THERMAL PERFORMANCE OF A HYBRID DOUBLE-ENVELOPE BUILDING MODEL

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ABSTRACT

This paper introduces a conceptual building model that integrates passive and mechanical environmental control systems. The general building configuration includes a central atrium, a double-envelope system, individual zone air-handling units, a direct/indirect evaporative cooling system, and a heat exchange system. Airflow through the building is designed to facilitate nighttime ventilation and economizer cooling and to enhance air distribution and indoor air quality. The research goal is to evaluate the thermal performance of the model under the assumption of hot, dry climatic conditions.

The Building Loads Analysis and System Thermodynamics program (BLAST) is used to simulate and compare three double-envelope variations of the proposed model with two variations of a single-envelope model. Typical climatic conditions for Phoenix, Ariz., are used to represent a hot, dry climate, where cooling loads are expected to dominate. Hour-by-hour simulations for the Phoenix summer and winter design days are performed for the five models and results analyzed and presented.

BLAST simulation results indicate that the double-envelope building model performs significantly better than the single-envelope building model. A 26% reduction in total peak cooling loads and a 66% reduction in total peak heating loads are indicated. Flexible control strategies applied to the double-envelope model can further reduce its cooling loads and completely eliminate heating loads. Orientation of a square-plan double-envelope model has no significant effect on its total peak loads. The integrated model design, as investigated, shows considerable energy-saving potential for hot, dry climates. The methods used in this research can be extended to encompass additional features and other climatic conditions.

INTRODUCTION

This paper is an investigation into the thermal performance of a conceptual building model. The building configuration integrates the environmental control system with the architectural design of a high-rise office building prototype. The concept is based on direct solar heat gain control within the double-envelope cavity using sun-tracking shading devices, a strategy that significantly could reduce cooling loads of the occupied zones. Conditioned exhaust air is used to remove unwanted heat gains before it is exhausted to the outside. A central atrium is used to provide partly cooled fresh air to the air-handling units in the occupied zones. Fresh air flows from the outside through the atrium to the occupied zones. Exhaust air flows through the light fixtures and the envelope cavity to the outside. The airflow pattern facilitates the use of passive ventilation, evaporative cooling, and nighttime cooling strategies when outside air conditions are favorable.

DESCRIPTION OF THE BUILDING MODEL

The building model is intended primarily for reducing cooling and heating loads and for reducing mechanical system size without compromising thermal comfort or indoor air quality. All systems and components are integrally designed to perform together as a coherent whole to control the building's thermal environment and to conserve energy. In the order of airflow, these components include a wind-assisted fresh-air supply unit, a two-stage direct/indirect evaporative-cooling system for outside air, an enclosed atrium, individual zone air-handling units, a double-envelope system, a heat exchange system, and a smart control system. Figures 1a and 1b show the location of these components in a schematic building section and plan. Each of the components performs a function that is complementary to the overall building system operation.

The Atrium

The atrium serves as the vertical fresh air distribution conduit in addition to its architectural role as a major common space in the building. A single-zone draw-through heating, ventilating, and air-conditioning (HVAC) system is provided to maintain the atrium space air at control conditions. Atrium air is used as precooled supply air for the occupied zone air-handling units.

Individual Zone Air-Handling Units (AHUs) A conventional mechanical HVAC system with terminal

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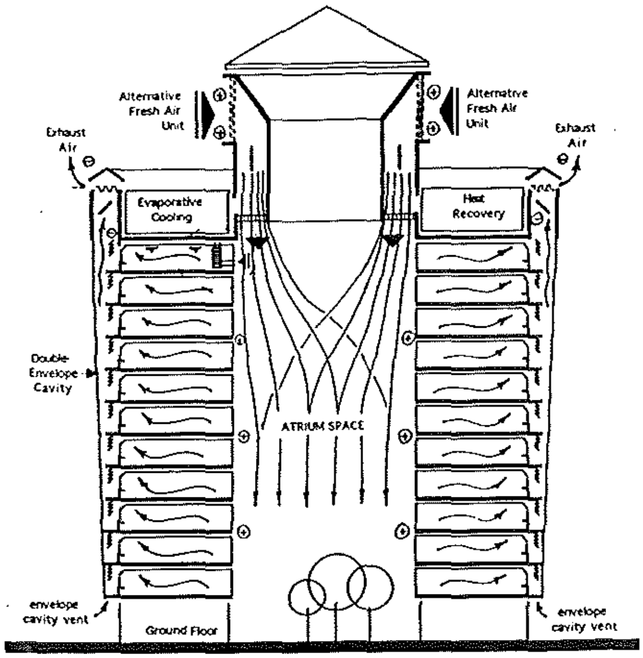

Figure 1a *Building section showing general airflow pattern.*

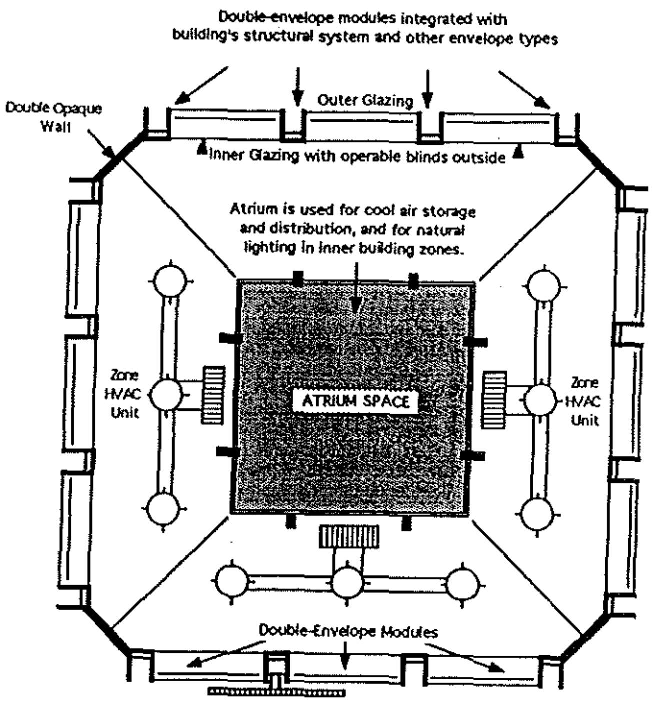

Figure 1b *Building plan showing components of the proposed model.*

air-handling units in each individual zone is proposed for conditioning the occupied spaces. Each AHU is locally operated and controlled within the zone it serves. AHUs draw partly cooled fresh air from the atrium and deliver fully conditioned supply air to accommodate local variations of loads. Supply air is distributed within each zone through a conventional horizontal duct system. Fan-coil units, induction units, or closed water loop heat pumps could be used.

The Double-Envelope System The double-envelope system consists of two glazed curtain walls, a 2-ft to 4-ft-deep vertical air cavity, and three sets of shading devices at each floor. The two larger sets are pivoting to track the sun and can be equipped with solar electric photovoltaic cells. The smaller set is made of vertically adjustable external blinds for windows. Electricity generated by the photovoltaics could be used for cooling, lighting, or other purposes. Photovoltaic cells also can be modularly integrated as major components of the outside skin of the double envelope. High levels of photovoltaic electric power production coincide with peak solar radiation, which also coincides with high demand for mechanical cooling.

