PERFORMANCE OF MIXED-MODE COOLING STRATEGIES FOR OFFICE BUILDINGS IN ARID CLIMATES

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ABSTRACT

Mixed-Mode ventilation is an innovative approach that maximizes the use of natural ventilation and uses supplementary mechanical cooling only when strictly required. The application of Mixed-Mode ventilation in severe arid climates and its integration with other passive cooling strategies is very challenging and has not been systematically studied. The paper will present an evaluation of the performance of different Mixed-Mode cooling strategies for a single-zone office space in four main arid cities that represent the diversity in arid climates. The results of the simulations are evaluated in terms of appropriate thermal comfort criteria and plant energy consumption. The most effective strategies are addressed for each representative arid city.

KEYWORDS

Mixed-Mode Ventilation, Cooling Strategies, Office Buildings, Thermal Comfort, Energy Savings, and Arid Climates.

INTRODUCTION

Contemporary recognition of climate change and global warming has brought building energy consumption into focus. The non-residential building sector consumes approximately one fifth of the energy of the United States (Energy Information Administration, 2007) and this can be considered an indicator of the importance of non-residential building energy in the developed world. A sample of 4859 U.S. non-residential buildings (Energy Information Administration, 2007) has shown the office building type to be the most common and the greatest energy consumer. Improving energy performance in office buildings can therefore lead to long-term energy and carbon emission savings.

Arid Climates do not receive great attention in low energy office building research although this is one of the world's dominant climate types. Hot desert arid regions cover 14.2 % of the entire earth's land area (Peel et al., 2007) and are characterized by high drybulb temperatures, scarcity of rain and severity of insolation. This work is concerned with examining the performance of hybrid office building designs and their potential to reduce energy demands in such climates.

Arid regions are often identified and categorized into four variants using the Köppen classification system (Peel et al., 2007). The arid classification is primarily determined by mean annual air temperature (MAT) and annual precipitation. However, the climates of cities in these zones also show variations in other parameters such as relative humidity and annual insolation. For the purposes of the analysis reported here four cities have been selected to represent these variations amongst cities in the world's arid regions. These are Alice-Springs in Australia, Bahrain, El-Arish in Egypt and Madinah in Saudi-Arabia. The range of temperature and humidity conditions, insolation and diurnal temperature swing are shown in Figure 1 (Ezzeldin et al., 2008).

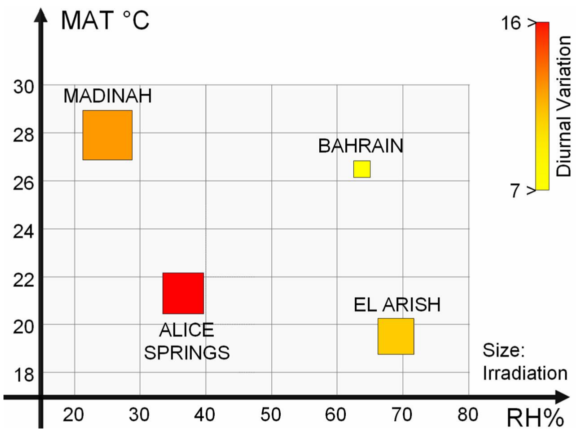

Figure 1 Mean Annual Temperature and Relative Humidity of the four representative arid cities. Symbol size and colour define the annual solar irradiation and average diurnal temperature variation respectively.

The effective cooling of office buildings in arid climates requires designers' particular attention. Cooling demands are affected not only by the severity of the ambient weather conditions but also by the high internal heat gains due to occupants, lights and equipment that can be expected in modern office buildings. As a result, designers are inclined to adopt fully air-conditioned designs for office building developments. This can, in most cases, ensure comfort conditions can be maintained but at the expense of relatively high carbon emissions.

Interest in energy efficiency and carbon emissions reduction has caused the revival of interest in integrated passive cooling strategies such as thermal mass, natural ventilation, evaporative cooling, radiant and earth cooling. Although these passive strategies are environmental friendly and provide wider range of occupant satisfaction that increases productivity (De Dear and Brager, 2002), designers are reluctant to adopt them in arid climates.

