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Dispersion pattern of contaminants in a displacement ventilated room - implications for demand control

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Synopsis

A passive tracer gas technique has been used in an experimental study of the distribution of contaminants in a room with displacement ventilation. Humans are simulated by heated metallic bodies and the tracer concentration in the breathing zone (exposure) is shown to be greatly influenced by both the position of the tracer source and the air convection current around the bodies. It is shown that pollutants emitted close to a body are completely and directly transported to the upper mixed zone and not mixed into the lower zone. Pollutants emitted at a small heat source or close to a wall in the lower zone are transported to, but do not directly penetrate the boundary between the two zones, thus accumulating below the interface. By natural convection currents, occupants will draw uncontaminated air from the lower zone, and experience a better air quality at the breathing level than that of the surrounding air - even if the interface is below the head.

It is concluded that air quality demand control of the supply air flow rate is a suitable means of securing the excellent air quality possible in a displacement ventilated room. A carbon dioxide sensor should preferably be positioned, so that the interface height can be maintained at a level slightly above the head of the occupants.

1 Background

1.1 Demand controlled ventilation

Demand control of the ventilation rate can be used advantageously in rooms and buildings where there are large variations in the pollutant emission strength with time. The aim is to save energy by minimizing the ventilation flow rate. The principle is to adjust the ventilation flow rate to the minimum required to attain an acceptable air quality, irrespectively of the pollutant source strength. Automatic control requires the use of an air quality indicator as a feedback to the regulation system.

The energy savings which can be attained by demand control, come from reduced power for ventilation fans and reduced need for cooling or heating of un-necessary outdoor air. The indicator should reflect the variation in the total contaminant level, otherwise demand control may affect the air quality negatively. Demand control is especially well suited when people are the predominant pollution sources. The carbon dioxide concentration being a suitable indicator of air quality in this case.

In an ideal fully mixing ventilation system, all locations in a room have the same pollutant concentration. Therefore, there would be no problem of where to locate an air quality sensor. However, the mixing in real systems can be very non-uniform. (Stymne *et al* 1990). A room ventilated by displacement constitutes an extreme case of incomplete mixing. It is not therefore self-evident where to place the sensor in this case. The aim of this work is to gain information on how pollutants are distributed in a room ventilated by displacement, and to draw conclusions on the most appropriate location of a carbon dioxide sensor for demand control.

1.2 Principles for ventilation by displacement

Ventilation by displacement is a type of ventilation where the buoyancy forces (induced by heat sources) govern the air flow. Because the air flow is thermally driven, this type of ventilation functions satisfactorily only, when excess heat is to be removed. Low temperature ventilation air is supplied at the floor level, while the warmed air is extracted at the ceiling level. By this arrangement one obtains two zones in the room, one lower zone with uni-directional flow and one upper recirculation zone. With regard to the air quality the aim of this ventilation principle is to create supply air conditions in the occupied zone. This is in contrast to traditional mixing type ventilation, where the aim is to achieve extract air conditions in the whole space. In order to avoid comfort problems, the cool air is supplied to the occupied zone by low velocity diffusers. Thus, the air enters the room as a gravity current in contrast to the high velocity jet streams usually used in traditional mixing ventilation. Some general features of the displacement type of ventilation are summarized in fig. 1.

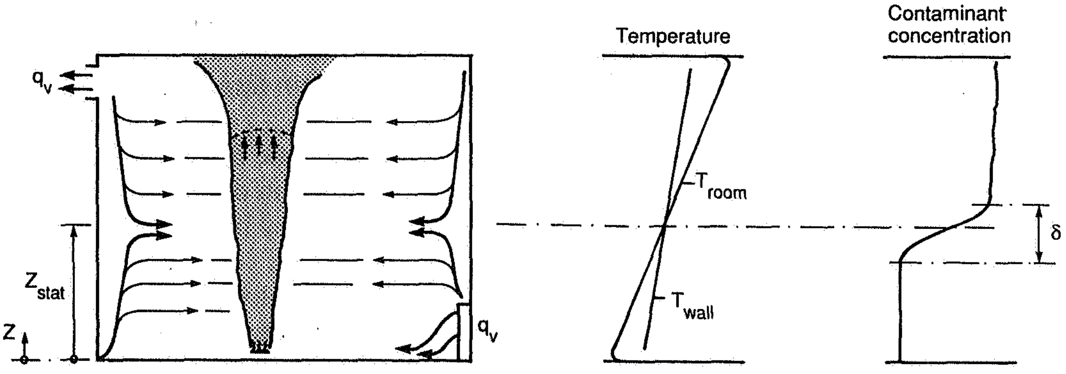

***Figure 1** Principle of ventilation by displacement*

It is shown in fig. 1 that although heat and pollutant have the same source in the lower part of the room, the temperature (density) stratification is continuous and nearly linear, whereas the vertical pollutant concentration profile shows a pronounced leap at a certain level. This difference in the distribution pattern is due to the fact that heat and contaminants are *not* transported by the same physical processes. Both are transported by a velocity field and by molecular diffusion. Heat, however, is also transported by radiation from warmer to colder room surfaces.

