Energy Impact of Ventilation and Air Infiltration
14th AIVC Conference, Copenhagen, Denmark
21-23 September 1993

Mixing VS.Displacement Ventilaton in Terms of Air Diffusion Effectiveness

N O Breum, E Ørhede

National Institute of Occupational Health, Lersoe Parkalle 105, DK-2100 Copenhagen, Denmark

SYNOPSIS

In occupational hygiene the common practice is to use dilution ventilation (MIXVENT) which ideally requires perfect mixing. Increasingly, however, displacement ventilation (DISPVENT) is being applied; ideally this involves fresh air displacing contaminated air without mixing. Keeping MIXVENT as a reference the approach of intervention was used to estimate the potential of DISPVENT for improving environmental conditions in a garment sewing plant. Air exchange efficiency of MIXVENT came to 49%. DISPVENT improved the efficiency to a level of 57%. In terms of local mean age of air DISPVENT improved conditions by a factor of 1.3. From the air diffusion effectiveness MIXVENT caused some short-circuiting of supply air to the exhaust grille. DISPVENT improved air diffusion effectiveness by a factor of 1.7, and no short-circuiting was observed. It is concluded that DISPVENT has potential for improving environmental conditions in industry.

1. INTRODUCTION

Ventilation systems based on the displacement design principle (DISPVENT) are rather common in Scandinavia. The aim of this design principle is to create supply-air conditions in the occupied zone, while the aim of traditional mixing systems (MIXVENT) is to create exhaust-air conditions throughout the room. Comprehensive data on the performance of displacement versus mixing ventilation are available from the laboratory. However, situations in real buildings may be different from those in the laboratory, and data from the laboratory may not be valid for real buildings. Therefore an intervention study of MIXVENT vs. DISPVENT has been made in a factory (a sewing plant). In this paper is given the data obtained on air renewal. Data on air quality and thermal conditions are reported elsewhere.(1) Models used for air renewal characterization are summarized first.

2. AIR FLOW PATTERNS

The age of a fluid element of air is defined to be the time that has passed since the element entered the space. Let the mean age at an arbitrary location, P, be denoted μ_P. A transit time is needed by the fluid element to be locally felt. Let the mean transit time be denoted ε_p. The fluid element is locally present for some time and then leave. Let mean presence time be denoted δ_P. The three time concepts are related by(2)

$$\mu_P = \varepsilon_P + \delta_P \tag{1}$$

An age distribution may be determined experimentally by labelling the supply air using a stimulus-response tracer-gas technique. In this study continuous injection of tracer gas ("step-up") was applied. Let injection at a constant rate, q, begin at t=0. Concentration at the air supply duct is C_S and air supply rate, Q_S, is obtained from $Q_S=q/C_S$. Concentration at time t at location P in the room is $C_P(t)$ and at steady state the concentration is $C_P(\infty)$. Then the cumulative age distribution is $F_p(t) = C_p(t)/C_p(\infty)$, and the mean age is

$$\mu_P = \int_0^\infty (1 - \frac{C_P(t)}{C_P(\infty)})\, dt \tag{2}$$

Let mean age obtained at the return grille be denoted μ_{RG}. Then the air diffusion effectiveness (ADE) is given by[3]

$$ADE = \frac{\mu_{RG}}{\mu_P} \tag{3}$$

Assuming a balanced ventilation process (no infiltration or exfiltration of air) room mean age of air, $<\mu>$, is

$$<\mu> = \frac{\int_0^\infty t\times(1 - \frac{C_E(t)}{C_E(\infty)})\, dt}{\int_0^\infty (1 - \frac{C_E(t)}{C_E(\infty)})\, dt} \tag{4}$$

where C_E is concentration at the exhaust duct.

Air exchange efficiency, β, is given by

$$\beta = \frac{\mu_E}{2\times<\mu>} \tag{5}$$

A balanced ventilation process was assumed. Validity of this assumption against air infiltration is obtained from an index of infiltration, PR, given as

$$PR = \frac{C_E(\infty)}{C_s} \tag{6}$$

Note that PR=1.0 may indicate a balanced ventilation process or exfiltration of supply air. PR<1.0 indicate infiltration of air.

Step-up stimulus-response tracer-gas technique requires constant air supply concentration. To allow some recirculation of exhaust air the injection rate has to be controlled by the air supply concentration. Let injection at a rate q(0) begin at t=0. When exhaust air concentration has come to steady-state, the injection rate has arrived at a reduced constant level of q(∞). From a tracer gas mass balance the proportion, RE, of supply air coming from exhaust air is.[1]

$$RE = (1 - \frac{q(\infty)}{q(0)}) \times \frac{C_s}{C_E(\infty)} \qquad (7)$$

RE is an index of recirculation, and RE=0 is achieved for a full outdoor air system.