Mixed-mode or Hybrid cooling systems are designed to make maximum use of passive cooling methods but incorporate supplementary mechanical cooling systems for use in the most extreme conditions (Brager, 2006). Energy can be potentially minimized using this approach while maintaining satisfactory comfort (Charvat, 2005). Considerable research into hybrid ventilation has been carried out within the International Energy Agency IEA-Annex 35 (Heiselberg, 2002) and recently within the University of California, Berkeley (Brager et al., 2007) but has mostly been concerned with applications in temperate climates such as that of northern Europe. The application of Mixed-Mode ventilation in severe arid climates and its integration with other passive cooling strategies is very challenging and has not been systematically studied.

This paper is a presentation of the initial findings of a research project concerning the application of mixed-mode cooling strategies in arid climates. The project aims to examine the potential energy and emissions reduction benefits of mixed-mode cooling strategies and to investigate design and simulation methodologies. For this study, a set of different mixed-mode cooling systems and common active systems in a prototypical office building have been simulated using EnergyPlus (Crawley et al., 2001). The results of the simulations are evaluated in terms of plant energy consumption and appropriate thermal comfort criteria. Particular attention is paid to making comparisons based on similar levels of thermal comfort satisfaction by adjusting the cooling setpoints. The feasibility of each proposed system is examined and energy savings are predicted so that the most effective strategies for each representative arid city are identified.

COOLING STRATEGIES

The ultimate objective in the design of building environmental systems is to maintain satisfactory thermal comfort. Satisfactory thermal comfort depends on several variables but for the purpose of evaluating the designs, the evaluation has been made in terms of adequate control of room operative temperature. Operative temperature can be approximated as the average of room air and radiant temperatures. Two strategies can be accordingly applied – to control either air temperatures or control surface temperatures directly (Figure 2). A number of systems can be devised that seek to do this and that can be thought of as either active (using fans and refrigeration) or passive. Hybrid systems seek to make optimal application of both active and passive measures.

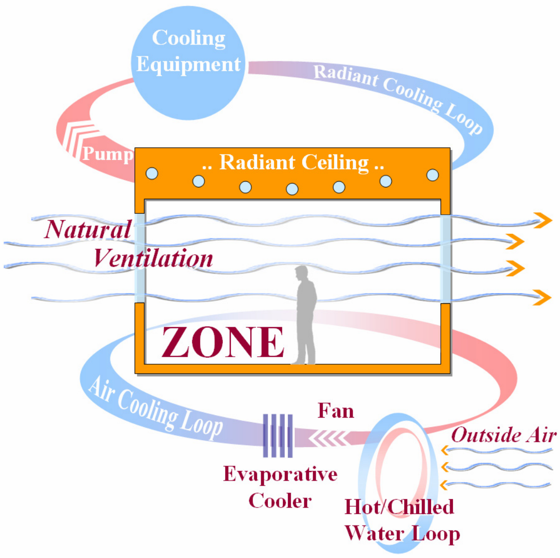

Figure 2 Mixed-Mode Cooling Strategies

Air Cooling

Three Air-cooling concepts can be applied in hybrid systems:

- Active Air Conditioning. The condition of the room air is manipulated by supplying a mixture of fresh and recirculated air that is cooled through heat exchange with a chilled water system. Energy is consumed by the systems fans as well as the refrigeration and heat rejection equipment;
- Natural Ventilation. Large quantities of fresh air flow through the room according to pressure differences that are determined by a combination of buoyancy and wind pressures. In hot climates movement of large quantities of air assists comfort by enhancing evaporation from the skin surface (Givoni, 1994);
- Evaporative Cooling. Introduction of water droplets or passage of the air across wetted surfaces causes an increase in air moisture content and reduction in drybulb temperature. Evaporative cooling can be applied both directly and indirectly in air handling equipment. Direct evaporative cooling can be applied passively by implementing indoor fountains, waterfalls to the design of atriums, by designing a lake at the windward side, or by supplementing moisture pads or sprinklers in integrated wind scoops in order to cool down the air before introducing it to the space (Santamouris, 2007).

If the main mechanism controlling operative temperature is air cooling then the fabric surface temperatures are always higher than room air temperatures.