It is not necessary to enclose the whole building with a double envelope of this type. Depending on other architectural considerations, such as view, facade design, and site considerations, several double-envelope modules can be used among other envelope types, such as solid masonry or concrete walls, curtain walls, opaque panels, and operable windows. These components also can be integrated with the building's structural system. Such variations will provide flexibility of design and building plan layout.

AIR DISTRIBUTION

General Airflow Pattern

Airflow through the building is based on a continuous, one-way circulation pattern from the outside fresh air units at the top of the building to the atrium to the conditioned spaces via the individual zone air-handling units. These units will draw precooled supply air from the atrium space and deliver fully conditioned air to occupied spaces. Room air is then exhausted to the envelope cavity as illustrated in Figure 2. Exhaust air is allowed to flow upward to the heat exchange system and then to the outside.

This airflow pattern is achieved by naturally and mechanically maintaining air pressure differential between the atrium space at the center of the building and the double-envelope cavity at the perimeter. While wind pressure on the fresh air intake units can help increase air pressure in the atrium, solar-powered thermosyphon effect can help reduce air pressure in the double-envelope cavity. The maintenance of a pressure differential and a uniform airflow pattern from the atrium to the envelope cavity modules is intended to reduce the overall fan power required for air circulation throughout the building. The atrium space and the double-envelope cavity will serve as the vertical air distribution conduits. Individual zone air-handling units use a conventional horizontal duct system to circulate air within each zone.

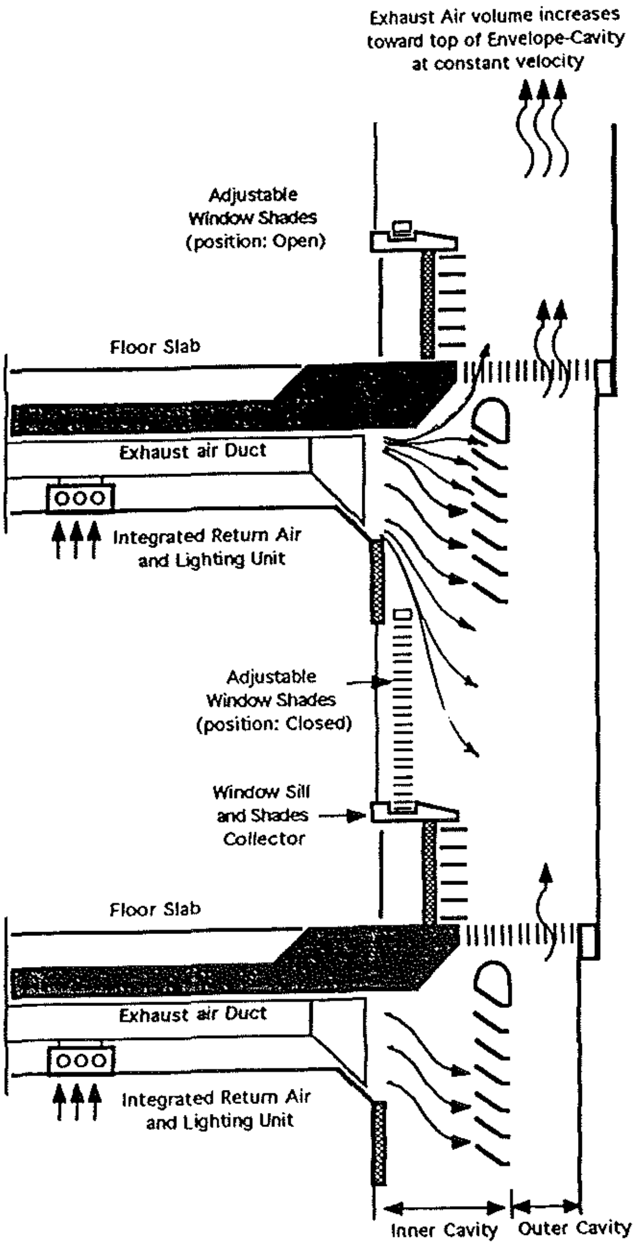

Figure 2 Detail of the double envelope showing air flow and stepped outer glazing.

Airflow Within the Cavity

Exhaust air is intended to carry away solar heat gains and maintain the inner zone of the double-envelope cavity close to room conditions. When conditioned exhaust air is delivered into the warmer envelope cavity, it is expected to flow downward (because it is heavier than cavity air), forming a tempered air curtain between the inner cavity wall and the warmer air in the outer cavity. Therefore, heat exchange across the inner cavity wall can be minimized and conditioned exhaust air is not wasted. As this air passes between the solar shades to the outer cavity, it will become warmer and flow upward to the top of the envelope cavity.

MODES OF OPERATION

The control system determines the overall building mode of operation, whereas occupants of each zone determine the operation of each individual zone AHU. Although it is possible to completely automate all system and component control, user control is proposed for zone units to accommodate user preferences in regard to comfort, schedule, and economy. The building model allows five modes of operation: the double-cooling, the nighttime cooling, the economizer cooling, the heating, and the system shut-off modes. Two modes are described below for the purpose of simulations presented in this paper.

The Double-Cooling Mode

This mode is implemented when outside air conditions are predominantly hot during the building operating hours to provide optimum comfort conditions in the occupied zones. In the double-cooling mode, outside air is cooled by the evaporative cooling system or by the atrium HVAC system to maintain the atrium air at set conditions. Individual zone air-handling units provide additional cooling and distribution of supply air to the occupied spaces. Dry outside air conditions allow utilization of two-stage evaporative cooling and reduce the energy needed for mechanical cooling.

The Heating Mode

Depending on climate and on the magnitude of internal heat gains from lighting, equipment, and occupants, demand for heating may be small or nonexistent. When heating is demanded, the heat exchange system can use the warm exhaust air to preheat outside air before it is introduced to the atrium. In effect, the double-envelope cavity will act as a solar heating system in addition to its improved thermal performance as an insulator between the inside and outside air.

RESEARCH PROBLEM AND OBJECTIVES

There is a need to evaluate the thermal performance of the proposed double-envelope building model as an integrated whole. It is not empirically clear how much improvement can be expected with the proposed building model, or variations thereof, compared to a typical single-envelope model, with or without external shading, operating under the same assumptions. While heating loads are expected to be much lower in a double-envelope building than in a single-envelope building, detailed analysis is needed for estimation and comparison of cooling loads. Therefore, the purpose of this research is to quantitatively investigate the thermal performance of the double-envelope building base model and compare its performance with that of a single-envelope building base model operating under the same assumptions. The research also aims at studying other variations of the double-envelope and single-envelope models and comparing their performance to that of the double-envelope base model. In all, five simulation models are identified for the study.

The objectives for this research are to estimate peak cooling and heating loads for the five simulation model variations, and to compare the thermal performance of the double-envelope base model with that of the single-envelope base model and the other model variations. These objectives are addressed in detail within the context of the building model described above, and under the assumptions of predominantly hot and dry climatic conditions. The components of the model that are simulated in this study are outlined below.

