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DILUTION VERSUS DISPLACEMENT VENTILATION—ENVIRONMENTAL CONDITIONS IN A GARMENT SEWING PLANT

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This paper compares the practice of dilution ventilation (DILVENT), which ideally requires perfect mixing, with displacement ventilation (DISPVENT), which involves fresh air displacing contaminated air without mixing. Keeping DILVENT 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 DILVENT came to 49%. DISPVENT improved the efficiency to a level of 57%. At workstation level DISPVENT improved air renewal by a factor of 1.3. DISPVENT reduced exposure to nonrespirable particles by a factor of 1.6–2.8. Exposure to respirable dust was reduced, but formaldehyde concentrations were left unaffected. DISPVENT improved conditions for control of bystander exposure by a factor of 7.7. DISPVENT improved thermal conditions. Draft risk was reduced by a factor of 1.9. It is concluded that DISPVENT has potential for improving environmental conditions in industry.

The main purpose of ventilating a room is to provide good air quality and thermal comfort for the occupants. This may be achieved in several ways. The more conventional method is to continuously dilute the indoor air contaminants by mixing the room air with "fresh" incoming air and remove the contaminated air from a suitable location. In this design air jets with high momentum are often supplied at ceiling level. Room air is entrained into the jets, thereby generating secondary air flows in the room (Figure 1). This dilution process diminishes a spatial non-uniform air temperature and contaminant distribution in the room.

From an air quality point of view the usefulness of the dilution design principle has been questioned.(1) As a general alternative to dilution ventilation (DILVENT) much attention has been paid recently to the vertical displacement ventilation (DISPVENT) design principle. In Scandinavia the present market share of such systems for industrial ventilation was estimated to be 50%.(2) The principle of DISPVENT is that cool air is supplied with a low momentum through large inlet devices near the floor (Figure 2). Air velocity at inlet is often less than 0.5 m/sec (100 ft/min). Due to such relatively high air velocities the floor area close to an inlet has to be restricted from occupancy. In the design procedure this near-field zone is considered to be an area exposed to air velocities above 0.2 m/sec (40 ft/min).(3) The cool air is heated by heat sources in the room, and convective plumes are formed above heat sources. The plumes may act as carriers of entrained contaminants. The heated air is exhausted at ceiling level. If the convective upcurrents are not balanced by fresh air supply and high-level exhaust, a layer of heated and contaminated air starts to descend. The layer stops at a level, Z, where air flow rate of convective upcurrents equals the supplied air flow rate (Figure 2). As a design goal the layer should be located above the zone of occupancy.

Keeping DILVENT as a reference, comprehensive data from the laboratory indicate a substantial potential of DISPVENT for improved air renewal and decreased contaminant levels in the zone of occupancy.(4,5) Test data from the laboratory may not be valid for conditions in actual buildings. However, consistent data obtained by the approach of intervention were reported from actual industrial buildings.(6,7) It is noted that the reported data did not include information on dust in air. Airborne particles, as compared to gases and vapors, have their own inherent properties of coagulation, sedimentation, and deposition. Therefore, an intervention study of air and contaminant flow fields of

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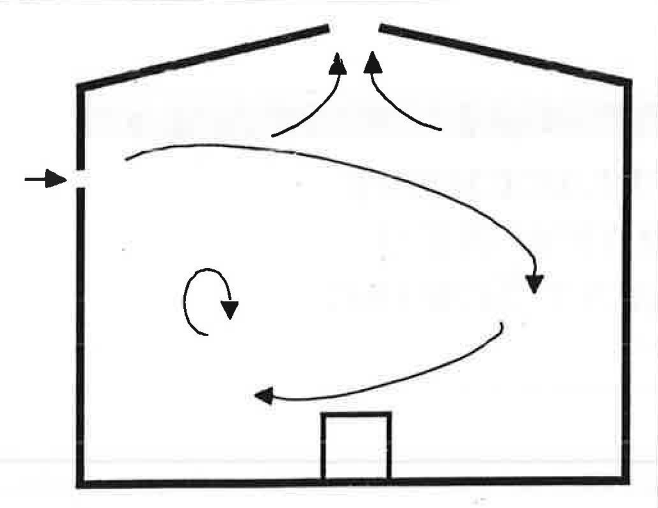

FIGURE 1. Dilution ventilation principle

DILVENT versus DISPVENT has been made in a factory (a ewing plant) having a complex mixture (dust and gases) of ir contaminants. Parameters used for comparison include hermal comfort, air renewal, and air quality. Models on which the study is based are summarized first.

MODELS FOR ENVIRONMENTAL CHARACTERIZATION

A contaminant source may have its own momentum flux reating its own flow pattern. Consequently, the flow pattern of contaminants usually differs from that of fresh air. It s therefore necessary to characterize flow patterns of air and contaminants separately. Models used for flow field characterization are summarized below. A mechanically ventilated room (volume V m^3 [ft^3]) with one supply duct (flow rate Q_s m^3/min [ft^3/min]) and one exhaust duct (flow rate Q_e m^3/min [ft^3/min]) is considered. A balanced system with a constant flow rate Q is assumed, i.e. $Q = Q_s = Q_e$. Nominal air change rate is denoted n, and $n = Q/V$. Nominal time constant of the ventilation process is τ_n, and $\tau_n = V/Q$.

