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IAQ AND ENERGY-MANAGEMENT BY DEMAND CONTROLLED VENTILATION

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ABSTRACT

As an alternative to conventional ventilation systems which modulate the outdoor dampers with respect to the air temperature, demand controlled ventilation systems allow ventilation air to be controlled based on a measure of indoor air quality. The concentration of carbon dioxide can be used as a surrogate measure of indoor air quality in occupied buildings. The energy savings possible using this technique makes buildings with variable occupancy schedules attractive applications. This paper compares the energy consumption and the indoor environment created by two different types of ventilation control systems in two floors of an office building.

INTRODUCTION

Demand controlled ventilation (DCV) systems are defined as systems where the outdoor air flow rate is controlled by a preset limit of a parameter, usually an airborne pollutant. Earlier work has identified a theoretical relationship between CO_2 concentration and air exchange rate in occupied buildings [1,2]. Other work has shown a relationship between the CO_2 and indoor air quality [3]. According to this work, there is no doubt that CO_2 is the most reliable control contaminant. This is valid when no other large pollution sources, such as smokers, are present. It is an excellent surrogate measure of ventilation rate per person, and hence, the ideal indicator for indoor air quality [4].

Some work has shown that CO_2 control alone can cause thermal comfort problems, especially during the summer [5]. Thermal comfort conditions have been found to affect occupant perceptions of indoor air quality, and elevated concentrations of CO_2 can affect perceptions of thermal comfort. As has been shown in many Danish studies, occupants are not able to clearly qualify indoor air quality when subjected to uncomfortable conditions since they tend to associate indoor air quality with thermal comfort. It has also been shown that occupants report they feel warmer with CO_2 control, although air temperatures were unchanged [6]. At the same time, other work has shown that occupants did not mention any feelings of discomfort with either CO_2 control or constant outdoor air flow [7,8].

Other research work dealt with CO_2 versus temperature control, with the temperature control being dominant [9]. It was shown that the temperature control is dominant when the outdoor temperature is above 10°C. When the temperature dropped, the CO_2 sensor called for more air first.

From an energy savings point of view, the highest savings were noted in rooms where the variation in occupancy is very high and/or unpredictable [4]. When actual measurements were taken, savings in energy consumption reported ranged from 8 to 40% [7,8,10,11]. One project actually reported a 70% reduction in running time, a 90% reduction in energy consumption (the CO_2 control was coupled with a heat recovery system), and a 20% reduction in maintenance [12].

The purpose of this study is to test a carbon dioxide controlled ventilation system in a commercial building as a method of controlling indoor air quality, occupant comfort, and energy consumption, and to compare them with the air quality, thermal comfort, energy demands, and occupant satisfaction resulting from a conventional system. This simultaneous monitoring was performed on two floors of an office building.

TEST FACILITY AND INSTRUMENTATION

The building monitored in this study was primarily chosen for the fact that each floor is serviced by its own independent, yet identical, ventilation system. Furthermore, the occupant density of the building was highly variable. The building envelope is considered to be tight, since the building had been built after the Energy Crisis of the early 1970's. All floors are covered with grey, synthetic carpeting, which is vacuum-cleaned nightly, during weekdays. The only cleansers used by the building maintenance personnel are ordinary, commercial cleaning products.

The two floors chosen for the study are the 8th and 9th. The criteria for their choice was to have two floors identical in occupation density, working hours, ventilation distribution, and workspace layout. The floors are divided into 60 to 80 open-area offices with 4 to 6 feet high partitions. Each floor is occupied by approximately 100 white collar workers, but since the building is open to the public, the number of people varies. The occupation density is approximately 6 people $100m^{-3}$.

The heating, ventilation, and air conditioning system (HVAC) consists of a double duct constant air volume system (CV) with the fresh air intake and exhaust on each floor, on the wall facing west. Each system used outdoor air for economy cooling when the outdoor air temperature was between 13 and 18°C. One hundred diffusers are located throughout each floor to supply the air flow to the various zones. The average air volume supplied per person is 90 $l\ s^{-1}$ $person^{-1}$ of total air. The supply temperature is maintained at 13°C during both the summer and winter.

The conventional system functions as follows: once the mixing temperature rises or descends to a temperature other than the ideal, the outdoor air dampers modulate. In the summer, if the supply temperature is too high, the outdoor air dampers begin to close; if the supply temperature is too low, the outdoor air dampers begin to open. The opposite is true for the winter season: if the supply is too high, the dampers open; if the supply is too low, the dampers close.

