EVALUATION OF INDOOR AIR QUALITY AND ENERGY USE IN AIR CONDITIONED OFFICE BUILDINGS

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Poor indoor air quality is a common problem in air conditioned office buildings in particular where the room air distribution has not been fully considered and fresh air supply has been reduced for the purpose of energy saving. Recent advances in technology and better understanding of indoor air quality issues have however led to the development of air conditioning systems that can provide better indoor air quality in office buildings. This research has evaluated the energy consumption of two groups of air conditioning systems relative to different levels of indoor air quality. The two groups of air conditioning systems considered were all air and the displacement ventilation systems. Both are capable of providing indoor air quality that complies with the ASHRAE standard. Computer models of these two systems were established and APACHE simulation software was used to evaluate their dynamic thermal and energy performance when different percentages of air are re-circulated. The ventilation decay equation, using carbon dioxide as the key indoor air quality indicator, was then used to evaluate the level of air quality. The results indicated that all air systems with over 20% air re-circulation would not achieve the recommended level of air quality. Re-circulating air would therefore not be an acceptable means of energy saving although an alternative is to incorporate heat recovery as an integral part of the air conditioning system. Displacement ventilation was found to provide the best indoor air quality. Results showed that the operating energy of displacement ventilation with chilled ceiling is only slightly higher than a comparable variable air volume system and further consideration should be given to their more widespread use in offices.

Keywords: air-conditioning energy, displacement ventilation, indoor air quality, thermal simulation.

INTRODUCTION

It is estimated that at least 750,000 workers were affected by poor indoor air quality in the United Kingdom in 1998, resulting in 13 million person days off work with a cost of £4-5 billion to the nation (Department of Health 1999). Poor indoor air quality is often associated with air-conditioned buildings yet despite the increasing environmental awareness and education of 'green' or 'sustainable' design, there is no slow down in the use of air-conditioning in the UK. The air conditioning market, estimated to be over 60% for office and retail buildings, has increased significantly between 1996 from £497 million to £592 million in 2000 with the predicted growth to £685 million in 2005 (Coyle 2002).

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In designing air conditioning systems for buildings, designers are often faced with the challenge of selecting systems that can provide acceptable indoor thermal environment and air quality, but with low level of energy consumption. This research attempts to address this dilemma by evaluating the energy consumptions of two types of air-conditioning system that are capable of providing good air indoor quality. The study commenced by identifying suitable types of air-conditioning systems. Energy performance of these selected systems were evaluated by using a commercial thermal simulation software APACHE (Application Program for Air-conditioning and Heating Engineers). The indoor air quality levels were subsequently calculated by means of the ventilation decay principle (Jones 1994). Two suitable types of air conditioning systems have been identified and eight system models were established and studied.

SELECTION OF AIR CONDITIONING SYSTEMS

The design and operation of air-conditioning systems play important roles in the resulting indoor air quality of office buildings. Apart from the cleanliness of the air-conditioning plants and equipment and the external air quality (Bluyssen *et al.* 2002), the two main factors affecting indoor air quality are the percentage of fresh air in the supply air and the air distribution within the room (Xing, Hatton and Awbi 2001). In an ideal scenario, the air-conditioning system should be able to supply and maintain good quality air at the breathing zone of the occupied space.

