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Paper 5

INDOOR AIR FLOW AND POLLUTANT REMOVAL IN A ROOM WITH TASK VENTILATION

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Abstract

In an experimental facility, we studied the performance of a task ventilation system designed for use in office buildings. With this system, occupants can adjust the flow rate and direction of air supplied to their work space through four floor-mounted supply grills. Air typically exits the ventilated space through ceiling-mounted return grills. To study indoor air flow patterns, we measured the age of air at multiple indoor locations using the tracer gas stepup procedure. To study the intra-room transport of tobacco smoke particles, cigarettes were smoked mechanically in one workstation and particle concentrations were measured at multiple indoor locations. Test variables included the furnishing of the chamber, the location(s) of air supply, supply flow rates, temperatures, and directions, and internal heat loads. Our major findings were as follows: (1) In most tests, deviations from a uniform age of air, and a uniform particle concentration, were less than 30 percent. (2) Some supply air short circuits to the return grill when the air is directed toward the return grill with a high velocity. (3) Low supply velocities resulted in a floor-to-ceiling displacement ventilation flow pattern. (4) Directing the supply air toward the occupant, or away from the center of the four supply grills, typically yielded an age of air at the occupant's breathing level that was 15 to 25 percent lower than the age at other breathing-level locations. (5) With low supply velocities and air directed toward the occupants, tobacco smoke particle concentrations in a ventilated non-smoking workstation were 50 percent of the chamber-average concentration.

1.0 RESEARCH OBJECTIVES

The primary objectives of the research described in this paper were to determine the spatial variability in ventilation and pollutant removal efficiency in a room ventilated with a floor-based task ventilation system under a variety of operating conditions. More specifically, we desired to compare the rate of ventilation (as indicated by an age of air) at the position of the occupant to the rate of ventilation elsewhere in the room; to determine if the system resulted in a displacement flow pattern; and to determine the efficiency of removing tobacco smoke particles with a task ventilation system.

2.0 INTRODUCTION

We define "task ventilation" as a method of ventilation that provides for individual control of some local air supply parameters such as flow rate, temperature, or direction. Two task ventilation (T.V.) systems are being introduced in the U.S. The Task Air™ system, manufactured by Tate Architectural Products, Inc., has occupant-adjustable, floor-level air supply modules, has been installed in all or part of approximately twelve North American buildings,(1) and is used extensively in South Africa. This system, hereinafter called the "Tate System," is the object of the investigation reported in this paper and is described in detail in a later section. Johnson Controls, Inc., has recently introduced their Personal Environments® system that allows occupants to adjust the flow rate, temperature, and direction of air supplied through desk-mounted supply diffusers. In West Germany, the Krantz Company markets T.V. systems with air supplies at floor level and, in some cases, at the desk top.(2)

The potential for improved thermal comfort, because occupants can (to some extent) adjust their local thermal environment, is a major impetus for the use of task ventilation. Improved indoor air quality is another potential benefit because the freshest (least polluted) air can be supplied more directly to the region around the occupant. T.V. systems may also, in some situations, result in a displacement (piston-like) air flow pattern in the floor-to-ceiling direction because slightly cool air, more dense than room air, is supplied at floor or desk level and air is typically removed from the room at or near the ceiling. Displacement flow often results in lower pollutant concentrations at the breathing level and higher concentrations in the ceiling-level exhaust air. However, the typically high air supply velocities of T.V. systems may inhibit displacement flow because of air mixing caused by entrainment of room air in the supply-air jets.

T.V. systems could potentially use less or more energy than conventional heating, ventilating, and air conditioning (HVAC) systems (i.e., systems with ceiling-level air supply diffusers and no provisions for occupant control) as discussed by Heinemeier.(3) Fan energy use and energy required for cooling or heating could differ between task and conventional systems due to: different supply temperatures (typically higher during cooling with T.V. systems); the large numbers of small supply fans and reduced supply-air ductwork in some T.V. systems; different indoor temperature profiles; different outside air requirements due to different efficiencies in pollutant removal; and the occupant use pattern of T.V. systems.