3. THE FACTORY

The study was performed in a sewing plant making uniforms for the army. The sewing operation was conducted in a production area with 70 sewing machines in close proximity to each other, each machine performing a separate operation on the component part of the clothing. Local exhaust systems were installed at all machines. Approximately 40 workers, mainly seated, were in the shop. Layout and a cross-section of the workshop (V=2,300 m^3) are shown in Fig. 1. Based on workshop floor area the estimated convective heat load came to 14 W/m^2.

At outset of the study MIXVENT (Fig. 1) was used. Fresh air was supplied at a constant rate by 14 diffusors at ceiling level. The heated and contaminated air was exhausted at the machines and from ceiling level by grilles in a duct running along the rear wall. Exhaust air was directed to a common duct. During second period of the study DISPVENT was used. Layout and a cross-section of the workshop are shown in Fig. 2, the only difference from Fig. 1 being a rearranged ducting of the ventilation system to serve air supply terminal devices standing on floor.

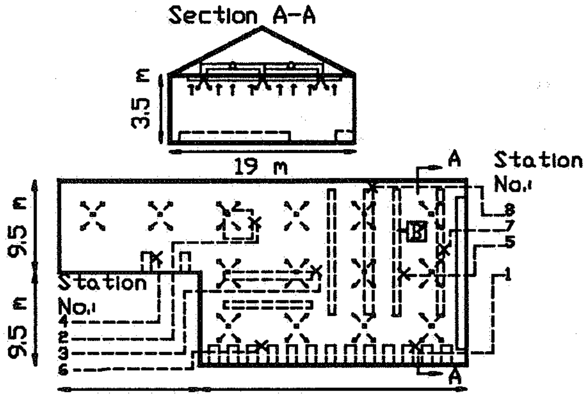

Fig 1. Layout and cross-section of the plant designed for MIXVENT (not to scale)

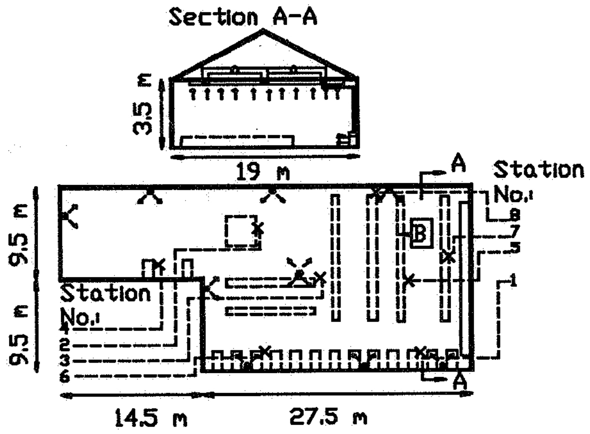

Fig. 2. Layout and cross-section of the plant designed for DISPVENT (not to scale)

4. EXPERIMENTAL PROCEDURE

Performance of MIXVENT was tested for a 3-week period in early winter. Data were collected once a week - on monday, wednesday, and friday, respectively. Data were collected as breathing zone samples at workstation Nos. 1-8 (Fig. 1). Data were also obtained from supply and exhaust air, respectively. Keeping identical test procedures the performance of DISPVENT was tested late winter in a period of expected outdoor weather conditions being similar to early winter. The paired t-test were used for statistical analysis of data. Tests were performed at a 5% (or better) level of significance.

4.1 Production rate of the plant

Throughout the study a constant production rate was assumed. Data on actual production rate were obtained for checking the validity of this assumption.

4.2 Flow fields of supplied air

Tracer gas (SF_6) was injected into the air supply duct. Some of the exhausted air was recirculated. To keep a constant supply air concentration the injected flow rate was manually adjusted to cancel out recirculated tracer gas. At t=0 the injected flow rate was $q(0)=4.25\ cm^3/min$.

Tracer gas concentrations at an estimated accuracy of ±5% were collected sequentially with a 9-s sampling interval using a multipoint measuring unit.[4] $F_P(t)$ was estimated by fitting the function $a(1-e^{-bt+c})$ to the data obtained. By integration, μ_P was estimated from Eq. 2. Mean transit time, ε_P, was estimated by solving the equation $F_P(t)=0$. Finally, δ_P was estimated by solving Eq. 1. In this study the ventilation system had no return-air plenum. Therefore mean age of air at the exhaust duct (μ_E) was substituted for mean age at the return grille (μ_{RG}) in estimating ADE from Eq. 3. Room mean age of air was estimated by integration (Eq. 4), and air exchange efficiency was obtained from Eq. 5. Air supply rate was estimated from $Q_s=q(0)/C_s$. Indices of infiltration and recirculation were obtained from Eq. 6 and 7, respectively.

