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MIXING VERSUS DISPLACEMENT VENTILATION - FLOW FIELDS OF AIR AND CONTAMINANTS IN A LARGE INDUSTRIAL BUILDING

N.O. Breum
National Institute of Occupational Health
Lersoe Parkalle 105
DK-2100 Copenhagen O

SUMMARY

There is very little quantitative documentation of actual improvements resulting from the installation of new general ventilation systems in industrial settings. Therefore the performance of the common mixing design principle was compared to the displacement design principle by means of an intervention study in a workshop (V=12.000 m^3), where thermoplastics were molded. A complex mixture of air contaminants may evolve from thermally stressed thermoplastics. For the present study a simulated mixture (tracer gas) was selected as a contaminant.

Contour plotting of exposure levels to contaminants was used as a "hot spot" identification technique. An experimental signal-response tracer gas technique was used for characterizing flow fields of air and contaminants. In terms of supplying fresh air to the zone of occupancy the displacement system was better than the mixing system by a factor of 2. In terms of exposure to a simulated contaminant (tracer gas) the displacement system was better by a factor 1.5-18.

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INTRODUCTION

A number of general ventilation system designs are in common use and, qualitatively, the pattern of air flow can vary from one extreme (short circuiting) to the other extreme (displacement flow). Between these there is perfect mixing. General room ventilation systems have traditionally been designed to provide for acceptable air quality and thermal comfort in the zone of occupancy under the assumption that supplied air is perfectly mixed in the room. The advent of displacement ventilation systems have brought the usefullness of the perfect mixing assumption under question [1]. The features of the two design principles are summarized below.

From the mixing design principle air jets often are supplied at ceiling level with a high momentum. Room air is entrained into the jets so generating secondary recirculating air flows in the room. This mixing process diminishes a spatial non-uniform air temperature and contaminant distribution in the room. Supply air is the main source of momentum, and therefore mixing ventilation may be called high momentum ventilation [2].

In recent years ventilation systems using displacement air flow have been installed at a growing rate. In Scandinavia the present market share of displacement systems for industrial ventilation was estimated to be 50% [3]. Ideally displacement flow involves fresh air displacing contaminated air without mixing. Cool air is supplied with a low momentum through large inlet devices near the floor. The cool air is heated by heat sources in the room, and convective plumes are formed above the heat sources. Convective air flow may act as a carrier of contaminants released from heat sources [4]. The ventilation air is both a source of momentum and buoyancy. Therefore displacement ventilation may be called low momentum ventilation [2]. If convective upcurrents leaving the occupied zone are not balanced by the supply of air and high level extract, a layer (a "front") of heated and contaminated air at the ceiling starts to descend. The front stops where the air flow rate of convective upcurrents equals the supplied air flow rate [2]. The level of the front in a room is an important air quality parameter [5]. As a design goal the front should be located above the zone of occupancy.

Keeping mixing flow systems as a reference it is of interest to validate the potential of displacement systems for improved air quality. Data on air flow fields of mixing versus displacement systems are available from the laboratory [2] and from industry [5,6]. However, flow fields of air are generally not identical to flow fields of contaminants [7]. Therefore an intervention study of air and contaminant flow fields of mixing versus displacement ventilation has been made in a workshop where thermoplastics were converted into products by injection molding. A complex mixture of air contaminants may evolve from thermally stressed thermoplastics [8]. For the present study a simulated mixture (tracer gas) was selected as a contaminant. Theory on which the present study is based (age analysis) is summarized first.