3.0 TATE SYSTEM

With the Tate System, air is supplied by a conventional air-handling unit (AHU) to a sub-floor supply plenum maintained at approximately room air pressure. The AHU may supply some recirculated indoor air but, according to the manufacturer, often supplies 100% outside air. In regions of the building with high heat loads, fan-coil units may be installed in the floor plenum to further cool the plenum air. Alternately, fan-coil units may be installed throughout the floor plenum and the central AHU used only for precooling and dehumidification. The supply plenum is the space beneath a raised access floor, i.e., a system of carpet-covered, removable floor panels suspended on a metal framework approximately 0.3 to 0.6 m above the permanent floor. Air supply modules, called task air modules (or TAMs), can be installed in place of any floor panel and easily moved to new positions. A TAM, depicted in Figure 1, contains a fan that draws air from the supply plenum and discharges air into the room through the slots (inclined 40° from vertical) in four plastic grills each 0.13 m in diameter. Using a recessed thumb wheel, the fan speed and, thus, air flow rate can be adjusted between approximately 40 L/s and 90 L/s resulting in maximum air supply velocities of 2 to 6 m/s (or the fan may be turned off). The direction of air supply can be changed by rotating any or all of the four grills. Occupants cannot control the supply air temperature which, to reduce the potential for cold drafts, is typically about 18 °C or 5 °C higher than the supply temperature of many conventional U.S. HVAC systems. Based on our experiments, the air supplied to the floor plenum may have a significantly lower temperature -- heat transfer through the floor will remove some space heat and increase the temperature of air supplied through TAMs. The Tate System may include some floor-mounted supply-air modules that are not subject to occupant control but instead are controlled by thermostats and some supply modules may contain electric-resistance heating elements. Air is typically withdrawn from the occupied spaces through ceiling-level return grills connected to return-air ducts or a return-air plenum located above a suspended ceiling.

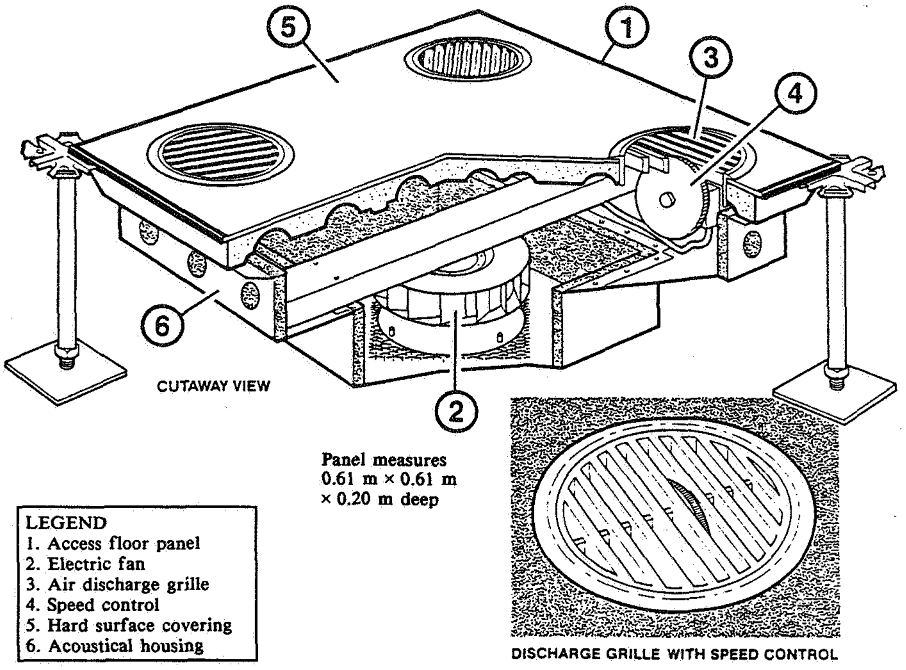

Figure 1. Cutaway diagram of a task air module (TAM).