- The atrium is simulated as one zone, which is controlled at a 24-hour constant temperature. Atrium air temperature is adjusted seasonally to correspond to the potential use of cool outside air in the winter, spring, and fall seasons. The assumed atrium temperature settings for these seasons are 65°F (18°C) in the winter, 70°F (21°C) in the spring and fall, and 75°F (24°C) in the summer. Atrium fresh air loads are not simulated or presented in the main body of this research. However, they are identical in all simulated models.
- Occupied spaces are simulated as four occupied zones—the north zone, the east zone, the south zone, and the west zone. Occupied zones are controlled at 75°F (24°C) during the workday hours and are allowed to float between 60°F and 80°F in the evenings and on weekends. Each occupied zone receives a specified amount of fresh air from the atrium zone, based on 20 cfm per person.
- Envelope cavities are simulated as four unoccupied, uncontrolled zones—the north cavity, the east cavity, the south cavity, and the west cavity. Consequently, the cavity air temperature is allowed to swing in each zone depending on its heat gains, losses, and internal mass and surface characteristics. Each cavity zone receives a specified amount of exhaust air from the corresponding occupied zone, which is equal to the amount of fresh air supplied to the occupied zone for the assumed level of occupancy.

RESEARCH PROCEDURE

Computer simulation using the Building Loads Analysis and System Thermodynamics program (BLAST),[1] has been selected to test the proposed building model. The analysis presented in this paper is based on BLAST's building simulation execution module. The following procedure is adopted to conduct this research.

1. The building model is designed with systems integration for cooling as first priority. The model is represented in schematic plans and sections to include all components of its environmental control system.
2. A computer simulation model is created to represent selected components and features of the proposed building model to be simulated by BLAST. General and special assumptions are made to adapt the building model to BLAST simulation.
3. Additional simulation models are created to represent the single-envelope base model and the three other variations to be tested.
4. BLAST simulation runs are performed and relevant data extracted from the output files. These numerical data are then presented graphically in charts.
5. Results are developed based on detailed analysis of each set of data.

THE FIVE SIMULATION MODELS

A total of five simulation models—three variations of the double-envelope building model and two variations of the single-envelope building model—are analyzed. Identical assumptions are made for all models as to their layout, location, climate, occupancy schedules, control profiles and schedules, construction components and materials, thermal mass, fresh air requirements, and internal heat gains. The five simulation models are given descriptive names and acronyms that are used in this paper.

The Double-Envelope Base Model (DE-BM)

This simulation model represents the basic double-envelope building shown in Figures 1a, 1b, and 2. The DE-BM includes nine zones—four occupied zones, the north zone, the east zone, the south zone, and the west zone; four envelope cavity zones, the north cavity, the east cavity, the south cavity, and the west cavity; and the atrium zone. The model is oriented so that its four facades face due north, east, south, and west, respectively. All occupied zones are controlled at 75°F (24°C) during occupancy hours. This temperature is chosen as a constant, all-year comfort temperature for simplicity. More typical settings of 72°F in the winter and 78°F in the summer are assumed for the flexible control model described below.

The Single-Envelope Base Model (SE-BM)

This simulation model represents a prototypical single-envelope building model with 33% single 1/2-in. bronze plate glazed facades. This model is similar to the double-envelope building model without the outside envelope skin. The purpose of simulating this model is to compare its thermal performance with that of the

[1]The BLAST program was developed by the U.S. Army Construction Engineering Research Laboratory (USACERL). The program has been extended and improved several times since its initial release. BLAST Version 3.0, level 193, is used to perform simulations in this research (USACERL 1985a).

double-envelope base model. Interior shading by venetian blinds is assumed for all exterior windows. The SE-BM includes five zones: four occupied zones and the atrium zone. No envelope cavity zones are present in single-envelope models.

The Single-Envelope with External Shading Model (SE-XS)

This simulation model is the same as SE-BM except that external shading devices are applied to all external windows to provide almost complete and continuous shading of windows on July 21, the date used as the Phoenix summer design day. External horizontal and vertical shading devices are specified for all windows to shade the bronze plate glazing on all four facades. This variation is added to compare the performance of the double-envelope base model to that of a prototypical, externally shaded, single-envelope building.

The Double-Envelope 45-Degree Model (DE-45)

This simulation model is the same as DE-BM except that it is oriented 45 degrees clockwise from due north. In other words, its facades face northeast, southeast, southwest, and northwest, respectively. This model is added to study the effect of changing building orientation on the thermal performance of the double-envelope building model. However, because all models compared in this study have a square footprint, total cooling and heating loads for this model may be similar to those of the DE-BM. On the other hand, individual zone loads are expected to vary significantly as a result of the 45-degree change in building orientation.

The Double-Envelope Flexible-Control Model (DE-FC)

This simulation model is the same as DE-BM except that occupied zone temperatures are allowed to deviate from the constant 75°F (24°C) setting assumed for the other models. However, occupied zones are still mechanically maintained between 72°F and 78°F during occupancy hours. This model is added to study the effect of flexible zone temperature control on the thermal performance of the double-envelope building model.

GENERAL SIMULATION ASSUMPTIONS

Except as noted above, identical assumptions are made in all of the five BLAST simulation models. These assumptions are as follows.

Building Location

Phoenix, Ariz., at 33.34° north latitude and 112.02° west longitude.

Building Size

The assumed building has a foot print of 72 ft (22 m) by 72 ft (22 m), ten floors, and four occupied zones in each floor. Each zone has a total area of 17,280 ft^2 (1,560 m^2). The total occupied floor area is 69,120 ft^2 (6,220 m^2). The atrium dimensions are 40 ft (12 m) by 40 ft (12 m) by 100 ft (30 m) high. Atrium floor area is not included in the total occupied floor area.

Phoenix Summer Design Day

Dry-bulb temperature high = 107°F (42°C), dry-bulb low = 72°F (22°C); wet-bulb temperature high = 71°F (22°C).

Phoenix Winter Design Day

Dry-bulb temperature high = 64°F (18°C); dry-bulb temperature low = 34°F (1°C).

Building North Axis

The building north axis is assumed to point to due north (0.00 degrees) in the DE-BM, SE-BM, SE-XS, and DE-FC models. In the DE-45 model, the building "north axis" points to the northeast (45.00 degrees). Nominally "north" zones in this model actually face northeast, "east" zones in this model face southeast, "south" zones in this model face southwest, and "west" zones in this model face northwest.

Office Occupancy and Schedule

Assumed maximum number of occupants in each of the four occupied zones is 250 persons per zone. This corresponds to approximately 70 ft^2 (6.3 m^2) per person on average—a relatively high-density occupancy, chosen to represent an extreme-case scenario. The number of occupants at any hour, however, is factored according to the office occupancy schedule. Thus, the actual workday occupancy is 200 persons per zone, and the night and weekend occupancy is 25 persons per zone. The assumed office occupancy schedule is:

Monday through Friday

80% of maximum office occupancy from 9:00 a.m. to 5:00 p.m.

10% of maximum office occupancy from 5:00 pm to 9:00 am.

Saturdays, Sundays, and Holidays

10% of maximum office occupancy for each hour of the day.

Windows

Exterior glazing in all models is assumed to be 1/2-in., single-pane bronze plate glass. All exterior windows have venetian blinds inside. External window shading is provided in all double-envelope models by shading devices within the envelope cavity, and in the single-envelope, externally shaded (SE-XS) model by fixed external horizontal and vertical shading devices. Atrium glazing in all models is assumed to be 3/8-in. clear plate glass with no internal or external shading.

