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AIR CONDITIONING SYSTEM OPERATION STRATEGIES FOR INTERMITTENT OCCUPANCY BUILDINGS IN A HOT-HUMID CLIMATE

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ABSTRACT

For many buildings, continuous operation of the air conditioning system is not necessary for achieving thermal comfort during the occupied periods. Depending on the building's thermal and operational characteristics the air conditioning system may be operated during a specific period of time that may partially or completely cover the occupancy period. In this case, a considerable amount of energy can be saved without compromising comfort conditions provided that the correct operation strategy is implemented. In this paper, the impact of HVAC operation strategies on energy consumption and thermal comfort in an office building in Dhahran, Saudi Arabia is investigated utilizing the VisualDOE energy simulation program. The results are useful for exploring potential energy conservation opportunities in buildings characterized by intermittent occupancy while maintaining the requirements for thermal comfort.

INTRODUCTION

In most climates, the heating, ventilation, and air conditioning (HVAC) system is increasingly becoming an integral and a necessary part of all modern buildings for maintaining indoor environmental conditions. Depending on the severity of climate, a substantial amount of energy can be consumed by the HVAC system. In Saudi Arabia, which is generally characterized by harsh climatic conditions, the bulk of produced electric energy is consumed by buildings (Electrical Affairs Agency, 1999), and the larger portion of this energy is used by the HVAC system (Abdelrahman and Ahmad, 1991). Although a major function of the HVAC system is to maintain acceptable indoor air quality by controlling contaminant concentrations below their harmful levels through the ventilation process, its prime function, however, is to control the thermal conditions necessary for achieving human thermal comfort.

Thermal comfort is determined by several personal and environmental variables, many different combinations of which can achieve thermal comfort (Fanger, 1972). Personal parameters such as clothing level and activity level are influential in determining thermal comfort given a set of environmental parameters, which include air temperature, air humidity and air velocity. The single most important index for thermal comfort is the air temperature, particularly when the relative humidity is controlled to within a 40% to 60% level (McQuiston and Parker, 1982). In a normally controlled environment (e.g., office space), where humidity, air velocity and personal parameters are maintained within certain ranges, the air temperature is the most reflective parameter of thermal comfort as it has a direct impact on the human body energy balance and indirectly influences other environmental parameters. Additionally, air temperature control is the prime target of HVAC system designers as it implies the control of other environmental parameters. Therefore, air temperature can be considered as being representative of the environment thermal quality when assessing thermal comfort status at different HVAC operation strategies.

Building operation strategies (including HVAC operation strategies) can greatly affect occupant comfort and energy use, especially in thermally massive buildings (Von Thun and Witte, 1991). When the HVAC system is improperly designed or operated, unnecessary energy can be wasted and the required indoor environmental conditions may not be attained. In most buildings, particularly those with intermittent operation, indoor environmental conditions can be maintained at acceptable levels during the occupied periods at reduced energy consumption when proper HVAC operation strategies are utilized. A study of the impact of various ventilation strategies on indoor air quality and energy consumption in an office building located in a mainly hot-humid climate revealed that by employing proper ventilation strategy, as much as 50% of ventilation energy could be reduced while maintaining acceptable IAQ (Budaiwi and Al-Homoud, 2001). Important energy savings in office buildings were also reported by Zmeureanu and Doramajian (1992) while maintaining thermal comfort by allowing the air temperature to drift in the afternoon period. In another study, Seppanen (1999) showed that when a proper ventilation strategy is used, including control of ventilation rate and utilization of natural ventilation and free cooling, improved IAQ can be obtained for the same level of energy consumption or reduced energy consumption can be achieved for the same level of IAQ.

Several other studies have investigated the impact of HVAC system control strategies on energy consumption. Liu et al. (1995) indicated the potential for a substantial reduction in energy consumption after implementing improved operation strategies involving resetting of the cooling deck or heating deck temperature to achieve maximum energy efficiency without compromising IAQ and comfort. In another study, Jekel et al. (1992) stated that sensible reheat requirement might be reduced through the re-circulation of supply air that bypasses a cooling coil. Utilizing detailed energy simulation programs such as BLAST and DOE-2, Kao (1985), Mutammara et al. (1990) and Norford et al. (1986) have indicated major influence, but variable under different climatic conditions, of the HVAC system control strategy on energy consumption.

