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DISPLACEMENT VENTILATION SYSTEMS IN INDUSTRIAL BUILDINGS

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ABSTRACT

In the past 15 years, displacement ventilation systems with floor-level-mounted air delivery devices have gained extensive use in the Scandinavian countries. This paper discusses the design principles and advantages of displacement ventilation systems. The paper also discusses the limitations of this kind of ventilation system and how some of these limitations can be overcome with the use of ceiling-mounted low-impulse air delivery devices (air showers) that are designed to produce a steady, slow, downward current of air that does not mix with the surrounding air.

Such ceiling-mounted air showers offer the heating, ventilating, and air-conditioning system (HVAC) designer a greater degree of flexibility, and the paper will discuss how the designer, by varying the spacing between the air showers, can tailor the system to solve various ventilation problems.

A limited number of air showers, mounted directly above a workplace, will create a local zone with improved air quality. With the air showers mounted in a suspended ceiling, at a center-to-center distance of six to nine feet, an area with cleaner (or air-conditioned) air can be created in a room where the general ventilation may be either a conventional or a displacement ventilation system. If the air showers are mounted even more closely (four feet center-to-center) and the air is introduced at a temperature equal to or slightly below the air temperature at the floor level, a protective effect is achieved where harmful air pollutants and substances, to a large extent, are prevented from entering the area underneath the air inlet. The ability of this kind of ceiling-mounted low-impulse air delivery device to create this protective effect has been studied by the National Institute of Occupational Health in Sweden.

INTRODUCTION

In the early 1970s, virtually all industrial ventilation systems in the Scandinavian countries were designed with conventional high-velocity, ceiling-mounted air diffusers (mixed-air ventilation systems). However, in the past 15 years, displacement ventilation systems with floor-level-mounted air delivery devices have become widely used and are today as common as mixed-air ventilation systems. Extensive research has been directed to further develop the displacement ventilation technology using the experiences and data gained from an increasing number of installations. However, a number of questions still require additional research. This paper will discuss these aspects, primarily as related to industrial ventilation systems.

DEFINITION OF TERMS

The Nordic Group of Ventilation (NVG) has suggested a few terms for measuring the efficiency of different ventilation systems and their ability to dispose of pollutants.

The *air exchange efficiency* (εra) is a measure of how fast the air in a room is exchanged. εra is defined as the ratio between the nominal time constant and the exchange time for the air in the room:

$$\varepsilon ra = \frac{\tau n}{2 \times \tau m} \times 100\,\%$$

where

τn = nominal time constant,
τm = mean "age" of the air in the room,
$2 \times \tau m$ = exchange time for the air in the room.

Examples:

Airflow	Exchange time for the air in the room	εra—Air exchange efficiency
Floor flow	τn	100%
Displacing flow	$> \tau n$	$<$ 100%
	$< 2\tau n$	$>$ 50%
Complete mixing	$2\tau n$	50%
"Short-circuit flow"	$> 2\tau n$	50%

(when the air flows from the air supply directly to exhaust)

Ventilation effeciency (εre) is a measure of how fast a pollutant is disposed of. εre is defined at a certain pollution discharge as the ratio between the concentration in the exhaust air and the average concentration in the room, i.e.,

$$\varepsilon re = \frac{Ce}{Cm} \times 100\,\%,$$

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where

Ce = balanced concentration in the exhaust air,
Cm = average concentration in the room at equilibrium.

Local ventilation index (εpe) is defined as the ratio between the concentration in the exhaust air (or surrounding air) and the concentration at a certain point in the room, usually a workspace or breathing zone above a certain process.

$$\varepsilon pe = \frac{Ce}{Cp} \times 100\%,$$

where

Cp = concentration in the point P.

Comments on the Definition of Terms

The air exchange efficiency, εra, and the ventilation efficiency, εre take into account the conditions of the entire room and are well suited to describe the conditions in offices, classrooms, conference rooms, and public buildings.

However, in an industrial building, the ventilation of areas not normally occupied by people is of less importance and the objective is to ensure higher air quality at the workstations.

With this in mind, the term *local ventilation index, εpe,* will instead be used to describe the conditions in industrial ventilation sytems. εpe is called the local ventilation index because it may be very large close to low-impulse air inlets in displacement ventilation systems.

CONVENTIONAL MIXED-AIR VENTILATION SYSTEMS

In conventional mixed-air ventilation systems, the air is introduced into the room at high velocities through ceiling-mounted air diffusers, a large air mass is set in motion, and all warm air currents and air pollutants are mixed. The εpe maximum is 100%, but the actual number is seldom higher than 50% to 75%.

The temperature gradient in a room with mixed-air ventilation is almost straight vertical (Figure 1). As a consequence, the air temperature in the workspace (typically three to six feet above floor level) is the same as the temperature of the exhaust air. In buildings with a high heat load from machinery, lights, people, etc., the make-up air often must be supplied at temperatures as low as 53° to 55°F to create a comfortable temperature in the workspace.

The need to condition the supply air is increased, as well as the required capacity of the air-conditioning equipment, which has to work at a lower evaporation temperature.

Advantages

- A more even temperature in the room.
- A higher temperature at the floor level than at the floor-mounted displacement delivery devices.
- Heated air can be supplied to the room.

Disadvantages

A higher than necessary concentration of air pollutants in the breathing zone (three to six feet above floor level) may occur. Stationary eddies of turbulent air may occur, with a very low ventilation efficiency and poor air quality (refer to thesis by Ljungqvist, Stockholm). High turbulence in the workspace may increase draft problems when cooled air is supplied. When the make-up air is heated, the average air velocity is low in the work zone, which increases the risk of stagnation zones.

Dimensioning of Airflow in a Mixed-Air Ventilation System

Well-established guidelines exist for dimensioning of airflow in a mixed-air ventilation system, and these will not be further discussed in this paper.

