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VENTILATION CONTROL OF INDOOR AIR QUALITY, THERMAL COMFORT, AND ENERGY CONSERVATION BY CO_2 MEASUREMENT

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SYNOPSIS

The use of indoor carbon dioxide levels is a good method for controlling indoor air quality in office buildings. The measured CO_2 is used to determine the amount of outdoor air needed to purge air contaminants and to obtain the desired CO_2 indoors. Two floors of a commercial building in Montreal were used in the study. Since both floors were identical in architectural layout, type of work being done, and in population density, and since they had identical yet separate ventilation systems, one floor was used as a control, and the other was modified to include a CO_2 and temperature control system. The strategy complies with the requirements of the ventilation, indoor air quality, and thermal comfort standards. The discomfort that did exist was due to HVAC system repairs. It also performs the ventilation service in an energy effective manner, with an annual saving of 12%, and a payback period of 0,4 years. However, the occupants' perception of their working environment does not reflect the measured results. They perceived that their productivity is proportional to their perception of the indoor environment. The DCV floor occupants complained significantly more of their indoor environment than the occupants of the other floor.

1. INTRODUCTION

The following study compares the indoor environment created by two different types of ventilation control systems in an eleven-storey office building, located along the St. Lawrence river, in Montreal. Experiments were conducted during an entire year. The two systems were electrically operated: a conventional system was controlled by outdoor temperatures, and a demand-controlled system used carbon dioxide and supply temperature as an indicator (see Figure 1). The main objective was to compare the air quality, thermal comfort, energy demands, and occupant satisfaction resulting from the two different controls, in two separate floors of an office building, and to rate these results according to their respective criteria, since operation of a ventilating system should always keep all of the contaminants and thermal comfort parameters within acceptable limits. Considerable research has gone into DCV systems over the past 10 years. Up until 1983, most papers on DCV systems stressed energy savings and pay-back times, but it is indoor air quality that is being emphasized in more recent works [1]. This studies emphasizes the impact on the indoor environment.

2. METHOD

Actual test data was obtained over four seasons--spring, summer, fall, and winter. Each scheduled test period consisted of one week per month, for 12 consecutive months. This plan was set up to evaluate system performance under different weather conditions. The testing was performed simultaneously on two floors of an office building--one floor operating under the normal mode, and the other floor operating under the carbon dioxide control mode. These two types of control were in operation throughout the total testing year (including the time between the scheduled test periods).

A set of relays was installed to enable the 8^{th} floor system to be operated in a "CO_2 mode"; while the 9^{th} floor system operated under the "normal mode". Under the CO_2 control the CO_2 state kept the outdoor air damper closed until the CO_2 level in the space reached the lower control point (600 ppm). The outdoor air dampers would open to a minimum when the CO_2 did reach 600 ppm. As the CO_2 increased further, so did the opening of the dampers, up to a maximum opening when the CO_2 reached the upper limit of 1000 ppm. The lower limit of 600 ppm was chosen due to the recent findings that headaches start at this point [2]. The upper limit of 1000 ppm was chosen since it is the ASHRAE recommendation [3]. The code-specified amount of outdoor air was provided under the normal mode (i.e. based on temperature demand). An indoor temperature control was installed to override the CO_2-control system, to certify that the indoor temperature would not exceed the comfort limits [4].

The following parameters were measured for one week per month, for 12 consecutive months: indoor air quality parameters (carbon dioxide, formaldehyde, volatile organic compounds, particles and ventilation performance); thermal comfort parameters (dry-bulb and operative temperature, relative humidity, vertical temperature gradients, air velocity, and thermal comfort PMV and PPD); and occupant perception. The energy demand was monitored continuously throughout the 12 months, i.e. 365 days. The sampling stations are shown in Figure 2 (both floors' stations are directly one above the other).

To verify if there was any significant difference between the variables, the confidence interval of $\mu_D = \mu_1 - \mu_2$ for paired observations was used. If d^- and s_d are the mean and standard deviation of the normally distributed differences of n random pairs of measurements, a $(1 - \alpha)100\%$ confidence interval for $\mu_D = \mu_1 - \mu_2$ is

$$d^- - t_{\alpha/2}\frac{s_d}{\sqrt{n}} < \mu_D < d^- + t_{\alpha/2}\frac{s_d}{\sqrt{n}},$$

where $t_{\alpha/2}$ is the t value with $v = n - 1$ degrees of freedom, leaving an area of $\alpha/2$ to the right [5].