Three recent papers provide information on the Tate System. Bauman et al.(4) and Arens et al.(5) report on an experimental investigation of thermal comfort conditions (velocities and temperatures) in a chamber with the Tate System. Their investigations of thermal comfort complement the research described in this paper and were performed coincident to the research in the same experimental facility. Major findings are: (1) the Tate System permits substantial adjustment of thermal comfort parameters at the occupant's location; (2) the system results in air velocities that often exceed the velocity limits of thermal comfort standards (however, the traditional limits on air velocity may be inappropriate for a situation with occupant control); and (3) with minimum air supply rates, the indoor temperature profiles resembled those obtained with displacement ventilation systems (i.e., substantial increases in temperature with height above floor). These papers also provide a brief review of available published information on task ventilation. Spoormaker(6) describes the use of the Tate System in 400,000 m^2 of office space within South Africa, describes the recommended system configuration, and presents indoor temperature and velocity data. Hedge(7) describes the results of a survey of six managers and 151 occupants of U.S. buildings with the Tate System. Building managers were very satisfied with the Tate System and indicated that occupants had fewer complaints about thermal comfort and ventilation compared to occupants of buildings with ceiling-level air supplies. Two thirds of the occupants indicated that the Tate System resulted in better temperature and ventilation conditions than the system with a ceiling-level air supply in their previous building.

4.0 EXPERIMENTAL FACILITY, INSTRUMENTATION AND PROCEDURES

4.1 Facility

All experiments were performed in a controlled environment chamber (CEC) with a 5.5 m by 5.5 m floor and a 2.5 m high ceiling. The CEC resembles a modern office space and has provisions for a high degree of control over the method of ventilation and indoor thermal environment.(8) The floor is covered with carpet tiles, finished gypboard walls are heavily insulated and painted white, windows in the two exterior walls provide a view to outside, the suspended ceiling contains patterned acoustical tile, and six recessed dimmable lighting fixtures are mounted in the ceiling. As shown in Figure 2, a raised access floor results in a 0.6 m high sub-floor plenum and the suspended ceiling provides a 0.5 m high ceiling plenum. A reconfigurable air distribution system permits air supply to and removal from any combination of ceiling and floor locations using ductwork and/or the plenums. Figure 2 illustrates the air flow configuration for the majority of experiments described in this paper. Supply air was directed into the sub-floor plenum and delivered to the room via TAMs installed in the access floor. In tests with the CEC unfurnished, return air passed through slots in the ceiling tiles, into the ceiling plenum, and then into the HVAC system. During the majority of tests, the CEC contained three workstations with furnishings typical of those in offices as shown in Figure 3, the slots in the ceiling tiles were sealed, and a duct connected a ceiling-level return grill (located in place of a ceiling tile) to the HVAC system.

The furnished chamber contained sources of heat and air motion typical of real offices including: overhead lights (with a total power of 500W of which roughly 100 W directly entered the chamber); 75 W task lights in each workstation; and a personal computer containing a small cooling fan and a monitor in each workstation (90 W each). Only one of the three workstations was occupied by a seated mannequin. Electric resistance heating elements wrapped around the mannequin released 75 W (a typical rate of release of sensible heat by an office worker). During a few tests, internal loads were increased by combinations of the following: operation of extra task lights; operation of a 200 W radiant heater beneath a desk; operation of mixing fans within the chamber; and operation of particle sampling and counting instrumentation within the chamber. In one test, the computers were turned off (to eliminate operation of the small cooling fans) and a small heater was operated to release approximately the same amount of heat.

The CEC's HVAC system provides a separate stream of conditioned air that is directed through plenums in the two exterior walls and between the inner two window panes called the annular space. During most tests, this system maintained the temperature of the interior window pane at approximately the average indoor temperature. Consequently, the exterior walls and windows were not a source of strong natural-convection airflow, but affected indoor airflow much like interior walls. During tests with heating of the chamber, cooled air was passed between the windows.

The CEC's HVAC system has a personal-computer-based direct digital control system. This system controlled and monitored various temperatures and air flow rates during the tests. For increased accuracy, supply and return air flow rates were generally also measured using pitot-static tubes centered in sections of plastic pipe. At the start and end of some tests, the rate of air supply through TAMs was measured with a flow hood.

