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THE AIR QUALITY AT THE BREATHING ZONE WITH DISPLACEMENT VENTILATION

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ABSTRACT

This paper presents the difference in the air quality between that perceived by the occupants (breathing zone) and that in the occupied zone as a whole. An environmental chamber with displacement ventilation system has been used to carry out the measurements with the presence of a heated mannequin and other heat sources. Measurements of the age of air distribution, the air exchange index and the ventilation effectiveness were carried out at different points in the chamber for different room loads. CFD simulations were also carried out for the purpose of flow visualisation as well as the calculation of air velocity, temperature and age of air distribution. The results from the CFD simulations were compared with those from measurements.

KEYWORDS

Indoor air quality, Breathing Zone, CFD, Displacement Ventilation

NOMENCLATURE

$C_p(t)$ Concentration at a point p at time = t
$C(0)$ Concentration at time = 0
$C_e(t)$ Concentration at the exhaust at time = t
$C_s(t)$ Concentration at the supply at time = t
E_p Local air change index
ε, ε_p Ventilation effectiveness
$\bar{\bar{\tau}}_p$ The local mean age of air at point p
$\langle\bar{\tau}\rangle$ The room mean-age of air
τ_n Nominal time constant = room volume/air flow rate

INTRODUCTION

Displacement ventilation (DV) is widely used in mainland Europe and is also gaining popularity in the UK. In DV systems, cool air supplied at low level is entrained by plumes rising from heat sources. In the case of a body plume, the air that is entrained by the plume rises to the occupant's head and subsequently breathed by the occupant, Stymne et al (1991). As a result, the air quality at the breathing zone (the nose) is expected to be better than that in other parts of the occupied zone, e.g. Brohus and Nielsen (1994) and Hatton, et al (1999). Although a considerable amount of research work has previously been done on DV systems, there has not been any major study of the air quality at the breathing zone.

This paper presents results of the local mean age of air, the air exchange index and the ventilation effectiveness in an environmental chamber using three types of DV units. Temperature distribution and air velocity were compared with the results from CFD simulations.

EXPERIMENTAL SET-UP

The experiments were carried out in the environmental chamber at the University of Reading. The chamber was ventilated by a single low level wall DV unit or two circular floor units. The chamber consisted of two compartments and was equipped with an open ventilation system which draws air from the laboratory and exhausts the contaminated air out of the building. The dimensions of the test compartment were 2.78m (length) x 2.78m (width) x 2.3 m (height). To provide a realistic office situation a light (36W fluorescent), a computer simulator (150W), a desk and a chair were placed in the chamber. Two heated plates of variable heat output giving 95W and 180W were used to represent areas of solar illuminance on a side wall.

A heated mannequin was constructed from 1mm aluminium sheet with an overall surface area of 1.60m^2. Heating elements inside the body, head and legs of the mannequin were controlled to provide a surface temperature equal to that of a typical naked human, Olesen (1982). A polyurethane tube was attached to a copper tube (the nose) inside the head and fed through the torso and out to the gas sampler. This location represented the sampling point for the breathing zone. Throughout the tests the mannequin was unclothed to avoid possible interference of clothes with the body plume.

Different distributions of these heat sources were used to simulate an office with different heat loads. The total heat load for the experiments were varied from 140 W to 502 W, which represent typical heat loads in an office of this size.

Three types of DV units were used in the tests: DV unit 1, a flat-faced wall unit with a size 0.5m x 0.5m. DV unit 2, a semi-circular wall unit with a size of 0.5m x 0.5m high and a radius of 0.25m and two DV unit 3, which was a floor swirl unit of 0.15m in diameter.

Four-wire Platinum Resistance Thermometer has been used to measure the air temperature, the mannequin temperature and the inside and outside surface temperatures of the chamber. Other measuring devices used in the tests were an accurate Wattmeter, DANTEC omnidirectional velocity sensors and a Bruel and Kjaer SF_6 gas sampling system. 12 gas sampling tubes, velocity and temperature sensors were positioned at different points in the room. Table 1 lists the sampling points and sensor locations in the chamber and Figure 1 shows the location of measuring stands.