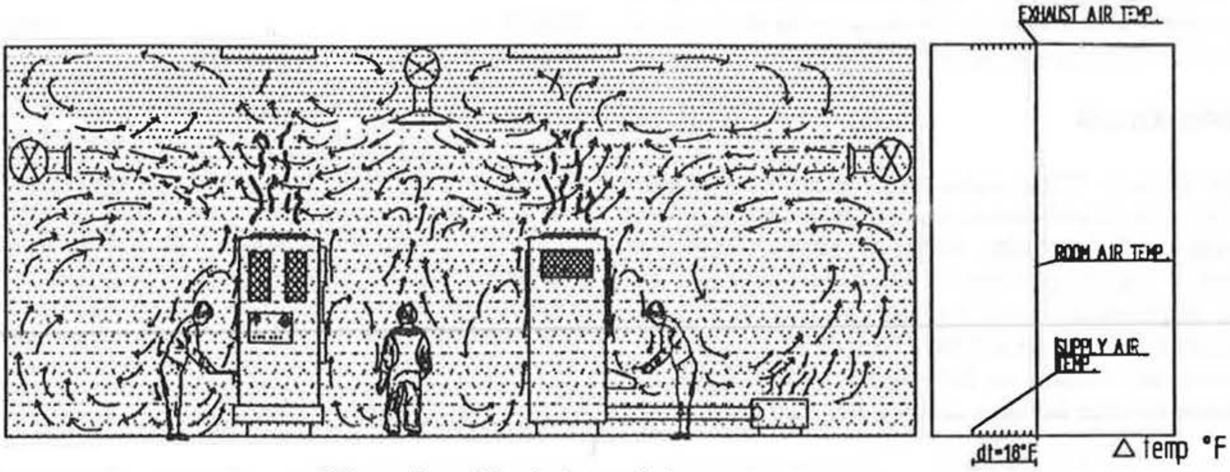

Figure 1 *Mixed-air ventilation system.*

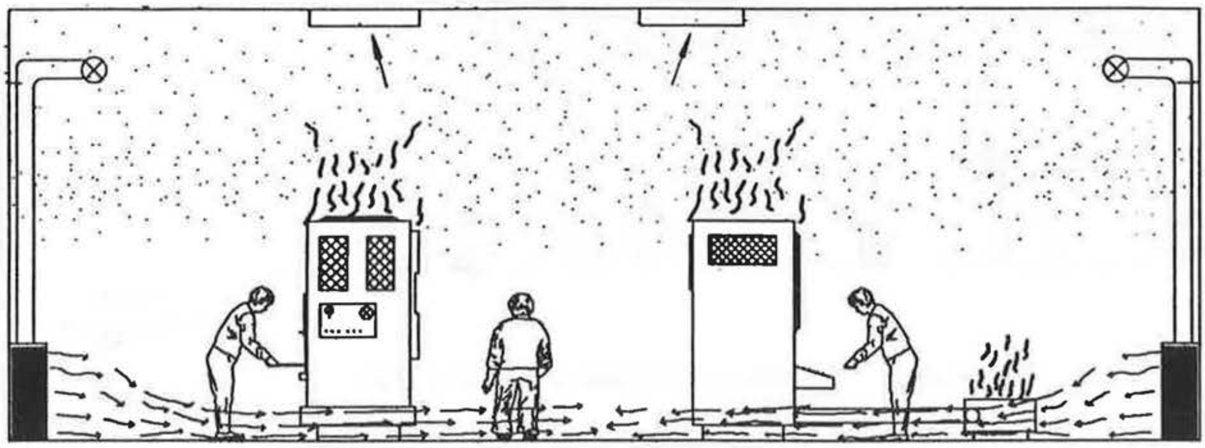

Figure 2 ***Clean, slightly cooler air supplied from floor-mounted delivery devices.***

If the system is designed with regard to the temperature, there is a direct relation between the total heat load of the room and the difference between the temperature of the supplied air and the desired temperature in the workspace. The limitations are given by the capacity of the air-conditioning system and the ability of the air diffusers to supply cold air without causing unacceptable draft in the work zone.

If the system is designed based on an acceptable concentration of air pollutants, it should be noted that a doubling of the airflow will not result in a 50% reduction of the concentration of air, as the *εpe* of the system always is lower than 100%.

For example, if the concentration of air pollutants is to be reduced by 50% in the work zone and *εpe* is 50%, the airflow must be increased by 400% if no other measures are taken.

DISPLACEMENT VENTILATION SYSTEMS

Displacement ventilation systems use the difference in density between cold and warm air. Clean, slightly cooler air is delivered at a low velocity ("poured") into the room through air delivery devices at the floor level. The denser air acts like a liquid and flows out, covering the entire floor (see Figure 2).

An upward air movement is then created by the thermal lift produced by heat sources in the room, such as machinery, lights, and people, which removes the pollutants from the workspace, and the air forms isothermic layers in the room from floor to ceiling. The air velocity depends on the heat load in different areas of the room. The highest velocities are found away from the air delivery devices, between the device and the strongest convective heat source in the room.

The amount of make-up air supplied must correspond to the sum of all convective flow at a certain distance from the floor level, usually calculated as 8 feet (2.5 meters) in industrial buildings. The sources of air pollutants are often located close to the major convective heat sources, which improves the removal of the pollutants from the work zone to the ceiling level, where they are exhausted (Figure 3).

However, it is important to observe that if the source of pollutants is located in an area with lower temperatures and the pollutants do not reach the stronger thermal lift produced by the main sources of convective heat, the pollutants will be concentrated in a lower isothermic layer closer to the workspace (Figure 4).

Design Criteria

The air delivery devices can be quarter-round, semiround, or round depending on their location in a corner, against a wall, or freestanding in the room. The design varies with the desired function of the device.

Devices with a front cover of filter mat are used when the difference between the temperature of the supplied air and the desired room temperature is small, but the requirements for air purity in the work zone are greater, as only a limited amount of mixing with room air will take place.

Devices with a front cover of perforated sheet metal cause greater mixing of the supply air (larger distances between the holes in the perforation pattern result in increased mixing between supply air and room air) and are used for lower supply air temperatures and lower requirements for purity of the air.

Currently, efforts are being made to increase the ratio of mixing between supply air and room air. This will make it possible to deliver the make-up air at slightly higher temperatures.

Local ventilation index, εpe, typically is between 100% and 200% and sometimes even higher. Delivery devices with a filter mat have the highest *εpe*.

Variation of the Temperature Gradient

The temperature gradient in a room with a displacement ventilation system will vary depending on the location of the

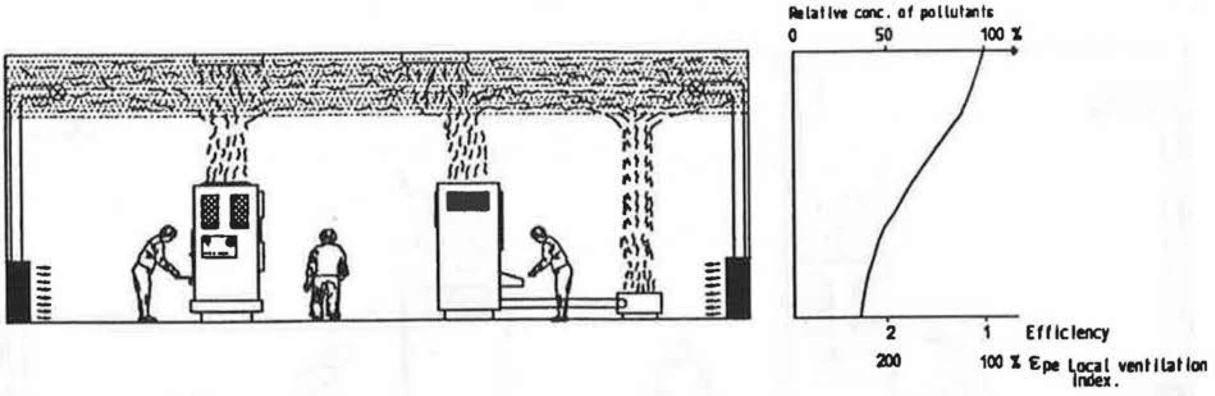

Figure 3 *Pollutants concentrated at the ceiling level.*

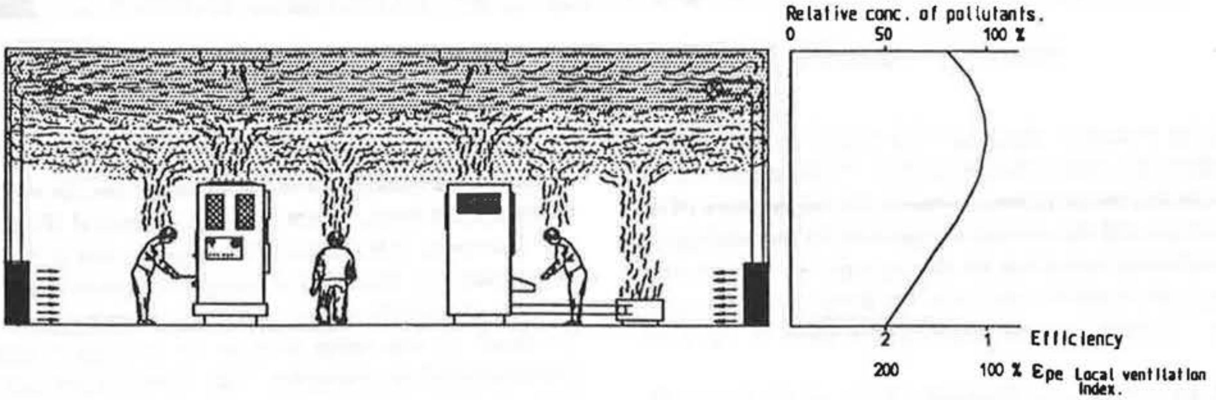

Figure 4 *Pollutants with lower temperatures reach lower levels.*

convective heat sources. Figure 5 shows an arrangement where the heat sources are concentrated at the floor level.

The floor is heated by the radiation from the layer of warm air next to the ceiling. As a result, the temperature of the supplied air will increase as the air flows over the floor. As the air inlet devices usually are located along the outside walls, this distance often is 15 to 30 feet and the rise in temperature may be as much as 2° to 4°F.

Four figures show some common arrangements. In Figure 6, the heat sources are located three to five feet above the floor level. In Figure 7, heat sources are located high up in the room; an example would be a telephone switching station. Figure 8 shows the temperature gradient in buildings with a high ceiling height. A desirable situation, in which all warm air is gathered together with the pollutants in a layer close to the ceiling, is shown in Figure 9.