Electric Lights and Equipment

Assumed maximum electric power is 150 kBtu/h per occupied zone. This amount corresponds to 8.68 Btu/h (2.54 W) per square foot of floor area and is assumed to account for both lights and office equipment. Thirty percent of the heat from lights is assumed to be removed directly by exhaust air. Electric lighting and equipment loads are factored according to the office occupancy schedule in all occupied zones. No electric lighting or equipment is assumed in the atrium zone or in the envelope cavity zones.

Ventilation

Fresh atrium air is introduced to the occupied zones, and equal volumes of exhaust air are delivered to the double-envelope cavities. In all five simulations performed, an equivalent amount of room air is exhausted to the outside. This assumption allows load comparison among the models at similar indoor air quality. Thermal loads associated with airflow between zones are accounted for in the BLAST simulations by specifying the amount and schedule of airflow between zones using an air "mixing" statement for each zone that receives air from another. In BLAST, a mixing statement accounts for thermal loads associated with the introduction of air to a zone from another zone at a different temperature. The maximum amount of air mixing is 5,000 cfm (2,360 L/s) per zone. This amount corresponds to 20 cfm (9.44 L/s) of fresh air per person, which is the amount required for ventilation in nonsmoking offices. Air mixing is adjusted according to the office occupancy schedule in all occupied zones.

Occupied Zone Temperature Control

Monday through Friday

Occupied zones are controlled at 75°F (24°C) from 9:00 a.m. to 5:00 p.m. The DE-FC model is controlled at 72°F to 78°F (22°C to 26°C).

Occupied zones are allowed to float between 60°F and 80°F (16°C to 27°C) from 5:00 p.m. to 9:00 a.m.

Saturdays, Sundays, and Holidays

Occupied zones are allowed to float between 60°F and 80°F (16°C to 27°C) all day.

Atrium Zone Temperature Control

The atrium zone is controlled at a seasonal setpoint as follows:

December 1 to February 28:	65°F (18°C) 24 hr/day.
March 1 to May 31:	70°F (21°C) 24 hr/day.
June 1 to August 31:	75°F (24°C) 24 hr/day.
September 1 to November 30:	70°F (21°C) 24 hr/day.

These settings are chosen to allow the use of evaporative cooling, economizer, and nighttime cooling strategies in different seasons. For example, the summer temperature setting of 75°F (24°C) is slightly higher than the outside air wet-bulb temperature high for Phoenix, Ariz. Evaporative cooling theoretically can reduce the outside air dry-bulb temperature down to its wet-bulb temperature. Therefore, it is theoretically possible to cool the atrium air using the evaporative cooling system only. In the winter, the atrium temperature is set to 65°F (18°C). This temperature is achievable by nighttime ventilation throughout the winter season in Phoenix. In fact, atrium air temperature could be passively reduced below 65°F (18°C); however, this setting is chosen as a tolerable temperature for short-time human occupancy of the atrium space. From this perspective, zone loads calculated under these assumptions can be reduced if the actual atrium temperature is less than 75°F (24°C) in the summer or 65°F (18°C) in the winter. This may be achievable either by additional evaporative cooling or nighttime ventilation.

BLAST SIMULATION RESULTS

When analyzing BLAST simulation results, performance comparisons are expressed as difference percentages between the peak loads of two models. Percentages are calculated as the ratio between the load difference and the load of a reference model. For example, if model X has a peak load of 731 kBtu/h and model Y has a peak load of 995 kBtu/h, then

$$\text{Load Difference \%} = [(731-995)/995] \cdot 100 = -26.53\%$$

The percentage is then truncated and the text describing this difference reads "Model X has a 26% lower load than Model Y." Loads are described as "almost identical" when the difference between the two models compared is less than 1%.

Summer Design-Day Peak Cooling Loads

Table 1 summarizes the total summer design-day peak cooling loads and individual zone peak cooling loads for Phoenix, Ariz. The first line shows the total peak cooling load for the north, east, south, and west occupied zones combined for each of the five models. Peak loads are used to determine the maximum capacity

TABLE 1 **Summer Design-Day Peak Cooling Loads in KBtu/h**

Zones	DE-BM	SE-BM	DE-45	DE-FC	SE-XS
Total N+E+S+W	731	995	737	559	928

	DE-BM	SE-BM	DE-45	DE-FC	SE-XS
North	172	221	189	129	219
East	201	281	190	151	239
South	178	237	189	135	223
West	191	298	180	148	253
Atrium	50	61	51	58	58

and, hence, the size of HVAC equipment. Figure 3 is a graphical representation and comparison among these loads and shows that:

- Double-envelope models have significantly lower peak cooling loads than single-envelope models.
- The DE-BM has a 26% lower peak cooling load than the SE-BM in the four occupied zones combined.
- The SE-XS has a 6% lower total peak cooling load than the SE-BM.
- The DE-BM has a 21% lower total peak cooling load than the SE-XS. This indicates that the double-envelope system has produced a significantly lower peak cooling load for the four occupied zones combined than the single-envelope model with external shading.
- The DE-45 has an almost identical total peak cooling load to the DE-BM. This indicates that variation in the double-envelope base model orientation has a negligible effect on peak cooling loads for the occupied zones combined.
- The DE-45 has 9% and 6% higher peak cooling loads in the north and south zones, respectively, than the DE-BM. However, the DE-45 has 5% lower peak cooling loads in the east and west zones, respectively, than the DE-BM. Accordingly, the variation in the double-envelope base model orientation did not produce a significant effect on peak cooling loads for each of the occupied zones individually.
- The DE-FC has a 23% lower peak cooling load than the DE-BM. This indicates that flexible control strategies produce significantly reduced peak cooling loads.
- The SE-XS has an almost identical peak cooling load in the north zone to the SE-BM. It has 14%, 5%, and 15% lower peak cooling loads in the east, south, and west zones, respectively, than the SE-BM. This indicates that external shading of the single-envelope model has produced significant reductions in the peak cooling loads in the east and west facades only.

Summer Design-Day 24-Hour Cooling Load Profiles

Figure 4a shows the total cooling load profiles for the four occupied zones combined over a 24-hour period for the summer design day of Phoenix, Ariz. The general pattern of these load profiles is affected by three major factors: building occupancy and operation schedule, outside air temperature, and direct solar radiation.