In intermittent occupancy buildings, it is unacceptable to maintain comfort conditions during the unoccupied period as unnecessary energy is expended. Furthermore, it is equally unacceptable to lower the comfort quality of the indoor environment for the sake of reducing energy consumption. An effective HVAC operation strategy is that which maintains the required comfort conditions during occupied periods while using the least amount of energy. In order to define an HVAC operation strategy for a particular building at reduced energy consumption but acceptable thermal conditions for comfort, the transient energy and thermal behavior of the building is required. In this case, the condition that needs to be maintained during a given period of time must be specified. Additionally, factors determining the building transient thermal response including thermal loads, building thermal mass, and type and characteristics of the HVAC system must be considered.

Assessing the impact of HVAC operation strategies while taking into account all these influencing parameters requires a sophisticated building thermal and energy simulation tool. Building simulation tools can provide HVAC system designers with detailed information about the dynamic behavior of a building, enabling them to optimize operating schedules of the HVAC system to take advantage of the thermal mass of the building (Von Thun and Witte, 1991). Available detailed energy simulation programs such as VisualDOE offer a powerful means to simulate all building parameters and investigate the impact of HVAC operation strategies on energy consumption and space temperature behavior. In this study, the VisualDOE program is utilized to model an office building operating under the weather conditions of Dhahran, Saudi Arabia and investigate the impact of various HVAC operation strategies on energy consumption and comfort conditions. The results are potentially useful in opening avenues to HVAC system designers and building operators seeking energy efficient operations without compromising the quality of comfort for the occupants.

THE MODELLED BUILDING AND HVAC SYSTEM CHARACTERISTICS

The modeled building is a five-storey 30 x 20 m office building with a floor-to-floor height of 4.5 m and its main axis oriented in an east-west direction. The building is occupied five days a week with a daily operation schedule starting from 7:00 am to 4:00 pm during which maximum occupancy occurs, except during the lunch break between 12:00 noon and 1:00 pm when 50% occupancy is assumed. To allow for the presence of janitors and maintenance personnel, 5% of the occupancy is assumed to occur one hour prior to the start of operation and two hours after the end of operation.

The maximum infiltration rate is assumed during the first hour of occupancy, at mid-occupancy period and at the end of occupancy when people movement into and out of the building occurs. At other times, a reduced infiltration rate (50% of the maximum value) is assumed. The lighting and the equipment loads are assumed to be at their peaks during normal occupancy, and at 10% of the peak load at other times. Each floor of the building is considered a single thermal zone and is served by a separate single-zone variable temperature (SZVT) system to maintain an indoor temperature of 23^{o} C during the occupied periods throughout the year. The system has both a heating coil and a cooling coil at the main air handler that delivers air at a temperature necessary to satisfy the zone load requirement. The fan is kept on only during periods when space temperature control is required. Table 1 provides additional information about the HVAC system and building's thermal characteristics.

THE MODELED HVAC OPERATION STRATEGIES

In order to investigate the impact of HVAC operation strategies on energy consumption and thermal comfort in the modeled office building and to define the strategy that results in minimum energy consumption while maintaining comfort requirements, several temperature and ventilation scheduling schemes shown in Table 2 are considered. The base case (i.e. Case 1) is taken when the HVAC system is continuously operated to maintain a constant temperature of 23^{o}C and provide a ventilation rate (outside air) of 7.5 l/s per person (15 CFM/person) during the occupied periods.