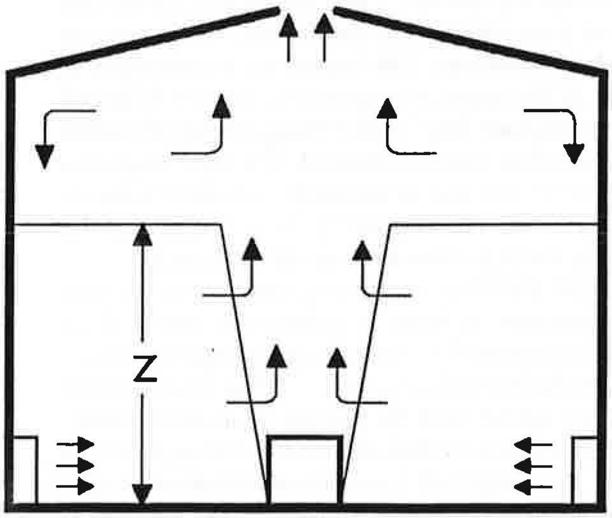

FIGURE 2. Displacement ventilation principle. At level Z air flow rate of convective upcurrents equals the supplied air flow rate.

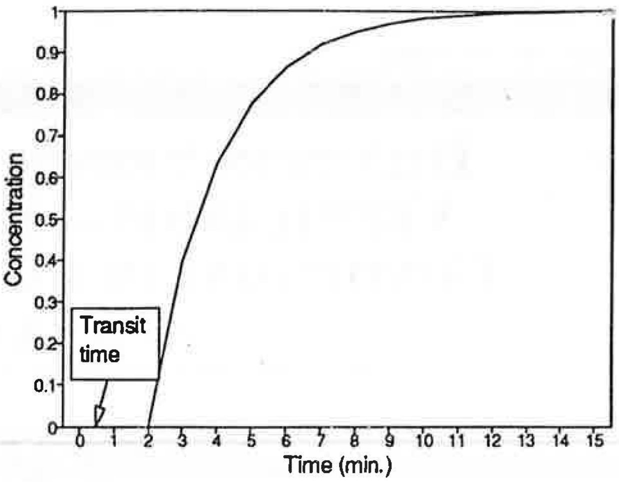

FIGURE 3. Transit time needed by fluid elements to be locally felt at a point p. The fluid elements (from $t = 0$) enter the room at a constant rate. The concentration is given as $C_p(t)/C_p(\infty)$.

Concept of Age Analysis

Age analysis has proven to be a powerful tool in flow field characterization. Part of the following presentation of some basic concepts has been adopted from a previous report.[5] The age of a fluid element of air is defined to be the time that has passed since the element entered the space. Let mean age at an arbitrary point p be denoted μ_p. A transit time is needed by the fluid element to be locally felt. For clarification, the transit time is shown in Figure 3 for the case of fluid elements (from $t = 0$) entering the room at a constant rate. Let mean transit time be denoted ϵ_p. The fluid element is locally present for some time and then leaves. Let mean presence time be denoted δ_p. Note that the reciprocal of presence time represents local air change rate.[8] The three time concepts are related by

$$\mu_p = \epsilon_p + \delta_p \tag{1}$$

Three populations of fluid elements of interest may be defined: (a) the total internal population of all elements within the space, (b) the local internal population of all elements within a small volume at an arbitrary point within the space, and (c) the external population of elements leaving the space. Each of the populations mentioned is characterized by a statistical cumulative age distribution F(t), which gives the fraction of the population younger than t. The corresponding age frequency distribution f(t) is the derivative of F(t), i.e.:

$$f(t) = \frac{dF(t)}{dt} \text{ or } F(t) = \int_0^t f(t)\,dt \tag{2}$$

Mean of the distribution is μ where

$$\mu = \int_0^\infty t f(t)\,dt = \int_0^\infty \left(1 - F(t)\right) dt. \tag{3}$$

An age distribution may be determined experimentally by labeling the air using stimulus response tracer-gas technique. Stimulus is a tracer signal input and response is the measured tracer-gas concentration. In principle any type of tracer signal may be used. However, in this study continuous injection of tracer-gas ("step-up" technique) was applied. Let injection at a constant rate begin at $t = 0$. Injection rate is q and air supply concentration is $C_s = q/Q_s$. At steady state, the concentration at point p is $C_p(\infty)$, and $F_p(t)$ is[9]

$$F_p(t) = \frac{C_p(t)}{C_p(\infty)}. \tag{4}$$

From Equation 3, the mean age μ_p at point p is

$$\mu_p = \int_0^\infty \left(1 - \frac{C_p(t)}{C_p(\infty)}\right) dt. \tag{5}$$

If point p is at the exhaust, the population of fluid elements leaving the room is also described by Equation 5. Note that the mean age of exhausted air is equal to the nominal time constant of the ventilation process.[1] Concentration at the exhaust is denoted $C_e(t)$, and the age frequency distribution of all fluid elements within the room is[9]

$$f(t) = \frac{1 - \dfrac{C_e(t)}{C_e(\infty)}}{\displaystyle\int_0^\infty \left(1 - \frac{C_e(t)}{C_e(\infty)}\right) dt}. \tag{6}$$

From Equations 3 and 6 room mean age $<\mu>$ of all the fluid elements is

$$\langle\mu\rangle = \frac{\displaystyle\int_0^\infty t\left(1 - \frac{C_e(t)}{C_e(\infty)}\right) dt}{\displaystyle\int_0^\infty \left(1 - \frac{C_e(t)}{C_e(\infty)}\right) dt}. \tag{7}$$

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

$$PR = \frac{C_e(\infty)}{C_s}. \tag{8}$$

Infiltration of air yields $PR < 1.0$, while $PR = 1.0$ indicates either a balanced ventilation process or exfiltration of supply 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 air supply concentration. Let injection at a rate q(0) begin at $t = 0$. When exhaust air concentration has come to steady-state, $C_e(\infty)$, the injection rate has arrived at a reduced constant level of $q(\infty)$. From a tracer-gas mass balance the proportion of supply air coming from the exhaust air is given by the recirculation index, RE, defined as

$$RE = \left(1 - \frac{q(\infty)}{q(0)}\right)\frac{C_s}{C_e(\infty)}. \tag{9}$$

RE is an index of recirculation, and $RE = 0$ is achieved for a full outdoor air system (100% makeup).