Building Occupancy and Operation Schedule BLAST input assumptions for all models set occupancy, artificial lighting, and system operation schedules to a

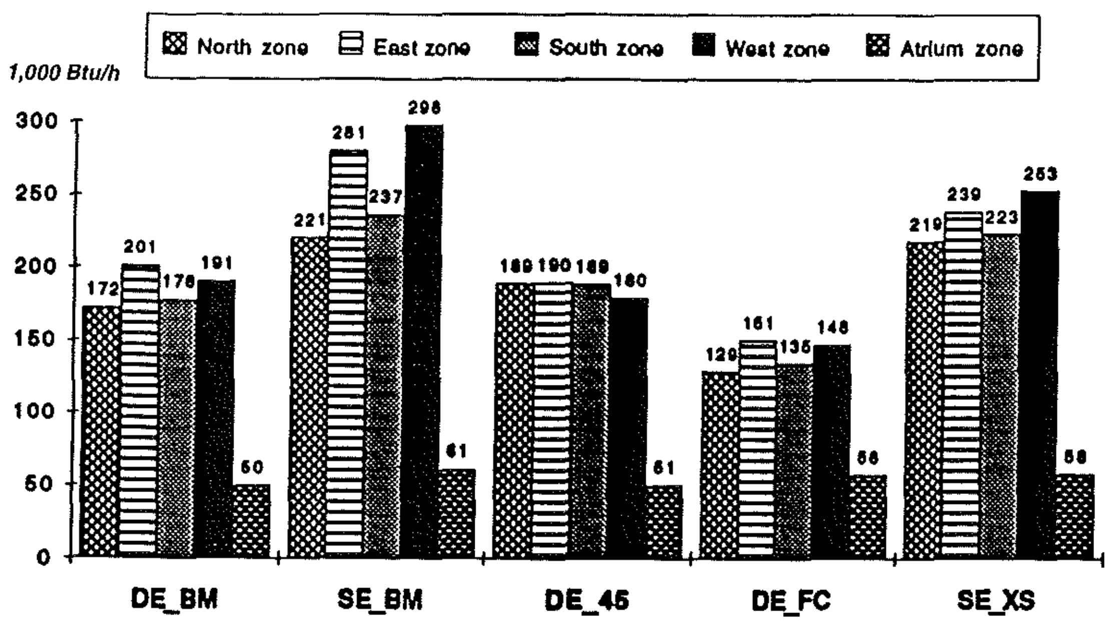

Figure 3 *Summer design-day peak cooling loads for the north, east, south, west, and atrium zones individually.*

typical 9:00 a.m.-to-5:00 p.m. operation schedule. The sharp change in load profiles at these two hours of the day is evident in all models, as shown in Figures 4a through 4e. Internal heat gains are set at 80% of their full capacity during the building operation hours and at 10% of the full capacity outside of operation hours.

Outside Air Temperature The outside air dry-bulb temperature for the summer design day reaches a maximum of 107°F at 3:00 p.m. and reaches a minimum of 72°F at 5:00 a.m.; the total diurnal swing is 35°F. This produces a slight increase in zone-cooling loads during the daytime hours and a decrease in zone-cooling loads during the night and early morning hours.

Direct Solar Radiation The effect of direct solar radiation on zone-cooling loads is strongly evident only when the facade orientation of each zone is considered. Figures 4b through 4e illustrate this effect.

- The north zone is exposed to direct solar radiation only in the early morning and late afternoon hours in the summer. This small exposure results in a slight increase in cooling loads between 6:00 a.m. and 8:00 a.m., and 5:00 p.m. and 7:00 p.m. as shown in Figure 4b.
- The east zone is exposed to direct solar radiation from sunrise until solar noon. This exposure results in a steep increase in zone-cooling loads between 6:00 a.m. and 9:00 a.m., as shown in Figure 4c. A moderate increase continues in all models after 9:00 a.m., except for the SE-XS model, where external shading is present.
- The south zone is exposed to direct solar radiation for most of the midday in the summer. This exposure results in a steep increase in the zone-cooling load between 9:00 a.m. and 4:00 p.m., as shown in Figure 4d. The DE-45 model continues to show a moderate increase after 5:00 p.m. due to its southwest facade orientation.
- The west zone is exposed to direct solar radiation only in the afternoon hours. This exposure results in a moderate to steep increase in the zone-cooling load between 1:00 p.m. and 7:00 p.m., as shown in Figure 4e.

TABLE 2 **Winter Design-Day Peak Heating Loads in KBtu/h**

Zones	DE-BM	SE-BM	DE-45	DE-FC	SE-XS
Total N+E+S+W	166	484	164	0	494

	DE-BM	SE-BM	DE-45	DE-FC	SE-XS
North	47	132	46	0	131
East	41	116	35	0	123
South	35	109	37	0	112
West	43	128	45	0	129
Atrium	0	0	0	0	0

Winter Design-Day Peak Heating Loads

Table 2 summarizes the total winter design-day peak heating loads and individual zone peak heating loads for Phoenix, Ariz. Figure 5 shows the peak heating loads for the north, east, south, and west zones. Comparison of peak heating loads among the models shows that:

- Double-envelope models have significantly lower peak heating loads compared to single-envelope models..

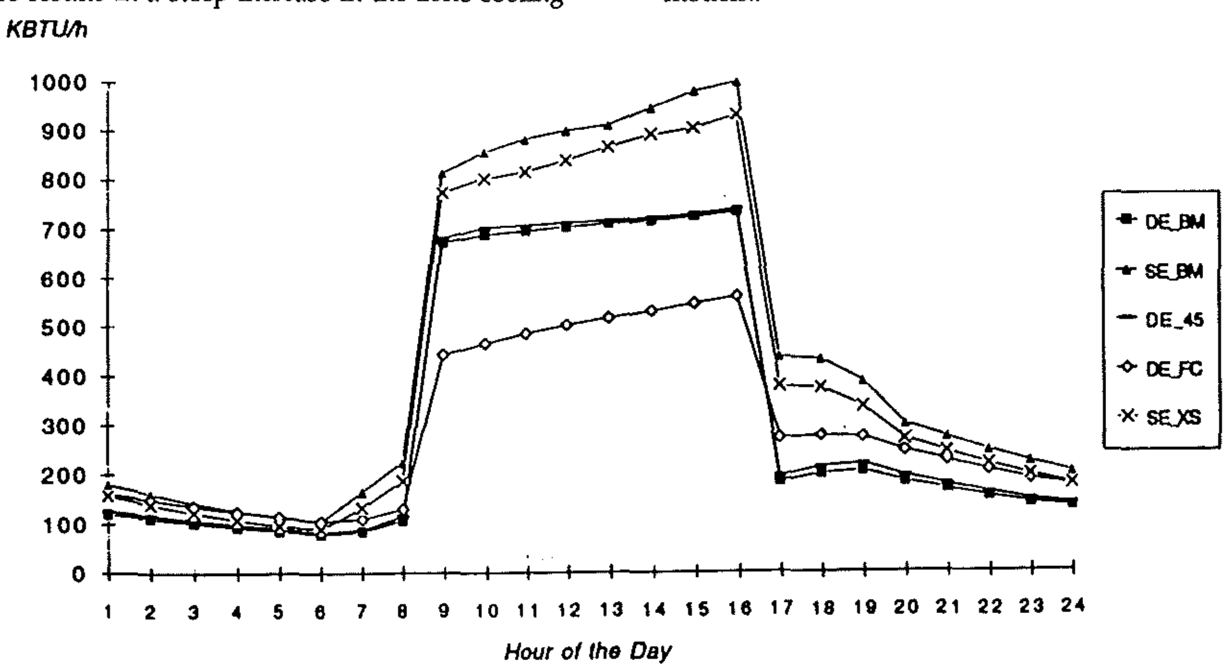

Figure 4a *Summer design-day cooling load profiles for the north, east, south, and west zones combined.*