The CO_2-based ventilation capability was added to the eighth floor air handling systems. The CO_2-based controller uses a highly sensitive infrared emission-type gas analyzer. The room air is pumped from the occupied zones to the gas analyzer through plastic tubing from the remote sensors located in the occupied space (2 $l\ min^{-1}$). The CO_2-based controller provides outdoor ventilation air to the space when the average space CO_2 concentration exceeds the control set point. The outdoor air dampers are opened to the minimum position when the lower limit set point is exceeded. As the CO_2 levels increase, the opening of the outdoor air dampers also increase, up to the maximum opening possible when the CO_2 levels reach the upper limit set point.

Both mechanical systems are in operation 24 hours a day, 7 days a week. To reduce the heating load, the floors are flushed with outdoor air at 11:00 P.M., nightly, if necessary.

The tracer gas decay technique was used to measure air change rates. Air samples were taken at 5 locations per floor. A direct reading instrument was used to measure CO_2 every hour from 7:00 to 19:00 for three consecutive working days each month at ten sampling stations. Formaldehyde and VOCs were measured at three sampling stations in the occupied zones for a duration of three consecutive days each month. Formaldehyde was collected on orbo adsorbent tubes, impregnated with N-benzylethanolamine, while VOCs were collected on activated charcoal tubes. The dust was collected for a period of three 10 hour working days each month. Personal air pumps at about 1.5 $l\ min^{-1}$ air flow rates with pre-weighed filters were used to collect total dust.

Operative temperatures and relative humidity were monitored at nine locations per floor and the total energy consumption was monitored for each floor.

Questionnaires were used to measure the subjective response of the occupants to their environment. No behavioural questions were asked. The questionnaires were distributed throughout the two floors, to all the occupants of the open-area offices, every third Wednesday morning of every month and were collected that same afternoon.

RESULTS

Prior to the study, a walk-through survey was conducted during which monitoring sites were identified on the two floors pre-selected for the study. A ten-week intensive study followed to determine the building's dynamic response to various outdoor air levels. It was found that the parameters monitored were uniform throughout the zone, both horizontally and vertically [13]. Therefore, the sampling was limited to desk-top level, and geographic locations. It was also found that all parameters monitored were identical on both floors.

The results of the tracer gas decay method are shown in Figure 1. The air change rates found during the summer months are much lower than those found throughout the remainder of the year. This is due to the fact that the outdoor air dampers were closed during these warm months. The 8th (CO_2-controlled) floor dampers also remained closed during the spring and fall seasons, whereas the 9th floor dampers opened to allow for free-cooling. However, both floors had opened dampers during the winter-time due to excessive heat gains in the occupied spaces.

The measurements indicated that the CO_2 levels remained well below the recommended limit of 1000 ppm set by ASHRAE. Throughout the course of the study the maximum CO_2 concentration attained was below 900 ppm.

The level of formaldehyde in the occupied zones was also found to be below the limits set by ASHRAE, the maximum approximately 63% below the accepted value. The results found during the summer months seem to be higher than those found throughout the remainder of the year, Figure 2. This is most probably due to the fact that the outdoor air dampers were closed during these warm months.

The individual VOC levels were all found to be under the ASHRAE limits (maximum stoddard solvent approximately less than 43% of the limit set by ASHRAE). The results indicated that the VOC concentration were also higher in summer than the remainder of the year, Figure 3. These results show that indoor air VOCs and formaldehyde tend to increase very quickly as ventilation decreases below a rate within the range of 0.6 to 1.2 ach. In this study the highest VOCs were observed when the air change rates were below 0.9 ach.

Similarly the total dust level during the course of the study was found to be below the limit set by ASHRAE, expect for one case (one work station) where the level exceeded the recommended value by 8%. The two sampling stations that were set up outside showed relatively elevated dust levels; indicating that the dust originates in the outdoor air.

The thermal comfort parameters studied are dry-bulb and operative temperatures, relative humidity, vertical temperature gradients, air velocities, and global thermal comfort indices. These were measured for three working days, every third week of every month. The 8th floor

