Perceived Control of Stratum Ventilation

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SUMMARY

Current control strategies for central air conditioning typically adopt a machine-centered, energy-consuming approach that focuses on creating constant, uniform neutrality-conditions which might actually be perceived by some occupants as thermal monotony or sensory deprivation. There are needs for more sophisticated and responsive environmental control strategies, enhanced levels of thermal comfort and acceptability among occupants. Stratum ventilation, a new ventilation mode proposed recently by the authors, has the potential to strike a balance between fully automated controls at the system side and manual controls that the users are able to alter. Stratum ventilation should be integrated with specific control strategies for various applications and varieties of control option available to occupants. A working example using CFD simulations is given to illustrate the performance of the proposed new system. Fresher air is directly introduced to breathing zone hence air age of the air layer should be younger. Air temperature gradient is low in the occupied zone. Because less fresh air bypasses occupants, fresh airflow rate may be reduced. The air supply temperature is usually high for stratum ventilation. The evaporating temperature of the refrigerating plant can also be lifted, which results in higher coefficient of performance.

INTRODUCTION

Conventional ventilation modes applied in an air-conditioned non-industrial indoor space are broadly categorised into two groups, namely: mixing ventilation and displacement ventilation as task ventilation is less widely applied.

Mixing ventilation is a traditional mode of ventilation and is still widely used. It could take care of both heating and cooling with highly varying load patterns. The mixing is achieved by supplying the ventilation air as a high velocity jet to entrain the air already in the room. Mixing ventilation could provide comparably uniform air temperature distribution in the occupied zone. However, it also leads to problems, such as poor IAQ, air draft in the occupied zone and some other thermal discomfort. In addition, it normally consumes more energy than displacement ventilation.

Displacement ventilation has been used quite commonly in Scandinavia during the past twenty years as a means of ventilation in industrial facilities to provide better IAQ and to save energy. More recently, its use has been extended to ventilation of offices, classrooms, commercial
buildings and other non-industrial premises. In contrast to mixing ventilation, buoyancy forces (induced by heat sources) govern the airflow in displacement ventilation. Because the airflow is thermally driven, this mode of ventilation functions satisfactorily only when excess heat is to be removed. In a room ventilated by displacement, the air quality in the breathing zone is usually better than in a mixing system operated with the same airflow rate. And ventilation efficiency of a displacement-ventilated room is also significantly better than that of the mixing ventilated room [1]. It has been found that an increase in ventilation efficiency is often achieved at the breathing level [2]. But there are more severe restrictions due to thermal discomfort in a displacement system than in a mixing system. ISO 7730 recommends a maximum air temperature gradient of 3K between 1.1m and 0.1m above the floor [3], which corresponds to a percentage dissatisfied of 5%. However, the ASHRAE Standard recommends the same temperature gradient between 1.7m and 0.1m above the floor [4], which related to a standing person. Otherwise it will cause thermal discomfort. So supply air temperature and airflow rate must be carefully studied to assure proper temperature distribution and velocity distribution. Often a displacement ventilation system excessively cools the lower part of a room, where usually heat sources are absent, resulting in discomfort and energy waste.

As far as the IAQ of breathing zone and energy efficiency are concerned, the most effective way is task ventilation. It may be used to remove excessive cooling load and maintain a comfortable indoor environment. Task ventilation systems supply air through nozzles located near occupants (e.g., at an edge of a desk). Potential draft exists because of the short distance between supply gears and the occupants. A field study found that workers in a task ventilated office satisfied with the thermal conditions because they could individually control local environment [5]. The occupants can control the temperature, flow rate, and direction of air from the nozzles. The measurements conducted by Faulkner et al. [6,7] showed that the age of air at the breathing level with task ventilation was approximately 30% less than that with mixing ventilation. However, application of task ventilation depends much on indoor furnishings. On one hand, sometimes it is difficult to equip nozzles and connect duct in various indoor spaces. On the other hand, some occupants in certain spaces do not normally stay in a fixed location, e.g., the situation in a retail shop. These limit the use of task ventilation.

DEVELOPMENT OF THE CONCEPT OF STRATUM VENTILATION

Mixing ventilation, displacement ventilation plus task ventilation all have their limitations. To overcome these problems, a new ventilation mode is proposed [8]. The new mode should be able to provide good IAQ in breathing zone, to have minimum temperature difference between head and ankle levels to obtain thermal comfort in occupied zone, to equip duct and terminals conveniently, and to have high energy efficiency.

The underlying principle of displacement ventilation implies that in an air-conditioned room, the conditions of IAQ and thermal comfort beyond the occupied zone (say H > 2 m) are of little interest. By the same token, the IAQ beneath the breathing zone (say H < 0.8 m) is less important unless the occupants are expected to be very young children. For conventional ventilation modes, the air for breathing is transported by the boundary layer around the body of a human occupant and the air quality is a weighted average of the air quality in the room from the breathing level to floor level. Ventilation efficiency would be maximized if air is supplied directly into the
breathing zone, and the air forms a well controlled “fresher air layer” to fill the breathing zone. The thickness of the fresher air layer depends on the nature of occupancy. At the same time, a quasi-stagnant zone is also form between the breathing zone and the floor (say 0 < H < 0.8 m). The temperature in the quasi-stagnant zone should not be as low as that of displacement ventilation. The problem of “cold ankles” could be solved. Energy can also be saved by avoiding over-cooling of the lower part of a room.