The velocity field in the room is set up by the vertical plume flow generated by the heat source. Surrounding air is entrained in the plume, and consequently the plume flow increases with height.

It is illustrative to write down the continuity equation, integrated over a horizontal plane. We make the assumption that the flow field at an arbitrary level in the room can be separated into two parts. The first is the primary air stream - the plume flow q_p. This primary air stream drives, by entrainment, a secondary air stream outside the plume. The horizontal velocity of the entrained air is inversely proportional to the distance from the plume. At each level the total vertical net flow rate must be equal to the ventilation flow rate, q_v. The equation of continuity becomes:

$$q_v = U(z)A + q_p(z) \qquad \text{eq. 1}$$

Where

A = room floor area

U = Average vertical transport velocity in the ambient outside the plume

In writing down the equation of continuity we have assumed that the area of the plume may be neglected when compared to the room area. The average vertical velocity outside the plume will be

$$U(z) = \frac{q_v - q_p(z)}{A} \qquad \text{eq. 2}$$

Because the plume flow starts from zero and increases with height, it follows that the vertical flow changes sign, i.e. direction, when the flow rate in the plume becomes greater than the supply air flow rate. We obtain three regions.

- *Uni-directional flow,* which occurs where the plume flow rate is less than the ventilation flow rate. When this occurs the direction of the flow in the ambient is concordant with the direction of the flow in the plume.

- *Horizontal ambient flow*, which occurs at the height where the flow rate in the plume is equal to the ventilation flow rate. At this height, Z_{stat}, the vertical component of the flow in the ambient is zero, so the only vertical transport occurs within the plume

- *Recirculating region*, which occurs where the flowrate in the plume is greater than the ventilation flow rate. Within this region the direction of the flow in the plume is upwards, whereas the direction in the ambient is downwards.

Centered at the level where only horizontal flow occurs outside the plume, there is an interface between the region with unidirectional flow and the recirculating region. At this interface the vertical velocities are so low that molecular diffusion becomes important. The thickness of the interface is controlled by a balance between convection and diffusion (Sandberg & Lindström 1990).

The net effect of the pure horizontal flow at the interface and the density stratification caused by the increasing temperature with height is that the transport of contaminants from the upper zone to the lower zone is hindered.

2 Experimental

2.1 Description of test room

The test space used for this investigation is a 4m x 3.45m (L x W) full scale office model, with 2.5 m height, built in the laboratory hall of the ventilation laboratory. The four walls are insulated with 5 cm styro-foam, while the floor, which is elevated above the concrete floor of the laboratory hall consists of a 2.5 cm hard particle board covered with a 1.5 cm plywood sheet. The ceiling consists of un-insulated glass panels.

The room is equipped with a conventional low velocity air supply unit with a face area of 0.15 m^2 (22% perforation degree) at the floor level. The extract terminal is situated on the same wall as the supply unit 0.2 m below the ceiling.

The experiment is carried out with nearly balanced flows, leaving a slight overpressure in the room. The supply air flow rate is appr. 80 m^3/h (2.3 room volumes per hour) and its temperature is kept at appr. 17°C.

Sitting persons are simulated by dummies constructed from metallic air duct tubes (20 cm diameter). The dummies which are of 135 cm height are heated from the inside with two bulbs (60 + 40 W). One or two dummies are used in the experiments. They are positioned in the measurement plane which divides the room into two equal halves. The ventilation air is entering from the supply unit at the center of a wall parallel to the measuring plane.

2.2 Measurement technique

150-200 passive sampling tubes for tracer gas made up a grid of measurement points in the measuring plane. The sampling tubes were positioned closer to each other in interesting regions. Two different tracer gases in permeation tubes were used to simulate pollutants. One tracer source (perfluorbenzene or PB for short) was positioned close to the ceiling (away from the measuring plane) in all experiments. The other tracer source (perfluormethylbenzene, PMB) was positioned in the measuring plane in the lower part of the room to simulate pollutants emitted in this region.
The integrating sampling was allowed to continue for 1-3 weeks under steady conditions. After an experiment, the passive samplers were analysed for the amount of adsorbed tracer gases with a gas chromatograph (GC) equipped with an electron capture detector (ECD). The analysis technique is described in another paper at this conference (Stymne & Eliasson 1991). During an experiment both the vertical air temperature and wall temperature distributions were intermittently monitored.