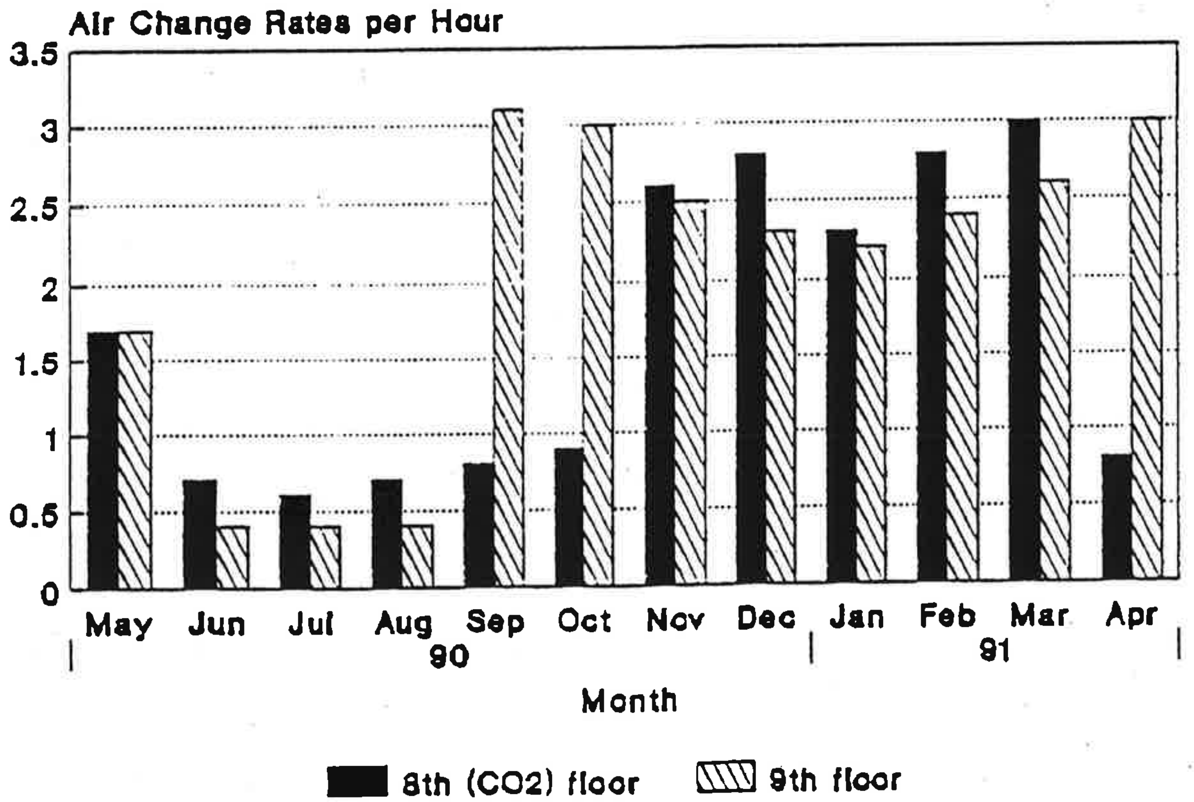

Figure 1. Monthly air change rates.