2.1 Indoor Air Quality Parameters

Ten CO_2 sampling stations were chosen as per Figure 2. A direct reading instrument (ADC, range 0-5000 ppm, infrared gas analyzer) was used to measure CO_2 hourly from 7:00 to 19:00, for three consecutive working days each month. The IRSST method #34-A was followed [6].

Three formaldehyde sampling stations were chosen as per Figure 2 (stations 1, 5, and 7). A sampling duration of three working days was used each month. The IRSST method # 216-1 was followed [6]. The formaldehyde was collected on orbo adsorbent tubes, impregnated with N-benzylethanolamine. These were attached to personal air pumps sampling at a frequency of 0,5 l/min. The tubes were then analyzed by gas chromatography.

Three VOC sampling stations were chosen as per Figure 2 (stations 1, 5, and 7). A sampling duration of three working days was used each month. The IRSST methods # 80-1, 16-1, and 101-1 for stoddard solvent, toluene, and xylenes (o,m,p), respectively, were used [6]. The VOC's were collected on activated charcoal tubes attached to personal air pumps sampling at a frequency of 0,2 l/min. These were then analyzed by gas chromatography.

Three dust sampling stations were chosen as per Figure 2 (stations 1, 5, and 7). The dust was sampled for a period of 3, 10-hour working days each month. The IRSST method # 48-1 was followed [6]. Personal air pumps at about 1,5 l/min air flow rates with pre-weighed filters were used to collect total dust. The filters were then weighed in a laboratory.

The decay tracer gas technique was used to measure air change rates during our monthly testing periods. The 9^{th} floor was tested on the first of three days, while the 8^{th} was tested on the third; to avoid the interzonal air movement problem from the 8^{th} up to the 9^{th} floor (due to the pressure differential). Approximately 4 liters of SF_6 was injected at the outdoor air dampers of the floor under study. A mixing period of about 30 minutes was allotted. Air samples were then taken at 5 locations throughout the floor (stations 1, 3, 5, 7, and 9, from Figure 2), in 9 continuous sequences, so as to average a time period of about 8 minutes between sequences (a total of about 80 minutes of sampling). These air samples were then sent to a laboratory for the SF_6 concentration. This method of calculating the rate of indoor-outdoor air exchange does not differentiate between the mechanisms of exchange (mechanical or infiltration) but includes both.

Analysis of the system performance was centred around evaluating the ability of the CO_2-based ventilation system to control the CO_2 concentration in the occupied spaces of the test site building.

2.2 Thermal Comfort

Operative temperature readings were taken at 9 locations per floor (see stations 1 to 6, and 8 to 10, in Figure 2), for 20 minutes per station, over a period of 3 working days, once a month. These were coupled with relative humidity and dry bulb temperature readings taken with a psychrometer.

A Thermal Comfort Meter was used to measure thermal comfort levels. Nine sampling stations per floor were chosen as in Figure 2 (stations 1 to 6, and 8 to 10), for 20 minutes per station, over a period of 3 working days, once a month.

2.3 Occupant Perception

The subjective response of the occupants to the environment was measured with a questionnaire. No behavioral questions were asked.

The questionnaire was distributed throughout the two floors, to all occupants in the open-area offices, every 3rd Wednesday morning of every month. These were then collected that same afternoon.

2.4 Energy Demand

Separate electric power meters were installed in all four ventilation systems; to measure all power used for heating and cooling.

Four XT-103 Electrical Current Stick-On Loggers were used. Each one has a range of 0 to 250 Amps (AC). The two loggers for each floor were added so as to arrive at a total energy consumption for each floor.

3. RESULTS

The system generally performed as expected. Under the CO_2 control mode, the outdoor air dampers remained closed for most of the year. The system is normally operated with the outdoor air dampers opened in cold weather because of the overheating inside (due to the poorly designed HVAC system location). There were never enough people at one time or for long enough to raise the CO_2 level to the control point. Operation of the overriding temperature control kept the building well ventilated (thermally). It was clear that the normal mode of control produced excess ventilation.

The ASHRAE ventilation standard offers two methods for controlling indoor air quality [3]. The first is to prescribe various amounts of outdoor air per person for different settings. The second allows the building operation personnel to reduce the outdoor air intake as long as there are no known contaminants at harmful concentrations. This project indeed showed that a CO_2 and temperature control was able to limit the amount of outdoor air and still keep all of the contaminants below the recommended maximum limits. Even though the contaminant levels were similar on both floors, the control system was able to save a significant amount of energy.

