Experience with occupant control of supplementary cooling in a naturally ventilated environment: some preliminary results from work in progress.

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Abstract. Thirty five occupants of twenty five naturally ventilated rooms can operate supplementary cooling and heating equipment and windows independently to control their local thermal conditions and ventilation in accordance with their personal comfort requirements. Preliminary studies suggest that the use of the supplementary cooling equipment is closely related to outdoor thermal conditions with limited recourse to it in mild weather and resultant substantial energy saving in comparison with consumption that might be expected in a conventionally air conditioned environment. The evidence also indicates a substantial improvement in perception of thermal comfort and air quality since installation of the cooling and heating equipment. A pilot study involving twelve occupants of seven similarly equipped rooms suggests that mechanical intervention is applied to limit indoor temperatures to about 25°C +/- 2 °C when they might otherwise rise to 30°C or more.

Introduction

Over the past half century the use of automated air conditioning systems to control the indoor thermal environment and ventilation of commercial buildings in developed countries has grown to the point where alternative solutions have, until recently, received little attention from mainstream owners and developers. In these buildings windows are fixed in the closed position and system operation is automatically controlled. Occupants have very little scope to make adjustments to preset conditions when they do not meet their current requirements or preferences.

However studies, for example Rowe and Wilke (1994), are showing that many occupants are less than fully satisfied with thermal conditions and air quality in these buildings despite the sometimes extravagant consumption of energy to achieve regulated indoor climates. In a 1984 study, Finnegan, Pickering and Burge found that prevalence of the symptoms of "sick building syndrome" was higher in air conditioned buildings than in those that were naturally ventilated through operable windows and doors. And Bordass, Bromley and Leaman, (1994) have demonstrated that satisfaction with the indoor environment of buildings is improved when occupants are able to operate controls to alter a set of conditions perceived as objectionable and to obtain a rapid response. Such actions may include opening or closing windows or doors, drawing blinds, switching on or off a piece of equipment or altering a thermostat setting.

Together with these concerns, growing realisation of an alarming potential for global warming and depletion of finite resources of fossil fuels is leading to interest in alternatives to air conditioning with fixed windows and mechanical ventilation. Such alternatives aim to make maximum use of passive energy flows and building construction methods and materials to establish comfortable conditions and thus limit to a minimum those occasions, if any, when supplementary mechanical cooling or heating is required. They will also provide opportunities for intervention by occupants to achieve rapid response to perceived need for change and will, as far as possible, provide means for adjustment of conditions to suit individual preferences. Design concepts will vary in response to climate, building type, proposed use and subdivision of interior spaces.

A subset of the challenge to design for a more sustainable use of energy is found in older naturally ventilated buildings in climates that do not provide comfort for occupants at current levels of acceptability during part(s) of the year. In such buildings conditions may be perceived as requiring supplementary cooling during the humid sub-tropical summers and some heating in the cool winters that are typical of Sydney and similar situations. Between seasons it is not difficult to maintain thermal comfort without supplementary cooling or heating.

This paper will present some preliminary findings from a planned study of the retrofit of supplementary cooling and heating equipment into twenty five rooms in the Architecture building at the University of Sydney where accommodation is cellular with each room containing one or only a few occupants. In this setting windows can be opened or closed to vary ventilation rates and occupants are free to operate fancoil units for cooling or reverse cycle heating; to vary thermostat settings; or to use hot water heated panel radiators for background heating in cold weather.

Instrumentation is being installed that will eventually provide a continuous record of temperatures in all rooms; their occupancy status; and operation of windows, external doors, fancoil units and supplementary hot water heated panel radiators. However information collected to date enables some preliminary conclusions to be formed. These include that:-

- Occupant perceptions of thermal comfort and air quality in the long term are much improved since installation of the supplementary cooling and heating equipment.
- The supplementary cooling and heating system under occupant control uses much less energy than would be expected if the same space were provided with a well designed conventional air conditioning system with mechanical ventilation and fixed windows.
- Use of fancoil units on cooling cycle is strongly related to outdoor weather conditions.