Table 1 Modeled HVAC system and building thermal characteristics

Peak Lighting Load (LPD)	13 W/m^2
Peak Equipment Load	8 W/m^2
Peak Occupancy Density	1 person / 15m^2 (during working hours)
Window Area to Wall Area Ratio	30% (for all walls)
Window U-Value	1.8 W/m^2-C (low-e clear double glazing)
Window Shading Coefficient (SC)	0.65
Wall U-Value	0.37 W/m^2-C
Roof U-Value	0.31 W/m^2-C
Ventilation Rate (outside air)	7.5 l/s per person
Thermostat type and (throttling range)	Proportional (1.5 ^{o}C)
Design cooling and heating temperature	23 ^{o}C

Table 2 Daily HVAC operation schedules for modeled strategies

Case No.	Ventilation Schedule	Temperature Schedule	Description
1 (Base case)	7:00 to 16:00 hrs	0:00 to 24:00 hrs	Continuous temperature control (all days), ventilation provided during occupancy (working days).
2	0:00 to 24:00 hrs	0:00 to 24:00 hrs	Continuous temperature control (all days), continuous ventilation provision (all days).
3	5:00 to 16:00 hrs	0:00 to 24:00 hrs	Continuous temperature control (all days), ventilation provided two hours before occupancy starts (working days).
4	9:00 to 16:00 hrs	0:00 to 24:00 hrs	Continuous temperature control (all days), ventilation provided two hours after occupancy starts (working days).
5	7:00 to 16:00 hrs	0:00 to 24:00 hrs	Continuous temperature control (working days), temperature is allowed to float during weekends, ventilation provision during occupancy (working days).
6	7:00 to 16:00 hrs	7:00 to 16:00 hrs	Temperature control during occupancy (working days), temperature is allowed to float all other times, ventilation provision during occupancy.
7	7:00 to 16:00 hrs	6:00 to 16:00 hrs	Same as Case 6 but temperature control starts one hour earlier.
8	7:00 to 15:00 hrs	6:00 to 15:00 hrs	Same as Case 7 but temperature control and ventilation provision end one hour before end of occupancy.

The impact of the ventilation schedule on energy consumption is investigated by Cases 2 through 4. In Case 2, the temperature is maintained at 23^{o}C and ventilation is continuously provided during occupied and unoccupied periods. Although employing such a strategy cannot be justified form the energy consumption point of view, it is not uncommon to see actual buildings operated under a similar strategy. Case 3 and Case 4 explore the impact on energy when ventilation leads or lags occupancy by two hours. Such ventilation scheduling schemes may be dictated by the indoor air quality requirements and energy conservation in buildings.

The impact of the temperature schedule on energy consumption and indoor temperature is investigated by Case 5 through Case 8. In these cases, the HVAC system is turned off during the weekend and ventilation is provided only during the occupied periods (i.e., from 7:00 am to 4:00 pm). In Case 5, the temperature is maintained at 23^{o}C during the working days, while in Case 6 the temperature is allowed to float during the unoccupied periods by turning the HVAC system off. The impact of starting the HVAC system one hour before occupancy is illustrated by Case 7, and the impact of starting it one hour earlier and terminating it one hour before occupancy ends is illustrated by Case 8.

ANALYSIS OF RESULTS AND DISCUSSIONS

The energy and thermal performance of the modeled building was predicted over a period of one year under the climatic conditions of Dhahran, Saudi Arabia. The Dhahran climate is characterized by being hot and humid during summer (the maximum temperature can reach 48^o C) and moderate during winter (the minimum temperature can reach 4^o C). Considering the different HVAC operation strategies given in Table 2, Figures 1 through 3 compare the cooling, heating and fan energy consumption for the different strategies with the exception of the strategy described by Case 8 as it is essentially the same as

Case 7 and was found to result in almost the same energy requirements.

Figure 1(a) illustrates the relative change in the building annual cooling and heating energy per unit area for the different ventilation control strategies (Case 1 through Case 4). In all these cases, the temperature is controlled at 23°C and ventilation is provided at the different schedules. In general, it can be noticed that appreciable variations in heating and cooling energy requirements can occur when employing different ventilation strategies. Additionally, a substantial amount of heating energy is required which can be explained by the HVAC system temperature control mechanism and the space temperature control strategies which require the maintenance of 23°C during the occupied and the unoccupied periods. In this case, heating is required to adjust the supply temperature to respond to the reduced space thermal load during the unoccupied periods.

