS

This paper has examined the influence of the building envelope – especially that of the glazed part – on the annual hourly energy loads of a typical office space having single exposure to the exterior under hot, dry climatic conditions. Much of the exchange of heat between a building and its environment occurs through the windows. This energy exchange can be modified by increasing or decreasing the allotted window area within the building envelope. The investigation showed that the heat lost or gained through windows varies, not only according to window size, but also with the orientation and glazing material/system.

Fenestration contributes significantly to energy loads. In hot climates, total purchased heating energy is reduced, indicating that increased fenestration can be an asset. Solar energy entering a building through glass surfaces can become a major natural heating element in the winter. Nonetheless, it is a major cooling load in overheated periods.

Based on the study presented, a windowless building space would be thermally optimum all year round in all orientations. When incorporating them into the envelope, windows for the optimal thermal design are to be placed on the north wall for hot, dry climates.

In this study, increased widow size resulted in increased annual energy use; however, it is possible that, with the use of special glazing systems, daylighting, shading, and/or heat storage, net annual energy could decrease with an increase in window size. Thus, it is recommended that further analysis be performed incorporating the effect of shading options (along with varying exterior wall mass) in addition to the integration of daylighting and then optimize energy loads based on balancing any conflicting lighting and thermal considerations. Such a study must include the thermal and optical characteristics of glazing materials as important parameters.

REFERENCES

Abdou, O. 1990. *A computer-aided process for simulating the thermal performance of buildings under different orientations*. *Proceedings of the 22nd Conference on Modeling and Simulations*, Pittsburgh, PA.

ASHRAE. 2001. *ASHRAE handbook – 2001 fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Carrier. 1972. Load estimating. *Carrier System Design Manual*. Syracuse, NY: carrier Corp.

LBNL. 1982. *DOE-2 Engineers manual version 2.1A*, University of California Berkeley.

James J. Hirsch & Associates. 2003. *DOE-2.2 building energy use and cost analysis program manual*, Lawrence Berkeley National Laboratory. Berkeley, CA.

James J. Hirsch. 2004. *eQuest (v 3.55) Quick energy simulation tool reference materials*, Lawrence Berkeley National Laboratory. Simulation Research Group. Berkeley, CA.

Givoni, B. 1976. *Man, climate and architecture*. London: Applied Science Publishers Ltd.

Olgyay, V. 1963. *Design with climate: Bioclimatic approach to architectural regionalism*. Princeton, NJ: Princeton University Press.

Yellott, J. 1979. Fenestration and heat flow through windows. In *Energy Conservation through Building Design*, ed. D. Watson. New York: McGraw-Hill.