Disadvantages with Displacement Ventilation Systems

The most important criteria for the proper operation of a displacement ventilation system in an industrial building is that the supplied airflow should equal the total convective airflow.

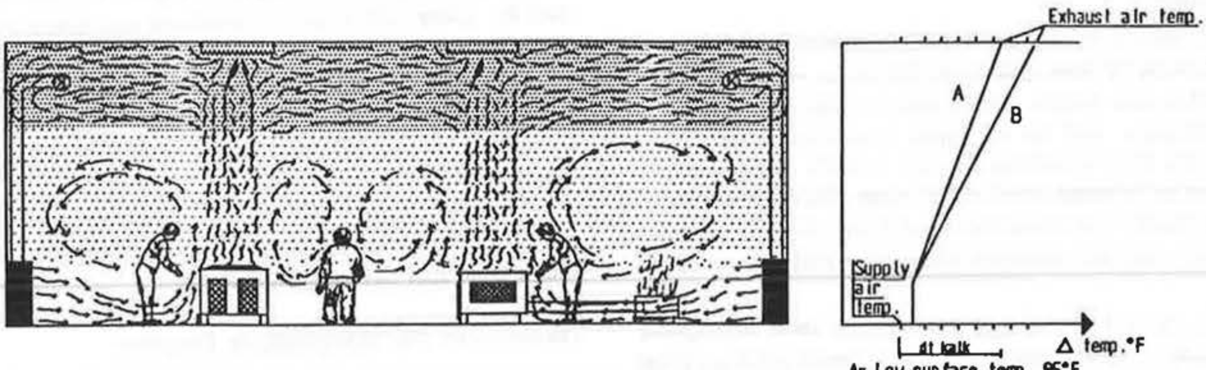

Figure 5 *Heat sources concentrated at the floor level.*

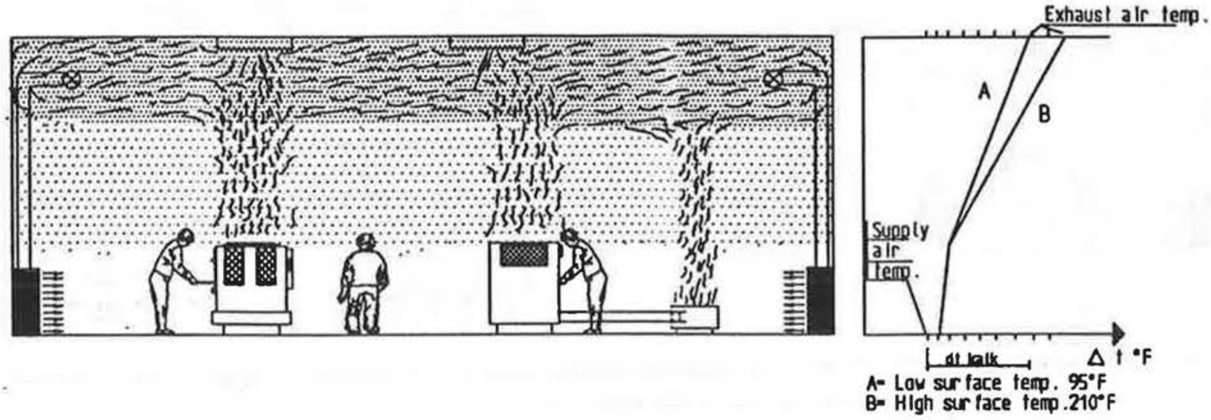

Figure 6 *Heat sources located at approximately 5 feet above floor level.*

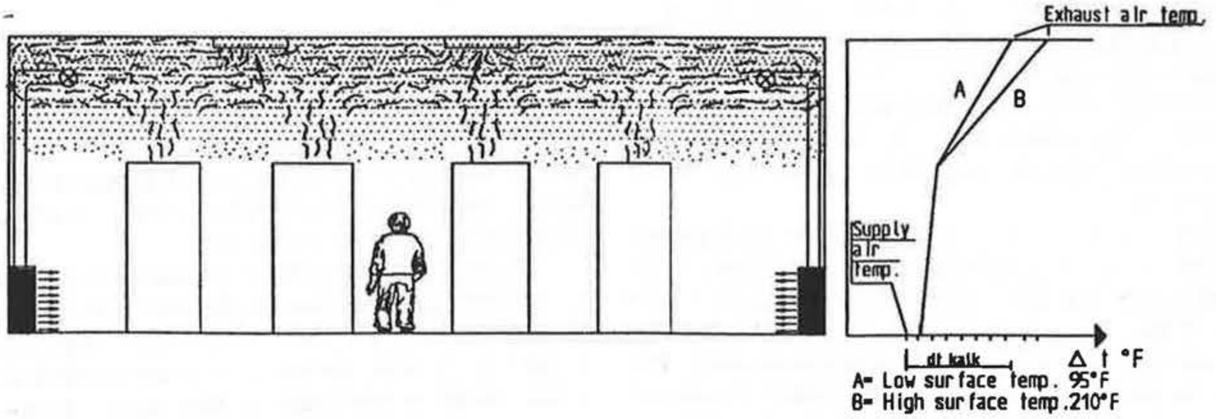

Figure 7 *Heat sources located high above floor level, e.g., telephone switching stations.*

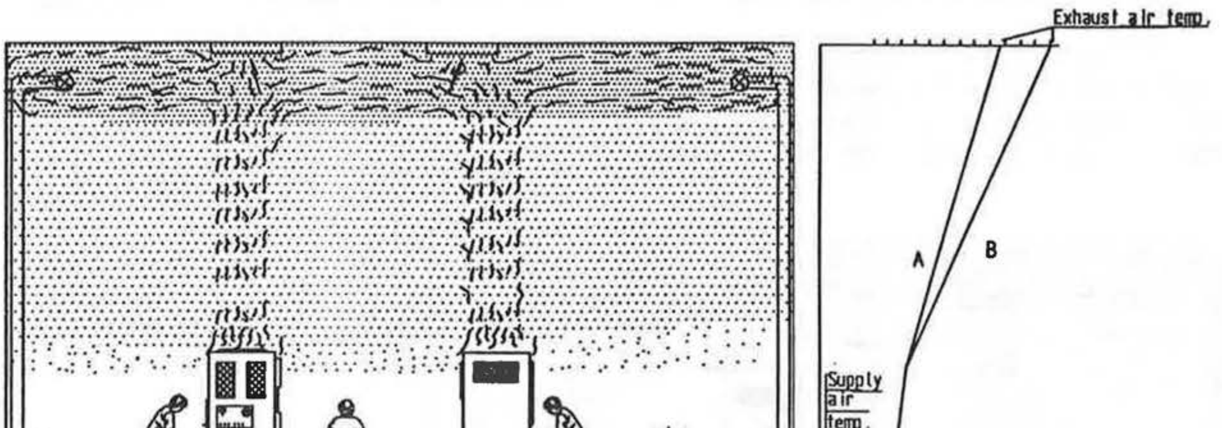

Figure 8 *Temperature gradient in buildings with a high ceiling level.*

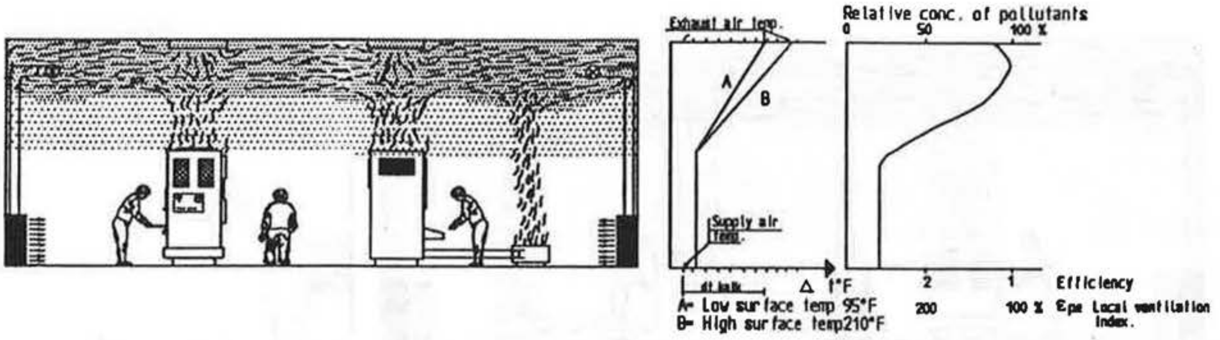

Figure 9 *Desired situation with all warm air gathered together with the pollutants in a layer close to the ceiling and straight vertical temperature gradient in the work zone.*

If this can be accomplished, displacement ventilation usually will improve the air quality significantly compared with conventional ventilation systems, especially if the generated air pollutants are hazardous and lighter than the surrounding air. With a displacement ventilation system, these pollutants will be removed from the workspace and gathered in the upper air layers close to the ceiling.