Three different experiments with displacement ventilation are reported here:

a Two heated dummies - one tracer source close to the ceiling and one tracer source close to one body.

b Two heated dummies - tracer source above an extra 4 W heat source between the bodies.

c One heated dummy - both tracer gas sources located close to a wall in the measuring plane - one in the upper part of the room and the other in the lower part of the room.

For comparison an experiment with mixing ventilation was carried out with the same tracer positions as in a above.

3 Results

The results of the measurements are displayed in graphic form in figures 2-6. The figures show the two-dimensional interpolated iso-concentration lines in the measuring plane. All concentrations are given relative to that found in the extracted air. Also displayed are the positions of the dummies and the tracer gas sources. In figure 2, the vertical temperature gradients in the air and at the wall are also shown.

Below are the main findings from the tracer gas distribution measurements.

3.1 Two heated dummies - tracer close to one body

Fig 2 shows how a tracer emitted in the upper zone is spread when there are two heated dummies in the room. The interface is at a height lower than the "breathing level" - at 0.85 m above the floor. Evidently, the ventilation flow rate (11 l/s, person) is too low to raise the interface above the head of sitting people. However, it is also obvious that there are regions above the heat sources that are depleted of tracer gas due to the dilution from the plume flows. This behaviour has also been observed by Holmberg *et al* (1990). The interface between the lower clean air zone and the upper contaminated zone is locally displaced appr. 0.2 m upwards around the heated bodies. In the upper zone, the tracer is otherwise relatively well mixed. The thickness of the interface is less than 0.2 m.

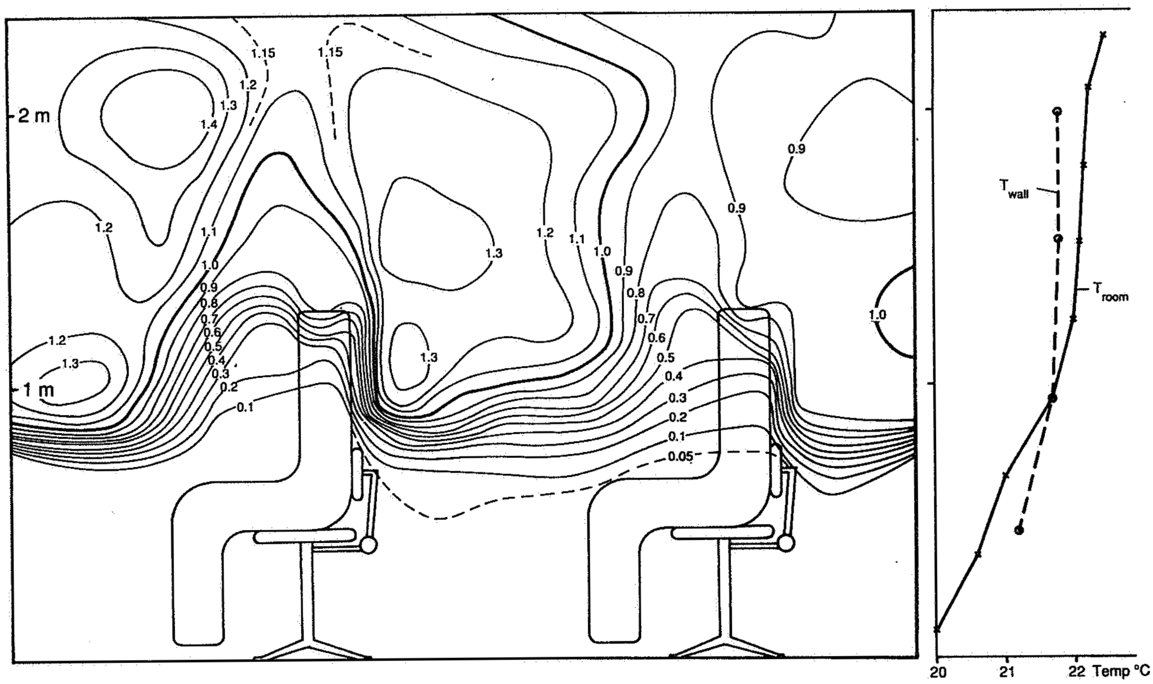

Figure 2 *Iso-concentration map showing the dispersion pattern of a tracer gas emitted close to the ceiling. The concentration figures are given relative to the concentration in the extract. The dummies are situated in the measuring plane and are heated with 100 W power. Also shown are the vertical temperature profiles at the wall and in the room air.*

Fig 3 shows the dispersion pattern of a tracer emitted close to one heated dummy. The tracer is directly and completely transported into the upper mixed zone. Moreover, it is apparent, that, although the "heads" of the dummies are above the transition zone, a person at that level is exposed to pollutants emitted from the other person to only a limited extent. This is due to the fact that the contaminants are transported directly to the upper zone and that each person is fed by fresh air from the lower zone.