Radiant Cooling

Cooling of a ceiling surface allows direct absorption of the radiant components of internal heat gains such as those from occupants, lights and solar irradiation. Some convective cooling is also provided by cooling the ceiling surface. Radiant Cooling can be achieved by circulating cold fluid through pipes in the fabric, through pipes attached to false ceiling panels or by evaporating water from the upper surface if the ceiling is part of a roof. Cool air can also be passed through passages in the structure to reduce surface temperatures. Incorporating tubes into a heavyweight structure is attractive in passive systems as some useful pre-cooling is possible. A number of passive and active cooling sources (heat rejecters) can be used. These include:

- Chilled water provided by a chiller system;
- Chilled water evaporatively cooled by a cooling tower;
- A geothermal borehole heat exchanger.

If the main mechanism controlling operative temperature is radiant cooling then the fabric surface temperatures are always lower than room air temperatures. This has the advantage, in passive and hybrid systems, that higher air temperatures can be tolerated for a given operative (comfort) temperature.

DYNAMIC THERMAL SIMULATION

Passive and hybrid system performance is very climate dependent. Dynamic thermal simulation using annual climate data is consequently the most appropriate method for investigating the performance of different mixed-mode cooling strategies. Simulations have been made with EnergyPlus (Crawley et al. 2001) using its network airflow and hybrid system control models.

Prototype Building Description

A prototypical office building has been used in this work for the purposes of establishing basecase energy demands and testing hybrid systems. The building is a single-zone rectangular space located at a typical mid-level floor of an office building with ratio 3:2 and internal dimensions of 30m x 20m x 3.5m (Figure 3).

The building envelope U-values and glazing SHGC were chosen to comply with ASHRAE standard 90.1 (ASHRAE, 2004). The requirements of the standard are similar to those of the International Energy Conservation Code (IECC, 2000) and a number of standards adopted by countries in arid zones. Since the research will include some passive strategies the fabric is of heavy weight construction. The building is simulated with high internal heat gain of 50 W/m² distributed as 13.5 W/m², 15 W/m² and 21.5 W/m² due to people, lights and equipment respectively (slightly above that normally considered feasible for natural ventilation alone).

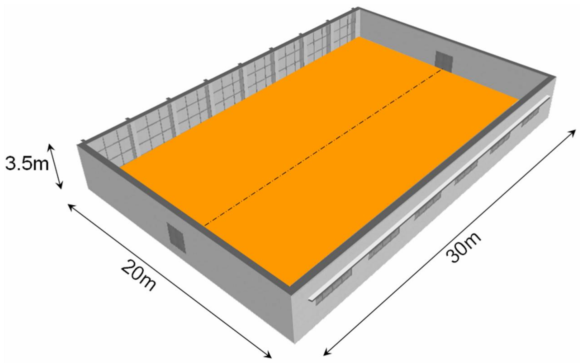

Figure 3 The Single-Zone Office Model Geometry

In order to allow reasonable comparisons between different modes of operation, and to represent good passive building design practice, some preliminary sets of calculations were performed to optimize the building form and fabric. The design was optimized for best total annual energy demand by varying shape, space arrangement, orientation, glazing percentage, shading devices and envelope construction. The following features were found optimal (Ezzeldin et al., 2008):

- A rectangular building shape with double-loaded corridor arrangement.
- East-West orientation of the building axis.
- Applying exposed thermal mass for walls and ceiling as a heavy-weight construction.
- 30% and 90% glazing for South and North facades respectively (North and South in the case of Alice Springs).
- 300mm overhangs for the 30% glazing.

Active Cooling strategies

In this research, the active cooling systems used as base cases are those thought to be typical of modern practice for arid climates, namely CAV and VAV air conditioning. These are denoted systems (A) and (B). The third base case system is a radiant cooling system with a CAV fresh air supply system (C). The latter CAV system allows control of the fresh air supply temperature and humidity - some additional cooling can also be achieved when required. The simple CAV system (A) is mainly included in the study to allow comparison with the Radiant/CAV system (C). In the base case active system simulations, a chiller is used as a cooling source for the air handlers and radiant system.

