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DILUTION VERSUS DISPLACEMENT VENTILATION—AN INTERVENTION STUDY

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Abstract—There is very little quantitative documentation of actual improvements resulting from the installation of new ventilation systems, or of the relative performance of systems designed in accordance with different principles, in industrial settings. Quantitative intervention studies are thus needed. The common practice in industrial hygiene is to use dilution ventilation. Increasingly displacement ventilation, which ideally supplies fresh air that displaces the contaminated air without mixing, is being introduced. By means of an intervention study at an electroplating plant the relative performance of the two principles of design was evaluated using an experimental signal–response tracer gas technique. The theoretical framework (age analysis) is summarized. In terms of supplying fresh ('young') air to the zone of occupancy the displacement system was better than the dilution ventilation system by a factor ranging from 1.6 to 6.6.

NOMENCLATURE

C	tracer gas concentration
$C(\infty)$	steady-state tracer gas concentration
$F(t)$	cumulative age distribution
$f(t)$	age frequency distribution
PR	proportion of the air supplied that is delivered by mechanical ventilation
Q	volumetric air flow rate
q	tracer gas injection rate
t	time
V	volume of the room
μ	mean

Subscripts

e	exhaust
i	infiltration
m	mechanical ventilation (supply)
p	arbitrary point in the room

INTRODUCTION

A number of types of design of general ventilation systems are in use. In industrial hygiene the common practice is to use dilution ventilation which ideally requires perfect mixing (ACGIH, 1988). Increasingly, however, displacement ventilation is being applied; ideally this involves fresh air displacing contaminated air without mixing (Skaaret and Mathisen, 1985; Breum, 1988). Very little is known about the relative performance in industrial settings of systems based on the two principles, and an intervention study of the air flow patterns in an electroplating plant has therefore been made. In industrial settings the flow field is usually very complex, involving turbulence, so that a detailed description is extremely difficult or even impossible

(NIEMELA *et al.*, 1987) and experimental methods characterizing average behaviour have to be used. The technique on which the present study is based (age analysis) is summarized first.

MATERIALS AND METHODS

Age analysis

Mixing processes in chemical reactor engineering are characterized by age distribution theory (LEVENSPIEL, 1963) and the concepts of this theory may be used to characterize the air flow patterns of ventilation processes (SANDBERG, 1981). Consider a ventilated room (volume V m^3) with one or more flow inlets and outlets. The mechanical ventilation system supplies air at rate Q_m (m^3 min^{-1}), and infiltration adds to this at rate Q_i (m^3 min^{-1}). The exhaust air flow rate is denoted by Q_e (m^3 min^{-1}), and it is assumed that $Q_e = Q_m + Q_i$. Elements of air entering the room remain in it for some time and then leave: their age is equal to the time spent in the room. Three different populations of air may be defined (SANDBERG, 1981): the total population of all fluid elements of air within the room, a local population of all fluid elements of air at an arbitrary point p within the room, and the population of fluid elements of air leaving the room. For each of the populations mentioned there is a cumulative age distribution $F(t)$, which is the fraction of the fluid elements of an age less than or equal to t. $F(t)$ is defined over $(0, \infty)$ so that $F(0)=0$ and $F(\infty)=1$. The corresponding age frequency distribution $f(t)$ is derived as

$$f(t) = \mathrm{d}F(t)/\mathrm{d}t \quad \text{or} \quad F(t) = \int_0^t f(t)\,\mathrm{d}t. \tag{1}$$

The mean of the distribution is μ where

$$\mu = \int_0^\infty t f(t)\,\mathrm{d}t = \int_0^\infty [1 - F(t)]\,\mathrm{d}t. \tag{2}$$