About the Building

The Architecture building is of heavyweight masonry construction on five levels with concrete floors, brick walls and brick interior partitions. Most rooms have full length glass exterior walls from sill to ceiling with metal framed hopper windows alternating with fixed panes. Some rooms also have metal framed glass doors opening onto a rooftop courtyard. The study area consists of 25 rooms located on parts of levels 2, 4 and 5. Orientation of windows in these areas is toward the south, south east and north west. Windows are externally shaded with 600 mm deep overhangs and most are fitted with adjustable blinds of various kinds. The large proportion of glass in external walls results in high heat gains in hot weather and losses in the winter. Hot water heated panel radiators are installed under windows in most rooms to provide background space heating for winter. Lighting is provided by fluorescent luminaires with a loading density of approximately 20 W/m^2. Personal computers are used in all the rooms.

The rooms are normally occupied between 9am and 5pm although use is often extended into the evening and some rooms are regularly occupied over weekends. Eighteen of them are occupied by only one academic staff member in each. The remainder have from two to four research students as occupants. All rooms are on the building perimeters and cooling and heating loads are therefore strongly influenced by outdoor conditions.

The supplementary cooling and heating system was commissioned in November 1997. Fan coil units, supplied with refrigerant from a modular variable refrigerant flow condensing set, are installed in each room in the study area. The refrigerant is conveyed in a three pipe system which permits fancoil units in some groups of rooms to be operated on cooling cycle while others are on reverse cycle for heating. The units can also be operated in fan only mode for air movement.

Operation of the fan coil units is initiated by the occupant(s) of the individual rooms who also are able to select the thermostat set point temperature and direction and velocity of air stream. It is noted that the system tends to default to off: initiation of supplementary cooling or heating requires the person in the room to switch on. If conditions on entry are satisfactory the unit remains switched off. All units are switched off automatically at 9 pm and again at midnight to avoid unnecessary use when rooms are unoccupied. They are, however, available for immediate re-starting in case of requirement late at night and there are instances when people in some rooms have used the system after midnight.

The condensing set is of modular design with six modules. One of these is provided with a variable speed drive. It operates up to full speed and when it is fully loaded a single speed unit starts and the variable speed unit cycles back to its lowest speed. Further increase in load is met by increase in speed of the variable speed unit and successive single speed modules are added until the load grows to its maximum value. This arrangement enables the system to operate efficiently over a wide range of loads.

The study to date

Outdoor thermal conditions are monitored continuously at a weather station on the roof of the building. The number of fancoil units in operation is logged each working day at noon and 3 pm. Energy is supplied to the whole system via a dedicated sub-main and consumption is recorded every half hour. A month by month estimation of energy consumption that would be expected of a conventional variable volume air conditioning system with outdoor air cycle for the same spaces has been carried out using the ESPII (1998) energy simulation software and this is compared with the measured monthly consumption of the system. The simulation is based on Typical

Reference Year (TRY) weather for Sydney, 1981. Occupancy schedules have been established with a view to matching as reasonably as possible the rather erratic hours of use of the space. People work varying hours depending on whether they teach day or evening classes or are occupied as postgraduate students, some of whom tend to work late at night or on weekends. The weekday simulation schedule applied to lights, equipment and occupancy begins with 50 percent occupancy at 10 am, rising to 90 percent at 11 am, falling to 50 percent at 2 pm, rising to 90 percent at 3 pm and falling to 30 percent between 6 and 9 pm, Monday to Friday. The maximum occupancy rate was set at 90 percent to allow for absences of staff on leave or attending conferences et cetera. On Saturdays and Sundays and public holidays occupancy is scheduled at a constant 30 percent between 11 am and 6 pm.

A survey of occupants was conducted in September 1997 to establish their long term perceptions of thermal comfort and air quality prior to installation of the system. A replica survey was conducted in September 1998, ten months after the system came into use to test variations of perceptions. The survey instrument was developed by Vischer (1987) in Canada and has been used over the past six years in fifteen other Australian office settings including nine that are conventionally air conditioned. Indices for thermal comfort and air quality have been calculated from responses to the surveys and are compared with those from the other settings in the database.

A continuous record of temperature has been kept since 1 January 1999 in a room that is not connected to the system but is similar in construction and occupation to many of the subject rooms. The purpose of this was to provide an indication of the conditions that would be met by people without the supplementary cooling equipment.