MATERIALS AND METHODS

Age analysis

Flow fields of air and contaminants in a confined space is very complicated and dificult to characterise. Concepts of age distribution theory provide usefull tools for quantification of flow fields [6]. Consider a ventilated room (volume V m^3) with one or more flow inlets and outlets. Air is supplied at a constant rate Q_m (m^3 min^{-1}) by a mechanical ventilation system, and infiltration adds to this at a constant rate Q_i (m^3 min^{-1}). Air is exhausted at a constant rate Q_e (m^3 min^{-1}), and it is assumed that Q_e=Q_m+Q_i. Fluid elements of air or contaminants entering a 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 fluid elements may be defined [9]: (a) total population of all fluid elements of air within the room, (b) local population of fluid elements of air at an arbitrary point p within the room, and (c) population of fluid elements of air leaving the room. Each of the populations mentioned is characterized by a statistical cumulative age distribution F(t), which is, for any t, the fraction of fluid elements younger than t. F(t) is defined over (0,∞) so that F(0)=0 and F(∞)=1. The corresponding age frequency distribution f(t) is derived as:

$$f(t) = \frac{dF(t)}{dt} \quad or \quad F(t) = \int_0^t f(t^*)\,dt^* \qquad (1)$$

The mean of the distribution is μ where:

$$\mu = \int_0^\infty t f(t)\,dt = \int_0^\infty [1-F(t)]\,dt \qquad (2)$$

The age distribution may be determined experimentally by labelling the air using a stimulus-response tracer gas technique. The stimulus is a tracer signal input and the response is the measured tracer gas concentration either at selected points within the room or at the flow exit. In principle, any type of tracer signal may be used. However, the most common signals in ventilation studies are [9]: decay ("step-down"), continuous injection at a constant rate ("step-up"), and pulse injection. Continuous injection was applied in the present study. Tracer gas response may be measured at given locations within the room or at the flow exits. In this study the response was measured only at locations within the room. A recorded curve of tracer concentration against time represents an age distribution. The equation of the age distribution depends on the tracer signal used and on the population of fluid elements considered. In the following only continuous injection and responses within the room are discussed.

Let tracer-gas be injected at a constant rate q (cm^3 min^{-1}), from t=0, into an air supply duct and mixed homogeneously with supply air, Q_m, before entering the room. Note that infiltrated air, Q_i, was not labelled with tracer gas. By this approach estimates of the mean age of air were obtained for only a sub-population (Q_m) of the total air supply (Q_m+Q_i). Supply air tracer gas concentration is denoted C_m. Concentration of tracer gas at a location p within the room at time t is denoted $C_p(t)$. Steady-state concentration is denoted $C_p(\infty)$. Local mean age, μ_p, of air or contaminant at a position p is [6]

$$\mu_p = \int_0^\infty t f(t)\,dt = \int_0^\infty [1-F_p(t)]\,dt = \int_0^\infty [1-\frac{C_p(t)}{C_p(\infty)}]\,dt \quad (3)$$

Local mean age of air is a very useful parameter in detecting stagnant regions in a room. In stagnant regions the local mean age is elevated compared to well ventilated regions.

At a point p within the room some of the supplied air may come from other sources than the air supply duct considered. The proportion , PR_p, delivered by Q_m can be estimated from [6]

$$PR_p = \frac{C_p(\infty)}{C_m} \quad (4)$$

In recent research [10] PR_p has been termed the "outdoor air supply indices" (OASI). Note that Q_m=q/C_m.

Description of the workshop

In the workshop thermoplastics were converted into products by injection molding. A wide range of injection-molding machines (Nos. 1-16; Fig. 1) were installed in the workshop. In the first period of the study the workshop was ventilated from the mixing design principle. Layout and cross-section of the workshop (V=12.000 m^3) are shown in Fig. 1. Fresh air (no recirculation) was supplied at a constant rate by two ducts located 5.0 m above the floor and delivered through grilles at the same level (Fig. 1). Throughout the test period the air supply temperature varied between 20.5 and 20.9 °C. For practical reasons it was not possible to obtain the temperature at the exhaust. Based on workshop floor area the generated heat load was approximately 10-15 W m^{-2}. The main heat sources were located at the machines. Some machines (Nos. 1-5, 7) were on stand-by. Data on individual heat sources were not available. No local exhaust systems were installed at the machines. Heated and contaminated air was exhausted by a duct located 7.5 m above the floor (Fig. 1). Ventilation was designed for an unbalanced system, $Q_e > Q_m$, to keep an inward air flow through two permanently open doors (2.2x2.4 m, each) to other heated, departments of the factory.