Air distribution and indoor air quality

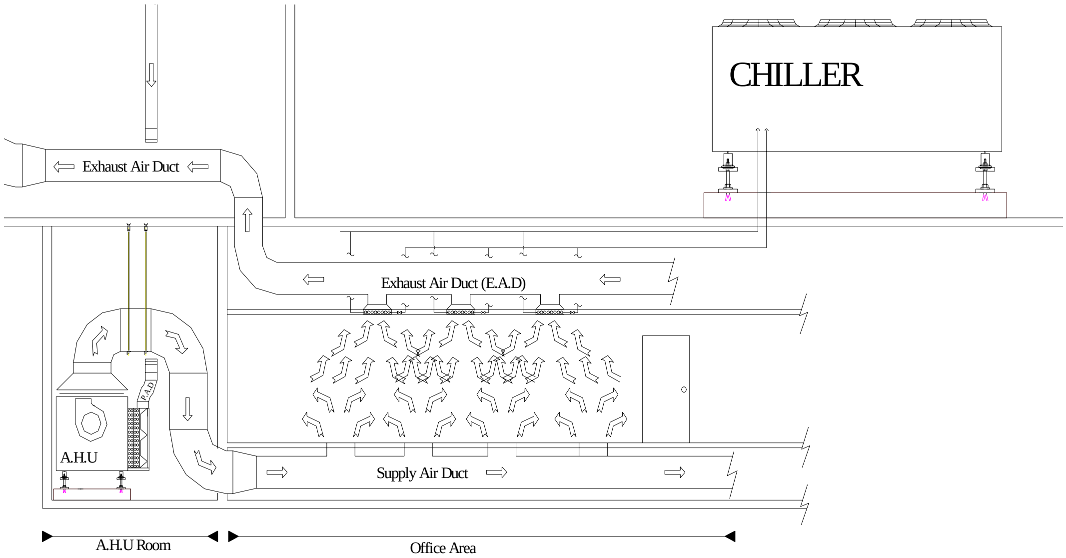
Even with good quality of supply air, the manner in which air is distributed has a significant impact to the quality of air being inhaled by the occupants. In conventional air conditioning systems, large volumes of air, commonly between six to eight air changes per hour, are supplied through diffusers into the occupied zone. Supply air is well mixed with room air; hence its quality is much deteriorated before the occupants inhale it. Oughton (Oughton D. R. 2002) described that successful air distribution for good indoor quality relies on low velocities of supply air to avoid mixing of the room air and that air outlets should not be directed only towards the occupants. This design concept formed the basis of ventilation principles that can provide good indoor air quality. It has also led to the increasing use of air distribution systems in which the low velocity air enters at low level and air exits from the room at ceiling level. This so called ‘displacement ventilation’ removes the contaminants as the air rises evenly across the room, creating a ‘piston’ effect with minimum turbulence during the process (Jackman 1990). Currently displacement ventilation with 100% fresh air is considered as the best available system that can provide high quality air to the occupants in air-conditioned buildings (Behne 1999).

Air conditioning systems for evaluation

Air-conditioning systems can broadly be divided into two groups: air-water systems and all air systems. Conventional air-water systems, such as fan coil units and induction units, are designed to maintain room temperature locally by re-circulating room air through the heating or cooling coils situated within the room. The fresh air is supplied separately at a rate to meet the fresh air requirement, typically at 10 l/s per occupant, for non-smoking rooms. Good air quality is not feasible due to the low volume of fresh air supply but high volume mixing of air within the room. However, one advantage of this kind of system is that contaminants are confined locally if the extract air, being replaced by the fresh air, is not re-circulated.

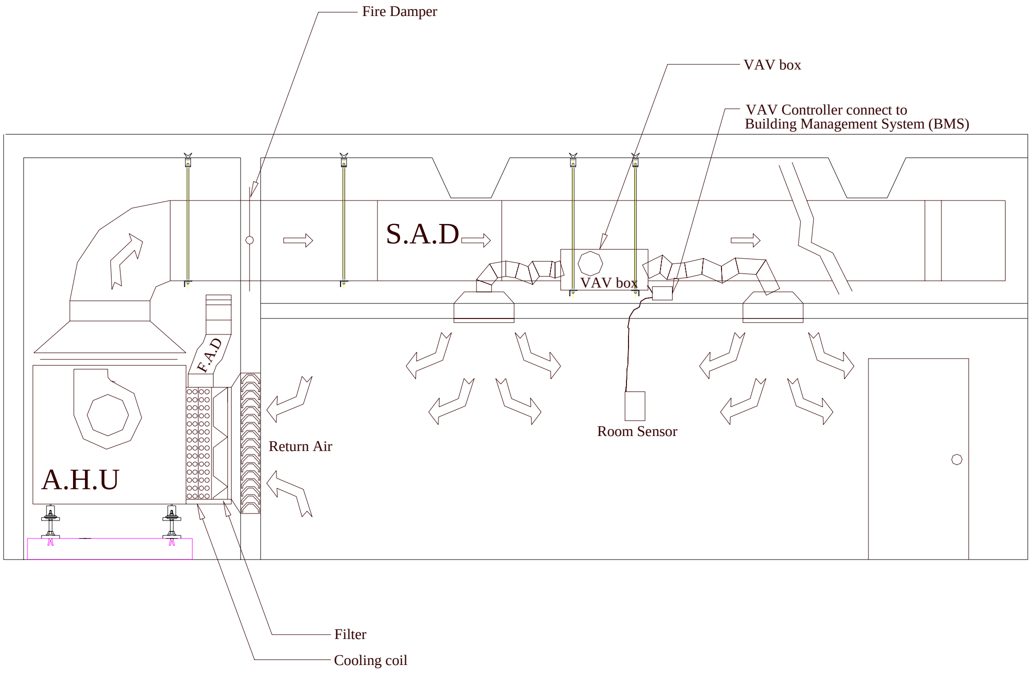
Nevertheless, an improved type of air-water system, the displacement ventilation with chilled ceiling system as shown in figure 1, has been developed to provide good indoor air quality. The principle of providing good air quality by displacement ventilation discussed in the previous section is adopted in this system. The use of low velocity supply air, however, limits the cooling capacity; hence chilled ceiling or chilled beams are often required to deal with the excess cooling load. This kind of system is more complex both in its design and in operation than traditional systems as well as taking up plenum space at both floor and ceiling levels and requiring careful control of air distribution. The chilled ceiling or beams surface adds to the complexity (Abbas 1999). Apart from the capital cost, the operating cost of this kind of system is considered higher (Olsen and Chen 2002).