EXPERIMENTAL CONDITIONS AND MEASUREMENTS

Table 2 lists the 12 configurations and the room ventilation loads that were investigated with the emphasis on the air quality at the breathing zone of the mannequin. The ventilation load used here is defined as the total heat load subtracting the heat loss through the wall by conduction. Full details of the test condition for each DV unit can be found in Hatton, et al (1999).

The first priority in this work was to establish whether there is a difference between the perceived air quality and the air quality in the rest of the occupied zone. Because the local mean age of air at a point represents the time the supply air takes to reach that point, this term has been assumed throughout this paper to represent the quality of the air at that point. This is considered a plausible measure of the air quality since the residence time should be an indicator of the degree of contamination of the air at a point. The tracer decay gas technique was used to determine the age of air at a number of points in the room using SF_6.

TABLE 1

THE GAS SAMPLING POINTS AND SENSOR LOCATIONS FOR THE TESTS

Stand No. / location	Concentration sample point No.	Velocity and temperature sample points	Height of sample point (m)
1		12, 14, 18	0.18, 0.61, 1.04
2		9	0.14
	3		0.17
		16, 13	0.35, 0.49
	5	3	0.62
		24	1.08
3		4	0.15
	10	17	0.6
	11	23	1.06
4		8	0.6
		22	1.1
5		2	0.15
		21	1.1
6		6, 1, 20, 5	0.15, 0.65, 1.1, 1.23
7	4	7	1.34
8		10, 15	0.12, 0.6
	12	19	1.1
9		11, 18	0.61, 1.04
	7		1.76
10*	3,4,5,7,8,10, 11 and 12		0.14, 0.55, 0.92, 1.18, 1.32, 1.55, 1.8
Breathing zone	9		1.21(Seated) 1.63 (Standing)
Plume of mannequin	8		1.63 (Seated) 1.8 (Standing)
Inlet	6		0.4
Exhaust	2		2.3

****This is for tests using a constant emission of SF_6 gas above the heated box to measure the neutral height and the concentration distribution of gas.***

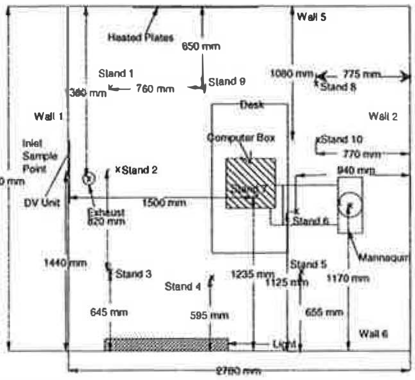

Figure 1: A plan of test compartment of the Reading Chamber and its contents

TABLE 2

CONFIGURATIONS TESTED IN THE CHAMBER

Config. No.	Man. posture	Air change rate ($hour^{-1}$)	Ventilation load (W)			Inlet temp. (°C)
			DV1	DV2	DV3	
1	Seated	5	100	129	136	20
2	Seated	5	185	250	241	18
3	Seated	5	238	299	298	18
4	Seated	5	328	281	318	18
5	Seated	7	369	401	n/a	18
6	Standing	5	175	170	142	20
7	Standing	5	256	247	265	18
8	Standing	5	293	260	302	18
9	Standing	5	329	339	306	18
10	Standing	7	379	430	n/a	18
11	Seated	3.2	300	281	n/a	18
12	Standing	3.2	310	282	n/a	18

The local age of air at a point and the mean age of air in the room can be calculated using the following expressions:

$$\bar{\tau}_p = \frac{\int_0^\infty C_p(t)\,dt}{C(0)} \qquad (1)$$

$$\langle\bar{\tau}\rangle = \frac{\int_0^\infty t\,C_e(t)\,dt}{\int_0^\infty C_e(t)\,dt} \qquad (2)$$