The temperature of the supplied air can be close to the desired air temperature in the work zone. In buildings with a high ceiling height, the temperature gradient is perceived as almost straight.

However, the actual operation of a displacement ventilation system is frequently less ideal. There may be several reasons for this. For increased production in the plant, it may have been difficult to calculate the heat emission from the machines with sufficient accuracy. For an altered machine layout, the consultant may not have had sufficient experience with displacement ventilation systems. Or the ceiling-mounted air diffusers may have been replaced with floor-mounted air delivery devices without a careful calculation of whether the airflow is sufficient. Figure 10 shows a case where the pollutants are drawn from the ceiling level to the breathing zone of the operators.

It should be noted, however, that the air quality in this case is still better than with conventional mixed-air ventilation. As the temperature at eye level often is perceived as being too high, the temperature of the make-up air is lowered, which frequently results in a draft along the floor. This draft and difficulty in finding enough space at the floor level are the two most common problems with displacement ventilation systems.

Airflow Calculation for a Displacement Ventilation System

The airflow for a displacement ventilation system can be calculated in several ways. All major manufacturers of floor-mounted air delivery devices offer instructions for manual and computer calculations.

The most common form of calculation is *temperature-based dimensioning*. Based on the surface temperature of the heat sources and their height above floor level, a suitable temperature difference between supplied air and exhausted air is calculated. A high surface temperature gives a more concentrated air current to a narrower isothermic layer close to the ceiling. As a result, the conditions in the work zone are not as affected as if the same heat load had been generated by a machine with a lower surface temperature.

The temperature difference can be calculated by

$$q_v = P / \zeta \times Cp \times dt,$$

where

q_v = airflow, cfm (m^3/s);
P = heat load (free heat emission to the room), Btu/min (kW);

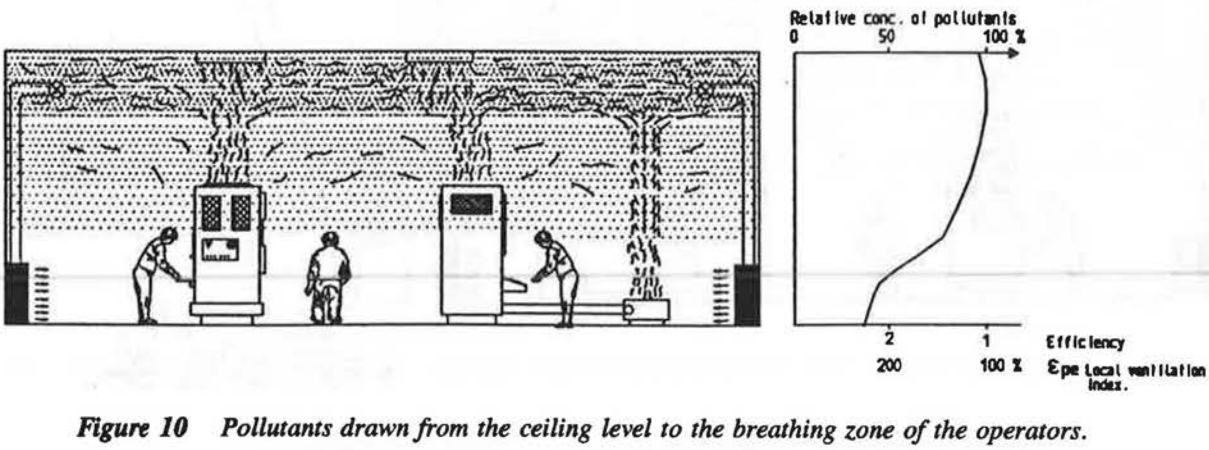

Figure 10 *Pollutants drawn from the ceiling level to the breathing zone of the operators.*

ζ = density of the air, 0.075 lb/ft³ (1.2 kg/m³);
Cp = heat capacity of the air, 0.239 Btu/16°F (1.0 kJ/kg·K);
dt = temperature difference between supplied air and exhaust air, °F (°C).

With the heat sources located at an average height above the floor of five feet, *dt* could vary with the ceiling height, which means that a high ceiling height allows a greater heat load at a temperature maintained at eye level and at the same airflows.

Ceiling Height	Temperature Difference between Supply Air and Exhaust Air (*dt*)
Less than 10 feet	11-13°F
10-20 feet	14.5-18°F
Less than 30 feet	18-21.5°F

The higher values of *dt* refer to machine surface temperatures of 200°F and the lower values to surface temperatures of 100°F.

If the average height is reduced by three feet, *dt* will be reduced by 1.8°F. An increase to an average height of six feet will result in an increase of *dt* of 1.8°F, due to less mixing of the air.

Figure 11 shows a summary of temperature gradients at different levels. From the diagram, a calculated temperature at eye level can be obtained. It also shows at what height the break point is located. The break point is the level above the floor where the supply airflow and the convective airflow from all hot surfaces are the same.

Determination of Convective Flow

If possible, it is highly desirable to measure the convective airflows from the machine on site. With a measuring tape, smoke generator, and an anemometer, the following data can be collected:

- surface area,
- temperature,
- velocity of all convective airflows from the heat source.

This will give an accurate estimate of the convective airflow. It is then possible to add up all convective airflows and compare the result with a temperature-based dimensioning, as described above, partly to select a suitable airflow and partly to be able to describe the different air layers according to Figures 3 through 10. Besides, bases are achieved to spot evacuate all pollutants that you don't want to be spread in the room.

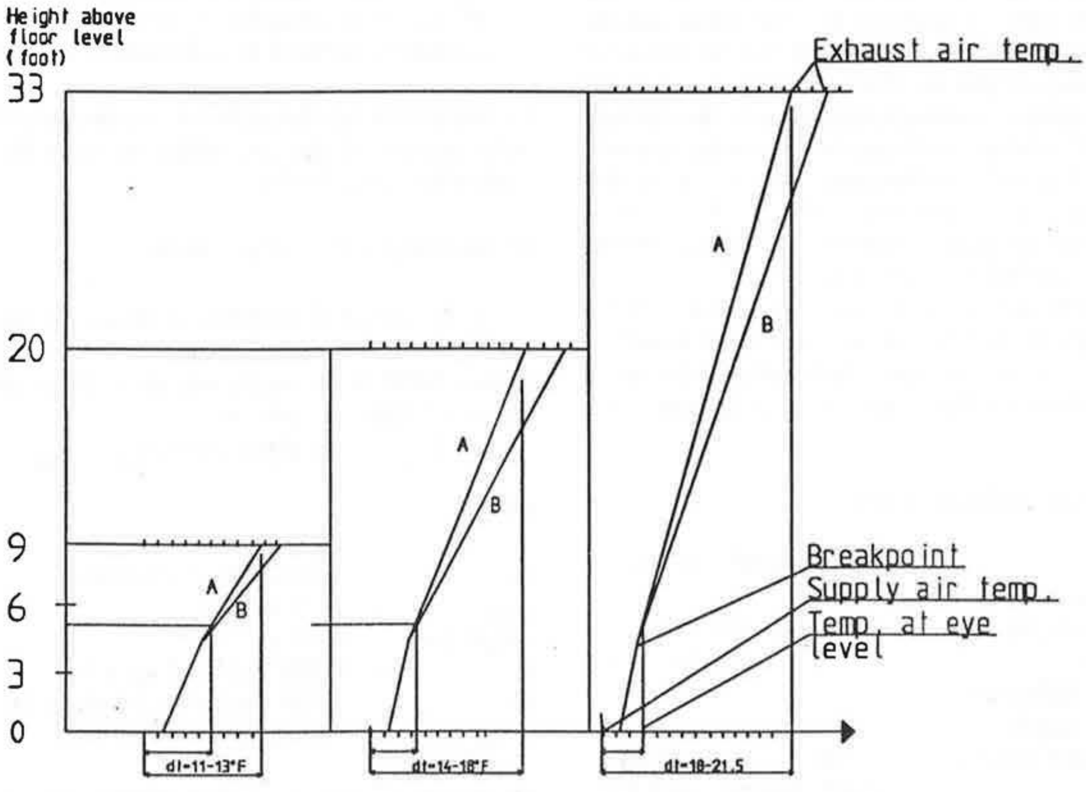

Figure 11 Summary of temperature gradient at different levels.