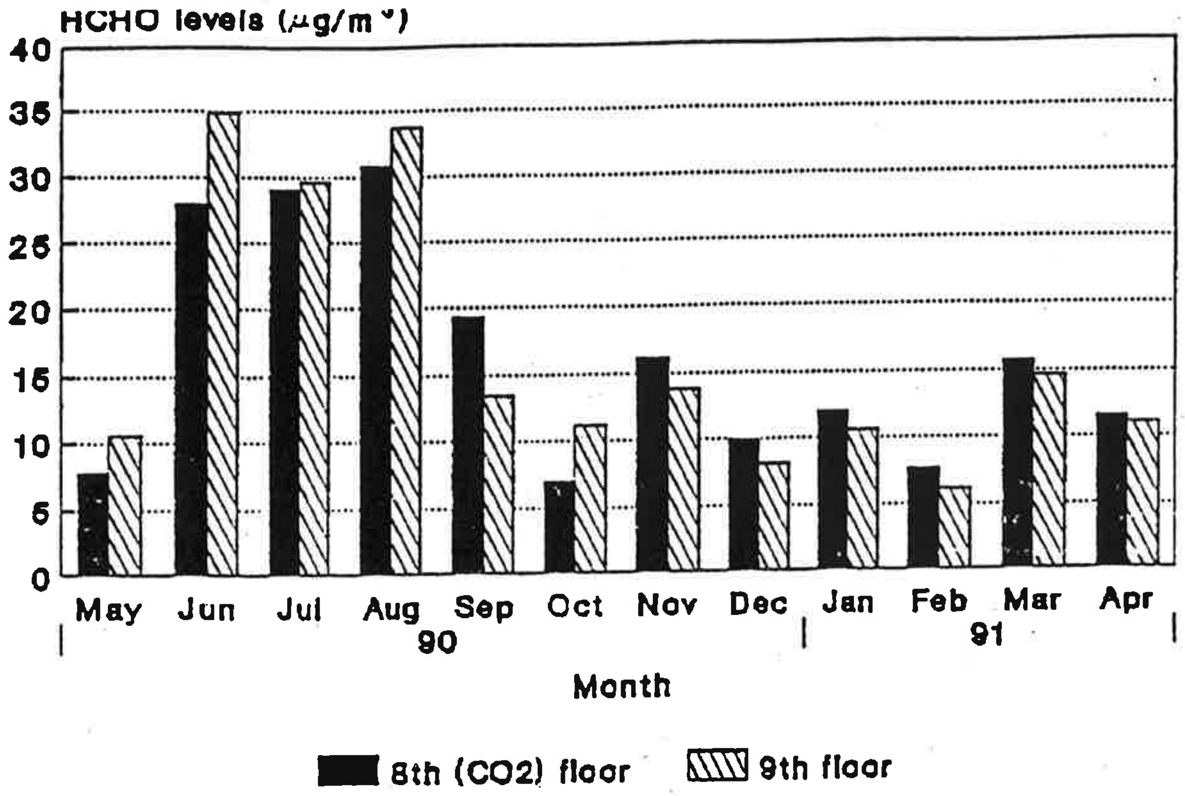

Figure 2. Monthly formaldehyde results.

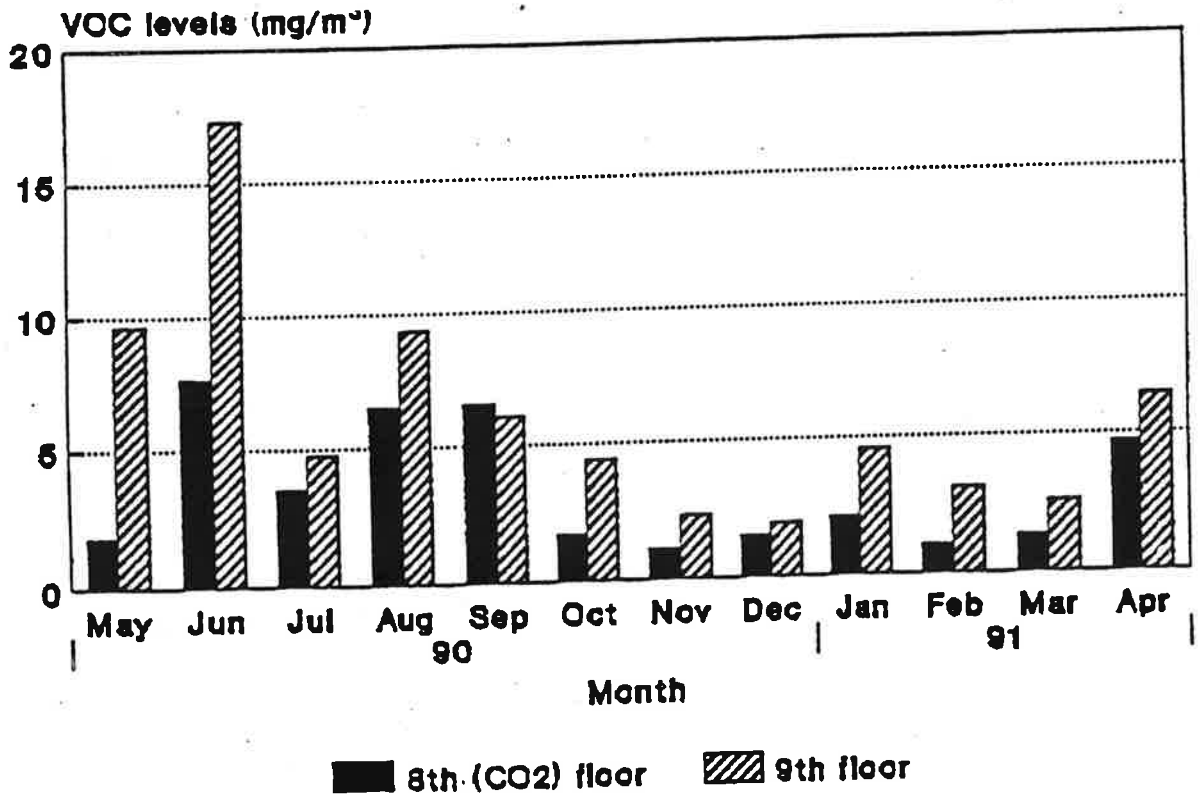

Figure 3. Monthly VOC results.