Figure 1: Displacement ventilation with chilled ceiling



The all air systems have greater flexibility to provide good indoor air quality as these systems allow a high percentage or even full fresh air supply. A commonly used system for office buildings is the variable air volume system, as shown in figure 2, in which the supply air volume is linked to the cooling load of the room. The attainment of thermal comfort in this kind of systems relies on turbulent mixing of room and supply air, the quality of air as experienced by the occupants is therefore worse than that of the displacement ventilation even when the same percentage of fresh air is supplied. However, the variable air volume systems are well established with many proven advantages, they will continue to be widely used in air-conditioned office buildings. For the purpose of this research two systems have been selected both of which the literature has shown are capable of supplying good indoor quality – the variable air volume system and displacement ventilation with chilled ceiling. The next phase of the study will focus on these two systems with the aim to evaluate the indoor air quality relative to their energy consumption.

Figure 2: Variable air volume system



EVALUATION PROCESS

To study the seasonal energy consumption of a building is complex. It involves not only the unsteady heat transfer through the fabric of the building, but also the varying indoor parameters such as the room occupancies, room temperatures, lighting loads, equipment use, as well as the type of air-conditioning systems and the associated modes of control. A dynamic computer modelling technique was deemed to be appropriate and effective for the analysis proposed in this study. Although there is programs, such as the IDA Indoor Climate and Energy (Equq 2003), developed to evaluate indoor air quality, software for direct assessment of indoor air quality that can take into account the dynamic thermal behaviour of the building and the associated plant and equipment is still under development. A two stage improvised evaluation process was adopted. The first stage was to model the thermal and energy behaviour of the case studies in a commercial dynamic simulation software APACHE. The results from APACHE were subsequently used to calculate the indoor air quality using the ventilation decay principle (Jones 1994), in the Excel spreadsheet.

Dynamic computer simulation

APACHE is a simulation program that can perform dynamic thermal analyses and energy evaluation of buildings (Ies 2003). The program allows users to specify a range of parameters that characterise the building and its operation. These include the external weather conditions, the materials used in the building fabric, the thermal requirements of the internal environment and the profiles of plant and equipment operation in each room of the building. An important feature of APACHE is its capability to simulate the air conditioning systems while performing the thermal analysis. The simulation program allows definition of different modes of operation and control mimicking closely actual buildings.

Simulation models

A two storey rectangular building of 50m by 35m as shown in figure 3 was used in this study. The building has 200mm medium weight concrete external walls and double glazed windows with a thermal transmittance of 2.8W/m^2 K. The roof is 150mm cast concrete flat roof with 25mm dense expanded polystyrene slab insulation. The building is occupied Monday to Friday from 0900 to 1700 and has an occupancy density of 10m^2 per person. The energy simulation was carried out between June and August using the weather data for London.

