6024

International Symposium on Room Air Convection and Ventilation Effectiveness
University of Tokyo, July 22 – 24, 1992

COMPARISON OF DILUTION AND DISPLACEMENT VENTILATION FOR THERMAL AND CONTAMINANT CONTROL IN A SIMULATED OFFICE ENVIRONMENT

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ABSTRACT

The performance of a full scale, well designed displacement ventilation system, versus a typical dilution system, was evaluated for a simulated Canadian office environment. The operating parameters which optimize the efficiency of the displacement ventilation system were also investigated. Eleven experimental runs were conducted in a 12.4 m^3 plexiglass chamber, measuring the vertical temperature profile across the chamber. Carbon dioxide was continuously injected into the chamber to monitor the performance of the ventilation system for air quality in the breathing zone.

The dilution and displacement experimental runs were subjected to low and high heat loads of 34 and 67 W/m^2 respectively and to varying supply air flow rates of 31 to 36 L/s.

The results indicate that displacement ventilation has a well defined temperature gradient across the vertical height of the chamber and maintains an overall lower temperature in the occupied zone, than does dilution ventilation. This suggests an energy savings for the operation of the displacement system in cooling applications. The displacement system also maintained 33% less carbon dioxide at the breathing zone, than the dilution ventilation system.

KEY WORDS Displacement ventilation; dilution ventilation; Zfront; energy

INTRODUCTION

A common practice in buildings is to use dilution ventilation for thermal and contaminant control. Air is supplied to the room through one or more supply vents near the ceiling, at a relatively high velocity and exhausted from vents near the floor. As air in the room becomes entrained, a nearly uniform distribution of temperature and contaminant results. If sufficient make up air is used, the system will provide acceptable air quality in the workplace. Dilution systems have disadvantages such as stagnation zones with low velocities, air contaminant accumulation and high cooling requirements in order to achieve overall moderate temperatures.

Researchers in Scandinavian countries have developed an alternative form of occupied space ventilation called displacement ventilation. Displacement ventilation systems supply air to the room at a low velocity and turbulence, through openings close to the floor, at a temperature lower than the room air temperature. The result is that the supply air 'floats' throughout the room and fills it from below. This cooler, denser air rises due to heating by sources in the room (people, machines, heating panels). Thus contaminants, chemical or heat, are transported by convection toward the ceiling, away from the occupied breathing zone. By controlling the supply air flow rate, the stratification layer, or Zfront, which separates the occupied zone from the contaminated zone can be positioned. An exhaust opening located in the ceiling, removes the upper heated and contaminated air layer. The major advantage of displacement ventilation is that it controls the environment in the occupied zone of the room, not the whole space as in conventional systems.

The objective of this study was to examine displacement ventilation for practical and economic application in Canadian office environments. An insight into a variety of different parameters affecting the performance of a displacement system was to be determined. As well, this experiment was performed on a room scale model where as many other studies were done on small scale models which require extrapolation to an office environment.

EXPERIMENTAL DESIGN

A 2.44m x 2.44m x 2.08m (12.4 m^3) plexiglass chamber was used to simulate a typical Canadian office environment. The existing dilution ventilation system was retrofitted with galvanized sheet steel ductwork, to operate under the principle of displacement ventilation. The duct extensions provided supply air, 0.5m above the floor (recommended by Svensson 1989) at a velocity of 0.1 m/s (32 - 36 L/s). Similarly the return duct was located near the ceiling on the opposite wall, sized for a removal rate of approximately 31 L/s. These ventilation rates positioned the Zfront at a height of 1.1m above the floor, for the experimental runs. Carbon dioxide was continuously injected and evenly distributed into the supply air for the duration of the sampling run. Heat loads of 34 W/m^2 and 67 W/m^2 were investigated for both dilution and displacement runs. Two hundred and four hundred watts of energy distributed over 5.9m^2 floor area, delivered the expected office heat loads. As well the supply air flowrate was investigated for 32 and 36 L/s delivery (see Grebenc 1991, for further design details).

Thermocouples constructed from copper and constantan , insulated with fibreglass, were used to monitor the room temperature at different positions. The concentration of carbon dioxide gas was monitored by a CO_2 infrared gas analyzer. All temperature and contaminant measurements were electronically read by a data acquisition unit and logged directly to a computer.

For each dilution and displacement ventilation run, three thermocouples were placed along the vertical, center axis of the chamber at heights of 0.1m, 1.1m and 1.7m. As well thermocouples placed at the opening to the supply and return ducts were used to monitor the incoming and outgoing air temperatures. The concentration of carbon dioxide at a height of 1.1m in the chamber was recorded for each experimental run. Preliminary studies on the chamber concluded that steady state conditions were reached for the chamber, after 65 minutes of operation.