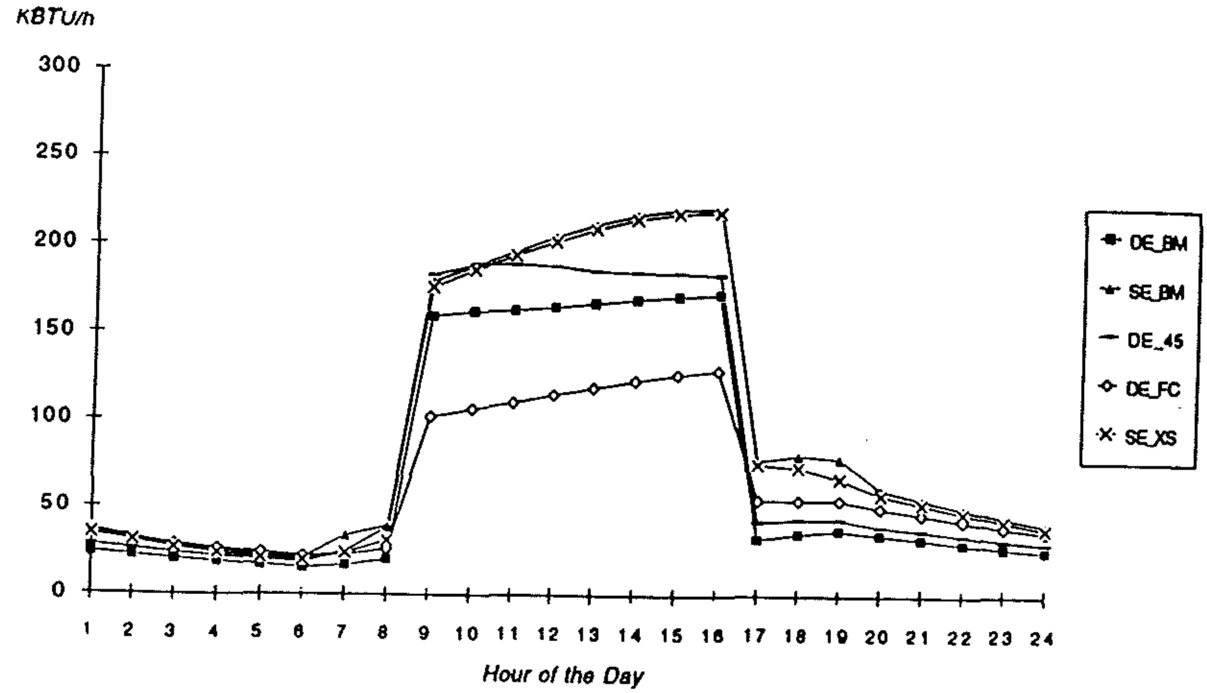

Figure 4b *Summer design-day cooling load profiles for the north occupied zone.*

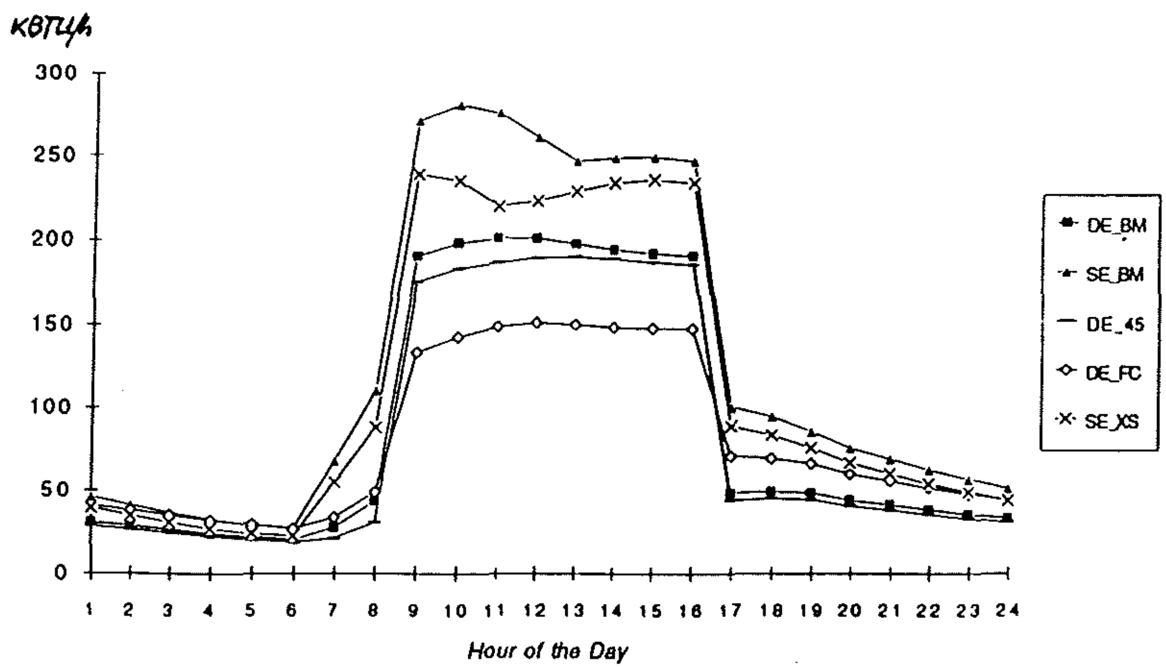

Figure 4c *Summer design-day cooling load profiles for the east occupied zone.*

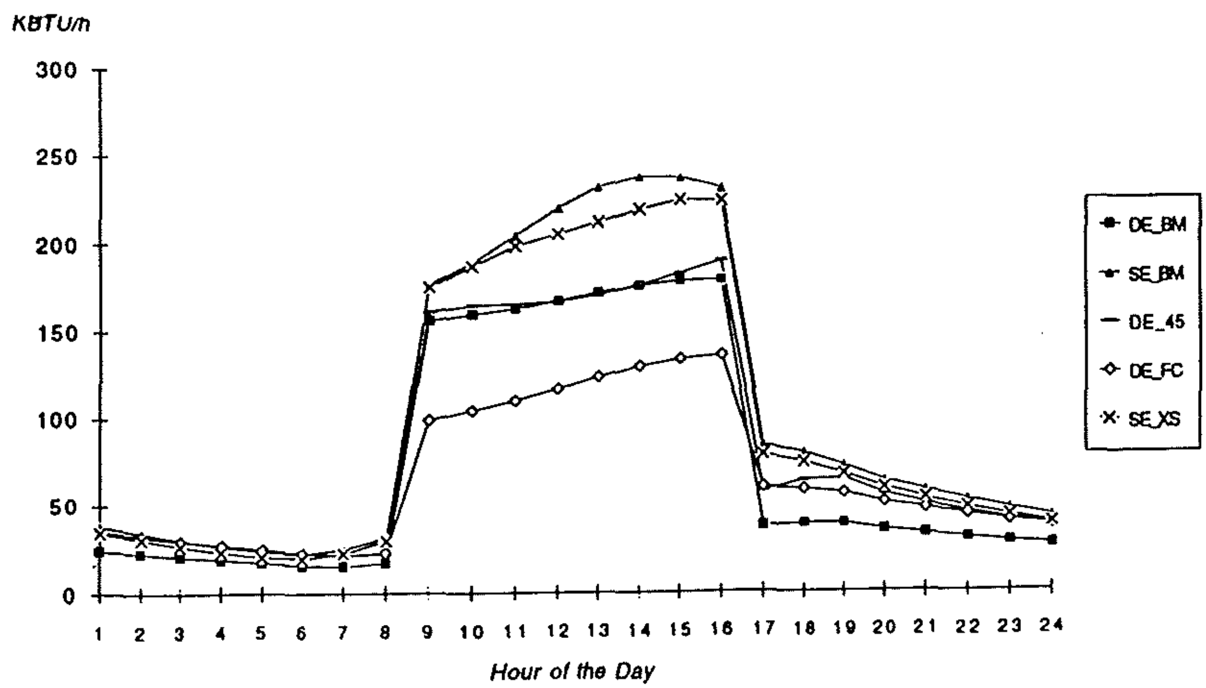

Figure 4d Summer design-day cooling load profiles for the south occupied zone.