EXAMPLE: AIRFLOW CALCULATION FOR A RUBBER FACTORY

Background

A producer of various rubber and plastic products, with annual sales of U.S.$80 million, employs about 450 people in one division at two plants. The Torekov plant in southern Sweden produces a wide variety of industrial rubber products and advanced rubber components for use in medical equipment. This plant was built in 1974, and the original ventilation system was a mixed-air ventilation system.

In 1982, the ventilation was changed to a displacement ventilation system in the section of the plant with the highest heat load—the press area for rubber components. This improved the air quality in this area, but, as more and larger presses were added, the temperature gradient was increased. The warm and polluted air layer that had previously been located at the ceiling now expanded into the work zone.

During this time, employee demands on the working environment also increased, together with requirements for more qualified and stimulating work tasks. The solution was an integrated approach, where the employees were given more responsibilities combined with a stated company policy that the environment in the production areas should be as good as the environment in the offices.

As the indoor air quality was regarded as one of the main environmental problems for many sections of the plant, finding ways to improve the ventilation and air quality in these sections, at a reasonable cost, soon became a key to the implementation of the company policy. In the following paragraphs, various actions taken by the company to improve the workplace air quality of the press area will be discussed. The results of these calculations were verified in a full-scale test conducted in 1990 and found to be accurate through on-site measurements in the plant after the ventilation system had been installed in 1992.

Although the actual numbers are only applicable to this particular plant, the general approach, the formulas, and the conclusions are valid for other plants with similar conditions, as has been verified in several other installations in Sweden.

Brief description of the press area:

Total area:	14,860 ft²	(1,380 m²)
Airflow, existing ventilation system:	46,000 cfm	(21.7 m³/s)
Ceiling height:	18 ft	(5.5 m)
Temperature difference between supply and exhaust air (*dt*):	22°F	(12°C)
Heat load:	17,800 Btu/min	(313 kW)
Temperature gradient:	1.2°F/ft	(2.2°C/m)

The criteria for acceptable air quality in the press area were defined as follows:

1. The temperature at eye level should not be more than 73°F (23°C) except when the outside temperature exceeds the design conditions for this part of Sweden—81°F (27°C) and 50% relative humidity. On average, this happens 50 hours a year.
2. The temperature at floor level should not be less than 68°F (20°C).
3. The layer with warm and polluted air should be located well above the work zone.

With the existing ventilation system, the temperature at eye level was 7.2°F (4°C) above the temperature at floor level. The temperature of the outside air was raised an average 3.6°F (2°C) before the air was introduced into the room through floor-mounted air-delivery devices, as the incoming air picked up heat from the ducts, fans, motors, etc.

As a result, the eye-level temperature in the press area was 11°F (6°C) above the outside air temperature, and the temperature exceeded the limit of 73°F (23°C) as soon as the outside air temperature was more than 63°F (17°C), which, on average, happens 1,500 hours annually.

Two different approaches were considered to improve the air quality in the press area:

- to lower the supply air temperature;
- to use a combination of measures including insulation of heat-emitting machine parts and a supply of cool air directly to the work area through air showers.

To simplify the calculation below, we have not included the water content of the air, which increases the required cooling load even further.

Lower Supply Air Temperature

If the eye-level temperature should be kept at 73°F (23°C) when the outside air temperature is 81°F (27°C) by cooling 100% of the supply air, the required cooling load can be calculated as follows:

$$P_{cooling} = qv \times \zeta \times Cp \times (t_{outside} - t_{supply\ air}) \qquad (1)$$

where

qv	=	46,000 cfm (21.7 m³/s),
$t_{outside}$	=	81°F (27°C),
$t_{supply\ air}$	=	63°F (17°C),
ζ	=	0.075 lb/ft³ (1.2 kg/m³),
Cp	=	0.239 Btu/16°F (1.0 kJ/kg·K),
$P_{cooling}$	=	14,800 Btu/min (260 kW).

The required cooling load of 14,800 Btu/min was regarded as too high, and as the lowering of the supply air in a displacement system often results in a temperature that is too low at floor level, this solution was not seen as acceptable.

As can be seen from the calculation below, the required cooling load in a building with a mixed-air ventilation system would be even higher. The amount of pollutants generated by the presses would not allow any recirculation of air and to offset the heat load of 17,800 Btu/min (313 kW) with the available airflow of 46,000 cfm (21.7 m³/s), the supply air temperature would have to be 22°F (12°C) below the room temperature. Hence, the power required to keep the room temperature below 73°F (23°C) with an outside temperature of 81°F (27°C) could be as high as 23,700 Btu/min (416 kW), as can be seen below:

$$P_{cooling} = q_v \times \zeta \times C_p \times (t_{outside} - t_{supply\ air}),$$

where

dt = 81°-52°F (27°-11°C),
$P_{cooling}$ = 23,700 Btu/min (416 kW).

Combination of Measures Including Use of Air Showers

This approach included a combination of several measures:

1. A reduction of the heat emitted from the machines through insulation and enclosing the hottest surfaces of the presses.
2. A rearrangement of the press positions to gather them around two rectangular work areas.
3. The supply of cool air directly to the work areas through air showers.

With this solution, the required cooling was reduced to 3,000 Btu/min (50 kW), as can be seen by the following calculation.

The rectangular work areas were 34.5 by 47.6 ft (10.5 by 14.5 m). Previous measurements and actual tests in another section of the plant with a similar heat load had shown that a total of 23 air showers located in a suspended ceiling above each work area in four rows with a center-to-center distance of 8.2 ft (2.5 m) and with an airflow of 320 cfm (0.15 m³/s) would be adequate to meet the air quality requirements.

With this arrangement, the airflow required for each work area would be 23 × 320 cfm and the cooling load would be:

$$P_{cooling} = q_v \times \zeta \times C_p \times (t_{outside} - t_{supply\ air}),$$

where

q_v = 7,200 cfm (3.4 m³/s),
dt = 81°-68°F (27°-20°C),
P = 1,500 Btu/min (25 kW) for each work area,
P_{total} = 2 × 1500 Btu/min (2 × 25 kW).

It should be noted that this solution will work equally well in a plant where the general ventilation is a mixed-air ventilation system. The cooling power required to ensure an eye-level temperature of less than 73°F (23°C) with an outside temperature of 81°F (27°C) and a total heat load of 17,800 Btu/min (313 kW) will be approximately the same as above, or 3,000 Btu/min (50 kW).

CEILING-MOUNTED LOW-IMPULSE AIR DELIVERY DEVICES

The ceiling-mounted low-impulse air delivery device (air shower) was developed to meet a need for local climate control experienced by many HVAC system designers, i.e., to make it possible to create a cleaner or cooler zone without having to consider the heat loads in all other areas of the room. With a very high εpe value within the area served, the air shower makes it possible to create a high degree of comfort in terms of the freshness of the air, CO_2 levels, and high ion values (excellent computer environment), and to create clean zones in otherwise polluted environments.