The age distribution can be determined experimentally using a signal–response tracer gas technique; the signal being the injection of tracer gas and the response the measured tracer gas concentration. Three strategies of tracer gas injection are widely used, decay ('step-down'), continuous injection at a constant rate ('step-up') and pulse injection (SANDBERG, 1981). In the present study continuous injection was used to label the air delivered by the air supply ducts (Q_m), i.e. air that infiltrated (Q_i) was not labelled. It is noted that by this approach estimates of the mean age of fresh air are obtained for only a sub-population (Q_m) of the total fresh air supply ($Q_m + Q_i$). Tracer gas response may be measured at given points within the room or at the flow exits, and in the present study the response was measured only at points within the room. The equation of the age distribution depends on the tracer gas injection strategy used and on the population of fluid elements of fresh air considered (BREUM and SKOTTE, 1986). In the following, however, only continuous injection at a constant rate and responses within the room are discussed.

Let us assume that from time $t=0$, tracer gas is injected at a constant rate (q l. min^{-1}) into the air supply duct and is mixed homogenously with the air before entering the room. If the supply air tracer gas concentration is denoted by C_m and the steady state gas concentration at any point p in the room is denoted by $C_p(\infty)$, the cumulative age distribution of the duct supplied fresh air passing this position is (BREUM and SKOTTE, 1986)

$$F_p(t) = C_p(t)/C_p(\infty). \tag{3}$$

The mean age of air, μ_p, passing this position is

$$\mu_p = \int_0^\infty t f_p(t)\, dt = \int_0^\infty [1 - F_p(t)]\, dt = \int_0^\infty [1 - C_p(t)/C_p(\infty)]\, dt. \tag{4}$$

As already mentioned infiltrating air (Q_i) was not labelled, so that the mean age estimated by Equation (4) relates only to the labelled air (Q_m) delivered by the ventilation duct. The total fresh air supply is $Q_i + Q_m$, and at p some air is delivered by Q_m and some by Q_i: note that the proportion, PR, delivered by Q_m may be estimated from the relation $PR = C_p(\infty)/C_m$ (OFFERMANN, 1988).

DESCRIPTION OF THE ELECTROPLATING PLANT

Electroplating incorporates a series of tanks that contain the appropriate cleaning and plating solutions. The plant studied used automatic processing equipment and the parts to be plated were automatically transferred from tank to tank in a predetermined sequence. There were two shifts, each of 5–10 persons mainly for loading and unloading. The conditions were basically the same throughout the period of the study.

During the first period (1 day) of the study the air flow pattern of the room was designed for dilution ventilation. The layout and cross-section of the workshop ($V = 12\,000$ m^3) are shown in Fig. 1. As indicated in Fig. 1 fresh (no recirculation) air (which varied in temperature between 19.0 and 20.5°C) was supplied by five ducts at roof level and delivered through grilles at the same level. The heat generated in the room was approximately 300 kW, and the main heat sources were located at the tanks shown in Fig. 1. Data on the intensity of the individual heat sources were not available. As shown in Fig. 1 the contaminated and heated air was exhausted through slot exhaust hoods at the tanks. The ventilation was designed for an unbalanced system ($Q_e > Q_m$) to keep an inward air flow (Q_i) through a permanently open door (2.5 × 3.0 m) to another heated, uncontaminated department of the factory. Recent data from a company file showed for each of the air supply ducts a flow rate of 183–200 m^3 min^{-1}, and Q_m was estimated to be 950 m^3 min^{-1}. Data on the exhausted air flow rate were not available, but smoke testing at the open door showed an inward air flow so that $Q_i > 0$, and therefore $Q_e > Q_m$.