Mixed-Mode Cooling Strategies

Since occupant adaptive behaviour leads to acceptance of a wider range of room conditions – where opportunities for adaptation exist – simply allowing periods of natural ventilation should save energy (De Dear and Brager 2002). Every mixed-mode cooling system presented in this study has the control setpoints of the active component adjusted to allow the maximum natural ventilation provided thermal comfort criteria are met. The first two basic mixed-mode systems are variations of the VAV and Radiant Cooling systems (systems (B1) and (C1) respectively) that operate by natural ventilation during the occupied period except when room temperatures exceed a hybrid control set point temperature.

The subsequent two systems (B2) and (C2) are similar but allow natural ventilation outside occupied hours to achieve convective night cooling. Systems (B3) and (C3) supplement the basic mixed-mode systems with moisture pad in the Air Handling Unit (AHU) to achieve direct evaporative cooling of the air stream. System (C4) and (C5) are hybrid ventilation radiant systems with alternative cooling sources. In system (C4), a cooling tower is coupled to the radiant system. In system (C5), 12 borehole heat exchangers are coupled to the radiant cooling system. In these latter cases, the energy demands of the refrigeration system is avoided. The mixed-mode cooling systems are listed below and shown together with the active systems in Table 1:

- System (B1) or (C1): Mixed-Mode Ventilation: Natural Ventilation at the working schedule with complementary cooling at deficiencies using one of the above mentioned active system (B) or (C);
- System (B2) or (C2): Mixed-Mode Ventilation as above + Night Convective Cooling;
- System (B3) or (C3): Mixed-Mode Ventilation + Direct Evaporative Cooling (Adding Moisture Pad in the AHU);
- System (C4): Mixed-Mode Ventilation with the radiant cooling components coupled to a cooling tower (Indirect Evaporative Cooling);
- System (C5): Mixed-Mode Ventilation with the radiant cooling components coupled to Borehole Heat Exchangers (Earth Cooling).

Evaluation Criteria

Comparisons between the performance of conventional air-conditioning systems and mixed-mode strategies are only meaningful if this is on the basis both systems achieving satisfactory thermal comfort. In all types of systems, as these climates are

Table 1

Simulated Cooling Strategies

Components of the Cooling System		Active Sys.			Mixed-Mode Systems							
		A	B	C	B1	B2	B3	C1	C2	C3	C4	C5
Compact HVAC Sys.	CAV	Active		Active				Active	Active	Active	Active	Active
	VAV		Active		Active	Active	Active					
Natural Ventilation	Day				Passive	Passive	Passive	Passive	Passive	Passive	Passive	Passive
	Night					Passive			Passive			
Evap. Cool.	Moist. Pad						Passive			Passive		
Radiant System	Rad. Ceiling			Active				Active	Active	Active	Passive	Passive
	Chiller			Active				Active	Active	Active		
	Cool Tower										Passive	
	BHE											Passive

Active = Active Components; Passive = Passive/Low energy Active Components

strongly cooling dominated, minimum energy demands occur where the operating setpoints are adjusted to the maximum allowable without compromising hourly thermal comfort criteria. Initial parametric calculations were made to adjust set points in this way. There are essentially two evaluation criteria. Firstly, thermal comfort and secondly, total system cooling energy.

Different models of perceived thermal comfort were applied depending on whether an active or mixed-mode system was being evaluated. The PMV-Model (Fanger, 1970) which has been incorporated in the past into number of standards and design codes (e.g. prEN ISO7730, 2005) is intended to be applied to assess only fully air-conditioned buildings. An alternative adaptive approach, proposed in the ASHRAE standard 55 (ASHRAE, 2004) and PrEN 15251 (prEN15251, 2005), is more appropriate where there is a sense of connection between the indoor and the outdoor environment. This approach was initially derived from a field survey project RP-884 commissioned by ASHRAE in 1995. The model equations are derived from a statistical analysis of this data rather than a heat balance approach based on climate chamber data. The model seeks to account for differing perception of thermal comfort where occupants have opportunity to adapt their activities, clothing and ventilation in response to varying external conditions. This is thought to be appropriate to passive and mixed mode buildings (Rijal et al., 2008). This adaptive model has accordingly been applied in evaluating the performance of the mixed-mode systems.