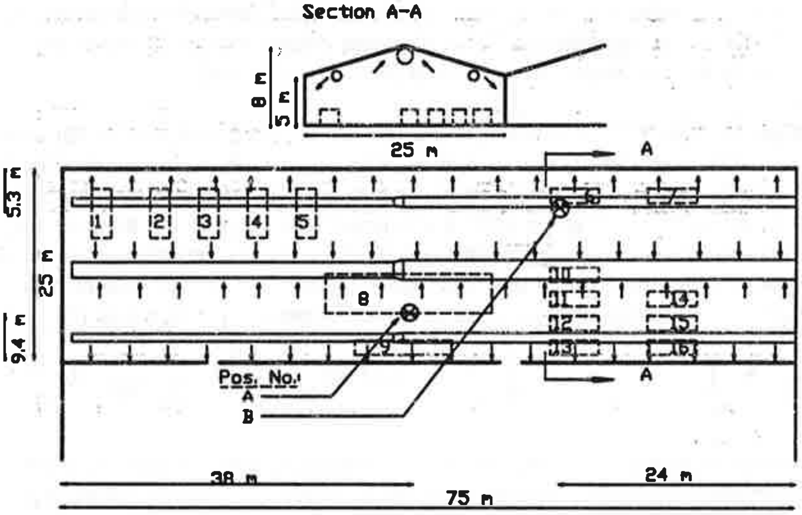

Fig. 1. Layout and cross section of the workshop designed for mixing ventilation (not drawn to scale).

During the second period of the study the workshop was ventilated from the displacement design principle. Layout and crosssection of the workshop are shown in Fig. 2, the only difference from Fig. 1 being a re-arranged ducting of the ventilation system to serve air supply terminal devices at floor level. Fresh air (no recirculation) was introduced at a constant rate into the zone of occupancy through large area terminal devices (semi-cylindrical: 2.1 m height, 0.4 m dia.). Throughout the test period the air supply temperature varied between 15.2 and 16.0 °C. Generated heat load was approximately 25-30 W m^{-2}. Some machines (Nos. 1 and 2) were on stand-by. Ventilation was designed for an unbalanced system to keep an inward air flow through the open doors.

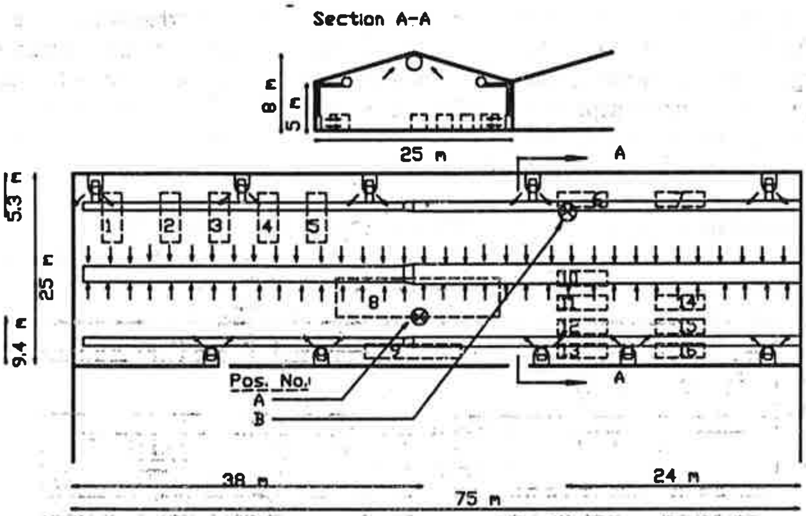

Fig. 2. Layout and cross section of the workshop designed for displacement ventilation (not drawn to scale).