Three months later during the second period (1 day) of the study the airflow pattern of the workshop was designed for displacement ventilation. The layout and cross-section of the room are shown in Fig. 2, the only difference from Fig. 1 being that there are supply air terminal devices at floor level and two outlets at roof level. As indicated in Fig. 2 fresh (no recirculation) air (which varied in temperature between 18.2 and 21.6°C) was introduced into the occupied area through low velocity supply air terminal devices (semi-cylindrical, 0.8 m dia., 2.5 m height). Company data showed a flow rate of 200–217 m^3 min^{-1} for each of the five air supply ducts, and Q_m was estimated to be 1050 m^3 min^{-3}. The flow rate of exhaust air from the two outlets at roof level was estimated from fan characteristics to be 150 m^3 min^{-1}. The air flow from the slot exhaust hoods at the tanks was basically identical during the two test periods. Data for

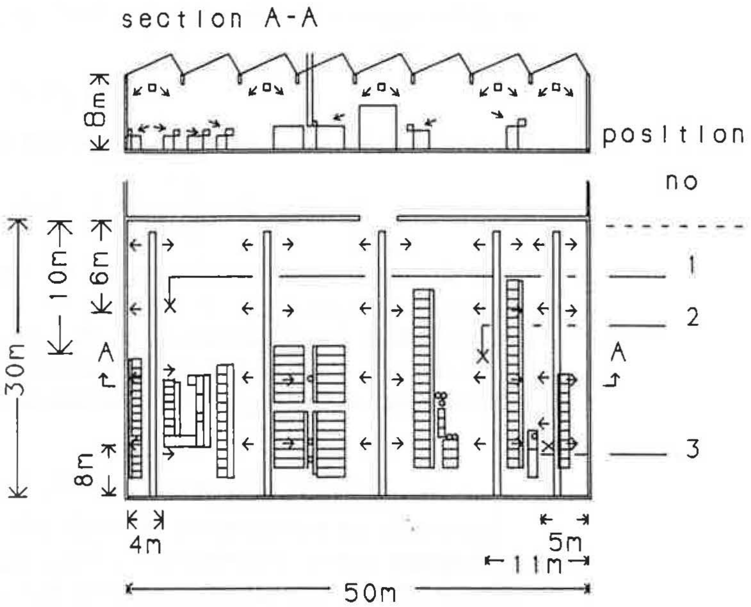

FIG. 1. Layout and cross-section of the electroplating plant designed for dilution ventilation (not drawn to scale).

the total exhausted air flow rate was not available, but smoke testing at the open door showed an inward air flow indicating that $Q_i > 0$, and therefore $Q_e > Q_m$.

EXPERIMENTAL PROCEDURE

Tracer gas (SF_6) from pressurized bottles was simultaneously injected into the five air supply ducts at a constant flow rate controlled by calibrated rotameters at an estimated accuracy of $\pm 3\%$. To allow homogenous mixing of tracer gas and supply air the tracer was injected at a distance of more than 80 times the duct diameter from an inlet (PRESSER and BECKER, 1988). During the first test period the injected flow rate of tracer gas was 8 l. min^{-1} for each duct, and the estimated concentration of tracer gas in the supply air was $C_m = q/Q_m = 42$ ppm. During the second test period the injected flow rate of tracer gas was reduced to 5 l. min^{-1} for each duct so as to reduce tracer gas consumption, and the estimated concentration of tracer gas in the air supply was $C_m = q/Q_m = 24$ ppm. Three separate identical experiments were performed during a test period, allowing sufficient time between the experiments to wash out any tracer gas left in the workshop. In an experiment the tracer gas concentration was sequentially measured (45 s step period) at three levels above the floor (0.1, 1.7 and 3.3 m) at a selected position in the room. The three selected positions for the two test periods were identical (see Figs 1 and 2). A multipoint measuring system (Fig. 3) was used for measuring the tracer gas. The concentration was measured by an i.r.-analyser (MIRAN 80, Foxboro Analytical) calibrated for SF_6 concentrations in the range 0.1–50 ppm, and the accuracy of the tracer gas analysis was estimated to be $\pm 5\%$. Air samples from the three measuring points were sucked by gas tight pumps through sample lines into a channel selector and delivered sequentially to the gas analyser at a