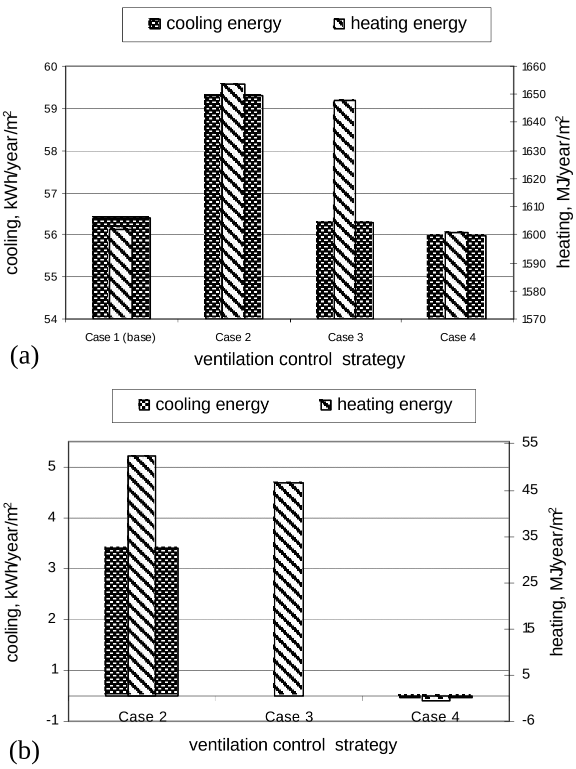

Figure 1 Change in annual cooling and heating energy requirements at different ventilation control strategies; (a) relative variations, (b) magnitude of change (relative to base case)

A comparison between Case 1, when ventilation is scheduled during the occupied periods, and Case 2, when ventilation is continuously provided, reveals about a 5% increase in the required cooling energy and about a 3% increase in the heating energy. Starting ventilation two hours before the commencement of occupancy (Case 3) (a possible ventilation scheme for controlling indoor air quality when indoor contaminant generation is independent of occupancy), results in little change in the cooling energy requirement, but a noticeable increase (about 3%) in heating requirement. A marginal reduction in the cooling and the heating energy is attained when delaying ventilation by two hours after occupancy (Case 4) (a possible ventilation scheme for indoor air quality control when contaminant generation is associated with occupancy).

The magnitude of change in the cooling and heating energy relative to the base case due to the different ventilation control strategies is illustrated in Figure 1(b). When continuous ventilation is employed, considerable additional cooling energy is required for the building over the year (i.e., about 9 MWh/year), but little change occurs when ventilation leads or lags occupancy by two hours. Variations in heating energy, however, are more pronounced when compared to changes in cooling energy. This can be attributed to the fact that when ventilation is provided outside the occupied periods, the outdoor air temperature is much lower compared to that during the occupied periods, particularly during the winter months. Additionally, little or no free heating energy is added to the air from internal sources during unoccupied periods, as they are either absent or substantially reduced. Starting the ventilation two hours before occupancy results in almost the same amount of annual increase in heating energy (i.e., 138000 MJ/year) as that of continuous ventilation, but no noticeable change occurs when delaying ventilation by two hours.

Besides the ventilation control strategy, the temperature control strategy can significantly impact building energy consumption. Relative variations and magnitude of change in building heating and cooling energy requirements for different temperature control strategies are illustrated in Figure 2. It can be seen that variations in heating energy requirements due to temperature control strategies are more dramatic than those corresponding to ventilation control strategies. By limiting temperature control to the working days (Case 5), the cooling energy is reduced by 23% (corresponding to about 13 kWh/year/m^2), and the heating energy is reduced by 35% (corresponding to about 560 MJ/year/m^2). A further significant reduction in cooling energy (about 59% which correspond to 33 kWh/year/m^2) is achieved and the need for heating is almost eliminated (more than 99% reduction) by limiting temperature control to the occupied periods and allowing it to float during other times (Case 6). A similar level of reduction in cooling and heating energy is obtained by starting the temperature control one hour before occupancy (Case 7). A close comparison between Case 6 and Case 7 reveals a marginal increase in cooling energy and a noticeable increase in heating energy due to the early start of the HVAC system.