Applications for an air shower are:

1. As a local system, to improve conditions for a specific workstation by creating a cooler and cleaner zone around a group of operators or machines. The air can be 5 to 10 times cleaner than the surrounding air (εpe = 500% to 1,000%, according to measurements performed in the field by the National Institute of Occupational Health.
2. Together with floor-mounted air delivery units in a displacement ventilation system, to create a zone with improved air quality. As the requirements for the supplied air are the same, the floor-mounted air delivery units and the air showers can be supplied from the same duct system, as shown by subjective experiences from a number of installations within the rubber-producing industry. Measurements will be performed during the autumn of 1993 on a big plant in Sweden.
3. As air delivery units in displacement ventilation systems, where a more vertical temperature gradient is required, or where floor-mounted air delivery units will take up too much floor space.
4. To create a zone with protective ventilation in an operation with hazardous pollutants. An air shower is uniquely suited for operations where very little heat is generated, such as hand lamination of fiberglass. Criteria for proper functioning are, among other things, that the air showers be mounted close enough for the individual airflows to unite (43 inches center-to-center at a flow of 355 cfm) and that the supplied air be cool enough to ensure that thermal lift from the convective heat of the operators' bodies is broken without causing unacceptable

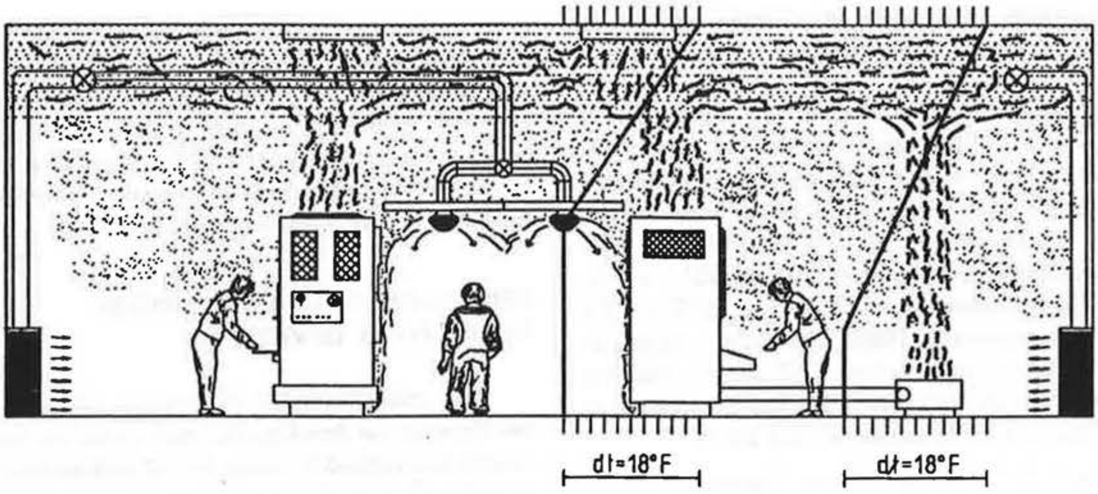

Figure 12 Suspended ceiling with air showers combined with floor-mounted displacement delivery units, $Q_T < Q_K$.

draft (vertical air velocity past the operators is 0.65 ft per second).

Combinations of the above-mentioned applications are possible. Figure 12 shows a suspended ceiling with air showers combined with floor-mounted displacement delivery units.

The methods for calculation of airflow in displacement ventilation systems previously mentioned should be used to calculate the air quality for areas outside the zone directly affected by the air shower (an area underneath the shower with a diameter of 3 to 5.2 ft). To ensure good air quality, the total cfm of the supplied air from all air showers and floor-mounted delivery units should be equal to the total convective heat airflow. If the airflow of the supplied air is slightly too low, the isothermic layers with more polluted air will be lowered outside the area covered by the air shower, and if the airflow is much too low, conditions in areas not covered by the air shower will not be affected at all.

Figure 13 is an idealized image of how it works. The pureness of the air outside the air shower's working area depends on the amount of pollutants beside the air shower and the temperature difference between the supply air and the surrounding air temperature.

Design Criteria

Design criteria for proper operation of an air shower are

1. To prevent the surrounding air from mixing with the supplied airflow, the air shower should use air-permeable filter material with a harder, load-bearing, nonflammable outer shell and an inner layer of softer material with a high air resistance.

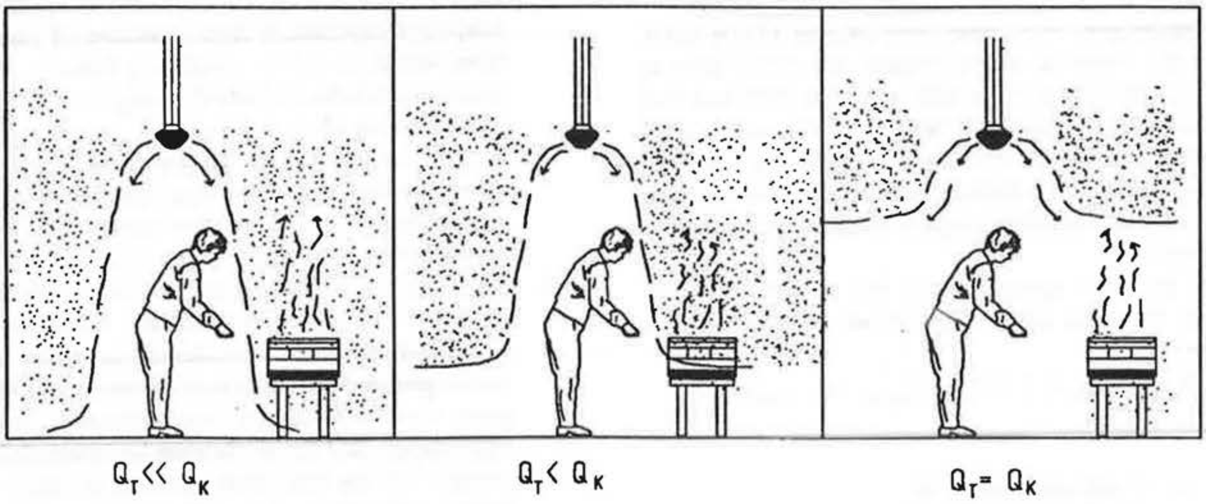

Figure 13 Displacement effect in areas not covered by the air shower at different supply airflows, Q_T, and convective airflows, Q_K.

This design requires that the supplied air be filtered.

2. The air showers should have a geometrical shape to ensure that the downward airflow from the air shower has a sufficiently wide diameter to counteract the natural tendency of the colder air to form a narrow cylinder of air.
3. Adjust the diameter of the downward airflow.

Installation

In a building with a displacement ventilation system, the air showers should be mounted in the cleaner zone, below the warmer and polluted layer of air closer to the ceiling. If the air shower is mounted in the polluted air layer, a certain amount of mixing between supply air and surrounding air will occur. The mixing is reduced if the air shower is mounted in a suspended ceiling, as the airflow from the air showers will prevent polluted air from entering under the suspended ceiling. Also, the ceiling reduces the vertical airflow.

If the exhaust air is warm, but more or less clear of pollutants, the mixing between the supply and surrounding air has no negative consequences and may, in fact, be desirable in an office to straighten the temperature gradient and provide a cooler temperature zone at eye level and a warmer zone at floor level.

Supply Air Temperature

If the supply air is delivered without mixing to the surrounding air, it must be possible to maintain a supply air temperature that is 2° to 4°F below the desired room temperature to avoid unacceptable draft beneath the air shower.

Heating through heated supply air is usually not recommended, as the air current will change direction and flow upward at a distance of, typically, 20 inches from the air shower, resulting in poor ventilation efficiency.

If heating is required only at night or during non-operating hours when ventilation requirements are less, air showers can be used to supply heated air at a maximum temperature of 86°F.

Cooling

Supplying air without mixing with the surrounding air means that only some of the heat generated in the room has to be cooled. A significant amount of the heat will rise to the ceiling, where it is extracted from an air current flowing in the opposite direction of the supply air.

With air exhausters located directly above major heat loads, the air-conditioning load may be reduced by 30%, provided that the make-up air is supplied from outside (there are no savings in a recirculating system). In addition, the supply air only has to be cooled to a temperature of about 65°F, resulting in a higher efficiency of the air-conditioning system due to a higher evaporation temperature and an extended period of the year where no air conditioning is required.

If the air shower is used locally to improve conditions for a specific workstation, the air-conditioning load can be calculated on the cooling requirements for that zone only and not on the heat emitted from other areas of the room. The energy savings depend on the size of the area that will be cooled.