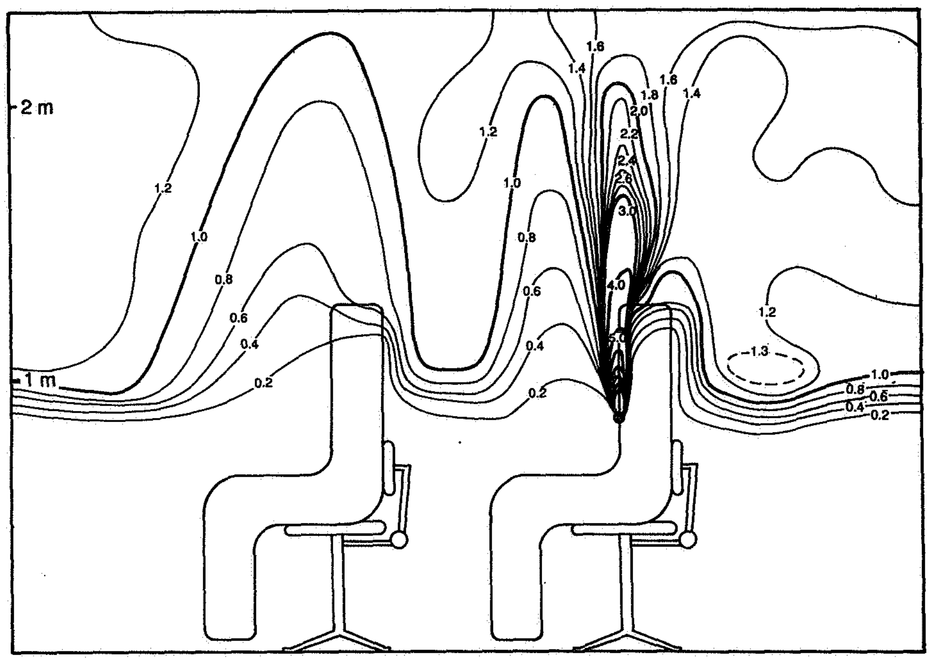

Figure 3 Iso-concentration map showing the dispersion pattern of a tracer gas emitted close to one of the two heated dummies. Concentrations are given relative to that in the extract

3.2 Two heated dummies - tracer at a low power heat source

Fig 4 shows how pollutants emitted from a low power heat source (4 W) do not penetrate directly through the interface. On the contrary they accumulate just below the interface and are transported into the upper zone only at the "holes" generated by the heated bodies. There is, however, only limited mixing within the lower zone. This type of accumulation of contaminants below the interface has been observed earlier (Sandberg & Blomqvist 1989).

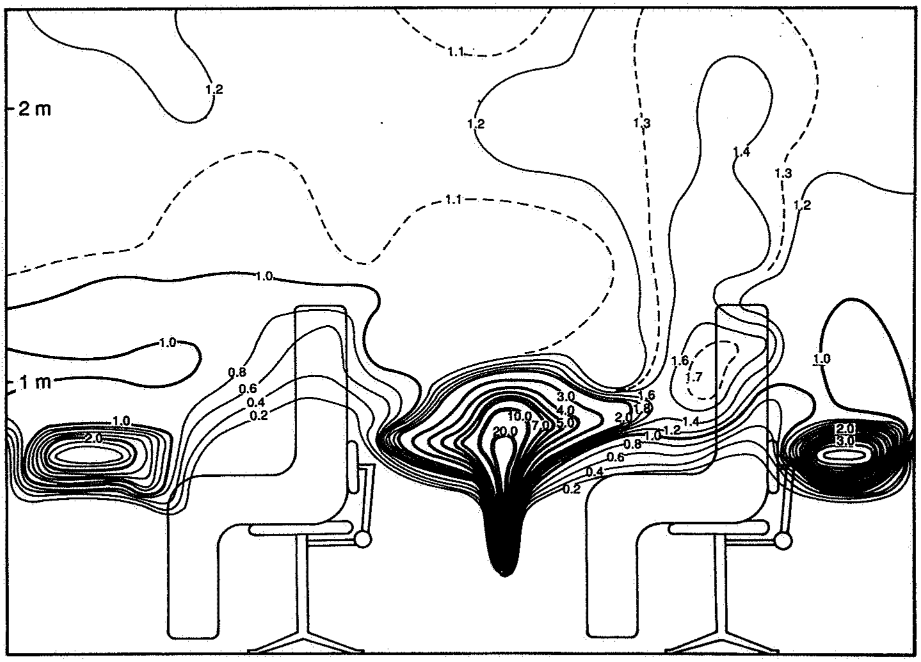

Figure 4 *Iso-concentration map showing the dispersion pattern of a tracer gas emitted directly above a 4 W heat source in the lower zone. Concentrations are given relative to that in the extract*