Thermal comfort indicators have been calculated for every hour of the occupied periods. This data can be conveniently represented graphically and used to evaluate annual performance and diagnose problematic periods. Examples are shown in Figure 4 and Figure 5 for the PMV and Adaptive models respectively. Each chart shows the acceptable range of thermal comfort with upper and lower boundaries for the 10% (continuous line) and the 20% (dashed line) predicted percentage dissatisfaction (PPD). Active cooling and mixed-mode control setpoints have been adjusted to the maximum possible without any hours falling outside the 20% band in the case of mixed mode systems and, equivalently, the +0.85 and -0.85 PMV comfort limits for active systems. Thermal comfort has been evaluated in this way before any energy demands have been derived.

The set points arrived at, for hybrid control, are noticably higher than those for completely active operation even though thermal comfort is always maintained. For example, the room air tempertaure set point can be raised from 21°C to 24°C for the VAV system operating in hybrid mode in Bahrain in July. Operation with night cooling alows it to be raised to 26 °C. Higher set point temperatures are posible in other cities.

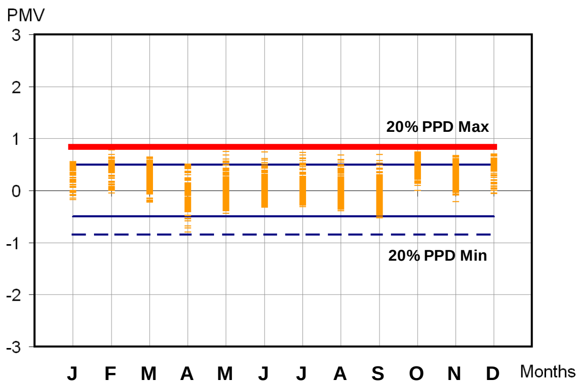

Figure 4 PMV-Model of Thermal Comfort with plotted hourly simulation results of the active system

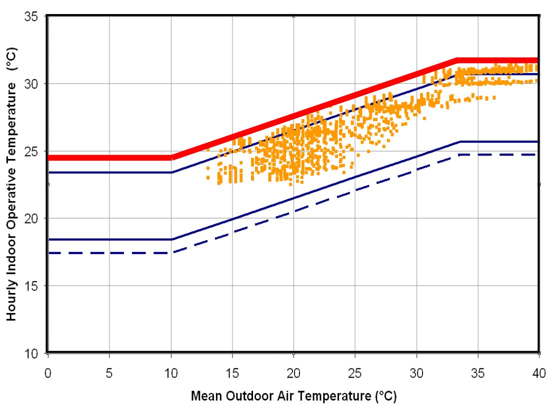

Figure 5 The Adaptive Model of Thermal Comfort with plotted hourly simulation results of one of the mixed-mode system

RESULTS AND DISCUSSION

The three active systems together with the eight mixed-mode cooling strategies were all simulated using EnergyPlus (Crawley et al. 2001) with the weather data files of the four representative arid cities. The simulation results were evaluated for thermal comfort and plant energy consumption. Feasibility of the proposed systems are discussed and the optimal design is suggested.

System Energy Consumption

Generally, as the cooling demands are (for a given level of internal gains) mainly driven by climate conditions so that, energy consumption is directly proportional to cooling degree days and mean annual temperature. Accordingly, the results of the base case simulations show the highest energy is consumed at the hottest city (Madinah) and is lowest in the mildest city (El-Arish), Figure 6 to Figure 9.

The base case results (systems A,B and C) show – as one would expect – that the VAV system (B) is more efficient than the CAV system (A). This is simply due to savings in fan energy. The CAV fan is sized for peak load conditions and runs during the whole occupied period irrespective of cooling demand. During the cooling season, these two systems supply air temperature at very low cooling setpoint temperatures in order to balance high zone mean radiant temperatures so that satisfactory operative temperature is maintained. On the other hand, system (C) maintains comfortable zone mean operative temperature with a balance of air-cooling using a CAV system and radiant-cooling. The air temperature set points can be higher with this system as radiant temperatures can be controlled. This system indicates the lowest energy consumption of all active systems for all arid cities and excels in Madinah with peak weather conditions.