At this stage detailed records are not available of the temperatures maintained in their rooms by occupants. However in a pilot study of seven rooms in the same building with similar arrangements for supplementary cooling and heating, temperatures were recorded continuously over a period from July 1996 to August 1998. From this record, temperatures at 3 pm in occupied rooms on work days were extracted. These are presented in figure 6 below as an indication of the range of conditions that are likely to be acceptable in this sort of environment.

Work in the future

Installation has commenced of instrumentation to monitor operation of the system. When complete it will enable the keeping of a continuous record of room temperatures, occupancy status and status of fancoil units, hot water heated panel radiators and windows and external doors in each room in the study area. These will enable predictions to be made more confidently about the adaptive behaviour of participants and the indoor temperature ranges that are acceptable under a variety of weather conditions within the range experienced in Sydney.

Results to date

A profile of outdoor thermal conditions at the site is presented as mean daily effective temperature (ET*) as shown by the heavy line in figure 1. Maximum and minimum daily values are shown as lighter lines. Mean outdoor effective temperature (MOET*) was selected as a suitable index for outdoor conditions following the rationale proposed by de Dear (1998). It provides an indicator that includes a weighting for moisture content of the air as it is likely to affect judgement of human thermal comfort. It will be observed that the daily range varies from about 3 °C to 10 °C or more. Swings of up to 10 °C or more are common over periods of a few days

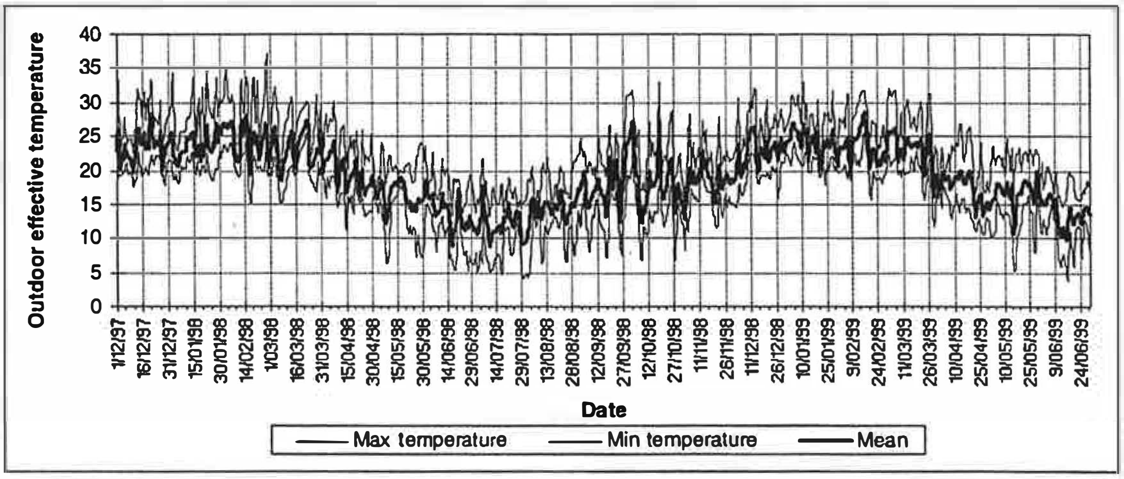

Figure 1. Daily outdoor maximum, minimum and mean effective temperatures (ET*) at the site from 1 December 1997 to 30 June 1999.

Maximum and minimum daily temperatures measured just below desktop level in a room of similar construction to those in the study area but without cooling equipment are displayed in figure 2. It will be observed that they were in the range from 26 to 30 °C or more on nearly all days between the first and 20th January. Maxima in February ranged from 24 to 30 °C. March temperatures were generally below 26 °C and in April and May they were generally in the range from 18 to 22 °C, falling to 14 °C and below at the beginning of June. In this year people could expect to be able to adapt to conditions as found with reasonable chance of success between March and May. It would be expected that most would prefer to moderate high temperatures in January and February and lower temperatures from June through the winter months.