RESULTS

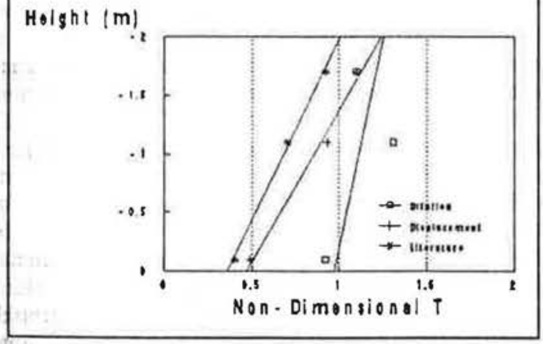
The air supplied to the chamber fluctuated sinusoidally because the chamber supply air source had thermostatic control. The supply air dependency for each run was thus minimized in order to compare temperatures at selected positions in the chamber. A non-dimensional temperature (Sandberg and Blomqvist 1989) was modified, taking the absolute value of the relationship as follows and then applied to the experimental data;

$$ND = | (T-T_s)/(T_e-T_s) | \qquad (1)$$

where ND= non-dimensional temperature
T = temperature in chamber
T_s= air supply temperature
T_e= air exit temperature

For the low heat load (33.6 W/m^2), Figure 1 illustrates the dilution and displacement temperature profiles across the chamber at the 65 minute equilibrium point.

Figure 1: Non-Dimensional T Profile Comparison



The slopes of the best fit lines for these graphs are in a ratio of 1 to 1.5 for the displacement and dilution systems respectively. Dilution has a more vertical temperature profile across the chamber, indicative of uniform temperature distribution throughout. Displacement achieves a prominent temperature gradient which consequently delivers a lower temperature to the occupied zone of the chamber, than did the dilution system. Results from a similar displacement ventilation test (Sandberg and Blomqvist 1989), are also compared in Figure 1. The displacement runs exhibit similar slopes, which provide a lower temperature in the occupied zone than the comparable dilution run.

The dilution and displacement ventilation systems are compared in Figure 2, based on their ability to maintain constant temperatures in the occupied zone with respect to time.

Figure 2: Temperature Variance with Time, at 1.1m height

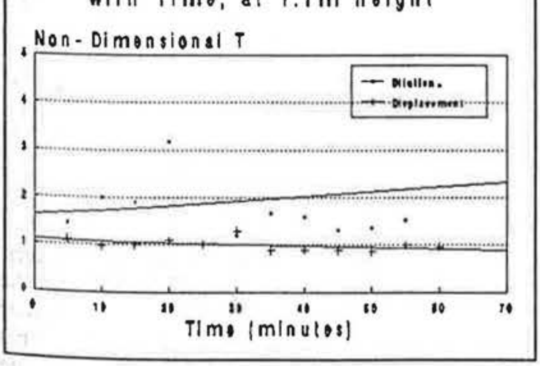
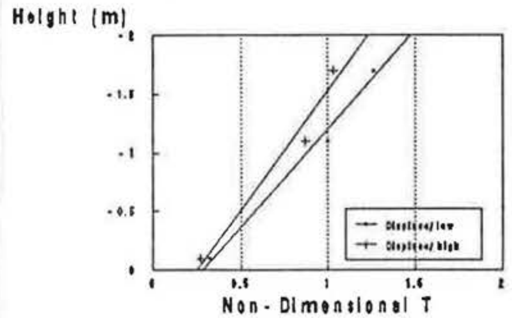


Figure 2 shows that the non-dimensional temperature measured at the occupied height of 1.1 m, increases over the course of the experimental for a dilution design, but remains very constant for a displacement system. This is important for thermal control and comfort over the working day. It is desirable to have the temperature remain the same and not increase as the day progresses, as delivered by the displacement system.

Figure 3 illustrates the vertical, non-dimensional temperature profiles for the two displacement runs at the low and high heat loads. The slopes of the best fit lines are in a ratio of 1 to 1.2 for the low and high loads respectively. This indicates that displacement ventilation can maintain a similar occupied zone temperature over a range of expected heat loads.

Figure 3: Non-Dimensional T Profile, High and Low Load



The following calculation is a prediction of the percent of employees who will feel discomfort due to a cool draft, for the ventilation operating parameters (Melikov and Nielsen 1989);

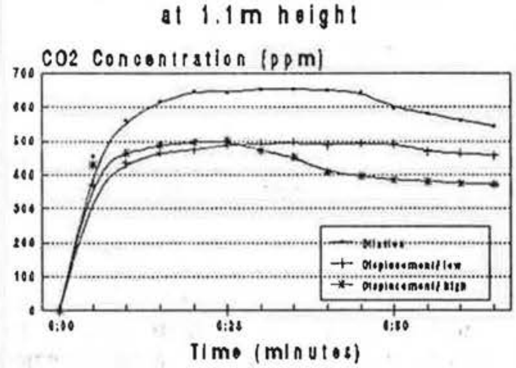
$$PD= (34-T_a)(V-0.05)^{.62}(3.14+.37VT_u) \quad (2)$$

where PD= percent dissatisfied
T_a= air temperature
V = mean air velocity
T_u=Turbulence intensity

For the experimental runs performed, the personnel expected to feel discomfort due to draft is calculated to be less than 10% for the displacement system compared to greater than 50% for the dilution ventilation system.

The displacement ventilation's ability to more effectively control the level of contaminants in the occupied zone is illustrated by Figure 4.