3.3 One heated dummy - tracer close to a wall

Fig 5 and **Fig 6** illustrate how a contaminant emitted close to a wall is transported in a room. In this case only one heated dummy was used, but the ventilation flow rate (22 l/s) was kept the same. Consequently the interface now appears at a considerably higher level (1.8 m). Fig. 5 shows how the tracer released close to the wall in the lower zone, follows the wall upwards. When it reaches the interface it is deflected and transported along the interface to the plume, where it is entrained and transported upwards. Fig 6 shows how the tracer released close to the wall in the upper zone flows downwards along the wall until it reaches the interface, before mixing into the upper zone. No evidence of the tracer emitted in the upper zone is found in the lower zone.

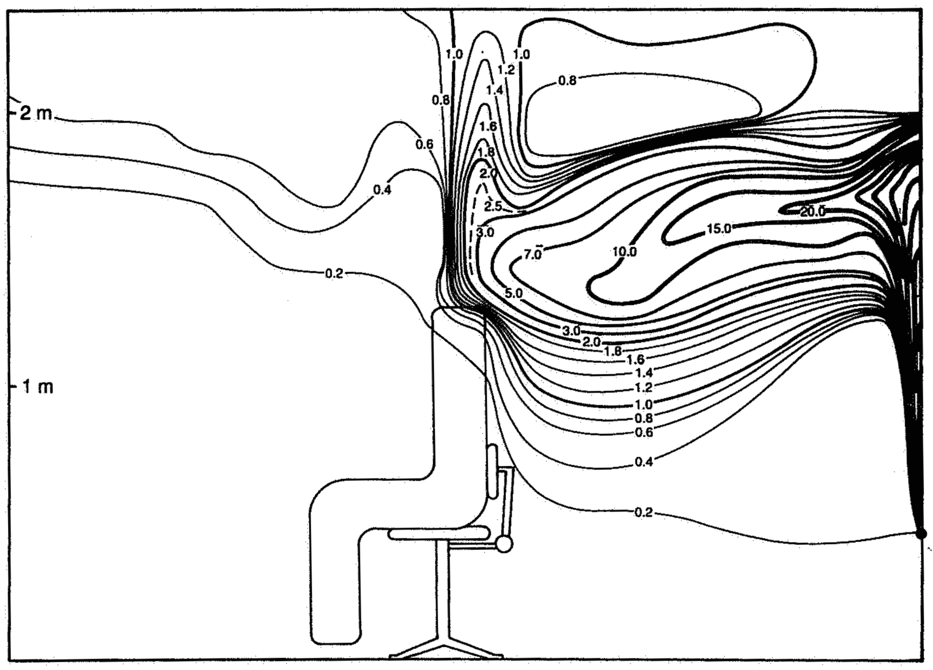

***Figure 5** Iso-concentration map showing the dispersion pattern of a tracer emitted close to the wall in the lower zone. One heated dummy is present.Concentrations are given relative to that in the extract.*