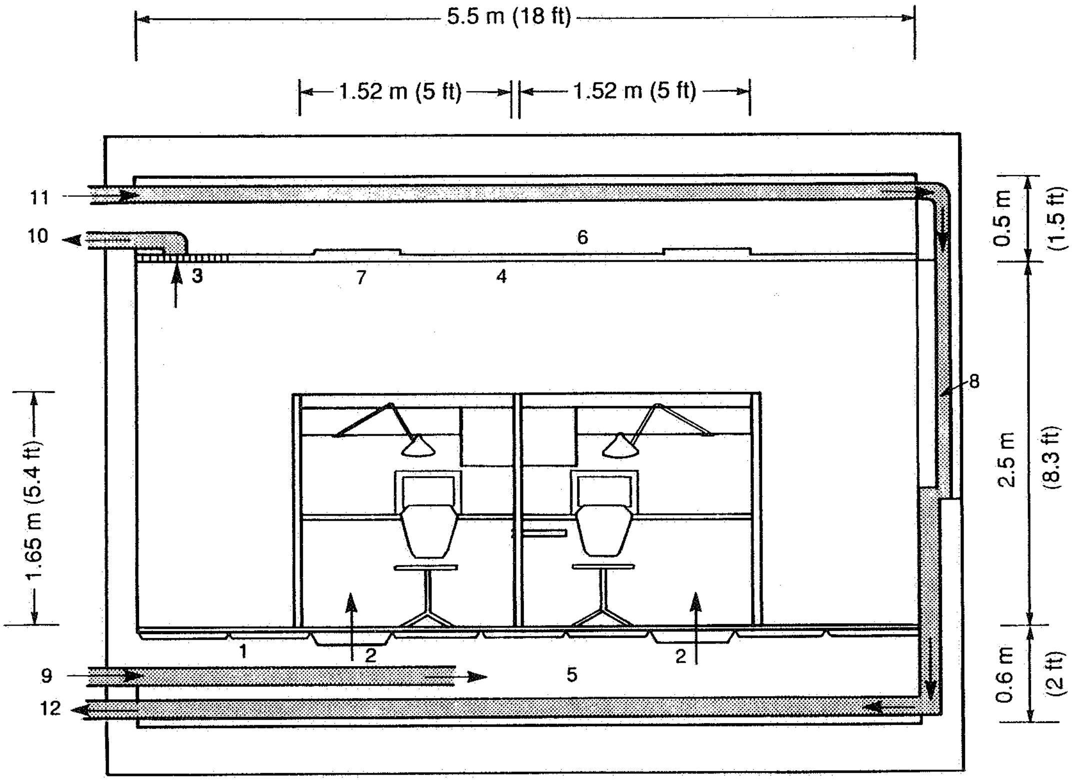

Figure 2. Cross section of CEC. Numbered items are: 1 = floor panel; 2 = TAM; 3 = return grill; 4 = suspended ceiling; 5 = subfloor plenum; 6 = ceiling plenum; 7 = light fixture; 8 = annular space between windows; 9 = air supply to subfloor plenum; 10 = air return to HVAC system; 11 = conditioned air supply to annular space; 12 = air return from annular space to HVAC system. The return-air grill is centered between the front and back walls.

4.2 Tracer Gas Measurements

The tracer gas stepup procedure (9,10,11) was used to study indoor airflow patterns and the spatial variability of ventilation. In this procedure, the supply air was labeled with a tracer gas and the rate of increase of tracer gas concentrations at a location indicated how rapidly the indoor air was replaced with "new" air that entered the building since the start of tracer gas injection. During the stepups, a mixture of 1% sulfur hexafluoride SF_6 in air was injected at a constant rate into the supply airstream. A peristaltic pump drew the tracer/air mixture from a storage bag and directed the mixture through a flow meter and tubing and into the supply duct. Injection rate was monitored using rotometers calibrated with a bubble flow meter and was generally stable within 2%. To ensure thorough mixing of the SF_6 in the supply airstream, an array of small propeller fans was installed downstream of the injection point. These fans were oriented to cause air flow perpendicular to the general direction of flow in the duct. Mixing was confirmed by collection and analysis of air/tracer samples. During the tests, air samples were drawn continuously through copper tubes from nine total locations to three gas chromatographs (GCs) equipped with electron capture detectors. Five of these samples originated from within the chamber at a subset of the locations illustrated in Figure 3 and four samples originated within the HVAC system. The GCs were capable of analyzing a sample within 1 minute using: a 0.38 m long molecular sieve main column; a backflush column with two sections (0.08 m of 5% phosphoric acid on Chromosorb GAW followed by 0.38 m of