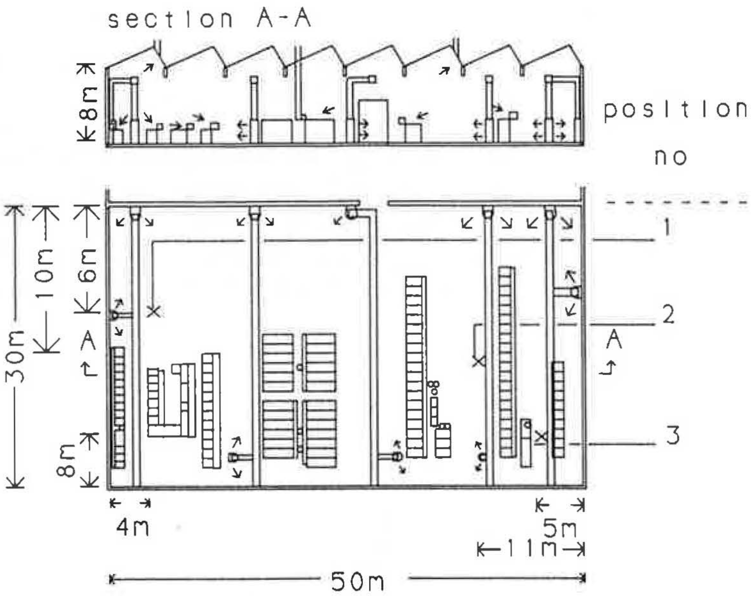

FIG. 2. Layout and a cross-section of the electroplating plant designed for displacement ventilation (not drawn to scale).

flow rate of 33 l. min^{-1}. In succession, once every 45 s the selector connected a different sample line to the gas analyser. The time constant of the gas analyser was 9.6 s at a 33 l. min^{-1} sampling rate. During an experiment the sequence of operations and the data acquisition was run by menu-driven software using a portable computer. From the data obtained $F_p(t)$ was estimated using an exponential curve-fitting procedure of the menu-driven software, and by numerical integration μ_p was estimated from Equation (4). During the test periods the air temperature and the air velocity were recorded at the three positions using a calibrated low-velocity flow analyser with an omnidirectional probe (DANTEC 54N50).

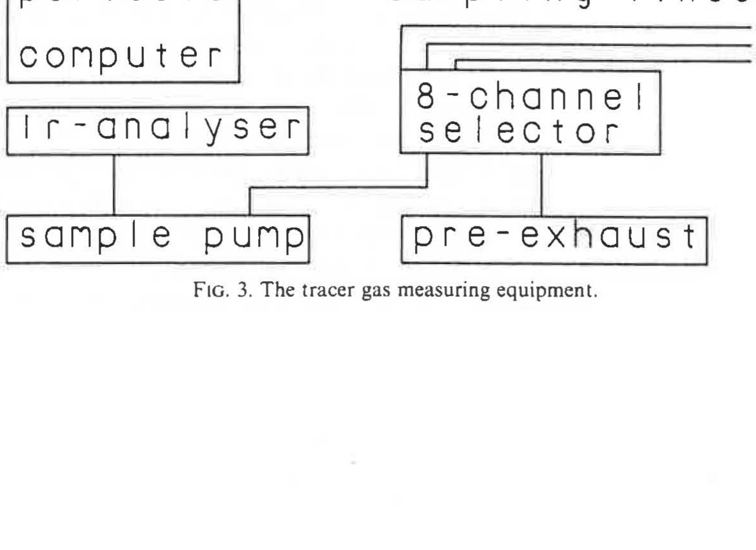

FIG. 3. The tracer gas measuring equipment.

RESULTS

During one experiment tracer gas concentrations against time were displayed on a video monitor and the test results were collected on the hard disc of the portable computer. As an example of the data obtained during the first test period the tracer gas concentration against time at position No. 2 is shown in Fig. 4. For comparison the data obtained during the second test period at position No. 2 are shown in Fig. 5. Age analysis was applied to explore air flow patterns. The mean age of the fresh air delivered by the air supply ducts was estimated by Equation (4), and the condensed results are listed in Table 1. Table 1 also includes the recorded air temperatures and air velocities.