This control system had no real effect on indoor air quality and thermal comfort (similar levels are found on both floors), but it had a great effect on energy consumption. The main reason is probably the low occupant density.

The air quality, as expected, was generally good. No significant contaminant concentrations were found. Carbon dioxide, formaldehyde, and VOC levels were all well below the recommended limits. Total dust levels exceeded the ASHRAE recommended maximum for three months of the year, on the CO_2-controlled floor.

The thermal comfort was generally adequate on both floors. Dry-bulb temperatures and air velocities satisfied the recommended levels. Discomfort would be felt during the winter months when very low relative humidities were recorded [7]. Very warm operative temperatures were also recorded during the summer months. Vertical temperature gradients exceeded the recommended level due to very warm air temperatures at the neck level. However, this discomfort was almost always due to some HVAC mechanical repair being done at that time. The Predicted Percentage of Dissatisfied was above the recommended maximum more than one third of the time due to a slightly cool to cool environment.

The occupants' responses did not correspond to the measurements taken objectively [8]. This may put in evidence the inadequacy of the "state-of-the-art" measuring equipment to read much lower levels. Also, it may indicate that the occupants are much more sensitive to irritants than the general population. The occupants perceived that their productivity is proportional to their perception of the indoor environment; indicating that higher productivity rates can be achieved by better controlling the working environment above satisfactory levels (see Figure 3). Finally, more than 20% of the occupants were unsatisfied with their working environment (indoor air quality and thermal comfort) all of the time (see Figure 4). The 8^{th} floor occupants complained much more of both indoor air quality and thermal comfort, however, the same significant differences could not be found in the measured data, indicating that other "global" factors may be influencing their environmental satisfaction [8].

A significant annual difference in energy consumption was found between both floors (see Figure 5). An energy savings of 12% was found by using the temperature and CO_2-control system. The payback period was calculated using a pre-determined cost schedule, and was found to be 0,4 years.

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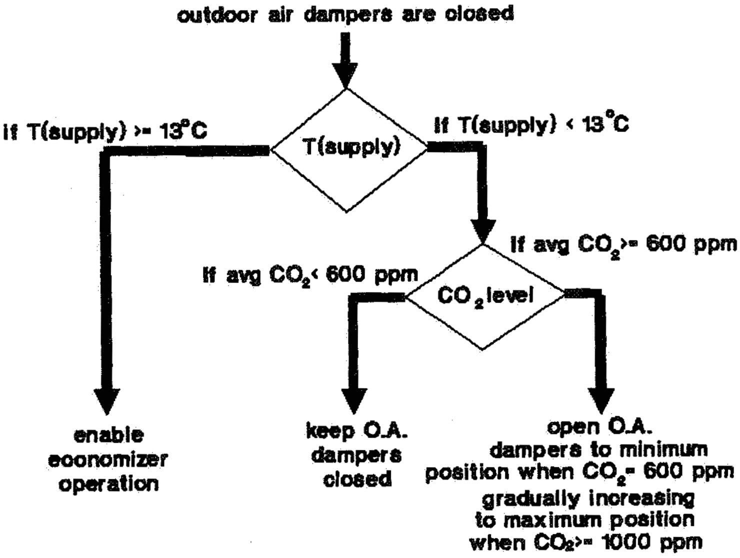