Comparison between the Air Shower and Floor-Mounted Air Delivery Devices

Generally, in a displacement ventilation system, the air forms isothermic layers in the room from floor to ceiling, with a bottom layer (B) of cleaner air closest to the floor. Within this air layer (B), a pattern of horizontal airflows will form toward the strongest convective heat sources. The vertical extension above the floor of the clean air layer (B) is given by the size of the convective heat source (*Qc*) and the height above floor level of this heat source. The aim is to design the system so that (B) extends past the breathing zone of the operators, i.e., to a distance from the floor of typically at least eight feet.

However, in conventional displacement ventilation systems, this is often not possible to achieve, as a secondary airflow (C) will form at the perimeter of the vertical convective airflow (E). This airflow may have a complex pattern of motion, including horizontal components to and from the convective airflow (E) as well as vertical components directed upward at (E) and downward at the airflow (A) from the supply air delivery device. This means that the amount of air in motion exceeds the supply and exhaust airflows, and it may be difficult to establish a bottom layer (B) with a vertical extension that is sufficient to ensure a breathing zone of clean air.

In the area covered by the air shower (an area beneath the shower with a diameter of 3 to 5.2 feet), the clean air layer be lifted up to a level above the breathing zone. A certain turbulence will occur at the perimeter of the airflow from the air shower between the downward-moving air from the air shower and the stagnant air layer (C). In theory, this turbulent action may bring pollutants down to the breathing zone. However, actual measurements at several installations using air showers have not detected any increase of pollutants due to this effect.

The warm and polluted air layer closest to the ceiling (D) should be kept from mixing with the air layers below. Therefore, it is important that the air shower be located below (D). Measurements on two installations in the same plant, with approximately 50 air showers in each hall, have shown the following results (Figure 14).

With an air shower, the vertical component of the airflow (C) directed downward at the perimeter of the airflow from the air shower (E) will be approximately equal

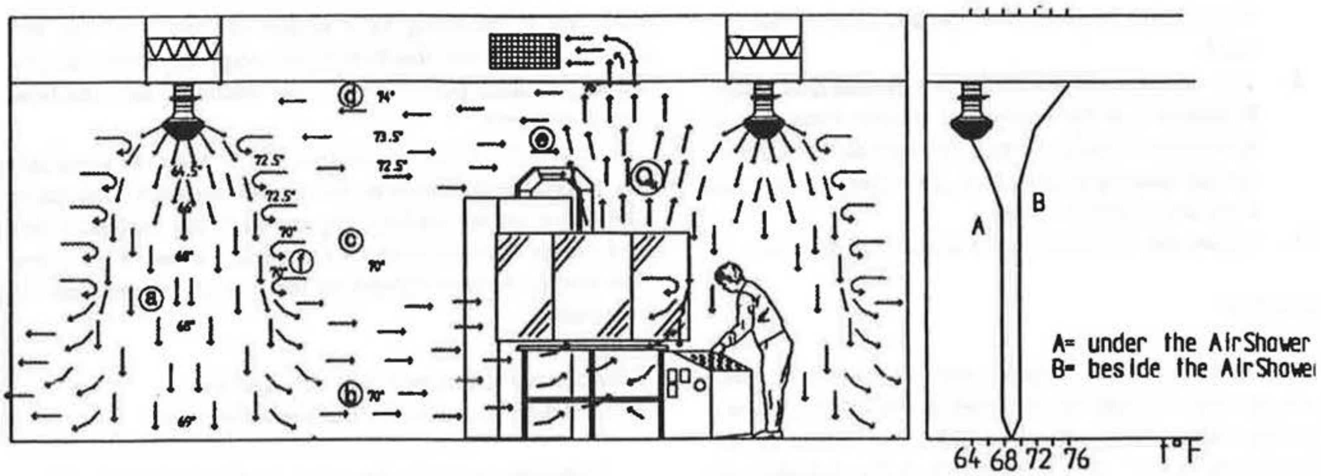

Figure 14 *Ventilation with air showers.*

to the upward flow at the convective airflow (E). As a result, a ventilation system using the air shower will have a more vertical temperature gradient with a temperature difference between the floor and the upper layer of (C) of only 2°F compared with 7° to 9°F for displacement ventilation systems using floor-mounted delivery devices only (Figure 15). A more vertical temperature gradient will significantly reduce problems associated with drafts and cold floors.

Beneath the air shower, the air temperature will actually increase as the air flows toward the floor, resulting in a higher air temperature at floor level. This is partly a result of a limited mixing of room air and supply air from the air shower (see discussion above).

TYPICAL APPLICATIONS

Air showers can be used for

- local improvement of air quality, i.e., to create cleaner or cooler zones around a group of operators or machines;
- office ventilation;
- cleanroom ventilation;
- protective ventilation.

Creation of a Zone with Cleaner Air

A zone with cleaner air can be created in a building with mixed-air ventilation, which is shown in Figure 16. $\epsilon pe = 200\%\text{-}500\%$ (measured figures).

Local Cooling

How to air condition individual workstations in buildings with high heat loads is shown in Figure 17.

PROTECTIVE VENTILATION

Design of protective ventilation systems, i.e., systems that will create a clean breathing zone for operators in an otherwise polluted environment, require detailed analyses of how the pollutants are generated and of their movement through the air space.