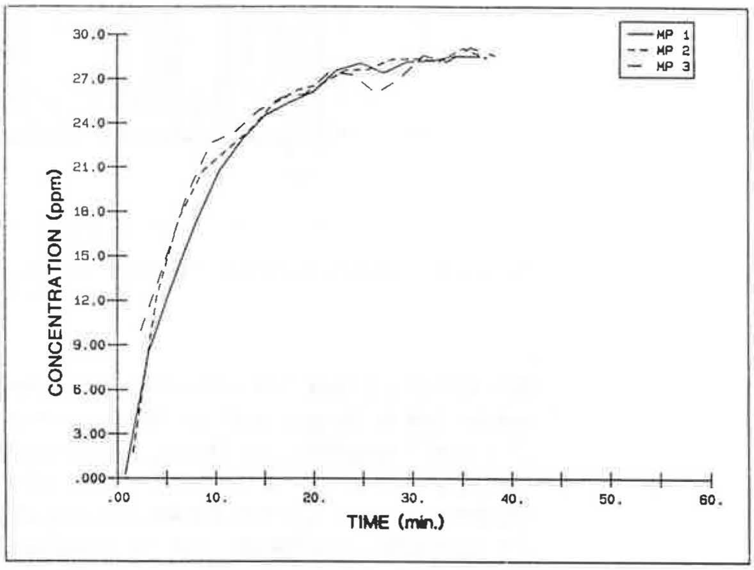

FIG. 4. Tracer gas concentration during test period A (dilution ventilation) at position No. 2. Measuring point (MP) level above the floor: MP 1 = 0.1 m, MP 2 = 1.7 m, MP 3 = 3.3 m.

DISCUSSION

Knowledge of air flow patterns are of vital importance in the design of an effective ventilation system. Tracer gas techniques are commonly used in industrial hygiene for field studies of air movements and the mathematical concepts of age analysis allow a convenient characterization of the ventilation process (SANDBERG, 1981; BREUM, 1988).

The data from the present study were obtained in normal conditions of production at an electroplating plant with no attempt to reduce disturbances caused by moving machines, traffic in or out of the workshop, etc. In the first test period the ventilation was designed for dilution ventilation by supplying fresh air at roof level and exhausting the heated and contaminated air through slot exhaust hoods at the tanks. The supply air temperature was 19.0–20.5°C, and within the workshop the temperature was 24.0–26.8°C. At some positions within the workshop (Nos 1 and 3) a vertical air temperature gradient was observed (0.5°C m^{-1}). This gradient was well below a