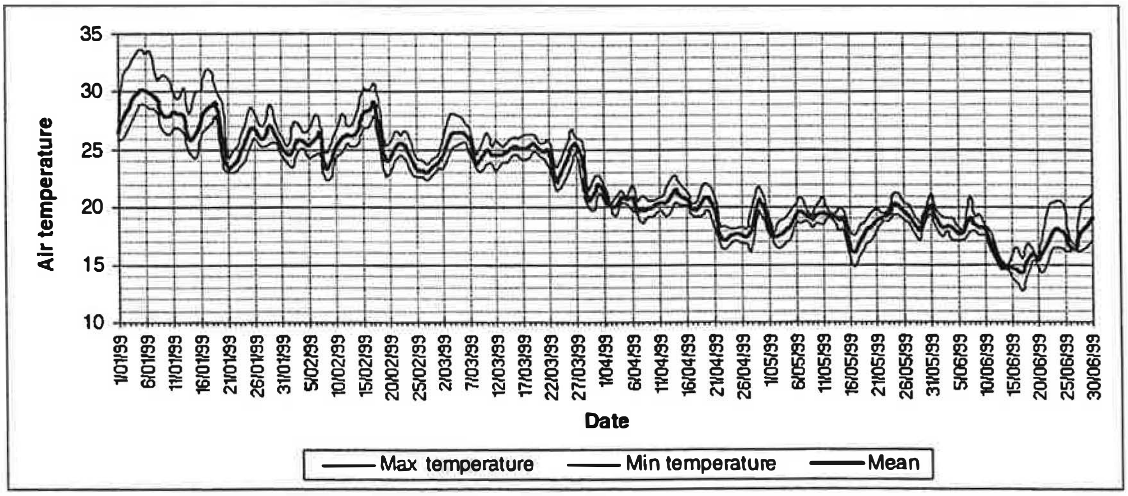

Figure 2. Daily maximum and minimum temperatures in a room without supplementary cooling from 1 January to 30 June 1999.

The number of fancoil units in use at 3 pm in rooms connected to the supplementary cooling and heating system has been recorded daily since December 1997 as shown in figure 3. It will be observed that a large proportion of them are in use during the months of December, January, February and March with much lower usage in April, May, September and October and an increase during the months of June, July and August for supplementary heating.

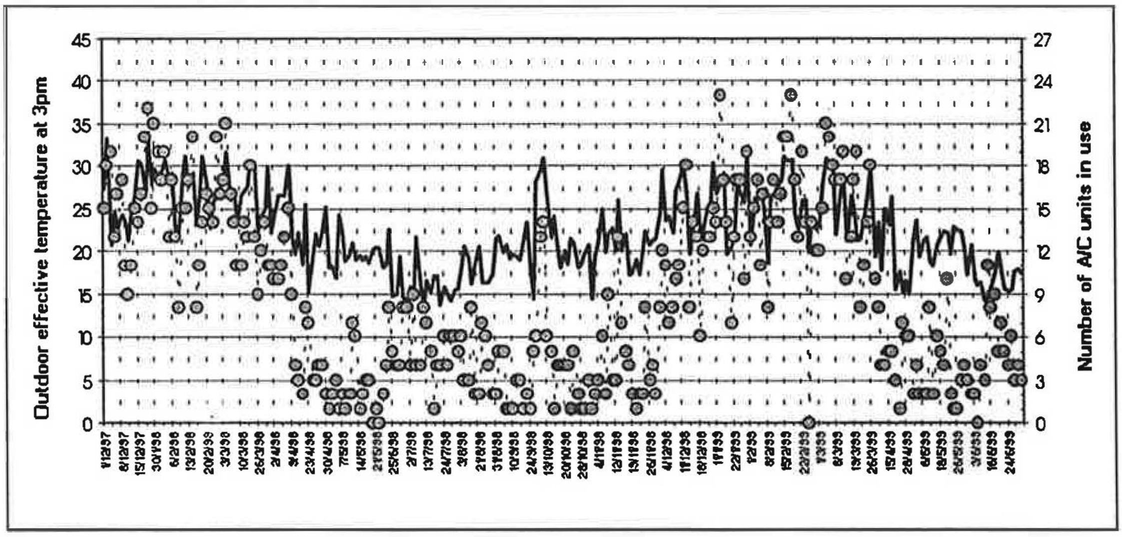

Figure 3. Fancoil units in use for supplementary cooling and heating at 3 pm on working days from December 1997 to June 1999. The heavy line indicates daily outdoor effective temperature, also at 3 pm.