Flow Fields of Supplied Air

As a design goal local mean age of air in the zone of occupancy should be low as compared to mean age of exhausted air. By definition, displacement flow pattern (plug-flow) is considered most efficient for exchange of air within a room.[1] If the flow pattern of the room investigated were like plug-flow, the mean age of air within the room would be "low." Let this mean age be denoted $<\mu_d>$. Then $<\mu_d> = \tau_n/2$. The actual flow pattern, however, may deviate from the defined ideal, and the mean age of air in the room would, therefore, be higher than $<\mu_d>$. Air exchange efficiency, β, is by definition[1]

$$\beta = \frac{\langle\mu_d\rangle}{\langle\mu\rangle} = \frac{\tau_n}{2\langle\mu\rangle}. \tag{10}$$

Note that $0 < \beta < 1.0$ An air exchange efficiency of $\beta = 1.0$ is achieved for ideal displacement flow and complete mixing is characterized by an efficiency of 0.5, while stagnant flow yields $\beta < 0.5$.

Flow Fields of Contaminants

In this study actual concentrations of air contaminants were used as indicators for contaminant removal performance of the ventilation system. However, a transient transfer coefficient was used to characterize flow patterns of a contaminant emitted from a local source. Consider a source of emission rate $q_B(t)$ located at Workstation B in the room. Let emission begin at $t = 0$. Concentration at Workstation A is denoted $C_A(t)$. Then for a period of $0 - t$ the transient transfer coefficient η_{B-A} is

$$\eta_{B-A} = \frac{\displaystyle\int_0^t C_A(t)\,dt}{\displaystyle\int_0^t q_B(t)\,dt}. \tag{11}$$

Note that the transfer coefficient depends heavily on location of the source and the sampling location. η_{B-A} is an

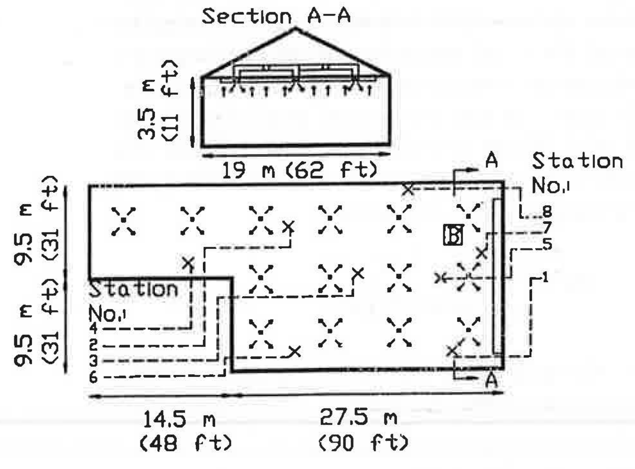

FIGURE 4. Layout and cross-section of the plant designed for DILVENT (not to scale)

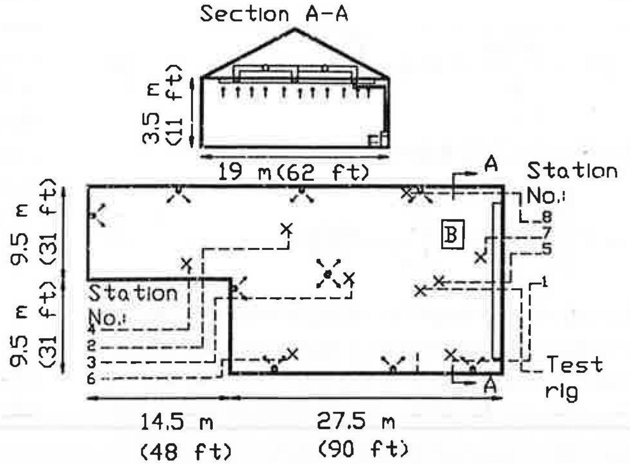

FIGURE 5. Layout and cross-section of the plant designed for DISPVENT (not to scale)

mportant parameter for control of bystander exposure. As a design goal the transfer coefficient should be kept at a minimum.

THERMAL ENVIRONMENT

Thermal comfort aspects are of vital importance in the design of a ventilation system. Criteria for comfort are given in an accepted standard.[10] This standard does not take into account the impact of air turbulence intensity on the sensation of draft. However, a model of draft risk has been included in a modified version of the standard.[11] The draft-risk model was used in this study. The model predicts the percentage of people dissatisfied due to draft as a function of air temperaure, T_a (°C), mean velocity, u (m/sec), and turbulence intensity, Tu (%). The percent dissatisfied, PD, is given by:

$$PD = (34 - T_a) \times (u - 0.05)^{0.62} (0.37 \times u \times T_u + 3.14) \quad \textbf{(12)}$$

For $u < 0.05$ insert $u = 0.05$ m/sec; for $PD > 100\%$ use $PD = 100\%$.