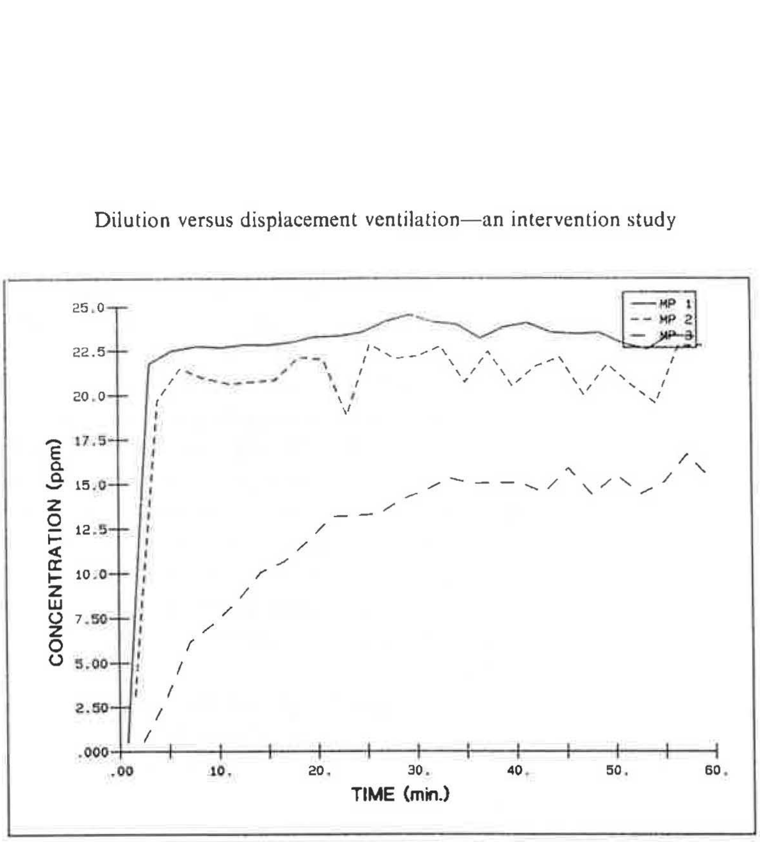

FIG. 5. Tracer gas concentration during test period B (displacement ventilation) at position No. 2. Measuring point (MP) level above the floor: MP 1 = 3.3 m, MP 2 = 1.7 m, MP 3 = 0.1 m.

TABLE 1. ESTIMATED PARAMETERS OF A TRACER GAS INTERVENTION STUDY OF AIR FLOW PATTERNS OF A PLATING PLANT

Design principle		Dilution ventilation				Displacement ventilation			
Position No.	Height above the floor (m)	$C_p(\infty)$ (ppm)	μ_p (min)	Air temp. (°C)	Air velocity (cm s^{-1})	$C_p(\infty)$ (ppm)	μ_p (min)	Air temp. (°C)	Air velocity (cm s^{-1})
1	0.1	27.7	9.3	24.7*	37*	25.1	1.4	21.9*	30*
1	1.7	26.6	9.0	—	—	25.3	5.5	—	—
1	2.0	—	—	24.9	46	—	—	25.0	20
1	3.3	26.4	9.5	—	—	15.3	12.3	—	—
1	4.0	—	—	27.4	33	—	—	28.0	3
1	6.0	—	—	27.6	19	—	—	28.2	6
2	0.1	29.3	5.0	25.3	38	22.3	2.7	22.8	18
2	1.7	28.5	6.0	—	—	21.8	2.9	—	—
2	2.0	—	—	25.8	21	—	—	24.9	8
2	3.3	28.0	6.0	—	—	17.0	8.0	—	—
2	4.0	—	—	25.5	41	—	—	26.3	8
2	6.0	—	—	24.0	59	—	—	27.2	10
3	0.1	28.2	6.5	23.8	24	23.4	1.7	22.0	19
3	1.7	28.3	7.0	—	—	21.4	2.3	—	—
3	2.0	—	—	24.3	27	—	—	23.8	12
3	3.3	28.9	8.5	—	—	15.6	13.7	—	—
3	4.0	—	—	25.3	29	—	—	26.9	6
3	6.0	—	—	26.8	19	—	—	27.0	14

*Mean value of 1 min sampling period.

recommended (ISO, 1984) thermal comfort limit ($3.0°C\ m^{-1}$) for light mainly sedentary activity during winter. The measured air velocities, however, exceeded the recommended comfort limit of $0.15\ m\ s^{-1}$ (ISO, 1984). A steady-state tracer gas concentration, uniformly distributed spatially, was observed (26.4–29.3 ppm). Assuming at steady-state a workshop average tracer gas concentration of 28 ppm and an air supply tracer gas concentration of $C_m = 42$ ppm the exhausted air flow rate was estimated from a tracer gas mass balance to be $Q_e = Q_m \cdot 42/28 = 1.5 \cdot Q_m = 1425\ m^3\ min^{-1}$. It is noted that the air flowing through the open door ($Q_i = Q_e - Q_m = 0.5 \cdot Q_m = 475\ m^3\ min^{-1}$) was unlabelled with tracer gas. As shown in Table 1 the estimated mean ages of the fresh air delivered by the air supply ducts ranged from 5.0 to 9.5 min, and the 'oldest' air was observed at position No. 1. From $PR = C_p(\infty)/C_m$ this fresh air supply came to 63–70% of the total fresh air supply delivered at the positions within the workshop.