5. RESULTS

5.1 Production rate of the plant

Actual production data on day of sampling were obtained from files kept at the plant. No statistical significant difference in production rate of the periods was observed.[1] However, a significant difference in convective heat load (Table 1) was observed - in the MIXVENT period the load was increased by a factor of 1.6 as compared to the DISPVENT period.

5.2 Flow fields of supplied air

At room level the flow field was characterized by air supply rate, infiltration index, room mean age of air, recirculation index, and air exchange efficiency. Condensed results are listed in Table 1. For convenience of comparison the table includes the relative performance (based on paired data) of MIXVENT vs. DISPVENT. From Table 1 air supply flow rate was reduced ($p=0.05$) in DISPVENT period. A tendency ($p=0.06$) towards an improved air exchange efficiency of DISPVENT was observed. Recirculation was increased ($p=0.02$) in DISPVENT period. Air supply temperature and calculated convective heat loads are included in Table 1.

Normal probability plots of parameters characterizing air flow patterns at workstation level are given in Fig. Nos. 3-6: mean age (Fig. 3), air diffusion effectiveness (Fig. 4), mean transit time (Fig. 5) and mean presence time (Fig. 6). Condensed results are listed in Table 2. From Table 2 DISPVENT reduced mean age of air ($p=0.002$), mean transit time of air ($p=0.002$), and mean presence time of air ($p=0.006$). Air diffusion effectiveness was improved by a factor of 1.7 ($p=0.001$).

Table 1. Air Supply Characteristics at Room Level.

	Ventilation design principle		Relative performance (MIXVENT/DISPVENT)
	MIXVENT	DISPVENT	
Air supply rate (m^3/min)	230±31[A]	200±10	1.2±0.1
Infiltration index, PR (%)	97±4	98±2	0.9±0.04
Room mean age of air, min	9.4±0.7	10.2±1.0	0.9±0.2
Air exchange efficiency (%)	49±5	57±1	0.9±0.1
Recirculation index, RE (%)	25±1	28±0.2	0.9±0.04
Air supply temp. (°C)	19.4±2.1	22.7±1.3	0.9±0.05
Convective heat load (W/m^2)	11.7±2.7	7.9±1.7	1.6±0.60

A: Arithmetic mean ± standard deviation (N=3).

Table 2. Air Supply Characteristics at Workstation Level

	Ventilation design principle		Relative performance (MIXVENT/DISPVENT)
	MIXVENT	DISPVENT	
Mean age of air (min)	11.3±1.7[A]	9.4±3.0	1.3±0.5
Air diffusion effectiveness	0.8±0.1	1.4±0.5	0.7±0.3
Mean transit time of air (min.)	1.4±0.5	0.8±0.6	2.5[B] 2.8[C]
Mean presence time of air (min.)	9.9±1.4	8.7±2.6	1.3±0.5

A: Arithmetic mean ± standard deviation (N=24).
B: Geometric mean (N=24).
C: Geometric standard deviation (N=24).