THE FACTORY

This paper describes a study performed in a sewing plant making uniforms and waterproof clothes for the army. Production rate of the plant was considered to be constant. The plant received fabrics already cut to pattern, and processes performed included sewing and packing. Quality control required constant fabric characteristics (±2%). Detailed information on the fabrics was kept in classified files. However, in broad terms fabrics were a mixture of cotton (50%) and polyester (50%) for uniforms and PVC for waterproof clothes.

Formaldehyde is a major component in resins used to treat cotton fabric for shrink-resistant and crease characteristics. Treated fabrics usually contain some residual formaldehyde and offgassing may occur during subsequent processing.

Fabric treatment systems may be divided generally into precure and postcure systems.[12] In postcure systems the final polymerization does not take place until the garment is manufactured. In precure systems, the final polymerization of the resin takes place in the finishing plant, and there is little residual formaldehyde. Cotton fabrics used in the garment sewing plant were precured.

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 ($V = 2300$ m^3 [81 000 ft^3]) are shown in Figure 4. Based on workshop floor area, the estimated convective heat load came to 14 W/m^2 (4.4 Btu/h ft^2).

During the first period of the study DILVENT (Figure 4) was used. Fresh air was supplied at a constant rate by 14 diffusers at ceiling level. The heated and contaminated air was exhausted at the machines and at ceiling level. Exhaust air was directed to a common duct. During the second period of the study DISPVENT was used. A layout and cross-section of the workshop are shown in Figure 5, the only difference from Figure 4 being a rearranged ducting of the ventilation system to serve air terminal devices standing on floor.

EXPERIMENTAL PROCEDURE

General Design

Performance of DILVENT was tested for a three-week period in early winter. A prerequisite of all statistics is that the individual measurements represent independent (uncorrelated) data. Consequently samples should not be collected during brief campaigns of a few consecutive days.[13] In this study data were collected once a week, on

Monday, Wednesday, and Friday, respectively. Data were collected as breathing zone samples at Workstations 1–8 (Figure 4) and as area sampling at a vertical test rig (Figure 4). Data at the rig were obtained at the following levels above the floor: 0.5 m (1.6 ft), 1.0 m (3.2 ft), 1.5 m (4.8 ft), 2.0 m (6.4 ft), and 2.5 m (8.0 ft). Data were also obtained from supply and exhaust air, respectively. Keeping identical test procedures, the performance of DISPVENT was tested in late winter during a period when outdoor weather conditions were expected to be similar to early winter. The paired t-test, and alternatively the Wilcoxon test (in case of non-normal data distribution) were used for statistical analysis of data. Probability plots were used in checking data for non-normality. Statistical tests were performed at a 5% (or better) level of significance. The arithmetic mean of a left censored log-normal data distribution was estimated following an approach published elsewhere.(14)

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.

Flow Fields of Supplied Air

Several tracer gases have been used in the past for characterizing flow fields of air 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.(7,15) The tracer gas was injected from a pressurized bottle at a flow rate controlled by a calibrated rotameter at an estimated accuracy of ±3%. The tracer gas was injected into the air supply duct at a distance from an inlet of more than 80 times the duct diameter.(16) When it enters the room the tracer may be considered homogeneously mixed with supply air. Some of the exhausted air was recirculated. To keep a constant air supply tracer gas concentration, the injected flow rate was manually adjusted to cancel out the recirculated tracer gas. At $t = 0$ the injected flow rate was $q(0) = 0.00425$ L/min.

Tracer gas concentrations at an estimated accuracy of ±5% were collected sequentially with a 9–s sampling interval using a multipoint measuring unit.(15) $F_p(t)$ was estimated by fitting the function $a(1-e^{-bt+c})$ to the data obtained. By integration, μ_p was estimated from Equation 5. As shown in Figure 3, an estimate of mean transit time, ϵ_p, is obtained by solving the equation $F_p(t) = 0$. This approach was used for this study. Finally, δ_p was estimated by solving Equation 1. Room mean age of air was estimated by integration (Equation 7), and air-exchange efficiency was obtained from Equation 10. Air supply rate was estimated from $Q_s = q(0)/C_s$. Indices of infiltration and recirculation were obtained from Equations 8 and 9, respectively.

Flow Fields of Contaminants

A recent review drew attention to the complexity of air quality issue in the textile industry.(17) However, dust and formaldehyde were selected as indicators for the present study. During full-shift periods of approximately 8 hours "total" airborne particulate matter (TPM) and respirable particulate matter (RPM) were collected side by side on 25 mm, 8.0 μm cellulose nitrate filters. TPM was collected using closed-face Millipore field monitors with a 5.6 mm inlet at 1.9 L/min (1.25 m/sec inlet velocity). RPM was collected using modified Higgins and Dewell cyclones at 1.9 L/min, according to the British Medical Research Council.(18) The collected mass was determined by weighing the filter before and after sampling. Concentrations below 0.08 mg/m^3 were considered below detection limit of the outlined procedure.