Experimental procedure

Several tracer gases have been used in the past for characterising ventilation processes in buildings. For this study SF_6 was chosen as it has desirable characteristics in terms of detectability, safety, and cost, and has been used successfully in several ventilation studies [5,6]. Tracer gas (SF_6) was injected from a pressurized bottle at a constant flow rate of 10 cm^3 min^{-1} controlled by a calibrated rotameter at an estimated accuracy of ±3%. When measuring the local mean age of fresh air, the tracer was injected into the air supply ducts at a distance more than 80 times duct diameter from an inlet. When it enters the room the tracer may be considered homogeneously mixed with supply air [11]. To simulate a true contaminant with a tracer it is important that the tracer is discharged in a pattern similar to the contaminant origination pattern [12]. Density of the tracer is of importance if un-diluted tracer is injected as a simulated contaminant from a local source [9, 13]. With a reference to air neat SF_6 has a relative density of 5.0. To enhance the mixing of tracer and air a large area device was used for emitting the tracer at a low flow rate (10 cm^3 min^{-1}). The tracer was emitted into the convective plume above the heated barrel (0.15 m dia., 0.5 m long) of the injection unit located at machine No. 11. Surface temperature of the barrel was 65 °C.

Tracer gas concentrations, at an accuracy of ±5%, were collected sequentially with a 9 s sampling interval using a rapid response multipoint measuring system [14]. The detection limit of the system (a portable gas chromatograph) was 0.03 ppb SF_6. Concentrations and air temperatures were recorded at two test rig positions (Nos. A-B, Fig. 1) in the room. At test rig No. A a propeller fan located 4.5 m above the floor was blowing air downwards for cooling of molded products. At each test rig data were obtained at the following five different levels (given in m) above the floor: 0.5, 1.5, 2.5, 3.5, and 4.5. Data were also obtained from the air supply ducts. For practical reasons data were not obtained at the exhaust. At steady-state (second test period) the concentration of simulated contaminant was measured, by traversing, at 52 different locations in the workshop. The locations were selected to construct a horizontal grid covering the workshop at a level 1.6 m above the floor.

The air temperature was measured (Pt 100 transducers) sequentially (9 s step period) using the multipoint measuring system. Based on tests in the laboratory the estimated accuracy was ±0.2 °C. The air velocity was measured using a calibrated temperature compensated omnidirectional low-velocity flow analyser with technical characteristics meeting an accepted standard [15].

RESULTS

In the first test period the estimated air supply rate was $Q_m=q/C_m=380$ m^3 min^{-1}. In the second test period the estimated air supply rate was $Q_m=q/C_m=370$ m^3 min^{-1}. Smoke testing at the open doors confirmed that $Q_s>Q_m$ throughout both test periods.

The estimated parameters characterizing the air flow patterns throughout all the experiments are summarized in Fig. 3 (local mean age of air) and Fig. 4 (PR_p-indices). The estimated parameters characterizing the flow fields of the simulated air contaminant are summarized in Fig. 5 (local mean age of the contaminant) and Fig. 6 (steady state concentration). Data characterizing the thermal environment are summarized in Fig. 7 (air temperature). A contour plot of steady state concentrations of exposure to a simulated contaminant is given in Fig. 8.

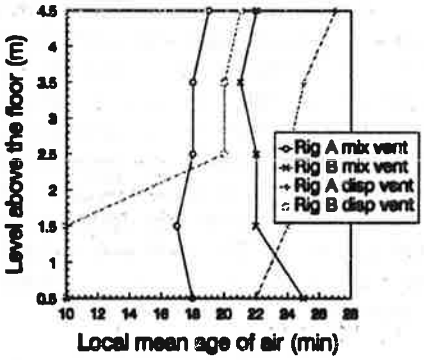

Fig. 3. Spatial distribution of the local mean age of air.