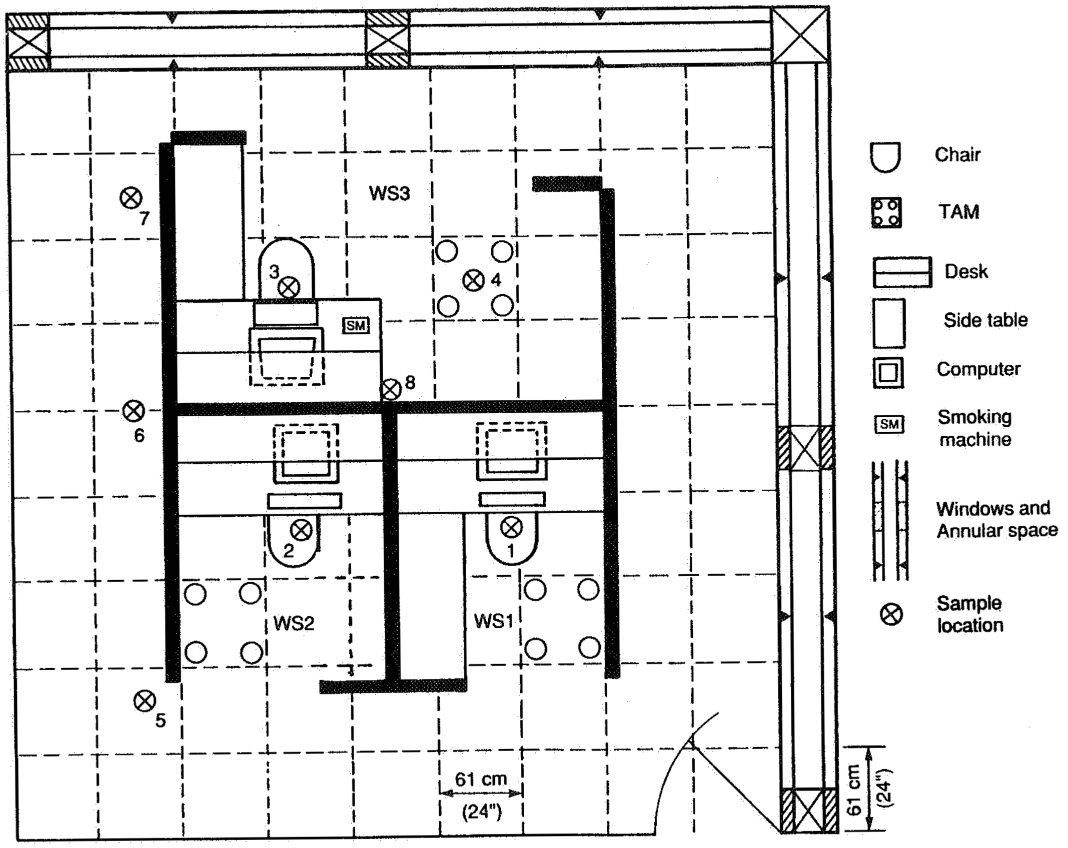

Figure 3. Plan view of CEC with workstations denoted WS1, WS2, and WS3. Tracer gas was sampled at points 1-4 (0.4 m, 1.1 m and 2.1 m above floor), at points 5 & 7 (1.1 m above floor), at point 6 (1.1 m and 2.1 m above floor), and at point 8 (2.1 m above floor). Particles were sampled at points 1-4 and 6 at heights indicated in Table 4.

molecular sieve); carrier gas (5% methane, 95% argon) flow rates of approximately 40 cc/min, and approximately a 12 s backflush time. (This measurement procedure was recommended by D. Harjje of Princeton University.) Therefore, at each sample location the tracer gas concentration was measured every three minutes. During the tests, bag samplers also directed air/tracer samples at a constant rate into 0.5 L sample bags. Bag sampling commenced at the start of tracer gas injection and continued until tracer gas concentrations were stable at which time syringe samples were collected manually from the same locations. The fourteen bag samplers collected samples from the locations within the chamber depicted in Figure 3. (Sample locations were slightly different during tests with an unfurnished chamber.) Air samples were directed to both a sample bag and a GC from two locations, thus, samples were collected and analyzed from 17 unique locations within the CEC. Bag and syringe samples were analyzed using the GCs immediately after completion of the tests. Equipment and procedures are similar to those used previously and described by Fisk et al.(10,11,12).