In addition to the gravimetric approach, analysis by microscopy was used for further characterization of TMP samples. Collected particles were counted by image analysis (Kontron Elektronik GMBH, IBAS Image Analysis System, Eching, Germany). A particle was quantified in terms of convex perimeter and area equivalent circle diameter. The aspect ratio was calculated, and particles exceeding a ratio of 5 were considered fibers. To classify particles as being respirable or nonrespirable, a number of samples ($N = 3$) obtained by side-by-side sampling of TMP and RPM were analyzed. As a function of area equivalent circle diameter the ratio of RPM over TPM was calculated, and the cumulative distribution was plotted on lognormal probability paper. The median of the distribution was used for classifying particles as being respirable or nonrespirable. The median was 32 μm for fibers and 13 μm for nonfibers.(19)

Formaldehyde samples were collected in 20 mL distilled water in impingers operated for a 60 min period at a flow rate of 1 L/min. Based on the Hantzsch reaction the collected formaldehyde was stabilized and analyzed fluorimetrically at a detection limit of 2 μg/m^3.(20) Samples were collected just after lunch break.

Tracer gas (SF_6) was used as a simulated contaminant to estimate the transient transfer coefficient. To simulate a true contaminant by a tracer it is important that the tracer is discharged in a pattern similar to the contaminant origination pattern. Density of a tracer is of importance if undiluted tracer is injected as a simulated contaminant from a local source. With reference to air, undiluted SF_6 has a relative density of 5.0. The tracer was emitted (0.0065 L/min) at a calculated low velocity (< 0.01 m/sec [2 ft/min]) on a warm (27 °C [81 °F]) surface on top of a sewing machine located at Workstation B (Figure 4). Using the above-mentioned multipoint unit tracer gas concentration versus time was measured for a period of 90 min just after lunch break.

Thermal Environment

Air velocity, turbulence intensity, air temperature, plane radiant temperature, and air humidity were measured using an indoor climate analyzer (Type 1213, Bruel & Kjaer, Copenhagen, Denmark) with technical characteristics meeting accepted standards.(21) At the workstations data were obtained at three levels above the floor: 0.1 m (0.3 ft), 0.6 m (2.0 ft), and 1.1 m (3.6 ft). Mean air velocity and turbulence intensity were obtained on a 3 min sampling period.(22) Mean radiant temperature was calculated from measured plane radiant temperatures.(23) As outlined elsewhere, the operative temperature was calculated from data on air temperature and mean radiant temperature.(10)

TABLE I. Air Supply Characteristics at Room Level

	Ventilation Design Principle		Relative Performance
	DILVENT	*DISPVENT*	*(DILVENT/DISPVENT)*
Air supply rate	230 ± 31[A] (m³/min)	198 ± 10 (m³/min)	1.2 ± 0.1
	8100 ± 1100 (ft³/min)	7,000 ± 350 (ft³/min)	
Infiltration index, PR	97 ± 4 (%)	98 ± 2 (%)	0.9 ± 0.04
Room mean age of air	9.4 ± 0.7 (min)	10.2 ± 1.0 (min)	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.	19.4 ± 2.1 (°C)	22.7 ± 1.3 (°C)	0.9 ± 0.05
	66.9 ± 3.8 (°F)	72.9 ± 2.3 (°F)	
Air humidity	35 ± 8 (%)	30 ± 14 (%)	1.5 ± 0.9

[A] Arithmetic mean ± standard deviation (N = 3)

RESULTS

Production Rate of The Plant

Actual production data on the day of sampling were obtained from files kept at the plant. A rather large day-to-day variation in production data was observed. During the DILVENT period the number (mean ± standard deviation) per day of finished uniforms and weatherproof clothings was 194 ± 25 and 42 ± 43, respectively. The figures for the DISPVENT period were 169 ± 79 (uniforms) and 15 ± 14 (weatherproof clothings). No statistically significant difference in the production rate of the periods was observed.

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 I. For convenience of comparison the table includes the relative performance (based on paired data) of DILVENT versus DISPVENT. Table I shows that the air supply flow rate was reduced ($p = 0.05$) in the DISPVENT period. A tendency ($p = 0.06$) towards an improved air-exchange efficiency of DISPVENT was observed. Recirculation was increased ($p = 0.02$) in the DISPVENT period.

At workstation level the flow field of air was characterized by mean age, mean transit time, and mean presence time. Condensed results are listed in Table II. As shown in Table II, DISPVENT reduced the mean age of air ($p = 0.002$), mean transit time of air ($p = 0.002$), and mean presence time of air ($p = 0.006$). Data obtained at the test rig are reported elsewhere,(19) but no vertical stratification was observed in the parameters used for flow field characterization.

Thermal Environment

Outdoor air temperatures for the two study periods were 9.5 ± 0.7 °C (49.1 ± 1.3 °F) (DILVENT) and 4.7 ± 5.5 °C (40.5 ± 9.9 °F) (DISPVENT). Air supply temperature and air humidity for the two study periods are given in Table I. Air supply temperature was elevated ($p = 0.02$) in DISPVENT period.

Thermal parameters obtained at workstation level are listed in Table III. As recommended elsewhere, operative temperature is given at the abdomen level, i.e., 0.6 m (2.0 ft) above the floor, for seated persons.(22) Air velocity, turbulence intensity, and draft risk are given as a maximum of the data obtained at the three different levels above the floor. Operative temperature ($p = 0.001$) and vertical gradient in air temperature ($p = 0.001$) were increased in DISPVENT period. Air velocity was reduced ($p = 0.001$), and so was calculated draft risk ($p = 0.001$). Temperature data obtained at the rig are reported elsewhere,(19) but no vertical stratification was observed.