In the second test period the ventilation system was designed for displacement flow by supplying fresh air in the zone of occupancy. From this design principle fresh cool air is filling the workshop from below owing to gravity, and 'old' air is displaced upwards. This air flow pattern is assisted by convective currents from any heat source in the zone of occupancy, consequently forming thermal stratification and two or more distinct flow regions (Skaaret and Mathisen, 1985). If the convection upcurrents leaving the occupied zone are not balanced by the supply of incoming air and high level extract then recirculation back down into the occupied zone can occur. The supply air temperature of the second test period was 18.2–21.6°C and within the workshop the air temperature ranged from 21.9 to 28.2°C. The vertical air temperature gradient ($0.7–1.1°C\ m^{-1}$) exceeded the gradient observed during the first test period, but not the recommended thermal comfort limit (ISO, 1984). A vertical gradient of the measured air velocities was observed, with high air velocities ($0.2–0.3\ m\ s^{-1}$) at floor level and low air velocities ($0.05–0.08\ m\ s^{-1}$) at the other levels investigated. Only at floor level did the velocity exceed the recommended comfort limit (ISO, 1984) though this is not a sedentary occupation. Table 1 shows elevated air velocities during the first test period compared with the second test period. The flow rate of the slot exhaust hoods was basically constant during the study. Taking into account the additional exhaust at roof level the flow rate of air through the open door may approximately be estimated from $Q_i = Q_e - Q_m = (1425 + 150) - 1050 = 525\ m^3\ min^{-1}$, i.e. basically at the same level as during the first test period. As shown in Table 1 the estimated mean ages of the fresh air delivered by the air supply ducts ranged from 1.4 to 13.7 min. This age parameter was stratified vertically with the 'oldest' air at roof level, and the 'young' air at floor level. A stratification of the steady-state tracer gas concentration was also observed indicating two or more distinct flow regions in the workshop. As estimated from PR approximately 90–100% of the fresh air delivered in the zone of occupancy (0.1 and 1.7 m above the floor) was supplied by the terminal devices at floor level. At roof level (3.3 m above the floor) approximately 65–70% of the fresh air was delivered by the terminal devices and consequently approximately 30–35% of the fresh air at this level was supplied by infiltration through the open door.

Throughout the present intervention study all conditions except the ventilation design may be considered approximately constant. The local mean age is a valuable tool in evaluating the performance of different ventilation systems (Davidson and Olsson, 1987) and the technique has been used in an experimental office room for characterizing flow fields of different ventilation design principles (SANDBERG, 1984). According to this age parameter displacement ventilation was more efficient in distributing fresh air from the supply ducts into the zone of occupancy than dilution ventilation. In the zone of occupancy changing the ventilation from dilution to displacement reduced the mean age of the air by a factor of 1.6–6.6 (see Table 1). This improvement of air renewal may not apply in general but the results show that the displacement flow principle may have potential application in industrial areas where heat sources create a natural buoyancy-driven flow carrying heat and contaminants towards roof level.

Air renewal process and contaminant removal are not in general identical, and consequently should be treated separately (SKAARET and MATHISEN, 1985). The study focused on air renewal, and the exposure levels of air contaminants were not measured. It is emphasized that ultimately the performance of a ventilation system should be evaluated from personal exposure levels (BREUM, 1988). It can be concluded, however, that the displacement ventilation design principle may have potential application in industrial settings with heat sources in the zone of occupancy. In terms of supplying fresh ('young') air to the zone of occupancy the performance of displacement ventilation may exceed that of dilution ventilation by a factor of 1.6–6.6.

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