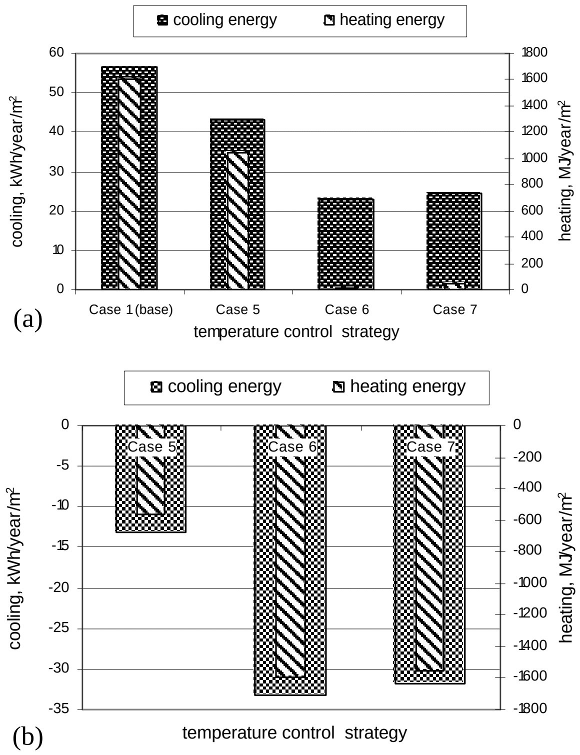

Figure 2 Change in annual cooling and heating energy requirements at different temperature control strategies; (a) relative variations, (b) magnitude of change (relative to base case)

In spite of the importance of heating and cooling energy in the air-conditioning process, substantial energy can be consumed by the fan, and this can significantly contribute to the overall energy performance of the HVAC system. Figure 3 illustrates variations in fan energy requirements for the different temperature control strategies. When continuous temperature control is maintained, which requires that the fan be continuously operated (Case 2), the amount of energy consumed by the fan exceeds the cooling energy requirements by 25%. A substantial reduction (27%, which is equivalent to 19 kWh/year/m^2) in fan energy requirement is obtained when the HVAC system operation is limited to the working days (Case 5). A more dramatic reduction (70%, which is equivalent to 49 kWh/year/m^2) of fan energy is attained by limiting the HVAC operation to the occupied period (Case 6). However, no major change occurs in the fan energy requirement by starting the operation one hour before occupancy starts (Case 7), as there is no significant change in fan operation time.

Considering that the main function of the HVAC system is to create a comfortable environment for occupants, the assessment of an operation strategy should not be limited to the energy requirements associated with it, but additionally to the ability of the HVAC system, operating under that strategy, to achieve the required comfort. It is not uncommon to have an HVAC operation strategy that results in reduced energy consumption, but does not achieve the required thermal conditions for comfort. Therefore, space thermal conditions must be simultaneously considered together with energy requirements to meaningfully assess the relevance and suitability of any HVAC operation strategy. According to the ISO comfort requirements, a person will be thermally comfortable if the temperature is maintained between 21.5^o C and 24.9^o C at normal activity and clothing levels for an office building (i.e., sedentary activity, and a clothing level= 1 clo which is equivalent to 0.155 m^2.C/W).