Figure 3: Plan of model office building

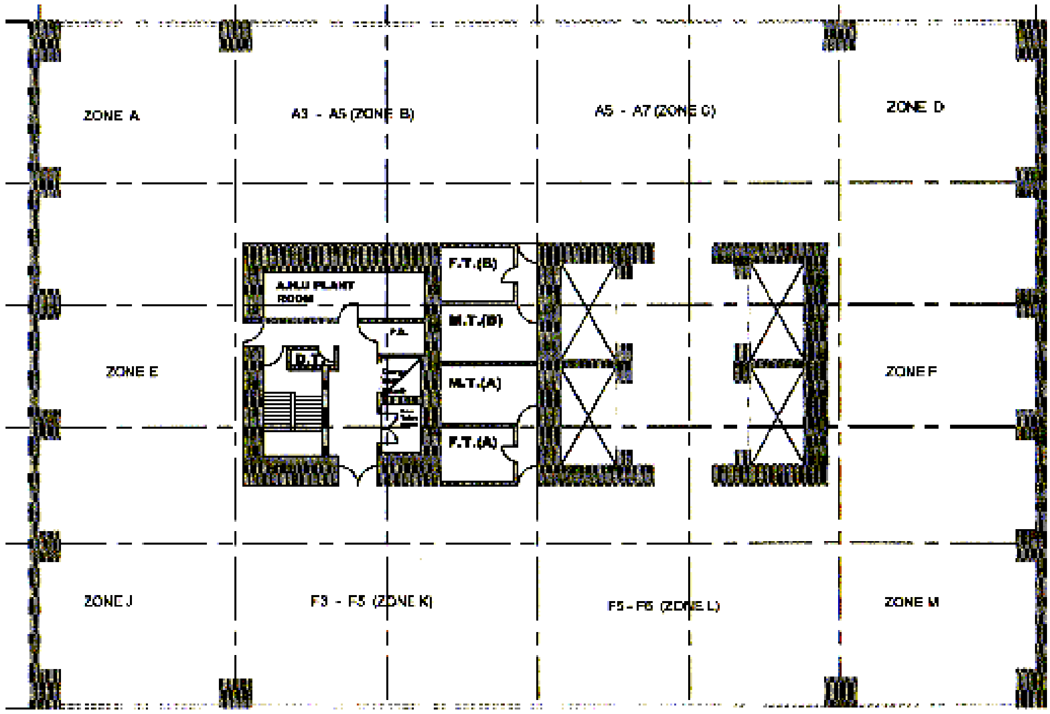


Table 1: System types and notation

System type	Notation
Displacement Ventilation with chilled ceiling and heat recovery	System A
Variable Air Volume with full fresh air with heat recovery	System B
Variable Air Volume with no re-circulation and no heat recovery	System C
Variable Air Volume with 20% re-circulation	System D
Variable Air Volume with 40% re-circulation	System E
Variable Air Volume with 60% re-circulation	System F
Variable Air Volume with 80% re-circulation	System G
Variable Air Volume with 100% re-circulation	System H

One displacement ventilation with chilled ceiling model and seven variable air volume systems with different percentages of air re-circulation were used in the study. The models in table 1 represent a hierarchy of air-conditioning system that can provide different levels of air quality. Systems A and B are full fresh air systems with heat recovery. As re-circulation of air is uncommon in displacement ventilation, only a full fresh air system was studied. System C is a full fresh air system without heat recovery. Systems D to H represent systems with declining indoor air qualities but increasing energy savings.

Indoor air quality evaluation

The task of quantifying air quality is overwhelmed by the number of contaminants, as high as 900 different contaminants (Brooks and Davis 1992) that can be found inside buildings. Although there are guidelines and regulations regarding outdoor air quality, indoor air quality standards are still not available in the UK. Taking into consideration that the air quality is mainly related to the human activities and occupancy within the building, the use of carbon dioxide concentration - not to exceed 1000ppm - as a representative indicator is deemed appropriate (ASHRAE 1989) and has been adopted in this study.

The concentration of pollutants and carbon dioxide in any part of a room is influenced by a number of factors such as the heat sources, surface temperatures, air inlets and outlets. Detailed evaluation of pollutant concentrations would require the application of computational fluid and thermal dynamics that is beyond the scope of the current study. A homogenous well-mixed air was therefore assumed, however, it is important to recognise that even with the same percentage of fresh air supply, occupants would experience better air quality with a displacement ventilation system than a variable air volume system (Waters 1998). The resulting carbon dioxide concentration in a room is directly related to the supply air volume, the carbon dioxide concentration of the supply air and the initial carbon dioxide concentration in the room.