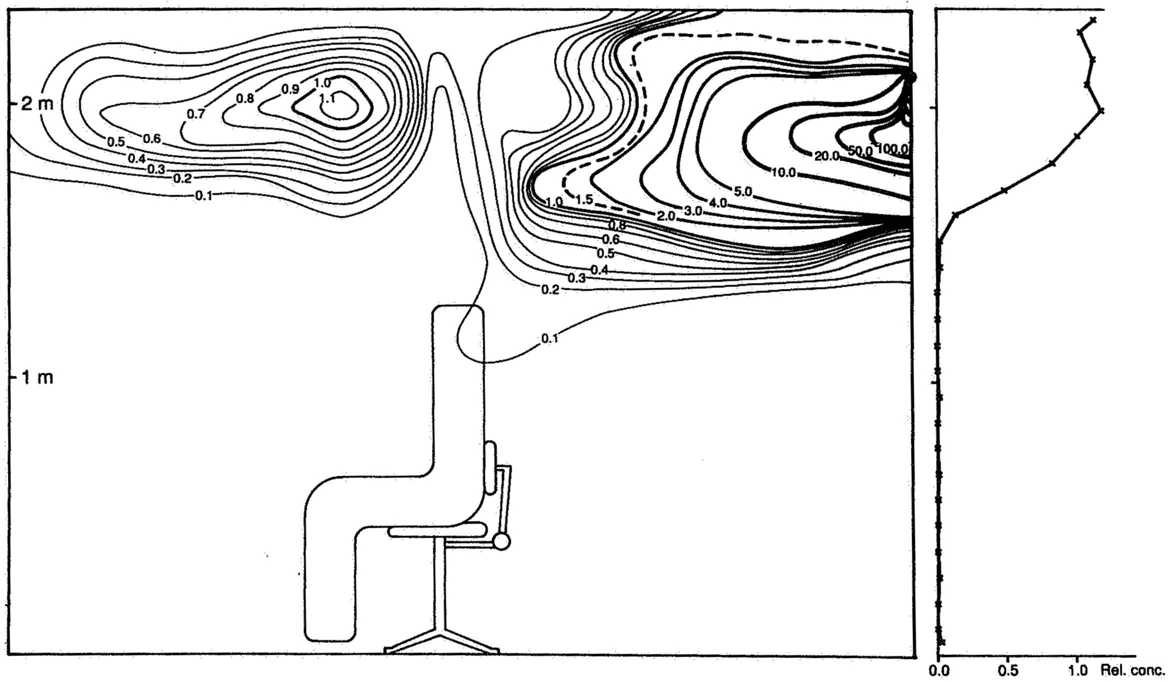

***Figure 6** Iso-concentration map showing the dispersion pattern of a tracer gas emitted close to the wall in the upper zone. Concentrations are given relative to that in the extract. Also shown (to the right) is the vertical concentration profile of a tracer released close to the ceiling.*

The observed behaviour can be explained by considering the heat balance in the room. In the lower zone, the wall temperature is higher than the room air temperature, whilst the conditions in the upper zone are the opposite. On the whole, the vertical temperature gradient of the walls is less steep than in the room air. This behaviour is illustrated from measurements displayed in fig 2. The levelling out of temperature differences at the walls is due to the radiative heat transfer between the surfaces in the room. The center of the interface is found at a "neutral point where the wall temperature is equal to the room air temperature. The created temperature differences between the walls and the room air will cause natural convection flows downwards above the neutral point and upwards below the neutral point. The observed kind of flow pattern has been noticed earlier in water model experiments (Sandberg & Lindström 1990).

3.4 Mixing ventilation

One experiment with mixing ventilation, utilizing a high velocity supply device close to the ceiling was also carried out. The plume flows above the dummies were not affected. This was evident from the locally high tracer concentrations above the tracer gas source located close to one dummy. The concentration profile over the dummy showed that the plume extends nearly unaffected to the ceiling level similarly as shown in fig 3. Outside the plume, however, the tracer concentration was uniform in the whole room and close to the concentration found in the extract. This indicates a complete mixing of contaminants in the supply air.

4 Discussion

4.1 Main findings

It should be noted that this laboratory experiment has a number of limitations, which make conclusions uncertain for behaviour in a real case. The main limitations are the absence of normal disturbances such as:

- Body movements
- Breathing
- Heat sources other than people
- Lighting
- Solar heat gain

The disturbances mentioned contribute to a more or less increased mixing, and consequently a lowering of the interface level. In the extreme case, there will be a complete disappearance of temperature and pollutant stratification.

For the time being it is not possible to estimate the effect of such disturbances. The following discussion is mainly valid for the extreme case of no such disturbances.

It has been shown that pollutants emitted from (simulated) people in a room ventilated by displacement are transported directly into the mixed upper zone and do not contribute to the contamination level in the lower zone. Pollutants emitted from the walls and small heat sources in the lower zone will flow directly towards the interface, where they accumulate and will be transported into the upper zone only by entrainment into the plumes generated by the stronger heat sources. Only limited mixing within the lower zone will occur.

Since people act as heat sources they will set up natural convection currents around their bodies, which draw uncontaminated air upwards, toward the heads. Thus, even if the supply air flow rate is not high enough to raise the interface above the head of people, they will breathe air of a better quality than that achieved by a mixing ventilation system, run at the same flow rate.

A ventilation system based on the displacement principle, therefore, inherently requires a lower ventilation air flow rate to give the same air quality as a mixing ventilation system.

This is in accordance with the aim of a demand controlled ventilation system - that is reduction of the ventilation flow rate in order to save energy.

4.2 Possibilities of demand control

A crucial question is whether it is an advantage to control the flow in a displacement ventilation system with an air quality indicator.

In this respect mixing ventilation systems and displacement ventilation systems have quite different characteristics. Both systems have their advantages and disadvantages when controlled by demand.

4.2.1 Mixing ventilation

Advantages

A mixing ventilation system can take care of both highly varying heating and cooling demands. The ventilation air temperature can be supplied either with a high over-temperature or a high under-temperature. Heating or cooling demand can also be satisfied by other means, like radiators, convectors, cooling panels etc., without affecting the performance of the ventilation system.