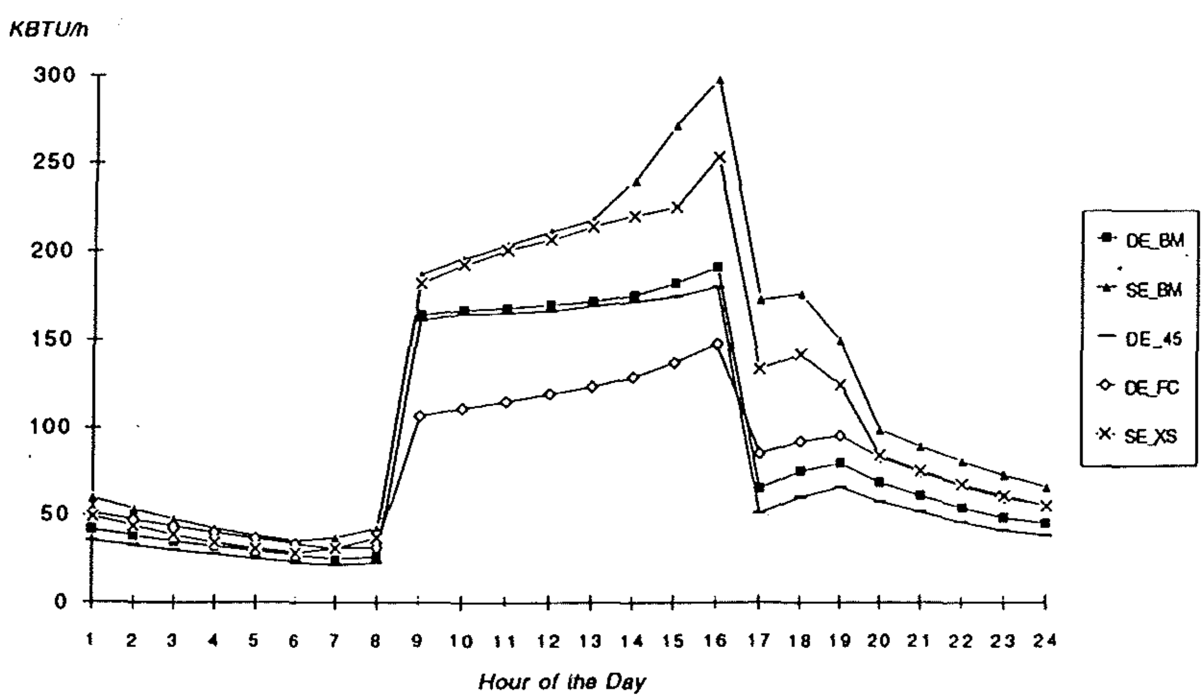

Figure 4e Summer design-day cooling load profiles for the west occupied zone.

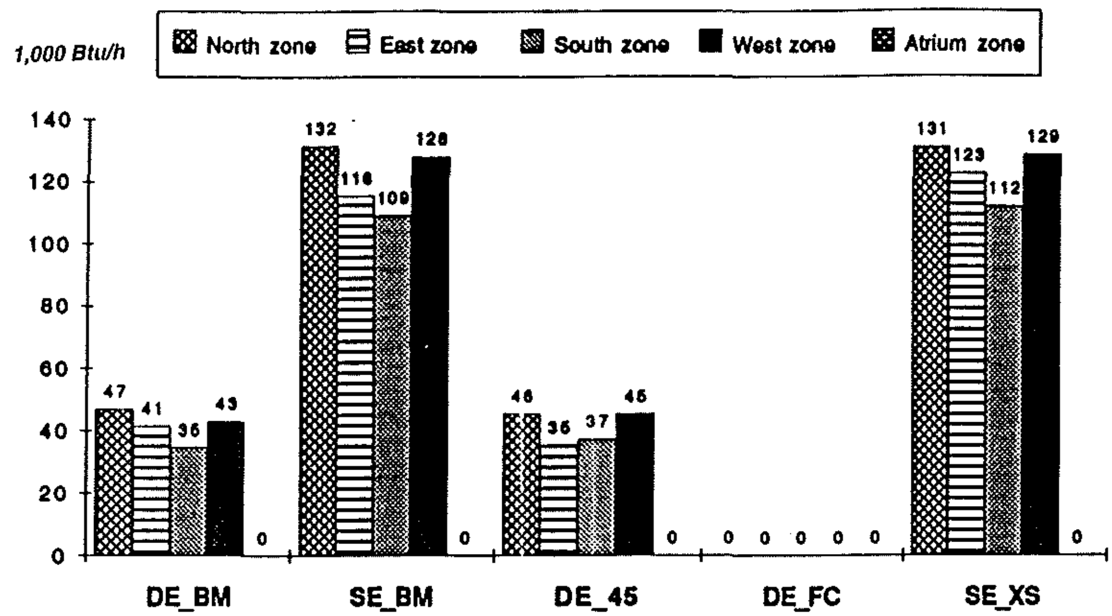

Figure 5a Winter design-day peak heating loads for the north, east, south, west, and atrium zones individually.