Flow Fields of Contaminants

At workstation level, flow fields of contaminants were quantified in terms of concentrations of TPM, RPM, formaldehyde, and the transient transfer coefficient. Concentrations in terms of number of respirable and nonrespirable particles (fibers and nonfibers) were obtained. Condensed test results (Workstations 1–8) are listed in Table IV. The gravimetric approach for quantification of dust in air came up with a number of samples (Table IV) having concentrations at or below detection limit. For respirable dust the number was increased ($p = 0.05$) in DISPVENT period. The arithmetic means were estimated (Table IV) assuming log-normal data distributions. However, more than 90% of samples in a dataset (RPM, DISPVENT) were at or below detection limit. For that dataset it seemed justified not to estimate the mean. From the number of nonrespirable particles in air DILVENT came out at increased concentrations as compared to DISPVENT. Concentrations were increased by a factor of 2.8 (nonfibers)

TABLE II. Air Supply Characteristics at Workstation Level

	Ventilation Design Principle		Relative Performance
	DILVENT	*DISPVENT*	*(DILVENT/DISPVENT)*
Mean age of air	11.3 ± 1.7[A] (min)	9.4 ± 3.0 (min)	1.3 ± 0.5
Mean transit time of air	1.4 ± 0.5 (min)	0.8 ± 0.6 (min)	2.5[B]
			2.8[C]
Mean presence time of air	9.9 ± 1.4 (min)	8.7 ± 2.6 (min)	1.3 ± 0.5

[A] Arithmetic mean ± standard deviation (N = 24)
[B] Geometric mean (N = 24)
[C] Geometric standard deviation (N = 24)

TABLE III. Thermal Environment at Workstation Level

	Ventilation Design Principle		*Relative Performance*
	DILVENT	*DISPVENT*	*(DILVENT/DISPVENT)*
Operative temp.	21.9 ± 0.9^A (°C)	23.3 ± 1.2 (°C)	0.9 ± 0.04
	71.4 ± 1.6 (°F)	73.9 ± 2.2 (°F)	
Vertical temp. gradient	0.7 ± 0.4 (°C/m)	1.2 ± 0.4 (°C/m)	0.7 ± 0.4
	0.4 ± 0.2 (°F/ft)	0.7 ± 0.2 (°F/ft)	
Air velocity	0.14 ± 0.03 (m/sec)	0.11 ± 0.03 (m/s)ec	1.4 ± 0.5
	28 ± 6 (ft/min)	22 ± 6 (ft/min)	
Turbulent intensity	52 ± 19 (%)	62 ± 22 (%)	1.0 ± 0.6
Draft risk PD	16 ± 6 (%)	10 ± 4 (%)	1.9 ± 1.4

^{A}Arithmetic mean ± standard deviation (N = 24)

and 1.6 (fibers). However this finding was significant (p = 0.0001) only for data on nonfibers. No difference between DILVENT and DISPVENT was observed in number of respirable particles (fibers or nonfibers) in air. No vertical stratification in data on airborne contaminants was observed at the test rig. The transfer coefficient was reduced by a factor of 7.7 (p = 0.001) in the DISPVENT period. Data obtained on transfer coefficient at the test rig are reported elsewhere,(19) but a vertical stratification (p = 0.05) was observed in DISPVENT period.

DISCUSSION

To achieve a high validity in an intervention study, it is important to keep all parameters equal other than the parameter under investigation. However, data of the present study were collected under normal conditions of production with no attempt to reduce disturbances caused by traffic in or out of the plant, fluctuations in daily production rate, etc.

From data obtained at the plant no difference in production rate of the two study periods was observed. The study was designed for a match in air supply flow rate of DILVENT and DISPVENT, respectively. However, the air supply flow rate of DISPVENT was reduced by a factor of 1.2 as compared to DILVENT (Table I). A balanced ventilation process is a basic assumption for the model of room mean age of air and air exchange efficiency, respectively.(1) From the obtained infiltration index (Table I) this was a valid assumption for the study. Consistent with data from the laboratory DISPVENT came out at an improved air exchange efficiency (57%) as compared to DILVENT (49%).(5) Air supply flow rate of DISPVENT came out to be reduced as compared to DILVENT. Nevertheless DISPVENT improved air renewal at local level (Table II). 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. Using the approach of intervention, recent field studies came up with consistent findings reporting reductions in local mean age of air by a factor of 1.6–6.6 and 2.0.(6,7) In terms of time concepts, vertical stratification in air supply is a characteristic feature of DISPVENT. However, no stratification was observed at the test rig. Perhaps turbulence generated by workstations surrounding the test rig ruined a vertical stratification.

The basic idea of DISPVENT is to create supply air conditions in the zone of occupancy, while the aim of DILVENT is to create exhaust air conditions in the zone of occupancy. Consequently DISPVENT allows a higher air-supply temperature than DILVENT. Previous research has estimated that DISPVENT can achieve up to 25% reduction in cooling energy cost.(24) In this study air supply temperature of DILVENT came to 90% of that of DISPVENT (Table I). At workstation level, thermal conditions of DILVENT as well as DISPVENT basically

TABLE IV. Contaminant Flow Field Characteristics at Workstation Level

	Ventilation design principle		*Relative Performance*
	DILVENT	*DISPVENT*	*(DILVENT/DISPVENT)*
Formaldehyde (mg/m^3)	0.021^A	0.022^A	0.9^A
	1.5^B	1.8^B	1.8^B
TPM (mg/m^3)	0.12^C	0.04^C	NA^E
	50^D	63^D	
Nonrespirable fibers	0.0020^A	0.0013^A	1.6^A
(particles per cc)	2.5^B	6.6^B	4.3^B
Nonrespirable nonfibers	0.0086^A	0.0033^A	2.8^A
(particles per cc)	1.5^B	2.9^B	2.9^B
RPM (mg/m^3)	0.05^C	NA	NA
	71^D	92^D	
Respirable fibers	0.13^A	0.23^A	0.48^A
(particles per cc)	2.2^B	4.2^B	6.7^B
Respirable nonfibers	0.64^A	0.63^A	0.97^A
(particles per cc)	1.6^B	1.6^B	2.2^B
Transient transfer coefficient	700^A	90^A	7.7^A
(ppb/[L/min])	2.6^B	9.3^B	5.6^B