Figure 1. DCV system strategy

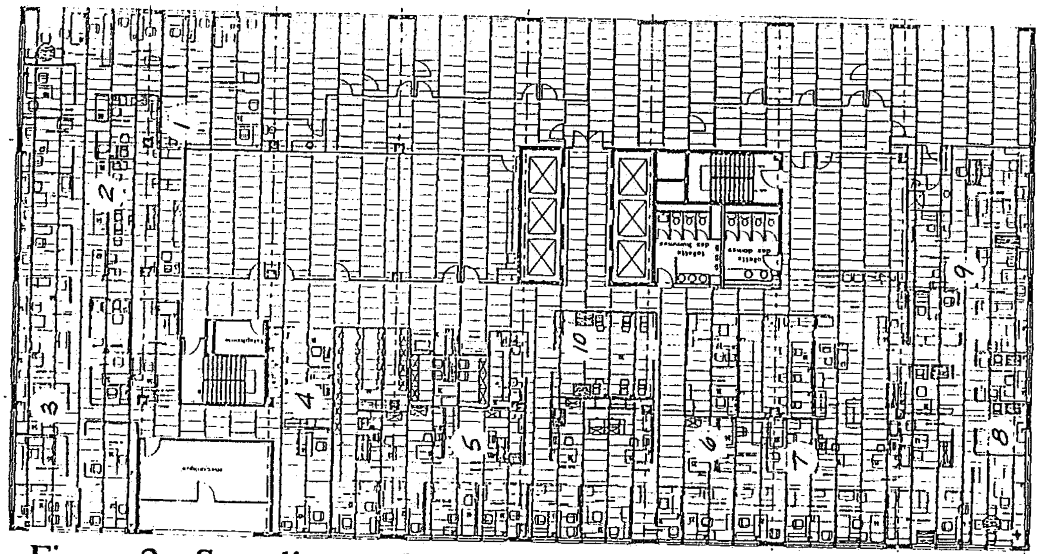

Figure 2. Sampling stations (one floor)

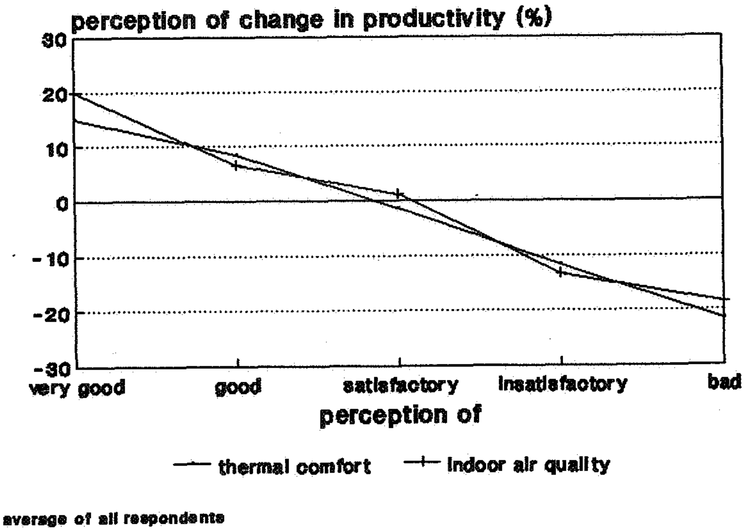

Figure 3. Occupant perception of productivity

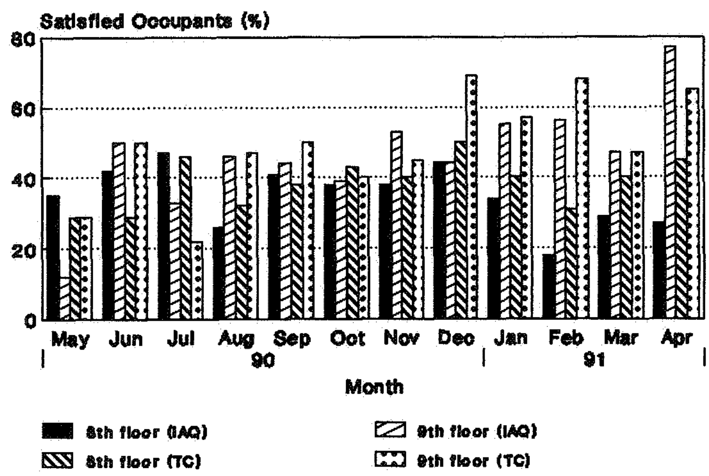

Figure 4. Percentage of satisfied occupants

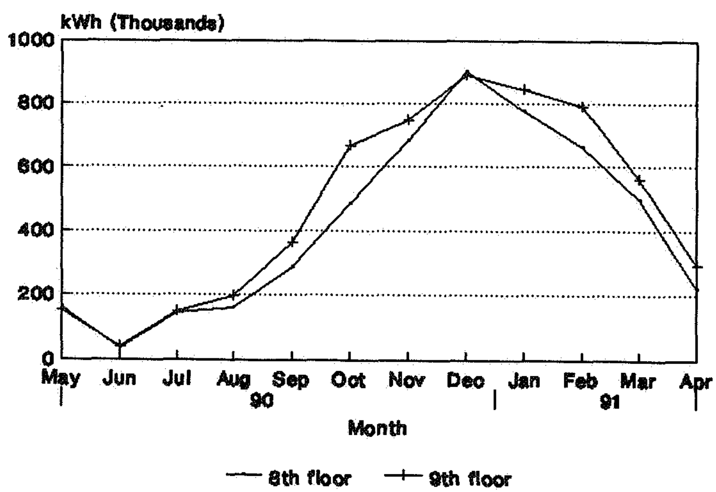

Figure 5. Difference in energy demand