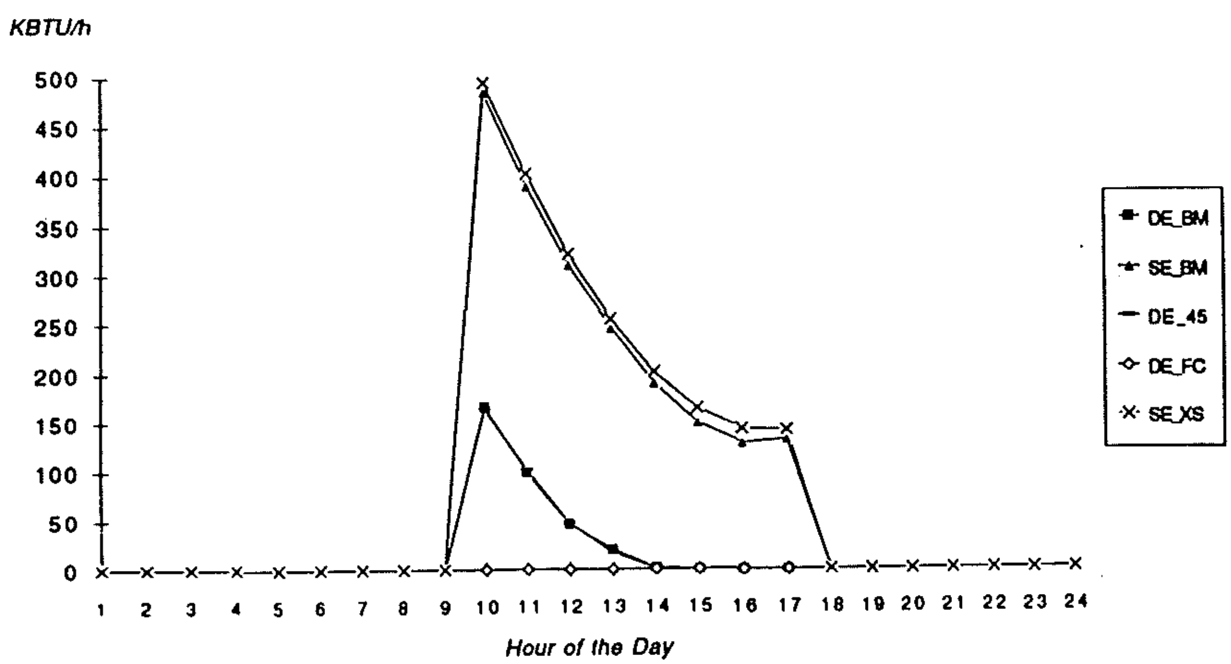

Figure 5b Winter design-day heating load profiles for the north, east, south, and west zones combined.

- The DE-BM has a 66% lower total peak heating load than the SE-XS
- The DE-45 has a 1% lower total peak heating load than the DE-BM. This indicates that variation in the double-envelope base model orientation has a negligible effect on the peak heating load for the occupied zones combined.
- The DE-FC has a zero peak heating load. This indicates that flexible control strategies have totally eliminated heating loads in the double-envelope building model. Theoretically, there is no need for mechanical heating equipment in any zone. The elimination of heating loads allows the use of simple and less expensive HVAC equipment.
- The DE-45 has 2% and 14% lower peak heating loads in the north and east zones, respectively, than the DE-BM. However, the DE-45 has 5% and 4% higher peak heating loads in the south and west zones, respectively, than the DE-BM. This indicates that variation in the double-envelope base model orientation has produced a significant reduction in peak heating load in the east zone only.
- The SE-XS has an almost identical peak heating load to the SE-BM in the north and west zones. It has 6% and 2% higher peak heating loads than the SE-BM in the east and south zones, respectively. This indicates that external shading of the single-envelope model has produced a slight increase in the peak heating load in the east and south zones.

ADDITIONAL PERFORMANCE ATTRIBUTES

In addition to cooling load and heating load reductions indicated in this research, the double-envelope building model is expected to outperform conventional single-envelope buildings in several areas as follows.

Alternative Energy Utilization

Additional energy savings may be achieved when passive cooling and heating strategies are accounted for. Photovoltaics also can be used to generate electricity directly from solar energy. Each strategy will reduce the need for purchased energy to some degree, depending on prevailing climatic conditions. More specifically, the model uniquely allows all of the following strategies to be used: (1) direct and indirect evaporative cooling of outside air before it is delivered to the atrium; (2) wind pressure at the fresh air intake to reduce energy consumption of supply air fans; (3) solar thermosiphon effect in the envelope cavity to exhaust heated air and to reduce energy consumption of exhaust air fans; (4) integrated photovoltaic cells within the double-envelope structure to provide a source of electricity for cooling, lighting, or other purposes; and (5) recovery of excessive solar heat collected within the envelope cavity to reduce demand for mechanical heating and for domestic hot water preheating.

Indoor Comfort Conditions

The thermal comfort conditions in the occupied spaces of the building model are expected to exceed those of conventional buildings using similar HVAC systems. Mean radiant temperatures of spaces at the perimeter zones are expected to improve because they are better protected from excessive solar radiation in the summer and drafts from cold window glass in the winter. Continuous air supply at the top of the atrium will improve air distribution and air mixing in the atrium space and will reduce the stratification effect.

Indoor Air Quality

Because 100% of the atrium air is fresh outside air, the proposed model conveniently can provide up to 100% fresh air as supply air, depending on the type of AHU selected. This is most applicable to the cooling season and between seasons. In addition, the proposed air distribution pattern from the atrium to the occupied zones to the envelope cavities is expected to improve air circulation within the occupied spaces. Each zone typically will have access to the atrium on one side and to at least one envelope cavity module on another. Air will systematically flow from the center of the building to the perimeter. This uniform pattern is sustained by an air pressure decrease from the atrium zone to the occupied zones to the envelope cavities.

Other Considerations

Additional assets of the proposed model are (1) initial cost reduction of ductwork due to the use of the atrium and the double-envelope cavities as vertical air conduits and to the simple airflow pattern, (2) simple use of nighttime free cooling and economizer cooling with potentially reduced fan power for both fresh air and exhaust air, and (3) shading devices can be designed to control and diffuse natural light and to prevent glare from the direct solar beam in the occupied spaces.

CONCLUSION

BLAST simulation results indicate that the double-envelope building model performs significantly better than both the externally shaded and the externally unshaded single-envelope building models in hot and dry climatic conditions such as those in Phoenix, Ariz. More specifically, the double-envelope base model (DE-BM) reduces the total peak cooling load by 26% compared to the single-envelope base model (SE-BM) and by 21% compared to the single-envelope with external-shading model (SE-XS). Flexible zone temperature control strategies for the double-envelope model further reduce its cooling and heating loads. When occupied, zone temperature is allowed to float between 72°F and 78°F, the total peak cooling load is reduced by 23% compared to the double-envelope base model. Heating loads are entirely eliminated, given the assumption of the 2.5% winter design-day conditions for Phoenix, Ariz. Orientation of a square-plan double-envelope building model has no significant effect on its total peak loads. However, the 45-degree variation from the north produced a more even distribution of thermal loads among the four occupied zones than the due-north-oriented base model.

Implementation in Architectural Design

The proposed double-envelope building model concept can be implemented in a variety of ways in architectural design and construction practices in several climatic regions. The concept is applicable to new and energy retrofit projects as long as a vertical air space, such as an atrium, and at least one double-envelope unit can be accommodated. Floor plans will vary significantly from the conceptual square plan assumed in this study. A combination of modular double-envelope and other envelope components may be used creatively in response to contextual and programmatic needs. Modular units of the double-envelope system, including its shading devices, photovoltaic cells, and exhaust air components, can be prefabricated, then assembled and integrated with other building envelope systems. Several small atria or vertical air shafts can be used instead of the one central atrium presented in this paper. Creative implementation of some or all of the components and ideas presented in this paper can produce a variety of architectural solutions and innovative design variations. However, before the concept is implemented in a particular building project, more specific analyses and evaluations based on actual assumptions in terms of location, climate, building materials, internal loads, and schedules are needed. In addition, extensive experimentation, research, and development are needed for each component of the building model, such as the double-envelope units, the atrium, the fresh air intake units, the evaporative cooling system, the heat exchange system, and the smart control system. Life-cycle cost analysis also is needed to determine whether the energy savings expected from the double-envelope model justify the increase in initial construction cost of a double envelope compared to other alternatives.

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