The local mean age of air was calculated for all the sample points within the working compartment of the chamber for each test condition, and these were averaged to obtain the room mean age. The data from these tests have been analysed and are presented in the result section. The local air exchange index, (the rate of exchange of air at a particular point within the room), E_p, and the local ventilation effectiveness, ε_p, were also calculated using:

$$E_p = \frac{\tau_n}{2\bar{\tau}_p} \quad (3) \qquad \varepsilon_p = \frac{C_p(t)}{C_e(t)} \quad (4)$$

Other tracer gas measurements were carried out using the steady state concentration method to measure the neutral height and the ventilation effectiveness for buoyant pollutant removal. The ventilation effectiveness, ε, was calculated from the measured concentration data using Eqn. (5).

$$\varepsilon = \frac{C_e(\infty) - C_s(\infty)}{C_p(\infty) - C_s(\infty)} \quad (5)$$

Other measurements carried out during the tests were air temperatures and velocities.

CFD ANALYSIS

Computational fluid dynamics is a useful tool for predicting the diffusion of airborne contaminants in a room. A CFD program called VORTEX (Gan and Awbi, 1994) was used to provide a microscopic prediction of the diffusion of the tracer gas in the whole space as well as air velocity and temperature data. A nominal grid of 80x80x80 was used for the simulation. The CFD simulations were found to be particularly useful for understanding, in greater detail, the air diffusion process in the room.

The CFD code was run for all test conditions listed in Table 2. The age of air, temperature and velocity measurements were compared with the predictions.

RESULTS AND DISCUSSION

The local mean age of air at the breathing zone and in the occupied zone are plotted against the room load in Figures 2 and 3 for DV units 1, 2, and 3 with seated and standing mannequin postures.

Figure 2 shows that the local mean age of air at the breathing zone of a seated mannequin is approximately 50% lower than that in the occupied zone for the flat faced DV unit (DV 1). This varies between 35 - 50% for the three diffusers tested with the smallest difference for DV unit 3, i.e. the floor DV units. This result suggested that the mannequin entrains air from the low fresh air zone into the breathing zone and thus creates better air quality in the perceived zone than that in the rest of the occupied zone. Figure 3 shows the local mean age of air at the breathing zone and the occupied zone for a standing mannequin. The difference between the data for the occupied zone and that for the breathing zone is lower than that for a seated mannequin.

The local air exchange index for a seated mannequin in a room fitted with DV unit 1 is plotted in Fig. 4. It is clear that the local air quality at the breathing zone is better than that at all the other points except those close to the DV units.

The ventilation effectiveness profile in the room has been calculated using the data from the constant emission measurements for obtaining the neutral height, see Xing and Awbi (2000). It can be seen from Fig. 5 that the ventilation effectiveness at the breathing zone is twice that at another point of the same height in the room. This confirms that the mannequin entrains air from the lower displacement air flow zone. Although the profile with DV unit 2 was similar to that with DV unit 1, the effectiveness at a height of 0.55m was much lower than that for the case of DV unit 1. This could be due to the fact that DV unit 2 produced a greater spread of air over the floor. The ventilation effectiveness in the lower part of the chamber was much lower for DV unit 3 than for the other two DV units.