^{A}Geometric mean (N = 24)
^{B}Geometric standard deviation
^{C}Arithmetic mean (N = 24)
^{D}Percentage of samples at or below detection limit
^{E}Not available due to left censored data distributions

complied with the following recommended thermal comfort limits for light, mainly sedentary, activity during winter: operative temperature 20–24 °C (68–75 °F), vertical air temperature gradient < 3 °C/m (1.6 °F/ft), and calculated draft risk below 15%.(11) Consistent with previous studies DISPVENT reduced air velocity in the zone of occupancy.(6,7) The level of turbulent intensity in the DILVENT period was consistent with a previous study of DILVENT systems reporting levels ranging 10–70%.(25) The level of turbulence intensity in the DISPVENT period was increased as compared to a previous study reporting levels ranging from 10–40% in an office building.(26) However, the inconsistency might have been caused by turbulence generated by sewing machines. From the draft-risk model DISPVENT reduced the estimated risk by a factor of 1.9 as compared to DILVENT. Inconsistent with previous field studies of DISPVENT systems, no vertical stratification in air temperature was observed.(6,7) Perhaps turbulence generated by workstations surrounding the test rig ruined the stratification.

The change in ventilation design principle from DILVENT into DISPVENT reduced exposure levels to RPM and nonrespirable particles, but formaldehyde concentrations were left unaffected (Table IV). It is emphasized that the reduced contaminant levels obtained by DISPVENT were under the influence of a minor increase in recirculation of exhaust air and a reduction in air-supply flow rate by a factor of 1.2 (Table I). It is well known that offgassing of formaldehyde from cotton fabrics finished with a formaldehyde-conaining crosslinking agent is positively correlated with air emperature and humidity.(27) No difference in air humidity was observed (Table I) for the two test periods of DILVENT and DISPVENT, respectively. However, air supply temperaure was elevated in the DISPVENT period. A previous inervention study from an actual building reported an mprovement (by a factor of 1.5–18) in air quality by changng the ventilation design principle from DILVENT into DISPVENT.(7) However, data were obtained by area sampling. In this study data were collected at workstation level, and an improvement by a factor of 1.6–2.8 was obtained for nonrespirable dust exposure. RPM levels were reduced, but formaldehyde exposure was not affected by changing from DILVENT to DISPVENT. Vertical stratification in air qualiy is a characteristic feature of DISPVENT,(7) but no stratification was observed at the test rig. Perhaps turbulence generated by workstations surrounding the test rig ruined the tratification.

Replacement of a true contaminant with a tracer gas calls or a case-by-case development of a technique for emitting he tracer. In this study tracer gas as a simulated contaminant was used for estimating the transient transfer coefficient. It is recognized that the estimated coefficient may not be valid or true contaminants. From the transient transfer coefficient Table IV) DISPVENT improved conditions by a factor of 7.7. Consistent with previous findings DISPVENT created a vertical stratification in transfer coefficient.(5) For control of bystander exposure the transient transfer coefficient should be kept at a minimum.

CONCLUSION

Keeping DILVENT as a reference, the potential of DISPVENT for improved environmental conditions was estimated by an intervention study in a sewing plant. Air exchange efficiency of DILVENT came to 49%. DISPVENT improved efficiency to a level of 57%. The study was designed for a match in air-supply flow rate of the two alternative ventilation systems. However, air-supply flow rate of DISPVENT came out to be reduced by a factor of 1.2 as compared to DILVENT. Nevertheless DISPVENT improved air renewal at workstation level. Local mean presence time of air was reduced by a factor of 1.3. The change in ventilation design principle from DILVENT to DISPVENT improved breathing zone air quality. Exposure to nonrespirable dust was reduced by a factor of 1.6–2.8. Exposure to RPM was reduced, but concentration of formaldehyde was unaffected. DISPVENT improved conditions for control of bystander exposure by a factor of 7.7. DISPVENT improved thermal comfort conditions. Draft risk was reduced by a factor of 1.9. It is concluded that DISPVENT has potential for improving environmental conditions in industry.