LOGIT regression of percent of available fancoil units in use on cooling cycle for the months from November 1997 to the end of April 1998 and from the beginning of October 1998 to the end of April 1999 as a function of daily mean outdoor effective temperature binned by half degree intervals is illustrated in figure 4.

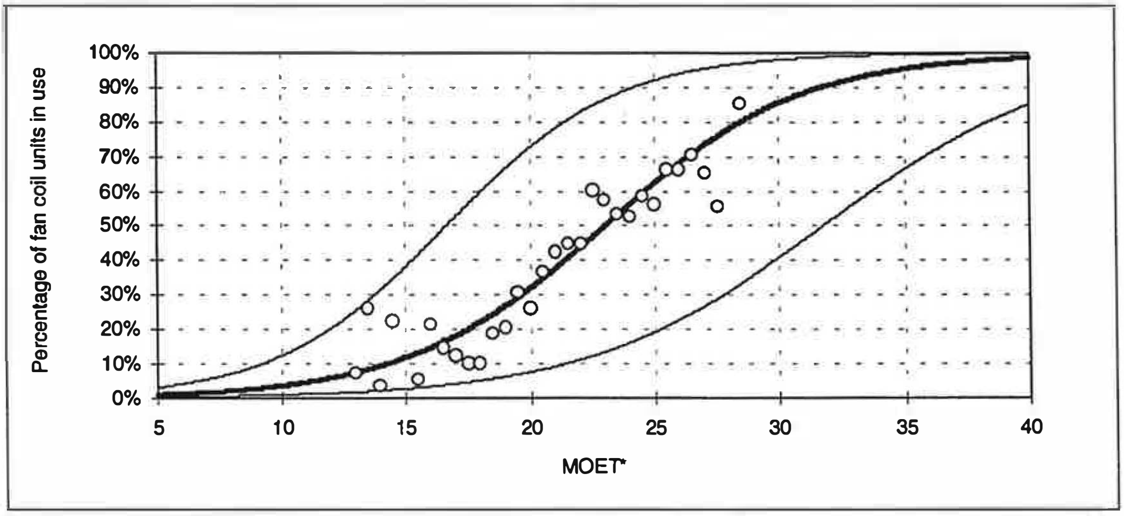

Figure 4. LOGIT regression of percentage of fancoil units in use at 3 pm on cooling cycle as a function of daily mean outdoor effective temperature. Light lines indicate Wald 95 percent confidence limits.

Only limited records of temperatures inside rooms are available as instrumentation is not complete. However daily temperatures in one of them (room 591) as recorded from 1 May to 7 July 1999 are shown in figure 5. This room is occupied on Mondays, Tuesdays and Wednesdays and is vacant on others. A fancoil unit was turned on only once to add heat during this period.