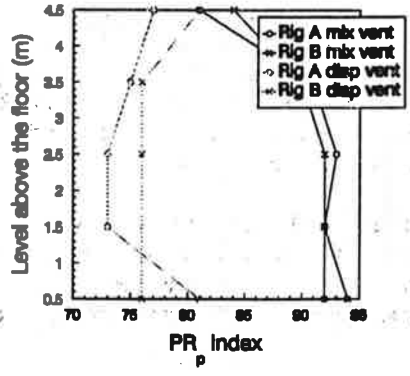

Fig. 4. Spatial distribution of the PR_p-indices.

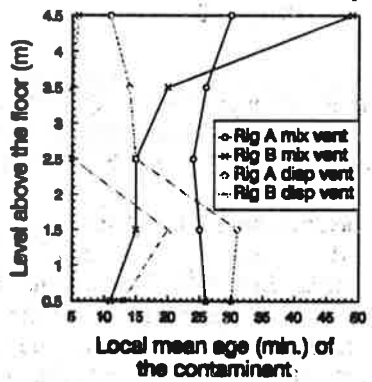

Fig. 5. Spatial distribution of the local mean age of a simulated contaminant.

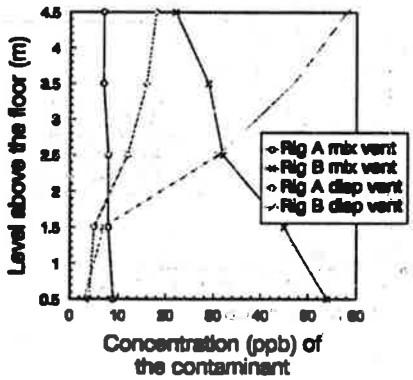

Fig. 6. Spatial distribution of exposure levels of a simulated contaminant.

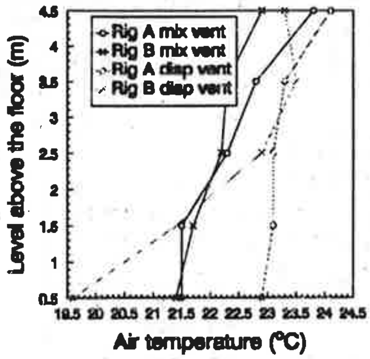

Fig. 7. Spatial distribution of the air temperature.

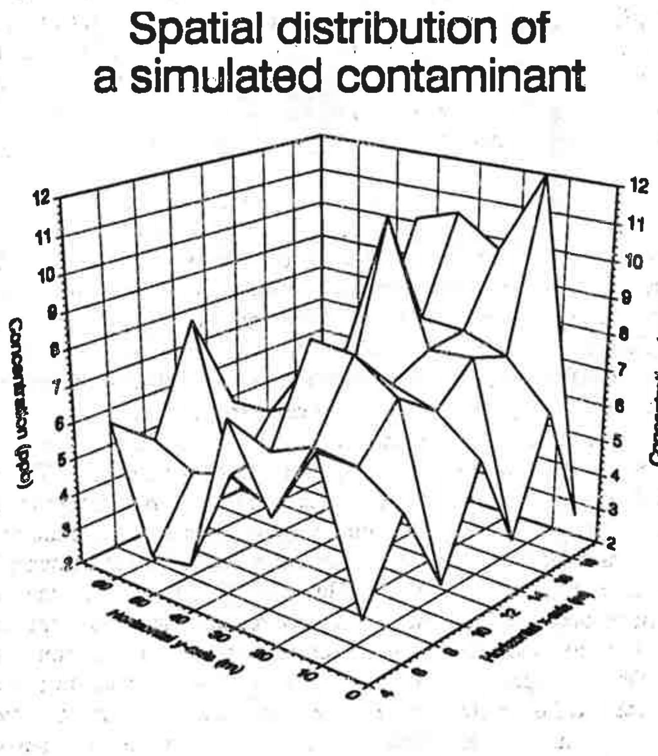

Fig. 9. Contour plot of exposure to a simulated contaminant (displacement ventilation).