Comparing the plant energy consumptions of the mixed-mode systems (B1) and (C1) with those of the active systems (B) and (C) respectively – Figure 6 to Figure 9 – simple mixed-mode ventilation can be seen to suggest remarkable energy savings. This is achieved not only because natural ventilation is encouraged at moderate ambient conditions and the active systems overall operable hours are decreased, but also as occupants have opportunity to adapt their own conditions. This effectively allows some hours at higher external temperature to be considered comfortable. Moreover, mixed-mode ventilation saves more energy at the hottest cities (Bahrain and Madinah) than the other two cities.

Mixed-mode systems that allow night ventilation offer further energy savings. The results for cases (B2) and (C2) in Figure 6 to Figure 9 show night ventilation is more effective at the mild cities (Alice-Springs and El-Arish) where the diurnal temperature variation is large and the night ambient temperature is sufficient to cool the space and the thermal mass at night. Conversely Bahrain, with much smaller diurnal temperature variation, shows the least savings, Figure 8.

The evaporative cooling model can be applied to air handling systems only and so it has not been possible to explicitly model passive evaporative cooling such as spraying water into the fresh air stream. By comparing the mixed-mode systems (B3) and (C3) with systems (B1) and (C1) respectively, Figure 6 to Figure 9, direct evaporative cooling (implemented in the Air Handler) is more efficient and offers better energy savings at the driest cities (Alice-Springs and Madinah).

Just as system (C) with CAV and radiant cooling is more efficient than system (B) with just VAV system, mixed-mode concepts using radiant cooling (systems C1, C2 and C3) consume less energy than those with VAV systems (systems B1, B2 and B3). This trend is due to the radiant cooling system reducing surface temperatures and hence operative temperature. This increases the number of hours of effective natural ventilation.

The system denoted (C4) uses a cooling tower as the heat rejection mechanism for the radiant cooling system. By comparing mixed-mode system (C1) with system (C4), Figure 6 to Figure 9, the latter is shown to consume the least plant energy at the driest locations (Alice-Springs and Madinah), as does direct evaporative cooling,. The effectiveness of the system increases as the weather conditions get hotter and drier. However, system (C4) still works effectively enough in a more humid arid city like El-Arish, Figure 9.

Although the simulation results for evaporative cooling show distinctive energy savings, this saving is associated with significant water consumption. By their very nature, adequate water supply can be an important issue in arid climates. The greatest and least annual water consumption are in Madinah (1249.6m³ per year) and El-Arish (383.5m³ per year) respectively. Water supply is provided in some arid locations by desalination and this may be used for evaporative cooling but has an energy penalty associated with it. Available data (California Coastal Commission, 1992) shows – taking mean values for the most common process – that 4.25 kWh of electricity are required to produce one cubic meter of water. When this is considered, the total energy consumed by evaporative cooling systems increases but only modestly. For example, the desalination energy raises the total energy consumption of system (C4) by 5% at the humid cities (Bahrain and El-Arish) to 15% at the driest city (Madinah).

Lastly, by comparing the mixed-mode systems that use borehole heat exchanges to reject heat from the radiant system (C5) with that using a chiller (C1), savings are seen to happen at milder locations (Alice-Springs and El-Arish). At these locations, the mean temperature of the deep ground reaches nearly 21°C and 20°C for Alice-springs and El-Arish respectively and, although relatively high, is still able to provide useful radiant cooling that can contribute to reducing operative temperatures, Figure 6 and Figure 9. In Bahrain and Madinah, the ground temperature is significantly higher so that ground heat exchange increases the cooling demands rather than offers further savings, Figure 7and Figure 8.