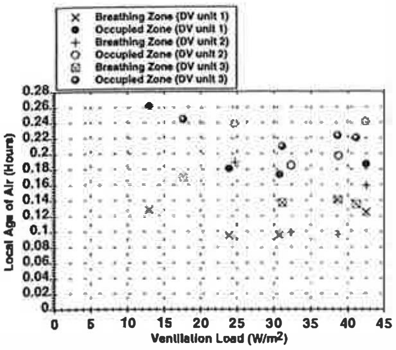

Figure 2: Local mean age of air for a seated mannequin

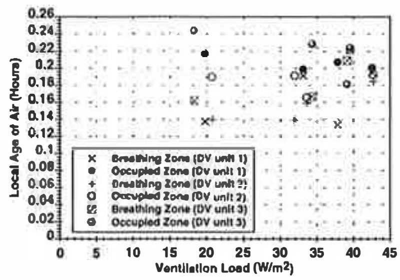

Figure 3: Local mean age of air for a standing mannequin

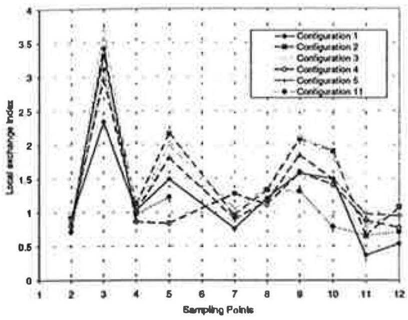

Figure 4: Local air exchange index for a seated mannequin for DV1

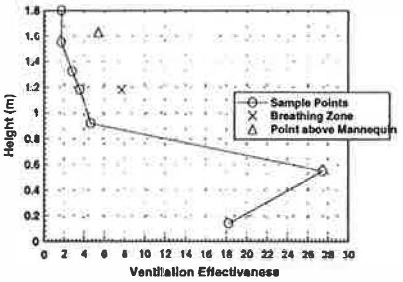

Figure 5: Ventilation effectiveness for DV1 configuration 2 with a seated mannequin

CFD simulations were carried out to compare the results with measurements. Generally, good agreement was found between the CFD prediction and experimental results. Figures 6, 7 and 8 compare the measured mean age of air, velocity and temperature with the CFD results for DV1 (configuration 4). Other comparisons can be found in Hatton, et, al (1999).

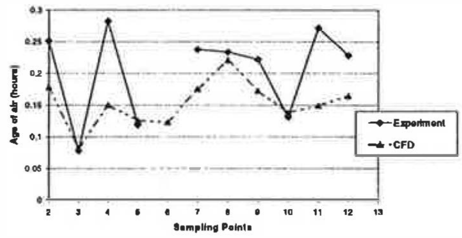

Figure 7: Comparison between measured and simulated velocity for configuration 4,DV1

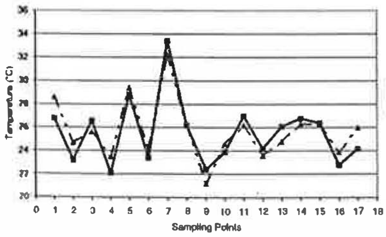

Figure 6: Comparison between measured and simulated age of air for configuration 4, DV1

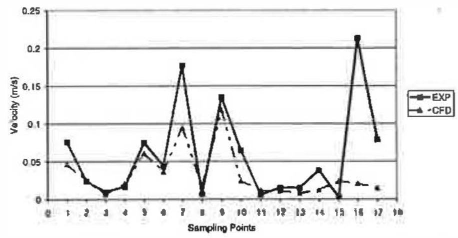

Figure 8: Comparison between measured and simulated temperature for configuration 4, DV1

CONCLUSIONS

The following conclusions can be drawn from the results presented in this paper:

- The perceived (breathing zone) air quality (represented by the mean age of air) for both seated and standing mannequin was better than the average air quality in the occupied zone for three types of DV units.
- The average perceived air quality for a seated mannequin was better than that for a standing mannequin for all three different DV units.
- The air quality in the occupied zone was found to be better for a semi-circular wall DV unit than for a flat wall DV units or floor DV units. Furthermore, the air quality was found to be better for a wall DV unit than for the floor DV units.
- The ventilation effectiveness at the breathing zone for both the seated and standing mannequin was greater than that for a point at the same height in the chamber for all the DV units.
- The local air exchange index was found to be highest close to the DV unit and at the breathing zone and was greater than at most other points in the room.
- A comparison between the CFD simulation results and the measured results showed a good agreement for most positions except those points near the DV unit.

Acknowledgement

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