The GCs were calibrated prior to each test using nine total calibration gases with SF_6 concentrations of 0 ppb to 185 ppb. Measurements of tracer gas concentrations were generally repeatable within a couple ppb.

4.3 Tobacco Smoke Particle Measurements

The efficiency of removing tobacco smoke particles, and intra-room particle transport, were investigated during some of the tests. A cigarette was smoked by a cigarette-smoking machine located on the desk in workstation number 3 and particle concentrations were measured as a function of time during and after the period of smoking at four locations within the CEC identified in Figure 3 and Table 4 and also in the supply duct and at the return grill. An optical particle counter (OPC), calibrated by the manufacturer immediately before the first test, measured particle number concentrations in 15 size bins ranging from 0.09 μm to 3.00 μm. Air samples were drawn (at a rate of 5 L/min) to the optical particle counter through lengths of 1.3 cm diameter copper tubing connected to electrically actuated ball valves mounted on a copper manifold. The OPC drew an air sample from this manifold at a rate of 3 cc/min.

5.0 TEST CONDITIONS

Table 1 lists the test conditions. Gaps in the sequence of test numbers are due to unsuccessful tests or tests with air supplied through a conventional ceiling-level supply diffuser which are not discussed in this paper. The initial tests were conducted with an unfurnished chamber and a single TAM installed near the center of the floor. An electric resistance heating film was placed over the surrounding floor. Power to the heating film was controlled by a proportional controller to maintain a temperature of 24 °C at a location 1.4 m above the floor and away from the direct influence of the supply jet. The supply air temperature was maintained at 18.3 °C, except during Test 8 when the CEC was heated. Based on the manufacturer's recommended operating procedure, the four supply grills were oriented so that air was directed inward toward a line perpendicular to the center of the TAM and also upward at an angle of 60° from horizontal. (This supply direction is designated "inward" in Table 2 and in subsequent text and figures.) At maximum air delivery, the four jets converge at a height of 0.20 to 0.25 m.

During the majority of tests (CEC listed as furnished in Table 1), the CEC was subdivided into three workstations by 1.65 m tall partitions with no gaps between the partitions and the floor. TAMs were installed in each workstation at the locations indicated on Figure 3 and the workstations were furnished as described previously. During most of these tests, only one TAM operated and the outlet grills of the other TAMs were sealed with plastic. Test variables included the supply flow rate, internal heat load, direction of air supply, the location of the operating TAM, and the percent of outside air in the supply airstream (generally 100%). Air supply directions include "inward," as described in the previous paragraph, and also "outward" and "toward." An outward supply direction refers to air supply away from the center of the TAM (toward the four corners of the TAM) and at an angle of 60° from the horizontal. "Toward" refers to air supply from all four supply grills directed toward the mannequin and at an angle of 60° from horizontal. The heated mannequin was always seated in a workstation with an operating TAM. In most tests, the CEC was cooled by air supplied through the TAM. During Tests 8 and 34, the windows were cooled, internal heat generation was reduced, and the supply air was used to heat the chamber. During Tests 20 33, and 38, designed to determine measurement precision by comparing the results of measurements at different locations, the air within the chamber was mixed vigorously with fans. Tests 20D and 38D were tracer gas decays (instead of stepups) with the tracer gas concentration uniform at the start of the decay and no tracer injection during the decay.