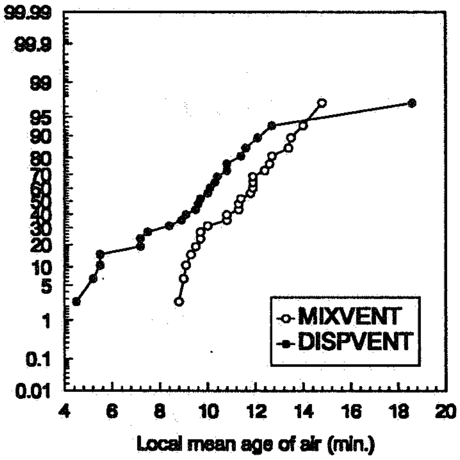

Fig. 3 Normal probability plot of local mean age of air

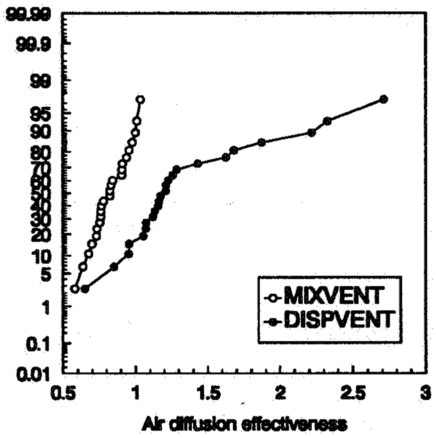

Fig. 4. Normal probability plot of air diffusion effectiveness

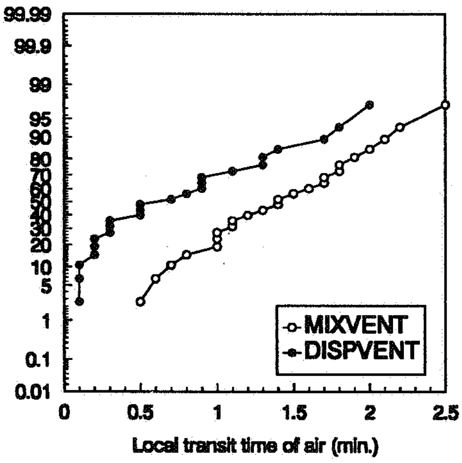

Fig. 5. Normal probability plot of local transit time

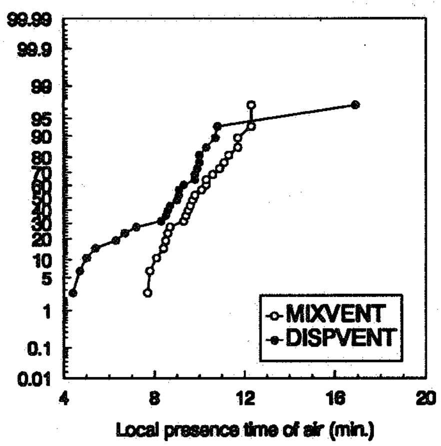

Fig. 6. Normal probability plot of local presence time of air

6. DISCUSSION

To achieve a high validity of an intervention study it is important to keep all other parameters equal than the parameter under investigation. Convective heat load is an important parameter for air flow patterns in a room. In this study convective heat load was increased by a factor of 1.6 in the MIXVENT period as compared to the DISPVENT period. No difference in production rate of the two study periods was observed, but outdoor air temperature was higher in MIXVENT than in DISPVENT period. The study was designed for a match in air supply flow rate of MIXVENT and DISPVENT, respectively. However, air supply flow rate of DISPVENT was reduced by a factor of 1.2 as compared to MIXVENT (Table I). A balanced ventilation process is a basic assumption for the model of room mean age of air and air exchange efficiency, respectively. From the obtained infiltration index (Table I) this was a valid assumption for the study.

At room level DISPVENT came out at an improved air exchange efficiency (57%) as compared to MIXVENT (49%). This finding was consistent with data from the laboratory.[2] Air supply flow rate of DISPVENT came out to be reduced as compared to MIXVENT. Nevertheless DISPVENT improved air renewal at local level (Table 2). Mean transit time of air was reduced by a factor of 2.5, mean presence time of air by a factor of 1.3, and local mean age of air by a factor of 1.3. Recent intervention studies came up with consistent findings reporting reductions in local mean age of air by a factor of 1.6-6.6[5] and 2.0.[4] If low-age supply air short-circuits to the return grille μ_{RG} should be less than μ_P; hence the ADE will be less than unity. The converse is true with a displacement flow pattern.[3] From Fig. 4 is observed that MIXVENT caused some short-circuiting (ADE<1.0) and that DISPVENT caused a displacement flow pattern (ADE>1.0). DISPVENT improved conditions by a factor of 1.7 calculated from paired ADE data.

7. CONCLUSION

Using the approach of intervention at a factory the performance of MIXVENT was compared to DISPVENT in terms of air renewal. At room level DISPVENT improved air exchange efficiency from 49% (MIXVENT) to 57%. At workstation level DISPVENT improved air renewal. In terms of local mean age of air DISPVENT improved conditions by a factor of 1.3. From the air diffusion effectiveness MIXVENT caused some short-circuiting of supply air to the exhaust grille. DISPVENT improved air diffusion effectiveness by a factor of 1.7, and no short-circuiting was observed. It is concluded that DISPVENT has potential for improving environmental conditions in industry.

ACKNOWLEDGEMENT

The study was supported by the Danish Working Environment Foundation (grant No. 1992-11).

8. REFERENCES

1. BREUM, N.O. and ØRHEDE, E.
"Dilution vs. displacement ventilation - environmental conditions in a garment sewing plant"
Am. Ind. Hygiene Assoc. J. 1993 (in press)

2. Breum, N.O.
"Ventilation efficiency in an occupied office with displacement ventilation - a laboratory study"
Env. Int. 18, 1992, pp353-361.

3. Fisk, W.J., Faulkner, D. and Prill, R.
"Air exchange effectiveness of conventional and task ventilation for offices"
ASHRAE Supplementary Proceedings of IAQ 91 Conference, 1991, pp30-34.

4. Breum, N.O. and Skotte, J.
"Displacement air flow in a printing plant measured with a rapid response tracer gas system"
Build. Serv. Res. Technol. 12, 1991, pp39-43

5. Breum, N.O., Helbo, F. and Laustesen, O.
"Dilution versus Displacement Ventilation - an Intervention Study"
Ann. Occ. Hyg. 33, 1989, pp321-329.