RESULTS AND DISCUSSION

Eight systems were simulated over the summer period between 1st June to 31st August. The simulation assumed constant outdoor air quality and the same level of indoor air quality in the morning.

Variable air volume systems (VAV) with air re-circulation

Five variable air volume systems with percentages of return air at 20%, 40%, 60% 80% and 100% were used in the dynamic simulation. The volume of supply air in this kind of system varies in response to the cooling load. While the temperature is maintained at the set point, the levels of indoor air quality fluctuate widely during the day. Figure 4 and 5 summarise the maximum and minimum levels of carbon dioxide concentration during the working hours over the summer period for variable air volume systems with air re-circulation. It shows the lack of control to the indoor air quality due to different percentages of fresh air and the variable supply air volume.

The results indicated that:

- For systems with 60% or higher percentages of fresh air in the supply, the indoor air quality reached steady state during the course of the day indicating that the rate of carbon dioxide generated within the space is balanced by the rate of removal. The greater the fresh air rate, the quicker the system approaches the steady state. This occurred within one hour for system with 60% or 80% fresh air;
- The indoor air quality level continues to deteriorate during the day if the supply fresh air is less than 60%;
- Carbon dioxide concentration is nearly eight times the maximum recommended by American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE 1989) in the system with only 20% fresh air in the supply;

Figure 4: Minimum carbon dioxide concentration during the working hours

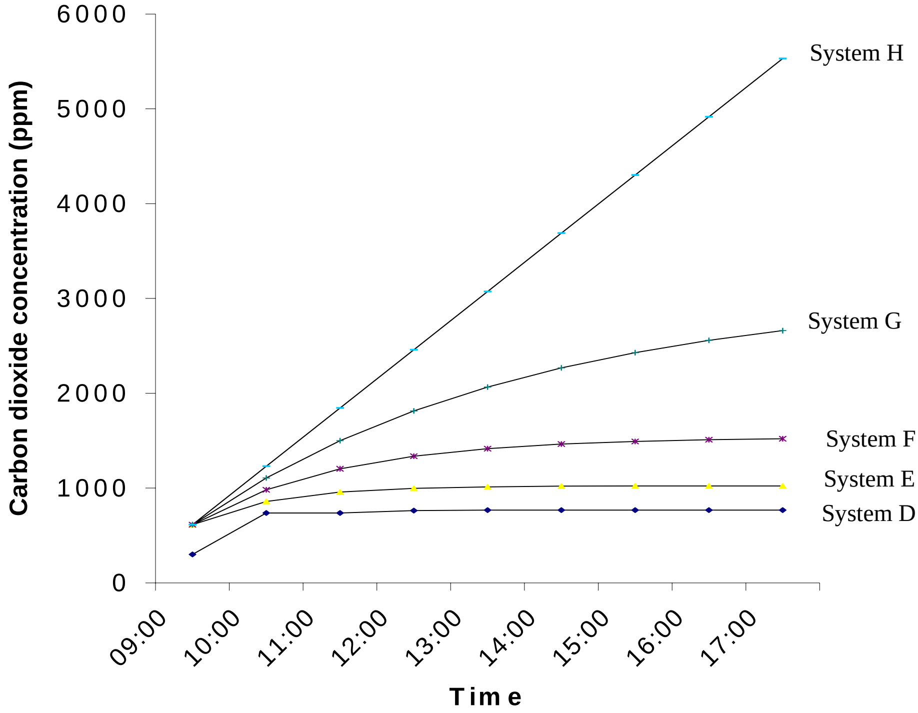
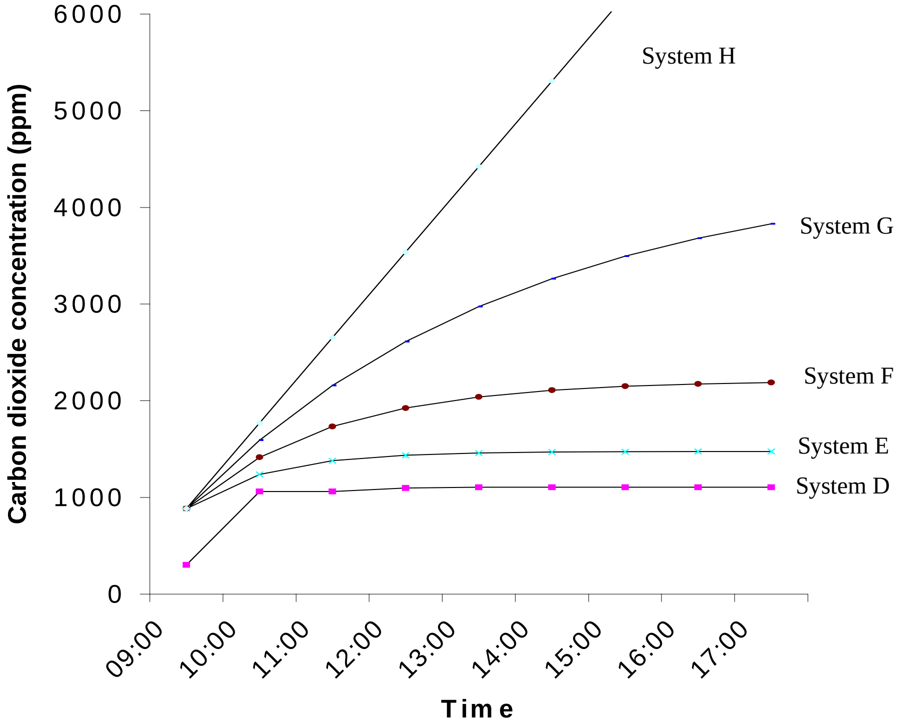