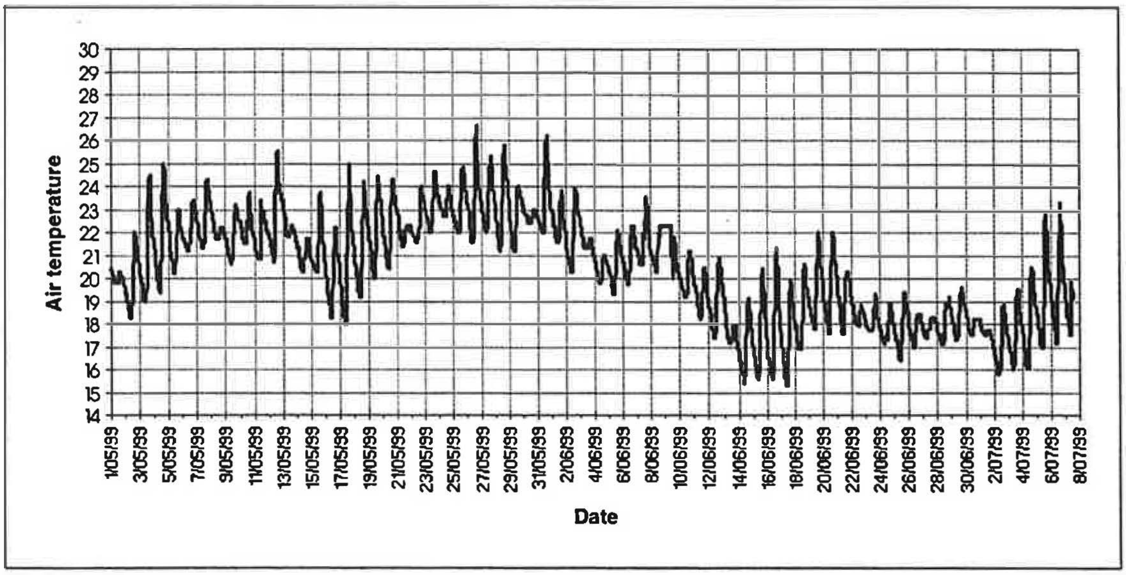

Figure 5. Temperatures recorded in room 591 from 1 May to 7 July 1999. The room is occupied on Mondays, Tuesdays and Wednesdays each week and is vacant at other times.

Records are not at present available to give an indication of acceptable indoor temperatures in other rooms in the study area. However data from the pilot study in seven rooms, illustrated in figure 6, suggest that an upper limit of about 26 °C is likely with a summer range of about 22 to 26 °C and a winter range of 20 to 24 °C. Outside these limits it can be expected that many of the occupants will choose mechanical intervention for either cooling or heating.

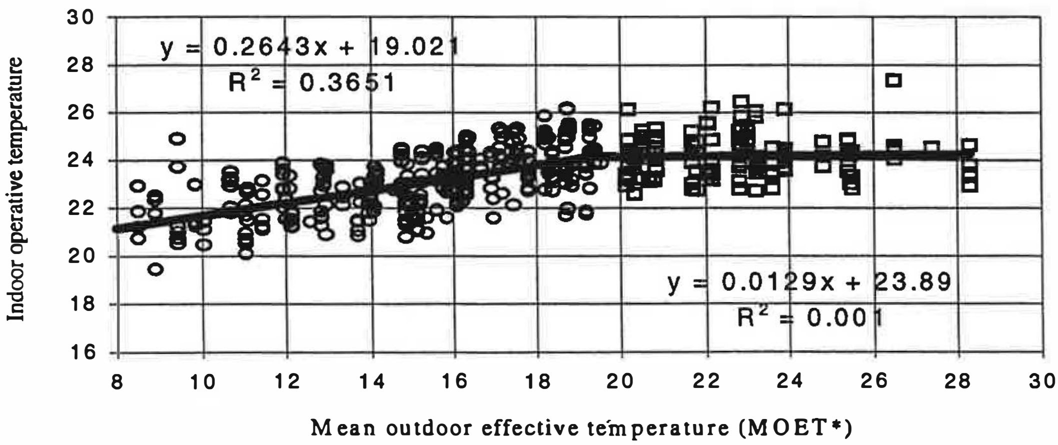

Figure 6. Temperatures recorded as acceptable during a pilot study in seven rooms with twelve occupants.