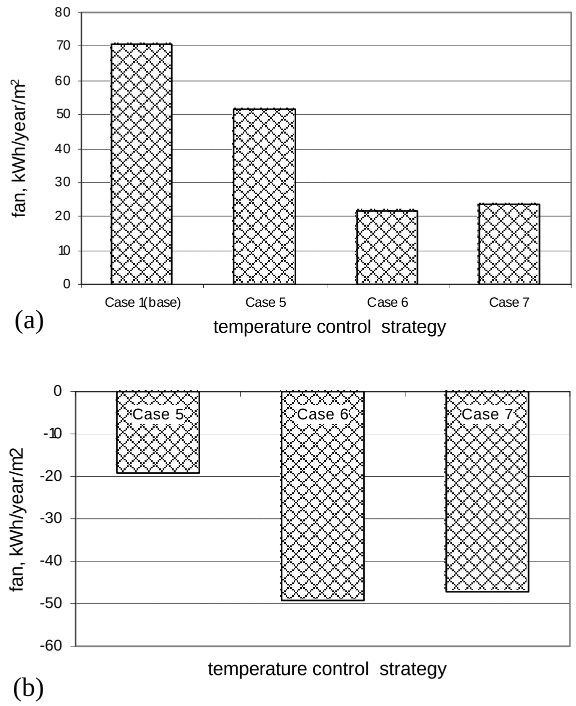

Figure 3 Change in annual fan energy requirements at different temperature control strategies; (a) relative variations, (b) magnitude of change

Figures 4 to 7 illustrate hourly space temperature variations relative to the comfort range over a 24-hour period of a summer day (7th of August) and a winter day (4th of December) for different HVAC operation strategies. When the temperature is continuously controlled, as in the base case (Case 1), the space temperature remains well within the comfort range all the time as shown in Figure 4. The marginal temperature rise within the occupied period occurs due to the increase in thermal loads resulting from internal gains and ventilation.

By limiting the HVAC operation during the occupied periods (i.e. from 7:00 am to 4:00 pm) and turning it off at other times (Case 6), the air temperature remains within the comfort range most of the time except during the first hour of occupancy during a summer day as indicated in Figure 5. It is evident that by turning the HVAC system off during the unoccupied period, the air temperature has increased substantially which required one hour for the HVAC system to bring the air temperature to the comfort range. Consequently, to obtain acceptable thermal conditions during the whole occupancy period, the HVAC operation should start prior to occupancy.

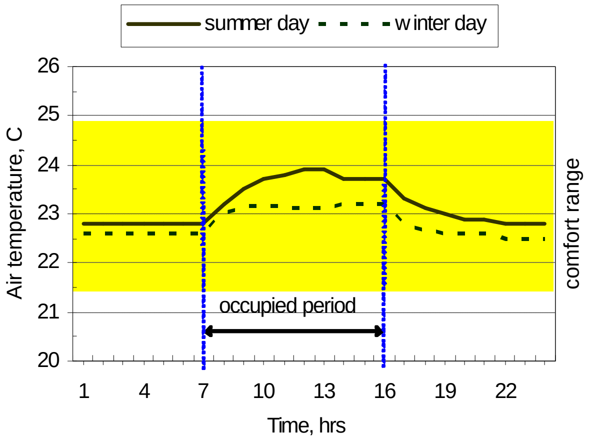

Figure 4 Indoor temperature variations for a summer day and a winter day when continuous temperature control strategy is employed

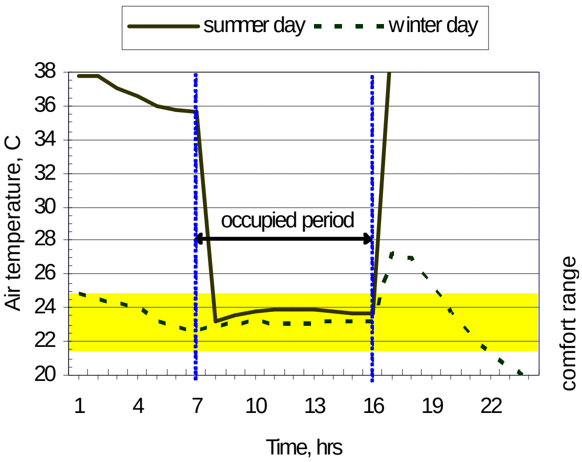

Figure 5 Indoor temperature variations when temperature control is limited to the occupied period

Figure 6 illustrates that by starting the HVAC operation one hour earlier (Case 7), the air temperature is maintained within the comfort range throughout the occupancy period. When the HVAC operation is stopped one hour before the end of occupancy (Case 8), the air temperature for both the summer and the winter days rapidly leaves the comfort range, as shown in Figure 7. This means that for an office building operating under the same or similar conditions, it is not advisable to terminate the HVAC operation even for a short time before the end of occupancy as it represents a critical time for the building thermal load. It should be stated, however, that space temperature behavior under a given HVAC operation strategy is dependent on building thermal characteristics and, to a great extent, on the characteristics of the HVAC system. Therefore, the space temperature under different operation strategies is expected to behave differently for different HVAC systems.