Thus the ventilation system and the system for maintaining good thermal comfort can be separated to a high degree. The supply rate of air can be solely determined by ventilation demand. Thermal comfort can be achieved by other means than with supply air.

Disadvantages

Usually, the mixing is achieved by supplying the ventilation air as a high velocity jet. If the air flow rate is decreased much below the design level, there is a risk of bad mixing. Warm air may short-circuit from the inlet to the outlet, while supply air with an under-temperature may fall down into the occupied zone - causing thermal discomfort. The ventilation efficiency might be low when demand is low.

4.2.2 Displacement ventilation

Advantages

In a room ventilated by displacement, the air quality in the breathing zone is usually better than in a mixing system operated vith the same air flow. This is due to the fact that people act as heat sources, drawing uncontaminated air from the lower zone along their bodies.

The ventilation efficiency is not adversely affected by decreasing ventilation flow rate at low demand.

Disadvantages

The flow pattern in a displacement ventilation system is set up by heat sources. Thus, there is a very strong coupling between thermal load, ventilation air rate and ventilation efficiency.

A ventilation efficiency, which is significantly better than with mixing ventilation can only be expected when the supply air flow rate matches the heat load. Thus, all heat sources require supply air, whether they are polluting the air or not. In a sense there is a short-circuiting of ventilation air between the clean lower zone and the contaminated upper zone at each heat source in the lower zone.

Controlling the supply air flow rate entirely by an air quality indicator in the exhaust will not ensure that people are surrounded by air of a better air quality than with a mixing ventilation system.

Displacement ventilation requires that the supply air has a lower temperature than the room air. Therefore, it is not possible to heat the room with the supply air.

There are more severe restrictions due to thermal discomfort in a displacement system than in a mixing system. This is especially the case whith high cooling demands. The thermal comfort aspect is discussed in a subsequent paragraph.

4.3 Ventilation demand contra cooling demand

In rooms ventilated by displacement the demand of air flow rate necessary for cooling, frequently dominates over that necessary for keeping the air quality acceptable according to current standards. This is because too low supply air temperatures can not be tolerated. This would lead to discomfort due to both the low temperature at the floor level and a steep vertical temperature gradient. An acceptable under-temperature of the supply air is 5-7 K. A special air diffuser equipped with an induction chamber which allows a ΔT of 10K has, however, been suggested (Holmberg *et al.* 1990)

One person dissipates approximately 100 W. To cool away that amount of heat with air ($\Delta T = 5K$) requires 15 l/s. This is more than that, normally assumed to be necessary from an air quality point of view. This amount of outside air per person would yield a carbon dioxide level of approximately 700 ppm in the extract.

Additional heat sources will call for even more supply air per person. This is often the case in offices. Thus, cooling requirements, combined with the requirements of thermal comfort often determine how much supply air is needed in a displacement ventilated system. An air quality indicator with a set point of 700-800 ppm carbon dioxide (which is usually recommended) would seldom take over the control, even if positioned in the extract.

A displacement ventilation system, however, offers the opportunity to achieve appreciably better air quality in the breathing zone than that which is normally assumed to be acceptable. This is reached without substantially increasing the supply air flow rate and energy consumption over the level needed to yield an acceptable thermal comfort.

Displacement ventilation can also advantageously be used in rooms where unusually polluting activities, such as smoking, are present. An acceptable breathing zone air quality can be achieved even in this extreme case, without increased demand for ventilation air, because the interface level is determined only by the strength of the heat sources - not the pollutant emission rate.

4.4 Concentration setting and location of an air quality sensor

The leading principle for controlling a displacement ventilation system by demand should be to establish the interface as low as possible, whilst at the same time allowing people to breathe air from the lower zone. This would secure the lowest possible flow rate from an air quality point of view.

To ensure the excellent air quality achievable with displacement ventilation, it is important to adjust the supply air flow rate, so that the interface level appears above the breathing zone of the occupants.

Demand control of supply air governed by an air quality sensor seems to be an excellent means of controlling the level of the interface. Carbon dioxide is a suitable indicator, both because it is emitted from heat sources (people) and because it indicates the presence or absence of people, requiring air quality control.

To ensure that the interface is at a sufficiently high level, the sensor should be located at the same height as the normal breathing zone. For sitting people this is at appr. 1.1 m above the floor.

The set point for the carbon dioxide concentration at the sensor position should be appreciably lower than that normally suggested for mixing ventilation (700-1000 ppm, ΔCO_2= 350-650 ppm). A reasonable value might be 500 ppm (ΔCO_2= 150 ppm). This value is low enough to ensure that the mixed zone is above the height of the sensor, but not so low that the interface is far above the sensor.