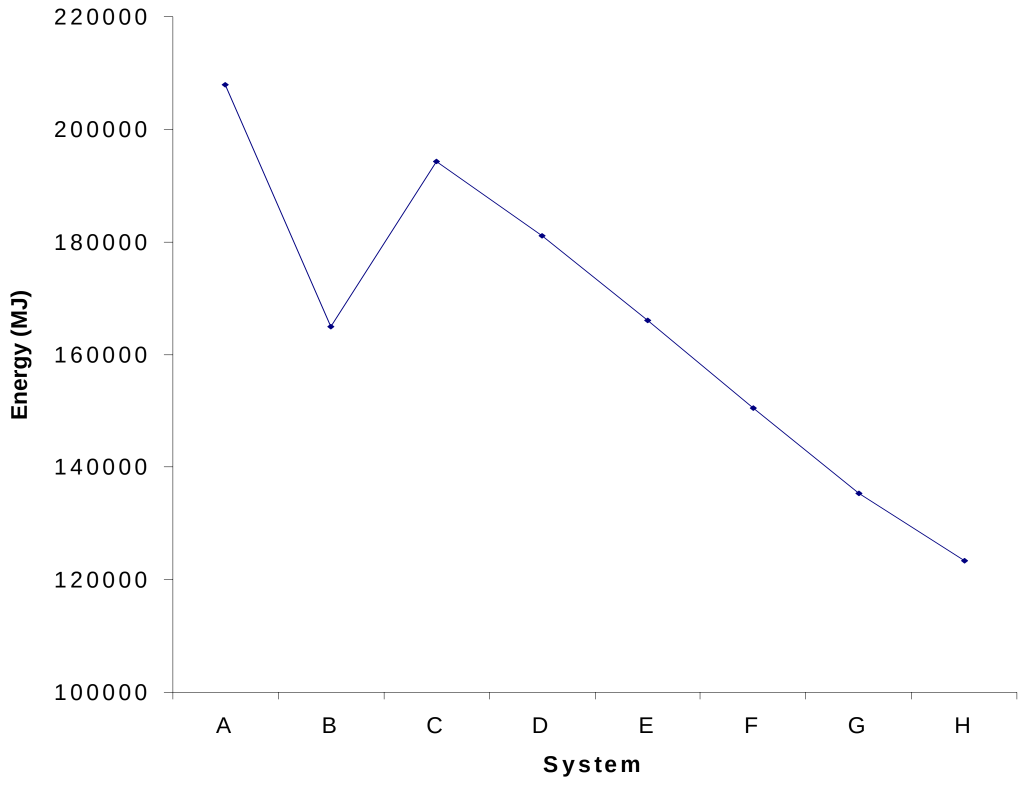
Figure 5: Maximum carbon dioxide concentration during the working hours



- The nature of variable air volume supply resulted in variable levels of indoor air quality. For instance, system D at maximum supply air flow rate produced a carbon dioxide concentration of 765 ppm but rises to 1105 ppm when the system is at minimum supply air flow rate;
- The systems that meet the ASHRAE standard for indoor air quality are the systems that used less than 20% re-circulated air and running at maximum air change rates;
- Carbon dioxide concentrations at the beginning of the day are considered to be the same as outside air. The levels of carbon dioxide will be higher if the air in the building is not fully flushed after office hours.