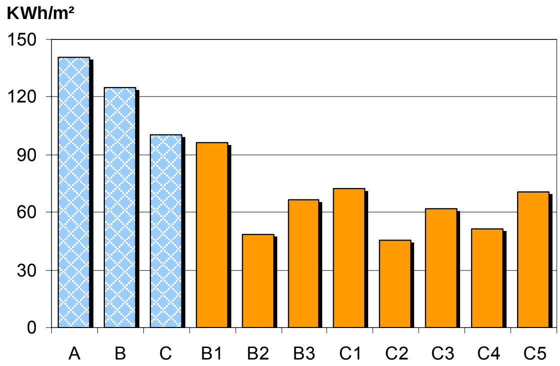

Figure 6 Plant Energy Consumptions in Alice-Springs

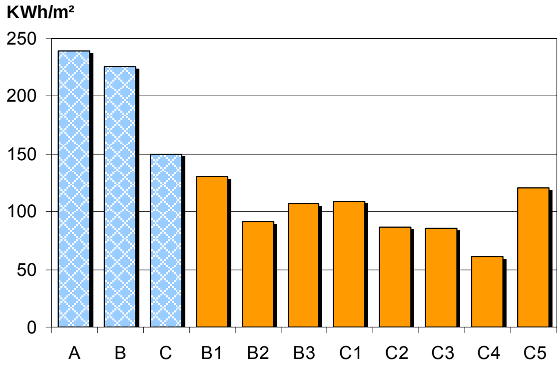

Figure 7 Plant Energy Consumptions in Madinah

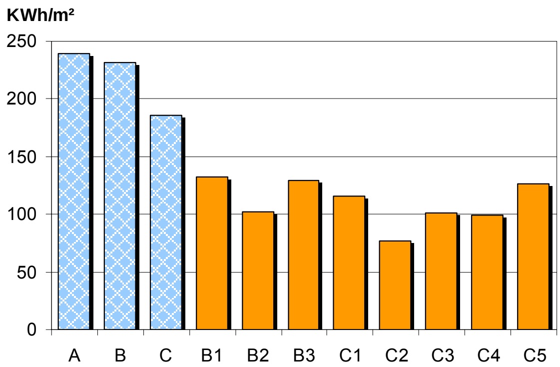

Figure 8 Plant Energy Consumptions in Bahrain

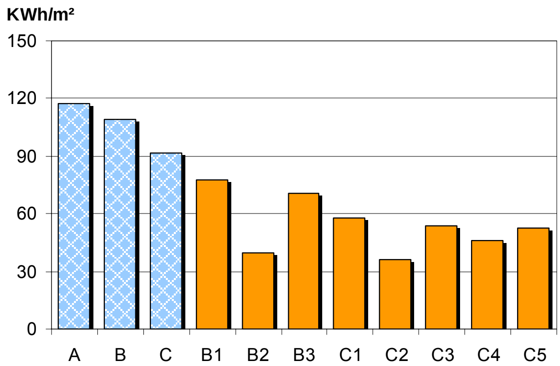

Figure 9 Plant Energy Consumptions in El-Arish

Relative Energy Savings

The amount of energy savings due to the application of the eight mixed-mode cooling systems have been expressed in terms of percentage reduction with reference to system (B, VAV) which is considered the common active case, Figure 10. The main observations can be summarised as:

- Significant savings can exceed 40% at the hottest cities (Madinah and Bahrain) by simply operating conventional active systems in a hybrid mode i.e. allowing natural ventilation and operating the active system at higher room setpoint termperaure;
- Adoption of night ventilation shows significant further reduction in energy demand: between 56% and 64% for the hybrid VAV system (B2) and between 62% and 67% for the hybrid radiant cooling system (C2);
- Direct evaporative cooling adds further savings to the base mixed-mode systems (B1) and (C1) especially at the dry cities (Alice-Springs and Madinah);
- Using a cooling tower to reject heat from the radiant system (system C4) is worthwhile – 7% to 21% more saving compared to hybrid radiant systems with chillers (system C1);
- Using borehole heat exchanges to reject heat from the radiant system is worthwhile just in the arid climates with lower mean average air temperature – up to 5% more savings in Alice-Springs and El-Arish.