To monitor a typical concentration at this level the sensor should not be positioned in the vicinity of people or heat sources. Nor should it be positioned very close to a wall, because of the natural convection currents occuring along the walls mentioned earlier.

At a set ΔCO_2-value of 150 ppm a demand controlled system will respond quickly even for one person present in a room of normal size.

4.5 Thermal comfort considerations

As in the case of a mixing ventilation system, there must be some indicator and feed back system for temperature and thermal comfort. While, in a mixing system the thermal comfort can be regulated with radiators, convectors etc., the thermal comfort in a displacement system has to be regulated by means of the temperature of the supply air.

The criteria for thermal comfort in displacement system, not only refers to the average room temperature, but also to the vertical temperature gradient and the supply air temperature. The temperature difference between 0.1 m and 1.1 m should not exceed 3K according to ISO/DIS 7730 (1984). An even lower difference (e.g. 2K) might be necessary in connection with displacement systems. The supply air temperature should not be lower than 17°C and the difference in temperature between extract and supply air should not exceed 7K.

The regulation interval for the supply air temperature (17°C-21°C) is rather limited. Internal heat loads of more than 30 W/m^2 can hardly be taken care of without thermal discomfort (Wyon & Sandberg 1990).

4.6 Disturbances occurring in real systems

There are few detailed measurements reported for real occupied rooms with displacement ventilation. There are, however, indications that the interface is lowered, and the thickness of the transition zone increased, by mixing actions created by human movement. The local displacement of the interface around heat sources are probably especially influenced by such movement (Holmberg *et al* 1990).

There are probably large local fluctuations of the carbon dioxide concentration. Such fluctuations can severely influence the behaviour of a demand controlled system governed by the carbon dioxide concentration close to the interface. The amplitudes and frequencies of such fluctuations caused by human movement, must be investigated further, before any firm conclusions can be drawn on the set point and location of the air quality sensor.

For selection of a suitable sensor location it is also important to identify the natural concentration fluctuations that occur. The most rapid fluctuations are due to the turbulent velocity field. The turbulent fluctuations are so rapid (fractions of a second) that no normal sensor respond to them. There are, however, slower natural fluctuations due to internal gravity waves, supported by a stratified environment. The magnitude of the frequency (f) of such waves is given by the Brunt-Väisäla angular frequency (N) (Turner 1973).

$$f = \frac{N}{2\pi} = \frac{1}{2\pi}\sqrt{g \cdot \frac{1}{T} \cdot \frac{\delta T}{\delta z}} \quad \text{[Hz]} \qquad \text{eq. 3}$$

where T is the room temperature in Kelvin

In our tests the maximum vertical temperature gradient amounted to 2°C/m which gives rise to an oscillation period of 25 seconds (0.04 Hz) according to eq. 3. We can conclude that there will be natural fluctuations with a period of about 1 minute. Experience shows that such fluctuations have their largest amplitude at the level of the interface (Mellin & Sandberg 1990).

5 Conclusions

The following conclusions refer to a ventilated space of simple geometry, where the air flow pattern is not disturbed by the mixing action of human movement.

It has been shown from tracer gas distribution experiments, that pollutants emitted from a (simulated) person are transported directly to the upper mixed zone in a space ventilated by a displacement system. Pollutants emitted close to a wall or a low power heat source in the lower zone flow vertically towards the interface between the zones, but do not directly penetrate to the upper zone. The pollutants accumulate below the interface and are transported to the upper zone only at the "holes" generated in the interface by the natural convection plumes from the heated bodies.

The interface is locally displaced upwards approximately 0.2 m around the heated bodies, thus ensuring the occupants a better air quality than the surrounding air, even if their heads are above the interface level. Pollutants, which are emitted in the upper mixed zone or transported to that zone from the lower zone do not appear in the lower zone.

It is also shown that the plume above a heated dummy is similar in a mixing ventilation system to the plume created in a displacement ventilation system. In the case of mixing ventilation, however, there is no sign of any vertical concentration stratification outside the plume.

It is concluded that demand control of the supply air flow rate in a room ventilated by displacement is a suitable means of controlling the level of the interface between uncontaminated air in the lower zone and the polluted air in the mixed upper zone. The location of an air quality sensor for demand control should preferably be positioned at the height of the heads of the occupants, thereby ensuring an excellent air quality in the breathing zone at the lowest possible air flow rate. The concentration set point for the sensor should be at an appreciably lower value than that (e.g. 800 ppm CO_2) normally considered to be appropriate for the air quality. Otherwise, the sensor would seldom take the control.

Acknowledgements

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