REFERENCES

1. **Skåret, E.:** Contaminant Removal Performance in Terms of Ventilation Effectiveness. *Env. Int. 12*:419–427 (1986).
2. **Svensson, A.G.L.:** Nordic Experiences of Displacement Ventilation Systems. *ASHRAE Trans. 95(2)*:1013–1017 (1989).
3. **Nielsen, P.V.:** "Velocity Distribution in the Flow from a Wall-Mounted Diffuser in Rooms with Displacement Ventilation." In *Roomvent '92*, ed. by P.V. Nielsen and P. Heiselberg. Vol. 3. Copenhagen: DANVAK, 1992. pp. 1–19.
4. **Sandberg, M.:** Displacement Ventilation Systems in Office Rooms. *ASHRAE Trans. 95(2)*:1041–1049 (1989).
5. **Breum, N.O.:** Ventilation Efficiency in an Occupied Office with Displacement Ventilation—a Laboratory Study. *Env. Int. 18*:353–361 (1992).
6. **Breum, N.O., F. Helbo, and O. Laustesen:** Dilution versus Displacement Ventilation—an Intervention Study. *Ann. Occup. Hyg. 33*:321–329 (1989).
7. **Breum, N.O. and J. Skotte:** Displacement Ventilation in Industry—a Design Principle for Improved Air Quality. *Build. Env. 27*:447–453 (1992).
8. **Gardin, P. and J.R. Fontaine:** General ventilation characterization. In *Roomvent '90*, ed. by P.O. Fanger and O. Strindehag. Oslo: Norsk VVS. Paper No. 43.
9. **Sandberg, M. and M. Sjöberg:** The Use of Moments for Assessing Air Quality in Ventilated Rooms. *Build. Env. 18*:181–197 (1983).
10. **International Standards Organization:** *ISO 7730—Moderate Thermal Environments—Determination of the PMV and PPD Indices and Specification of the Condition for Thermal Comfort.* Geneva: International Standards Organization, 1984.
11. **International Standards Organization:** *ISO 7730–Moderate Thermal Environments—Determination of the PMV and PPD Indices and Specification of the Condition for Thermal Comfort.* (Modified Version—October 5, 1990) Geneva: International Standards Organization, 1990.

12. **Luker, M.A. and R.W. Van Houten:** Control of Formaldehyde in a Garment Sewing Plant. *Am. Ind. Hyg. Assoc. J. 51*:541–544 (1990).
13. **Buringh, E. and R. Lanting:** Exposure Variability in the Workplace: its Implications for the Assessment of Compliance. *Am. Ind. Hyg. Assoc. J. 52*:6–13 (1991).
14. **Owen, W.I. and T.A. DeRouen:** Estimation of the Mean for Log-Normal Data Containing Zeroes and Left-Censored Values, with Application to the Measurement of Worker Exposure to Air Contaminants. *Biometrics 36*:707–719 (1980).
15. **Breum, N.O. and J. Skotte:** Displacement Air Flow in a Printing Plant Measured with a Rapid Response Tracer Gas System. *Build. Serv. Res. Technol. 12*:39–43 (1991).
16. **Presser, K. and R. Becker:** Mit Lachgas dem Luftstrom auf der Spur [Air Flow Fields Characterized by Tracer Gas Technique]. *HLH 39*:7–14 (1988). [In German].
17. **International Agency for Research on Cancer:** *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: Some Flame Retardants and Textile Chemicals, and Exposures in the Textile Manufacturing Industry.* Vol. 48. Lyon: International Agency for Research on Cancer, 1990 pp. 215–234.
18. **Higgins, R.I. and P. Dewell:** A gravimetric Size-Selective Personal Dust Sampler. In *Inhaled Particles and Vapors,* ed. by C.N. Davies. London: Pergamon Press, 1967.
19. **Breum, N.O. and E. Ørhede:** *Opblandings—eller fortrængningsventilation i textilindustrien* [Dilution vs. Displacement Ventilation in Textile Industry]. Copenhagen: Working Environment Foundation, 1993. pp. 1–120 [In Danish].
20. **Rietz, B., Å.M. Hansen, and J.L. Murer:** *Sampling Method No. L 14—Formaldehyde in air.* Copenhagen: National Institute for Occupational Health, 1985. [In Danish].
21. **International Standards Organization:** *ISO 7726—Thermal Environments—Specifications Relating to Appliances and Methods for Measuring Physical Characteristics of the Environment.* Geneva: International Standards Organization, 1982.
22. **Olesen, B.W.:** *Local Thermal Discomfort.* [Technical Review No. 1] Copenhagen: Bruel & Kjaer Ltd. 1985.
23. **Bruel & Kjaer:** *Indoor Climate Analyzer—Type 1213.* Copenhagen: Bruel & Kjaer Ltd., 1990.
24. **Chen, Q., T.G. Hoornstra, and J. Van der Kooi:** Energy Analysis of Buildings with different Air Supply and Exhaust Systems. *ASHRAE Trans. 96(1)*:344–356 (1990).
25. **Hanzawa, H., A.K. Melikov, and P.O. Fanger:** Airflow Characteristics in the Occupied Zone of Ventilated Spaces. *ASHRAE Trans. 93(1)*:524–539 (1987).
26. **Melikov, A.K. and J.B. Nielsen:** Local Thermal Discomfort due to Draft and Vertical Temperature Difference in Rooms with Displacement Ventilation. *ASHRAE Trans. 95(2)*:1050–1057 (1989).
27. **Reinhardt, R.M. and B.A. Kottes Andrews:** Loss of Free Formaldehyde from Cotton Fabrics. *Textile Res. J. 56*:144–150 (1986).

APPENDIX

Nomenclature

C	concentration
$C(\infty)$	steady-state concentration
F(t)	cumulative age distribution
f(t)	age frequency distribution
p	level of statistical significance
PD	percent dissatisfied
PR	infiltration index
RE	recirculation index
Q	volumetric flow rate
q	constant tracer injection rate
q(0)	tracer injection rate at $t = 0$
$q(\infty)$	tracer injection rate at steady-state
t	time
T	temperature
Tu	turbulence intensity
u	air velocity
V	volume of the room
β	air exchange efficiency
δ	presence time
ϵ	transit time
η	transfer coefficient
μ	mean
τ	time constant

Subscripts and Other Symbols

a	air
d	displacement
e	exhaust air
n	nominal
s	supply air
p	arbitrary location in the room
< >	room average
A-B	two related locations