Figure 4: CO2 Concentration at 1.1m height



For the experimental runs, displacement ventilation maintained 33% less carbon dioxide in the breathing zone. As well this graph illustrates that the displacement ventilation system maintained similar air quality in the breathing zone (1.1m), for the varied supply air flow rate. Thus the displacement ventilation system was operating as expected by theory and was keeping the contaminants above the positioned Zfront and breathing zone.

DISCUSSION

Thermal Control

The dilution and displacement ventilation runs were operated under similar parameters. The displacement system was able to maintain lower temperatures in the occupied zone, with the same temperature supply air. This means that displacement ventilation can utilize slightly warmer supply air and achieve the same temperature in the occupied zone. Reducing cooling requirements for the supply air may significantly reduce energy requirements during the cooling season. The displacement ventilation design, provided a consistent temperature through the duration of the experimental run which suggests that the temperature should not increase in the occupied zone over the course of the day. This will provide better thermal comfort for the occupants and should not require additional cooling of the supply air in order to maintain a constant daily temperature. As well the displacement system maintained a vertical temperature gradient of less than 2.5° C between the ankles and head, which complies with the ASHRAE standard (1988). This means that workers will not feel a significant temperature difference over their body, which contributes to improved thermal comfort.

Percent Dissatisfied

The local discomfort due to draft should not exceed 15% of office personnel (Melikov and Nielsen 1989). Since the experimental displacement system predicts that 10% of personnel will be dissatisfied due to draft, this system should be considered as providing good thermal comfort.

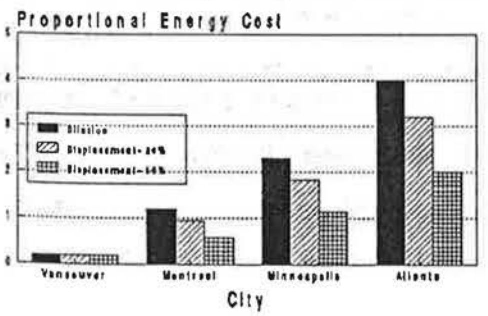
Contaminant Control

High CO_2 levels in the breathing zone are undesirable, as CO_2 build up suggests poor control of air in the room. Excess contaminants contribute to stale air, headaches, fatigue, ill feelings and subsequent lack of productivity. The displacement ventilation design was better able to control the level of CO_2 in the occupied space which would be less likely to compromise the productivity of office workers over the duration of the day.

Cost Analysis

Energy costs were obtained for office buildings in selected North American cities, based on current electricity and natural gas tariffs (Eto and Meyer 1988). Canadian offices in Vancouver and Montreal had lower operating costs than offices in the southern United States, due to obvious climatic differences. It is evident that cooling costs are more expensive than heating costs on an annual basis. As Vancouver is a Canadian city with a very moderate climate and virtually no cooling degree days, this city's energy costs must be due to heating requirements. It is assumed that a linear relationship exists between heating days and energy costs, since the thermal conductivity and specific heat capacity of air, are linear over the temperature range experienced in an office. From this, the annual dilution ventilation costs, due to cooling requirements can be estimated as shown in Figure 5.

Figure 5: Relative Cooling Costs Dilution and Displacement Ventilation



Previous research has estimated displacement ventilation can achieve from 20% (Kvisgaard 1990) to 50% (Davidson 1989) reduction in cooling energy cost. Figure 5 compares the relative cooling cost savings that may be expected when using a displacement ventilation system. The more cooling that is required, the greater the economical advantage of displacement ventilation. Thus the implementation of displacement ventilation for Canadian businesses will result in equal or greater energy savings than for Scandinavian companies currently using the displacement design.

CONCLUSIONS

Displacement ventilation offers some advantages over traditional dilution ventilation for thermal and contaminant control in Canadian office buildings. For the experiments performed, the displacement system maintained lower temperatures in the occupied area as the dilution system. Thermal control over the course of the experimental runs appeared to be consistent, with no degradation in performance. At the same time the displacement system provided more efficient control of the contaminant CO_2 in the breathing zone.

Since displacement ventilation is capable of maintaining a lower temperature in the occupied zone, less cooling of the recirculated air is required. This realizes a reduction in energy consumption and consequently a financial savings.

The ability of the dilution system to control temperature deteriorated slightly as the experiment progressed. Displacement ventilation was able to maintain a fairly constant non-dimensional temperature with respect to time. This suggests that a displacement system will offer better thermal comfort over the course of the day.

Displacement ventilation demonstrated the capability to control the temperature in the occupied zone in a similar manner, independent of the thermal heat load applied.

Displacement ventilation shows promising applications in a Canadian climate, for cooling purposes. Since the overall annual energy costs are more dependent on cooling requirements, cooling cost reductions will have a significant impact on the yearly expenditure. Energy savings are presently being achieved in Scandinavian countries using displacement ventilation. Thus Canada should realize similar cost savings due to our slightly longer cooling season.

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ACKNOWLEDGEMENTS

The University of Toronto, Department of Chemical Engineering and Applied Chemistry, and the Gage Research Institute are recognized for their contribution of facilities and equipment for this project.