(CO_2-controlled) and the 9th floor were monitored simultaneously. To compare the results with the ASHRAE standard, the data is plotted on the ASHRAE comfort chart. To be able to compare the results, it was assumed that the occupants were clothed in typical seasonal clothing, and that their work was mainly sedentary. The results indicated that these parameters did not always remain within the ASHRAE comfort limits. The readings taken in the spring, summer, and fall were almost all within the limits. The readings taken in the winter were mostly below the comfort limits with very low relative humidity and uncomfortable conditions, Figures 4 and 5. This is due to the fact that heating the outside air removes more moisture than the humidifier can supply to the air. Vertical temperature gradients were measured at 0.1 and 1.7 m from the floor. They were always below the maximum of 3°C as recommended by ASHRAE, expect for 4 occasions out of 48 (due to broken compressors).

Global thermal comfort indices, the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD), were also measured directly, for 20 minutes per stations, over a period of 3 working days, once a month. The data is plotted on the PMV and PPD chart to facilitate the comparison with the recommended limit. The comfort indices seemed to indicate dissatisfaction levels ranging from 5 to 78% (from slightly warm to cool sensations), surpassing the maximum of 20% dissatisfaction as recommended by ASHRAE 33% of the time, divided more or less evenly throughout the whole year, Figures 6 and 7.

The energy demand for the floor that had the CO_2-based controller was lower than for the floor with the conventional control system, Figure 9. The greatest energy saving occurred during the month of October, when little outdoor air was supplied on the CO_2-controlled floor, indicating that the supply air temperature and the CO_2 levels were adequate. The 9th floor admitted almost always 100% outdoor air to take advantage of free cooling. One would expect that the free-cooling

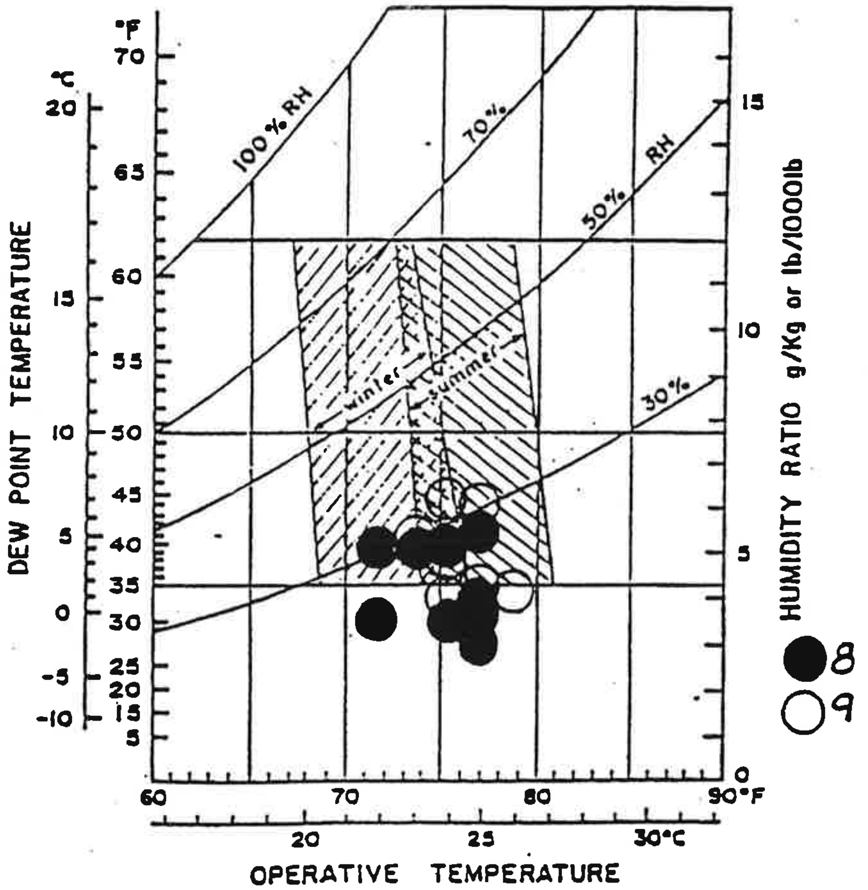

Figure 4. Comparison with ASHRAE thermal comfort chart (December 1990).