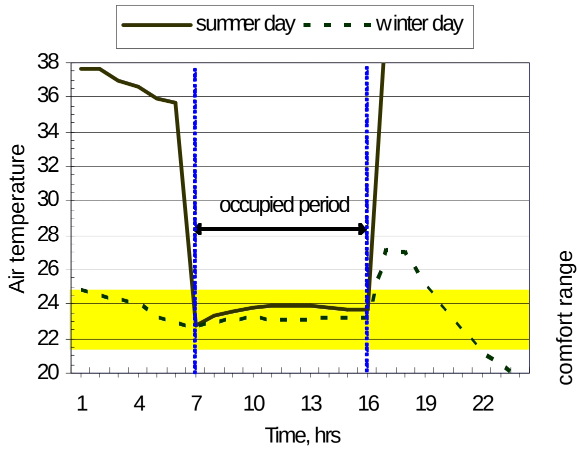

Figure 6 Indoor temperature variations when temperature control starts one hour prior to occupancy

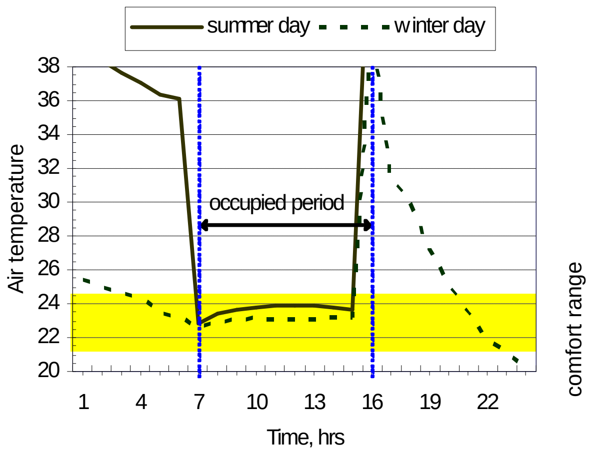

Figure 7 Indoor temperature variations when temperature control starts one hour prior to occupancy and ends one hour before the end of occupancy

From the above discussion, it can be concluded that the operation strategy represented by Case 7 is the most relevant for the modeled office building under the modeled conditions as it satisfies the two requirements of reduced energy consumption and occupant thermal comfort. In addition, an, accurate assessment of any operational strategy in terms of energy requirements and comfort achievement requires a careful consideration of the HVAC system characteristics as well as thermal characteristics and operating conditions of the building.

CONCLUSIONS

The overall performance of any HVAC system is highly dependent on the way it is operated as well as the thermal characteristics of the building it serves. Finding a proper operation strategy that results in minimum energy consumption while achieving thermal comfort is a challenging but a necessary exercise for effective building operation. The available detailed energy simulation models can be utilized to assess different HVAC operation strategies and thus identify the most relevant one. The VisualDOE energy simulation program was utilized for investigating the energy and thermal behavior of an office building located in Dhahran, Saudi Arabia.

The simulation results reveal that a substantial amount of energy can be saved if proper ventilation and temperature control strategies are employed. Compared to the continuous ventilation and temperature control strategy referred to in this study as the base case (Case 1), operating the HVAC system according to the scheme of Case 7 outlined in this study, more than 50% of the cooling energy, 90% of the heating energy and 60% of the fan energy can be saved without compromising conditions for occupant comfort. For a different building with different operational, thermal and HVAC system characteristics, a different HVAC strategy could be more suitable, particularly when different climatic conditions are considered. Additionally, when indoor air quality concerns are addressed, an HVAC operation strategy may include a ventilation control strategy in addition to the temperature control strategy. This will result in a unique comprehensive HVAC operation strategy with unique energy requirements.

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