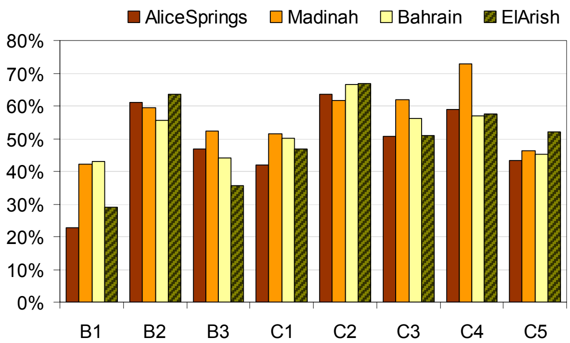

Figure 10 Plant energy savings due to application of mixed-mode cooling strategies in arid climates

Considering monthly variations in energy savings using mixed-mode systems (see Figure 11) gives some insight into the relationships between climatic conditions and energy savings. The mixed-mode systems using VAV and where natural ventilation is permitted for day and the night-time (B2), most of plant energy savings occur at moderate outdoor temperatures. In hot arid climates, outdoor temperatures are moderate during winter and equinox periods. Figure 11 shows savings reach 100% in some months as internal heat gains are sufficient to offset heat losses. Energy savings are inversely proportional to the cooling degree days and the mean monthly dry-bulb temperature; energy savings are least during the hottest summer periods. During summer months, the savings are mainly due to night ventilation lowering fabric temperatures and improving conditions in the following day.

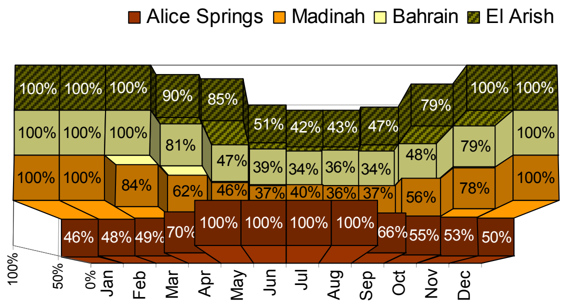

Figure 11 Monthly plant energy savings for system (B2) referred to a common active System (B). Note Alice Springs is in the Southern Hemisphere and cooler months are in the middle of the year.

CONCLUSIONS

Arid climate data has been analysed and four cities representative of variations in the data have been identified for the dynamic thermal simulation analysis of different cooling strategies. Although these locations are classified as arid there are noticeable differences in their annual mean humidity levels.

A series of computer simulations using a model of a prototypical office building have been conducted. These have been simulated in three fully air-conditioned active systems as well as eight mixed-mode systems that integrate passive and low energy active concepts.

For the office building that has been modelled with mixed-mode systems, the dynamic simulation results suggest there may be a significant number of hours over the year where active cooling would not be required. For all arid cities, most of plant energy savings occur during periods of moderate temperature at winter months and at the equinoxes.

The energy consumption of the mixed-mode cooling systems shows remarkable energy savings compared to that of the common active systems. The simulation results indicate that mixed-mode cooling strategies are therefore very attractive and should be considered in the design of office buildings in arid climates.

Some of the most significant energy savings (more than 40%) can be achieved at the hottest cities at low capital cost by simply allowing active systems like

VAV air-conditioning to operate using a hybrid control scheme. Schemes that also allow night ventilation show reductions up to 67%.

Since the potential of direct and indirect evaporative cooling is dependent on wet-bulb depression, the application of these strategies is more effective at the driest cities (Alice-Springs and Madinah). Energy savings due to the implementation of either cooling towers or the borehole heat exchangers coupled to a radiant cooling system may provide further energy savings in arid cities with relatively lower mean annual temperatures.

Systems offering greatest savings for Alice-Springs and El-Arish could combine all the passive measures tested (natural and night ventilation, direct and indirect evaporative cooling, and earth cooling) For Madinah a similar system but excluding earth cooling, is promising. Whereas, for Bahrain, a simple mixed-mode system using a hybrid control scheme for natural and night ventilation is expected to produce the most significant energy savings.

FURTHER RESEARCH

This paper presents initial findings of a larger project. Further issues to be addressed are improvements of existing mixed-mode cooling systems, advanced control strategies, evaluation criteria concerning indoor air quality, development of design methodologies and guidance for architects to apply mixed-mode cooling strategies for office buildings in arid climates. Similarly, mixed-mode heating and lighting could be encouraged.

ACKNOWLEDGEMENTS

This paper is part of an ongoing 36-months research project sponsored by the Institute of Energy and Sustainable Development, De Montfort University.

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