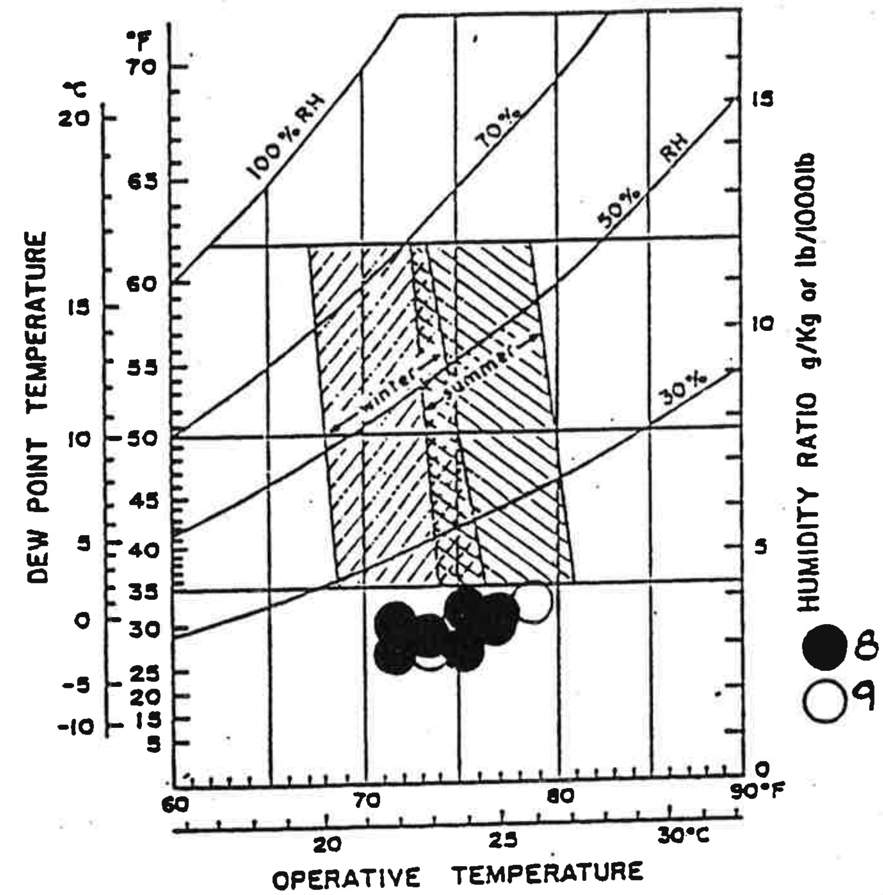

Figure 5. Comparison with ASHRAE thermal comfort chart (January 1991).

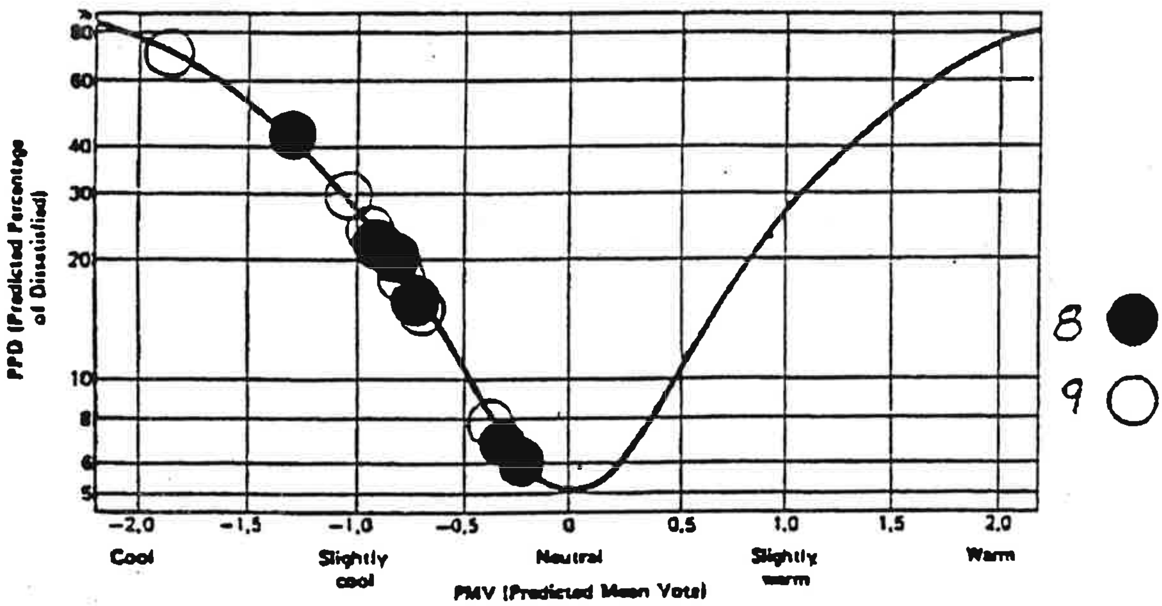

Figure 6. Comparison with PPD and PMV chart (May 1990).