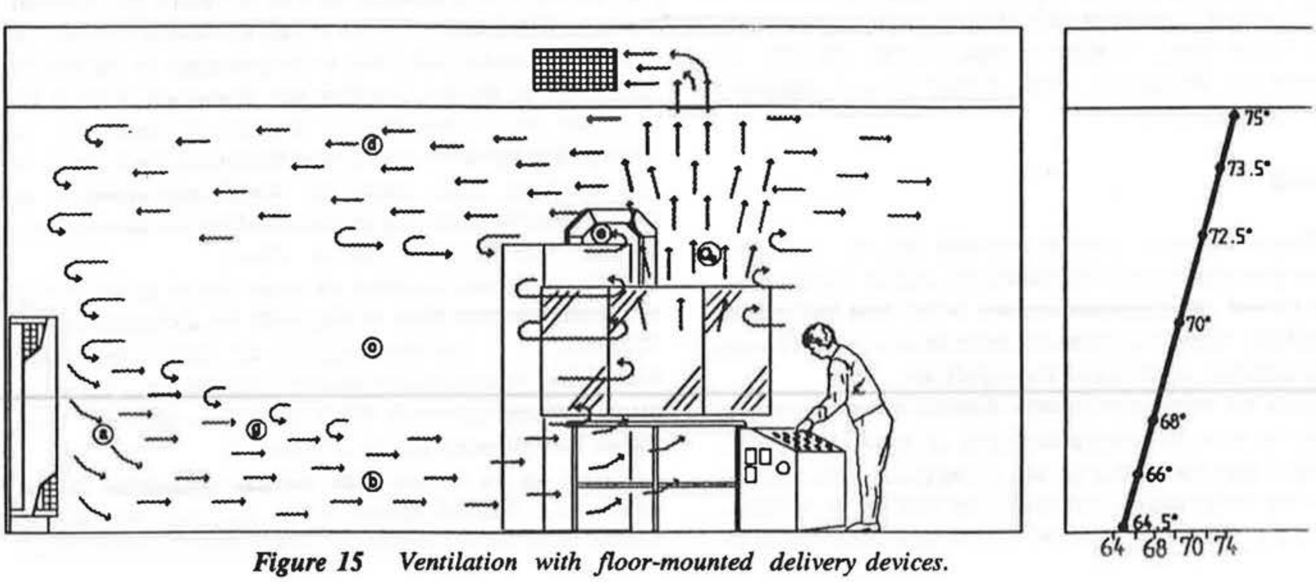

Figure 15 *Ventilation with floor-mounted delivery devices.*

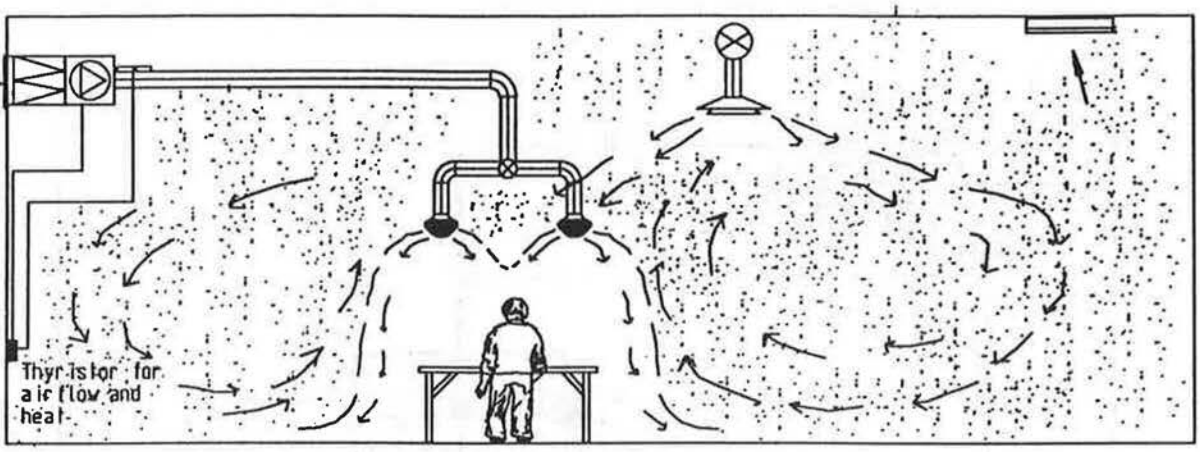

Figure 16 Local ventilation using air showers in an industrial environment.

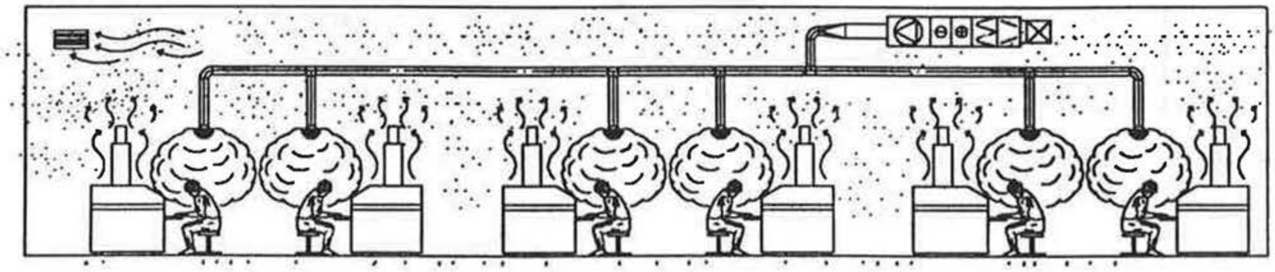

Figure 17 Air conditioning of individual workstations in buildings with high heat loads.

A unique aspect of protective ventilation is the requirement to stop the convective airflow generated by the operator's body heat. This convective airflow may have a velocity of 0.5 feet per second and will draw pollutants from adjacent sources into the operator's breathing zone. To counteract the convective airflow, an airflow in the opposite direction is required, with a velocity of about 0.65 feet per second.

Air showers placed at a center-to-center distance of 43 inches will create a laminar airflow that does not mix with the surrounding room air. The air will flow by the operator's face and fill the breathing zone with clean air and, subsequently, transport pollutants to the exhaust. The exhaust is designed for the specific operation and may be either downdraft or an exhaust located at the floor level (the latter arrangement requires that the temperature of the supply air be equal to the air temperature at the floor level).

The supply air temperature has to be 2° to 3°F below the room air temperature, and the pollutants should be moving upward as a result of either thermal or gravitational forces. By varying the supply air temperature, the vertical extension of the clean air zone can be controlled, as the downward flow of clean air will continue to an isothermic layer with the same temperature as the supply air.

The downward air velocity must equal the velocity of any existing cross-draft, i.e., for conditions perceived as draft-free, the cross-draft should not be greater than 0.65 to 0.80 feet per second.

According to a study by the Swedish National Institute of Occupational Health, such a protective ventilation system typically will reduce the amount of pollutants in the breathing zone 5 to 10 times (εpe = 500% to 1000%) and, in extreme cases, as much as 200 times. These extreme situations can occur when a person is standing still by a table with volatile solvents and the body's convective heat transports the solvents into the breathing zone. A reduction of the amount of pollutants in the breathing zone by as much as 200 times has been recorded when the supply air from the air shower is turned on and the volatile gases are forced down by the cool stream of air.

The air inlet device was mainly evaluated by the PIMEX method, in which the worker is filmed on video at the same time as his/her exposure is measured with a personal, direc-reading measurement instrument. The measurement signal is transmitted by telemetry to a receiver. The video image and measurement signal are merged into a composite image with a video mixer and subsequently displayed on a TV monitor. Exposure is then designated as a bar on the left side of the video frame. The composite image is recorded on a videotape recorder (Taylor et al. 1977). Figure 18 shows protective ventilation with air showers.

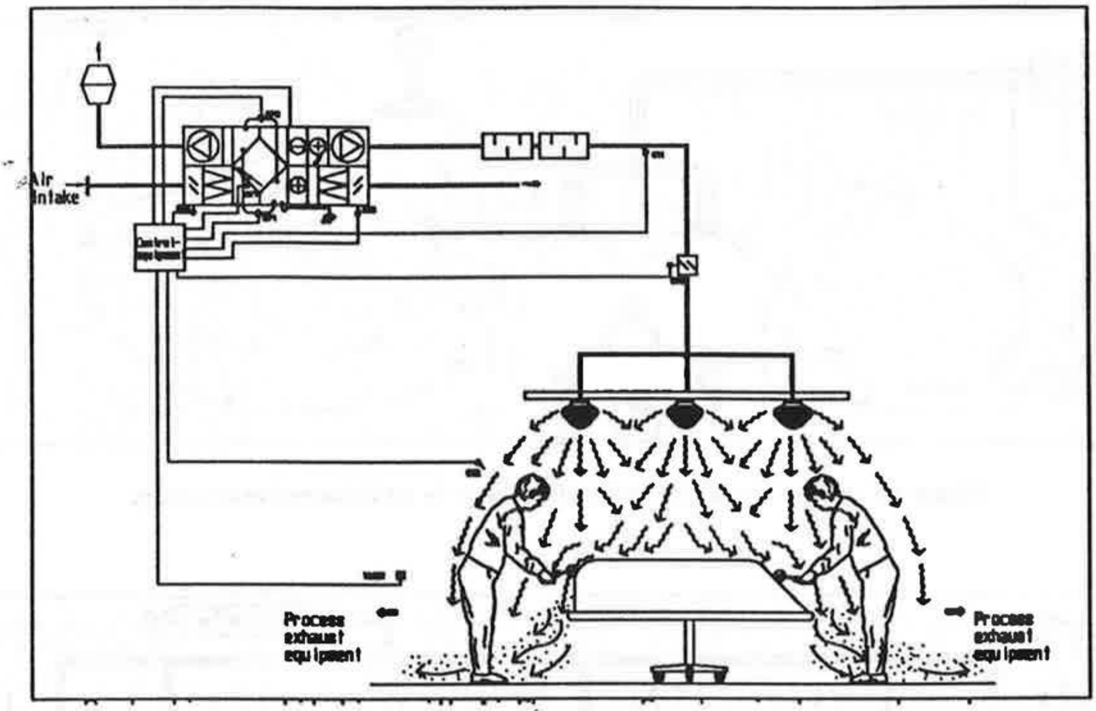

Figure 18 *Protective ventilation with air showers. Supply air temperature is lower than the room air temperature.*

If the cross-draft requires unacceptably high downward air velocities or the work is performed very close to the pollution source, the fresh air can be delivered through the collar of a protective jacket, which is shown in Figure 19.

This solution will reduce the amount of pollutants by at least 30 times and often by as much as 100 times. The cross-draft can be at least 3.2 feet per second. The protective jacket has been laboratory-tested by the Swedish National Institute of Occupational Health in Sweden and Germany. Pending a standardized European test procedure for certification of this kind of equipment, a user's manual has been developed in cooperation with the Swedish National Institute of Occupationai Health.

Figure 19 *Protective jacket.*

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