The stratum ventilation works by creating a layer of fresher air in the occupants’ breathing zone. This is done by placing large supply inlets at the side-wall of the room just above the height of the occupants, sedentary or standing depending on modes of occupancy. The fresh air enters the room and then gradually loses momentum, further away from the supply. The fresh air supply is sufficiently strong enough to provide adequate fresh air of young age. The range of face velocity and the locations of air supply and exhaust should be carefully optimized to break the boundary layer around the body of a human occupant, to minimize risks of draft and cross contamination. The thickness of the fresher air layer required depends on the nature of occupancy. At the same time, a quasi-stagnant zone is also form between the breathing zone and the floor (say 0 < H < 0.8 m). The temperature within the quasi-stagnant zone should be reasonably controlled. In addition the supply of air at this level increases the convection effect of the heat and helps to displace the contaminants into the unoccupied zone. It brings fresher air to breathing zone than that of conventional modes of ventilation. Indoor air should mix well and air temperature gradient should be low hence not to cause thermal discomfort. Because air is supplied directly to breathing zone, less fresh air bypasses occupants. Thus there are also possibilities to reduce fresh airflow rate resulting in energy savings. Also because air is supplied directly to breathing zone, the air supply temperature should usually above 20°C. This implies that the evaporating temperature of the chiller(s) could also be higher, which could result in higher coefficient of performance (COP), an indicator of refrigerating plant energy performance.

**STRATUM VENTILATION FOR ENHANCING PERCEIVED CONTROL**

Non-isothermal airflows enter a room via the air supply outlets positioned in a convenient way as long as it is slightly above the breathing height. A horizontal air layer should be formed with no reflux and minimal entrainment. Air age of the air layer should be young. Compared with more conventional modes of ventilation, it would bring a greater amount of fresh air into the breathing zone. The range of face velocity and the locations of air supply and exhaust should be carefully optimized to break the boundary around the body of a human occupant layer. Indoor air should mix reasonably well and air temperature gradient should be low so as not to cause thermal discomfort. Because air is supplied directly to breathing zone, less fresh air bypasses the occupants. There are also possibilities to reduce fresh airflow rate resulting in energy savings. The range of air velocity and supply types should be carefully matched to form the fresher air layer at the breathing zone. The positioning of the supplies should be carefully studied to avoid any reflux flows in the breathing zone of the room.

The occupants may opt for a control mode— manual or automatic:

- For the manual mode, temperature and air velocity (air recirculation) should be adjustable in wider ranges by the occupants; and
For the automatic mode, multiple control options based on combinations of different temperatures and air velocities should be available to the occupants. To avoid the problem of draft, each air outlet will be equipped with an occupancy sensor to determine the proximity of occupants. The occupancy sensor and volume control damper of each and every air outlet are linked via a central control system. The control system will hence be able to control the supply air accordingly. As a starting point, a simple control strategy is adopted. If an occupant is less than 0.5 m to the face of the outlet then the air supplied will be stopped. If the occupant is greater than 0.5 m but less than 1 m to the outlet then the volume flow rate is reduced by up to \(\frac{3}{4}\), but the face velocity is not less than 0.1 m/s. The basic principle is illustrated in Figure 1.

![Figure 1. Automatic control of stratum ventilation](image)

To maintain the required air supply volume to the room, the control system increases the fresh air supplied to the other parts of the room. The increase in supply will be optimized so that the increase will be for those outlets not far away from the closed outlet (the occupants). A fuzzy logic system consisting of a database relating the drop distance of an air jet based on the Archimedes number could be developed.

By directly or indirectly opting for a higher temperature setpoint, the occupants actually lower the cooling load of the room and save energy. This should be made known to the occupants. The research also attempts to increase the air recirculation applied in the design in order to remove a cooling load up to 200 W/m² of floor area. This is an inevitable problem because more and more equipment that generate a considerable amount of heat is being introduced indoors. The study assesses the stratum ventilation for enhancing perceived control in terms of IAQ and thermal comfort.

**METHODOLOGY**

The new concept of stratum ventilation needs to be tested. Two main approaches are available for the study of airflow and pollutant transport in buildings: experimental investigation and computer simulation. Direct measurements give the most realistic information but are expensive and time consuming. The purpose of the research at the first stage was to find out whether the new ventilation mode is feasible. Computational Fluid Dynamics (CFD) technique was applied. Due to limited computer power and capacity available at present, turbulence models have to be used in the CFD technique in order to solve flow motion. The use of turbulence models leads to uncertainties in the computational results because the models are not universal. Therefore, it is essential to validate a CFD program by experimental data [9].
A CFD model based on the Re-Normalised Group $k-\varepsilon$ model and wall function was used for simulation. Validated for both mixing ventilation and displacement ventilation, the model has been tested for hundreds of cases, including offices, classrooms, shops and workshops with air supplied upwards and downwards [10]. The flow characteristics between displacement ventilation and mixing ventilation are similar – both have strong pressure and buoyancy driven flows [11]. The condition of stratum ventilation is found to be between those of mixing ventilation and displacement ventilation based on identical internal layout and similar boundary conditions. The very model was also validated recently for stratum ventilation with air supplied horizontally. A commercial CFD code CFX was used for the computations. By default, the code uses the finite-volume method and the upwind-difference-scheme for the convection term [12]. Simulation results agree well with experimental results [13].