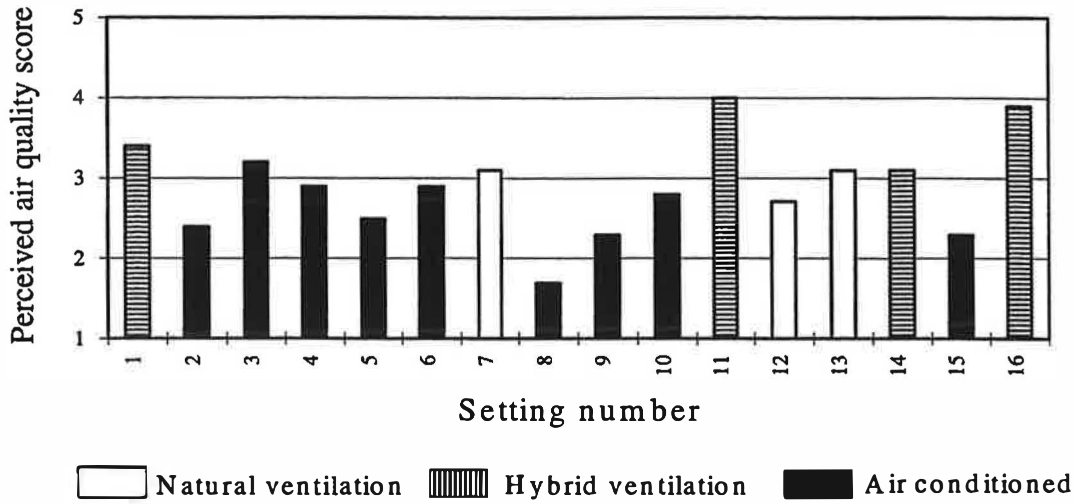

Figure 8. Scores for long term perceived air quality in sixteen office settings including the study group before (13) and after (16) the provision of on-demand supplementary cooling and heating equipment.

As an aside it is worth noting that perceived air quality exhibits quite a strong dependence on thermal comfort in these sixteen settings as indicated in figure 9 below.

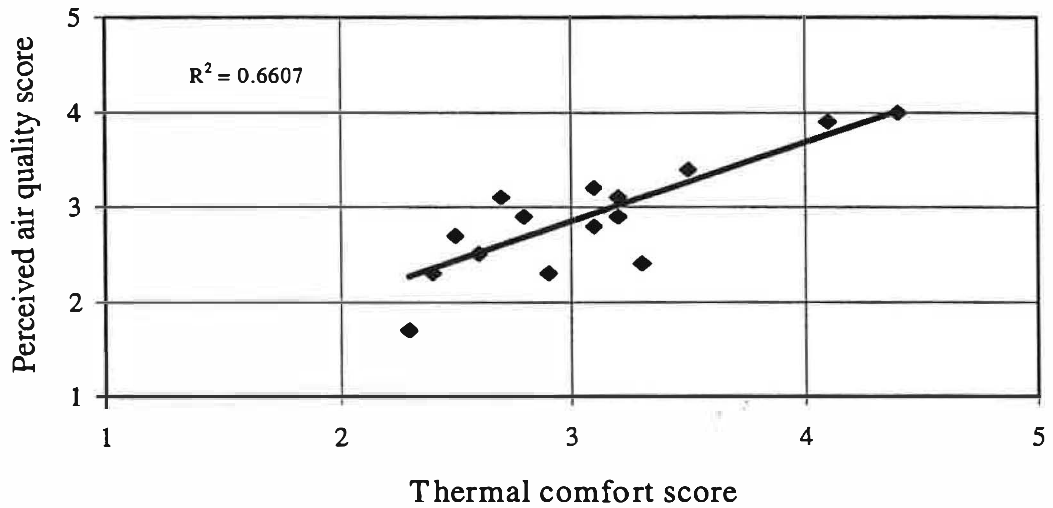

Figure 9. Dependence of scores for perceived air quality on thermal comfort.

The high scores for thermal comfort and air quality in the study group are achieved with a comparatively low outlay of energy. Figure 10 presents month by month metered energy consumption from December 1997 to May 1999, the latest month for which figures are available. Also shown for comparison are month by month estimates of energy that would be expected to be consumed by a conventional variable air volume system providing conditioned air for ventilation to the same group of rooms as produced by the energy simulation programme ESPII (1997). The software model includes three separate VAV air handling units serving south, south-east and north-west zones respectively. It also includes a zero energy band of 2 °C and an outdoor air from their study of the impact of a task/ambient conditioning system with user operated controls for temperature and air movement where large increases in occupant satisfaction for thermal and air quality were noted. Availability of refrigerated cooling is clearly appreciated in the warm and humid summer weather and some of the users also find supplementary heating useful in the comparatively short and mild winters. It seems probable that the effect noted by Bordass, Bromley and Leaman, (1994) where access to control elements improves comfort sensations is also responsible for at least some of the satisfaction reported by participants in this study. Figure 7 also demonstrates the difficulty of maintaining thermal comfort in naturally ventilated buildings in this climate without special measures to control heat gains and losses as exemplified by settings 7, 12 and 13.

The Architecture building is located on City Road, the main traffic route to the South coast of New South Wales and the major regional city of Wollongong. Six lanes carry heavy traffic throughout the day and the atmosphere quite heavily polluted with vehicle exhaust gases yet the highest scores for air quality were recorded for settings 11 and 16 which are housed in it. It seems probable that the improvement in perception of air quality following the installation of the cooling/heating system can be attributed in large measure to the dependence of perception of air quality on thermal comfort as demonstrated in figure 9.