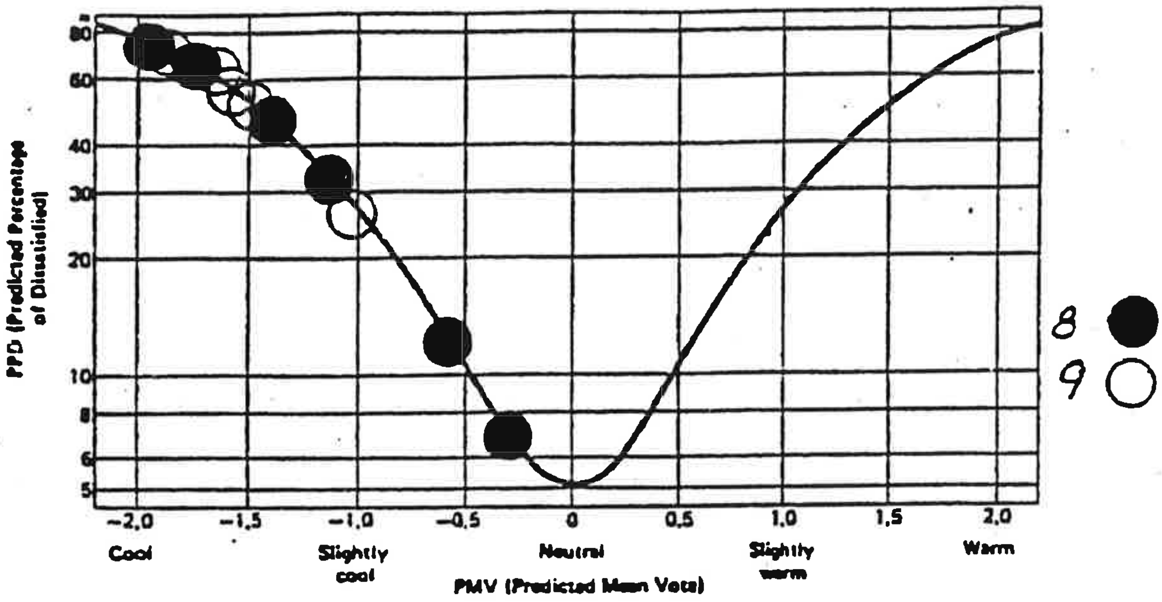

Figure 7. Comparison with PPD and PMV chart (June 1990).

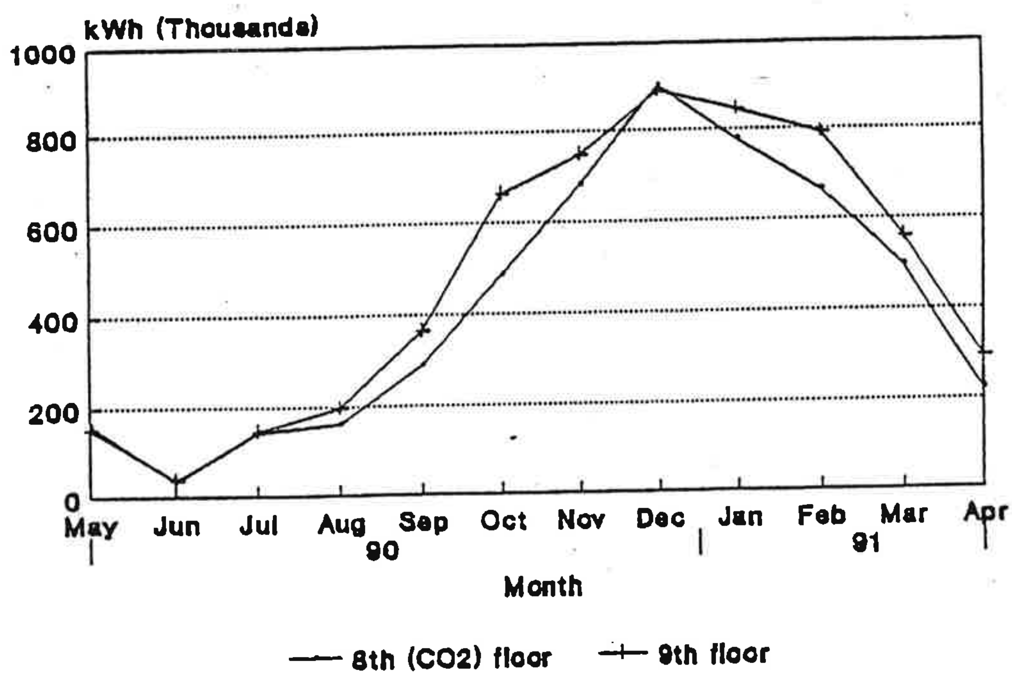

Figure 8. Monthly difference in energy consumption.

period would consume much less energy; but the opposite is true in this building.