Table 1. Major parameters for the typical classroom

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<td>41</td>
<td>900</td>
<td>3168</td>
<td>350</td>
<td>1170</td>
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**TEST CASE**

The air velocity, the percentage of dissatisfied people due to draft (PD), and the predicted percentage of dissatisfied for thermal comfort (PPD) are widely used as criteria to evaluate thermal comfort [14,15]. All these performance parameters are determined by the thermal and flow boundary conditions, such as the size and geometry of the space, rates and temperatures of airflows and heat sources.

The case of a typical classroom is used to illustrate the effectiveness of the stratum ventilation. The classroom layout is shown in Figures 2. The major parameters are shown in Table 1. The classroom is supplied by 6 supply inlets located at the east wall ($x = 8.4$ m), and also by another 6 supply inlets at the west wall ($x = 0.0$ m). There are a total of 40 sedentary occupants and 1 standing occupant in the room. There is a long window at the west side of classroom.

**DISCUSSION OF RESULTS**

**Airflow Pattern**

The supply velocity is set low at 0.3 m/s to minimize any draft effect to the occupants. The air initially enters the room and gradually loses momentum and falls towards the floor under gravity. The air falls across the tables. This forms a stratum layer of fresher air in the breathing zone. This can be clearly seen in the cross-section $y = 6.0$ m and $x = 0.5$ m in Figure 3. The convection effects of the air can also be seen to rise near the external wall and window as it is heated. This effect is not observed on the other three internal partitions, as the adjacent rooms are at the same temperature.

The air velocity can be seen to be low in the order of less than 0.3 m/s in the occupied zone. Higher velocities however are observed near the external wall. Velocities tend to be in the range
of 0.3 to 0.5 m/s. At the external wall location the airflow rises rapidly into the ceiling area. The highest velocities are at the window location with velocities averaging between 0.4 and 0.5 m/s. This area is the location of the most intensive heat source.

Figure 2. Layout of the typical classroom

Figure 3. Airflow pattern

Figure 4. Temperature distribution

Figure 5. PD index (%)

**Temperature Distribution**

The temperature is nearly uniform in the horizontal direction, except close to the supply inlets as shown in Figure 4, which reduces any draft effects due to temperature differences. The temperature is 23°C at the floor level and at the vicinity of the supply inlets, and is 26°C at the centre of the room. The supply temperature is 21°C. The room temperature at a distance away
from the air supplies increases due to the various heat sources, such as external heat transmission, equipment, occupants, etc. As a result the temperature at the floor is higher than that of the supplied air. The temperature is even higher at the ceiling due to the loads including the heavy lighting. However the ceiling is within the unoccupied zone so the high temperature (slightly above 30°C) has little effect on thermal comfort. The effect of radiation due to temperature stratification of this kind is also insignificant because of the small temperature difference. The highest temperature in the occupied zone is near the projector in front of the teacher, which is 3°C higher than the average room temperature. Temperature gradient is maintained within the range of 3°C as stipulated in ISO 1984 and ASHRAE 1992.

**Predicted Dissatisfied (PD) and Predicted percentage of dissatisfied (PPD)**

The PD levels are higher at the supply inlets, at around 16% to 20%, Figure 5. This is at a distance of approximately one meter from the supply. The rest of the room is around 6% and rises slightly to 12% close to heat sources such as occupants and the projector. The PPD levels are mostly around 8% in the occupied zone and 10% in the unoccupied zone, as shown in Figure 6. In the vicinity of a supply outlet (< 1 m), the PPD levels increase gradually from 6% at the face of the supply outlet. The recommended level is 15% for both PD and PPD (ISO 7730).

**Mean age of air**

The mean age of air is a good indicator for the effectiveness of the stratum ventilation. As shown in Figure 7, at the centre of the room the air age approaches 160 s. Approaching the side of the room the air age decreases progressively from 120s to 80s. The location of the inlets at the side of the room means that air is supplied into the room unimpeded by furniture, resulting in fresher air throughout the classroom.

**CONCLUSION AND IMPLICATIONS**
For the illustrative example, the stratum ventilation with perceived control has shown the potential to be effective in providing satisfactory indoor thermal comfort and air quality. In general the calculated PPD and PD levels are satisfactory in most parts of the classroom. The system is able to provide air of young age to the breathing zone without the penalty of overcooling lower part of a room.

The results indicate that there is potential application for this system. Further research needs to be conducted to investigate the effects of various parameters such as air velocity, temperature and locations of supply to improve the performances the new type of ventilation system under perceived control.

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REFERENCES