DISCUSSION

Data from the present study were collected under normal conditions of production 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 a mixing system. Consistent with previous field studies [5,6] and with data obtained from an experimental room under isothermal conditions [16] the mixing system succeeded in creating a basically uniform vertical distributions of the local mean age of air (Fig. 3), the PR-index (Fig. 4) and the air temperature (Fig. 7). Note that conditions at test rig No. A were under influence from the propeller fan. As observed from Fig. 3 the circulating air flows were not sufficient on the horizontal level to create a uniform distribution of the local mean age of air. In zone of occupancy the air temperature complied with the recommended [17] thermal comfort limit (20-24 °C) for light, mainly sedentary activity, during summer. The vertical air temperature gradient did not exceed the comfort limit (3 °C m^{-1}). The spatial distribution of a contaminant and resulting concentration levels are a result of properties of the contaminant itself and the distribution of the supplied air within the room [9]. A vertical stratification of the contaminant concentration was observed only at test rig No. B (Fig. 6). It is noted that the mean age of the contaminant was low at floor level and high at ceiling level so indicating that the contaminants arrived first in the zone of occupancy for subsequently to rise towards the ceiling (Fig. 6). Due to the propeller fan no vertical stratification was observed at rig No. A.

In the second test period the ventilation system was designed for a vertical (upwards) displacement air flow. From the age parameter of air delivered by the air supply terminals, two distinct flow regions of the workshop was observed (Fig. 3, rig No. B) with the front located at a level of 1.5 m to 2.5 m above the floor. Below the front the mean age of the air was 10 min; above the front the mean age was 20 min. This finding of a vertical stratification was consistent with recent tracer gas studies of displacement ventilation in workshops [6,18] and in the laboratory [2]. No vertical stratification of the PR-index was observed (Fig. 4). The measured contaminant concentrations (Fig. 6) were stratified vertically consistent with the spatial distribution of the local mean age of air. A substantial increased concentration level was observed above the front. This finding was consistent with recent data on the spatial distribution of true contaminants in a workshop ventilated from the same design principle [14]. It is noted that the mean age of the simulated contaminant in the zone of occupancy was elevated compared to the conditions of the upper flow region (Fig. 5). This finding, supported by the observed concentration levels of the occupied zone indicate recirculating air flow from the upper flow region down into the lower region. As observed from the contour plot of steady-state contrations (Fig. 8) a spatial non-uniform air quality was created in the zone of occupancy. Data obtained from a fluid model have shown that the interface between the upper and lower zone acts as a lock that will hinder the transport of contaminants between the zones. However, differences in temperature between the fluid and the surfaces were of importance for setting up boundary layer flows. It was observed that cool surfaces located in the upper flow region to a degree caused boundary layer flows from the upper flow region to penetrate down into the lower region [19]. Basically the recommended thermal comfort limits were not violated in the zone of occupancy (test rig No. B).

The local mean age of air is a valuable tool for the evaluation of the performance of different ventilation systems. The technique has been used in experimental rooms [9] and in the field [5,6] for characterizing flow fields of different ventilation design principles. Throughout the study all conditions except the ventilation process may be considered approximately constant. It is noted that the heat load in the second test period was elevated compared to the first test period. According to this age parameter, and consistent with previous field studies [5,6], displacement ventilation was more efficient in distributing fresh air from the air supply ducts than mixing ventilation. Changing the ventilation design principle from mixing to displacement reduced the mean age of air in the zone of occupancy by a factor of 2 (test rig No. B). This improvement of the air renewal may not apply if cooling fans are used (test rig No. A). In terms of air quality the change in ventilation design principle reduced the exposure levels to the simulated contaminant by a factor 1.6-18.

CONCLUSION

In terms of supplying fresh air to the zone of occupancy the performance of displacement ventilation exceeded that of mixing ventilation by a factor of 2. This finding did not apply in situations where cooling fans were blowing air downwards. In terms of air quality the performance of displacement ventilation exceeded that of mixing ventilation by a factor of 1.6-18. Consequently, the displacement design principle has potential for improving air quality in workshops with a heat load.

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