The subjective response of the occupants to the environment was measured with a questionnaire. The questionnaire was distributed throughout the two floors. The average response rates for the 8th and 9th floors are 60% and 56%, respectively, which is an adequate number. The results of the questionnaires showed that most of the time the occupants felt that the temperature was comfortable except for a few cases where the occupants felt cool. The air was considered to be slightly dry to dry all of the time for the majority of the occupants. The ventilation was considered to be adequate on the 8th floor at all times, expect for a few cases where it was found to be drafty. The ventilation was never considered adequate by the majority of the occupants on the 9th floor. The air quality on both floors was considered satisfactory for less than half of the time by the majority of occupants of these floors; the majority of the occupants found that their physical environment had a direct impact on their productivity. Overall, less than 80% expressed satisfaction with the indoor air quality, and also less than 80% found the environment thermally acceptable for the entire testing period, Figure 9. Comparing the answers from both floors, one cannot say that one floor is more uncomfortable than the other.

CONCLUSION

The primary goals of demand-controlled ventilation systems are to guarantee an equivalent or better indoor air quality and thermal comfort, and to save energy. This study was undertaken to show that a supply air temperature and carbon dioxide sensor that measures the occupant generated carbon dioxide could be used to control the use of outdoor air in a more efficient manner. This study was designed to measure indoor air contaminant levels, thermal comfort levels, subjective occupant response, and energy consumption for heating and cooling.

The study verified that the energy consumption lessened with the CO_2-controlled ventilation system as compared to the conventional ventilation system. It was also observed that this did not worsen the quality of indoor air and thermal comfort, and the occupants did not perceive a deterioration in their working environment.

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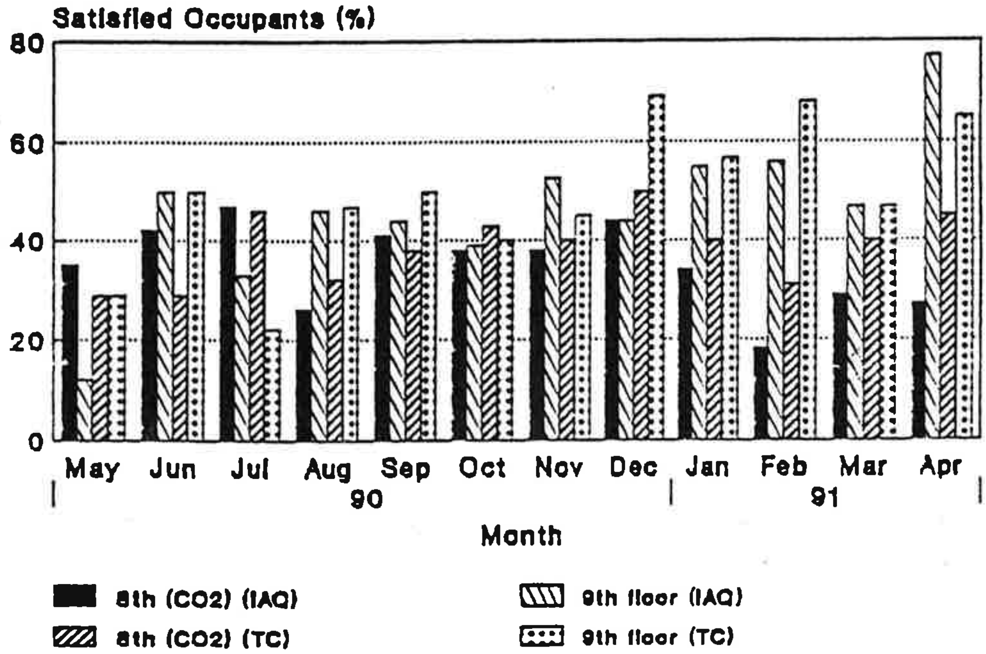

Figure 9. Monthly satisfied occupants.

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