A strong positive relationship ($R^2 = 0.9$) between fancoil units in use on cooling cycle and outdoor temperature has been demonstrated by LOGIT regression as shown in figure 4 although the 95 percent confidence limits suggest the model is not, in its present form, suitable for prediction purposes. The model might be improved by a more accurate separation of units on cooling and heating cycles in the cooler weather which will be possible when instrumentation is complete. This relationship, supported as it is by a system that can operate with reasonable efficiency over a wide range of loads, is, in large part, responsible for the low energy consumption demonstrated in figure 10.

Records are not yet available to provide the means for analysis of acceptable temperature ranges for the people in the study area. However the distribution of indoor temperatures in occupied rooms from the pilot study as illustrated in figure 6 suggests that acceptable conditions are strongly related to mean outdoor effective temperature (MOET*) and are concentrated in a band with a lower limit of 19 to 23°C in the coolest weather to 23 to 27°C in warm weather. The regression equation yields predicted indoor mean temperatures of 21 °C when MOET* is 10 °C and 24.2 °C when MOET* is 20 °C. Although the regression slope is steeper, these results are quite similar to those calculated **for this range of outdoor conditions** from the equation proposed by de Dear et al. (1997) for naturally ventilated premises which predicts 21.5 °C and 24 °C respectively. However at higher outdoor temperatures it would seem that indoor conditions are being prevented from further rise above a mean of about 25 °C by active occupant intervention. Examination of individual records from this pilot study group indicates that there is considerable variation in sensitivity between the participants. Some maintain temperatures quite strictly near 23 °C throughout the seasons. At the other extreme some can adapt successfully to a range from 19 to 27 °C. It is probable that the mean of the range from about 21 to 25 °C would be considered acceptable by a large majority of these people. Availability of individual control of conditions in the personal environment will, of course, improve satisfaction and will help reduce energy consumption because it is not necessary to maintain a narrow range of conditions throughout the space. And, of course, if a room is vacant, energy is not being used to maintain a control setpoint as it would be in more conventional arrangement.

Conclusion

A group of twenty five naturally ventilated rooms in the Architecture building at the University of Sydney is equipped with on demand user-controlled supplementary cooling and heating equipment. Fancoil units installed in the rooms are connected to a modular reverse cycle variable refrigerant flow condensing set so that individuals can choose mechanical intervention among a range of options to change a thermal condition that is considered unsatisfactory. When instrumentation is complete it is intended to study the use of the system in detail by measuring indoor temperatures, and recording occupancy status of rooms and status of cooling and heating equipment and windows and doors over at least twelve months. It should then be possible to determine with reasonable accuracy relationships between outdoor and indoor acceptable thermal conditions in this mixed mode arrangement where occupants have a range of intervention options available to them.

Initial studies have shown a dependence on outdoor thermal conditions of the number of rooms using the supplementary cooling and heating system although it is hoped that more accurate differentiation of use of the system for cooling and heating and records of room occupancy status will improve the predictive power of the tentative LOGIT model illustrated in figure 4. Availability of a larger population will enable confirmation of the range of acceptable indoor conditions as suggested in figure 6 with more confidence.

A clear improvement in occupant perceptions of thermal comfort and air quality is shown in figures 7 and 8 following installation of the supplementary cooling and heating system. Further surveys will test whether this improvement persists over time as expected. Whilst indoor conditions as recorded in figure 2 are likely to be considered comfortable by a majority of occupants for much of the year in the climate of Sydney and similar locations there is no doubt that the ability to apply limits in the hottest and coolest months is appreciated.

In summary, at this stage it can be concluded that:-

- Occupant perceptions of thermal comfort and air quality are much improved since installation of the supplementary cooling and heating equipment.
- The supplementary cooling and heating system under occupant control uses much less energy than would be expected if the same space were provided with a well designed conventional air conditioning system with mechanical ventilation and fixed windows.
- Operation of fancoil units on cooling cycle is strongly related to outdoor conditions with very little use in mild weather.

Acknowledgments

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