There was a direct correlation between indoor air quality and energy use. Energy use decreases as the percentages of re-circulation air increase. Figure 6 summarises the energy use of the systems. Energy saving of 60% can be achieved if the percentage of air re-circulation is increased from 0% to 100%. The simulation outcomes of the air conditioning energy consumptions are comparable to the energy consumption figures quoted in the EEO energy consumption guide 19 (DEFRA 2003), as in the case of system D at 35 kWh/m^2.

Figure 6: Energy consumption June to August



VAV with full fresh air

The calculated concentration of carbon dioxide for a variable air volume system with full fresh air supply varied between 590 ppm and 900 ppm. This level of indoor air quality is well within the ASHRAE recommendation. However, the use of full fresh air would result in much higher energy consumption unless alleviated by introducing a heat recovery system. Simulation of a heat recovery system with a recovery efficiency of 50% resulted in an energy saving of approximately 20% in comparison with a full fresh air variable air volume system. The air change rate has significant implications on energy use as well as indoor air quality; hence, a balance must be determined.

Displacement ventilation with chilled ceiling

Unlike the variable air volume systems in which the carbon dioxide concentration in the room is related to the cooling or heating loads, the displacement ventilation system maintains the carbon dioxide concentration at a level of 590 ppm when operated under a constant occupancy profile. This level of carbon dioxide is 40% lower than that recommended in the ASHRAE standard. Hence, there is room for reducing energy consumption by reducing the fresh air supply. Even at the same calculated carbon dioxide concentration the displacement ventilation will have a better indoor air quality. This is due to the fact that contaminants are continuously replaced in a laminar flow manner in the occupied space. However, the evaluation of this actual level of carbon dioxide would involve the use of computational fluid dynamics that is beyond the scope of the current study.

Simulation results showed that this kind of system would use 207882 MJ during the summer season, which is higher than all the variable air volume systems. The higher energy consumption is partly due to operation of the chilled ceiling system. However, results showed that it is only 6.5% more than the full fresh air variable air volume system with heat recovery.

CONCLUSIONS

Displacement ventilation, in which room air is effectively replaced by fresh air, is the best option for achieving good indoor air quality. Although the results showed that the carbon dioxide level in a displacement ventilation is 40% lower than that specified in the ASHRAE guide, the actual level at breathing level would be even lower as current analysis assumed homogeneous mixing. On the other hand indoor air quality varies significantly in the variable air volume systems ranging from 600ppm to 8000ppm of carbon dioxide. Poor indoor air quality is often a result of attempts to save energy through high percentage air re-circulation and the results showed that a tempting cost saving of 60% could be achieved by such a practice. This study also demonstrated that variable air volume systems that use more than 20% of air re-circulation would not achieve the acceptable level of indoor air quality as recommended by ASHRAE.

Although the displacement ventilation with chilled ceiling will involve higher capital cost, this study indicated that the operating energy is comparable to the variable air volume system with full fresh air supply. Current model shows a 6.5% higher cost but further saving can be achieved by the dynamic control of fresh air supply and optimising the capacity of the chilled ceiling.

This study has identified that displacement ventilation can provide acceptable indoor air quality in air-conditioned office buildings. It shows that computer simulation is a versatile and inexpensive tool for the study of indoor air quality and energy consumption. Of those studied only three simulation models meet the acceptable indoor air quality levels and this study highlights the importance of using heat recovery to improve the energy efficiency. As indoor air quality is becoming an important issue in sustainable and healthy design of buildings, it is necessary to develop strategies of achieving and maintaining acceptable indoor air quality. This study has also identified the need to develop computer simulation software that can incorporate the influencing parameters, such as the thermal and fluid dynamics, which affects the air quality at different locations of a room. Within the limitations of the current study, results showed that the operating energy of displacement ventilation with chilled ceiling is only slightly higher than a comparable variable air volume system and their application should certainly be considered for future office building.

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