Table 1. Test Conditions

Test #, Type*	CEC Furnished	Internal Load W/m^2	TAM Location†	Supply Flow L/S	Supply Temp. °C	TAM Supply Direction‡	CEC Temp. °C	Window Temp. °C #	Comments
3,T	N	NA	Central	101	NA	Inward	24	18	
7,T	N	NA	Central	80	18	Inward	24	24	
8,T	N	NA	Central	84	25	Inward	21	13	Heating test
9,T	N	NA	Central	57**	18	Inward	24	24	
10,T	Y	19	WS1	95	NA	Inward	24	24	Unsealed TAMS in WS 1&2
12,T	Y	19	WS3	98	20	Inward	24	24	
13,T	Y	19	WS3	98	22	Inward	26	26	
14,T	Y	19	WS3	94	23	Inward	26	26	
15,T	Y	19	WS3	97	23	Inward	26	26	
16,T	Y	19	WS1	97	19	Inward	24	21	
17,T	Y	19	WS1	98	25	Inward	28	29	
18,T	Y	19	WS2	96	17	Inward	24	24	
19,T	Y	19	WS2	98	22	Inward	28	28	
20,T	Y	30	WS3	95	17	Inward	24	24	Mixing fans in CEC
20D,T	Y	19	WS3	97	19	Inward	24	24	Tracer decay
26,T	Y	23	WS2	95	19	Inward	24	24	Computers off
27,T	Y	26	WS3	94	18	Toward	24	23	
29, T&P	Y	63	WS3	90	16	Inward	26	24	High internal load
30,T	Y	35	WS1	90	17	Inward	24	24	Unsealed TAMS in WS 2 & 3
31, T&P	Y	35	WS3	105	17	Outward	24	24	
32, T&P	Y	35	WS1&3	73	16	Toward	25	24	Low-supply velocity
33,T&P	Y	43	WS3	105	15	Toward	24	24	Mixing fans in CEC
34,T&P	Y	16	WS3	103	NA	Toward	24	13	Heating test
35,T&P	Y	35	WS3	108	17	Outward	24	24	20% Outside air
36,T&P	Y	35	WS3	111	17	Outward	24	24	
37,T&P	Y	35	WS3	101	16	Inward	24	24	
38,T&P	Y	43	WS3	107	16	Toward	24	24	Mixing fans in CEC
38D, T&P	Y	35	WS3	107	17	Toward	25	24	Tracer decay

* D = Tracer decay, all other tests are tracer stepups, T = tracer gas test, P = tobacco smoke particle removal test

† WS1 = work station #1, WS2 = work station #2, WS3 = work station #3

‡ Inward = four grills direct air inward and upward; Outward = four grills direct air outward and upward; Toward = four grills direct air toward mannequin

\# Temperature of air passed through annular space between window panes

** To obtain low-supply flows, floor plenum was depressurized relative to interior of CEC

6.0 DATA ANALYSIS METHODS

6.1 Tracer Gas Data

Equations based on age distribution theory(9) were used to calculate the ages of air. We present only the equations for a tracer gas stepup, similar equations for data from tracer gas decays are presented elsewhere.(9) Using tracer gas concentrations as a function of time, the following equation was employed

$$A = \int_{0}^{t_{ss}} [1 - C(t)/C(t_{ss})]dt \qquad (1)$$

where: A is the age of air; t is the time variable set equal to zero at the start of tracer gas injection; C(t) is the tracer gas concentration at time t, and t_{ss} is the time when concentrations have stabilized. The integral is evaluated numerically. Using the tracer gas concentrations in bag and syringe samples, C_{bag} and C_{syr}, respectively, age of air was determined using the equation

$$A = t_{syr}[1 - C_{bag}/C_{syr}] \qquad (2)$$

where t_{syr} is the time when the syringe sample is collected.

To indicate the spatial variability in age of air, we use various ratios based on the ages. For example, the age of air in the return duct divided by the age at breathing level in the "occupied" workstation (with mannequin and operating TAM) is an indicator of ventilation efficiency -- higher values of this ratio indicate more efficient air flow patterns with increased ventilation (lower ages) at the location of the occupant. When ratios contain an average of the age measured at several locations, we use volume-weighted averages assuming that each measurement is representative of a volume that extends half way to adjacent measurement points and/or to the edge of the workstation.

6.2 Particle Data

To evaluate the particle data collected at the different sample locations, we compute total particle number concentrations (for all size bins) minus the "background" particle concentration (i.e., the concentration before the cigarette is smoked and after an extended period of ventilation). To indicate the spatial variability of particle concentration and the efficiency of particle removal, we compare time-average values of these background-corrected particle concentrations measured at different indoor locations. Concentrations are averaged over the time period between the start of smoking and the time when particle concentrations have returned to the background concentration (i.e., over the period of tobacco smoke exposure).

7.0 RESULTS

7.1 Test with Mixing Fans in CEC

If the air in the CEC was perfectly mixed and measurement precision was perfect, ages of air (and particle concentrations) measured at each location within the CEC, and in the return duct, would be identical and all ratios based on these measurements would equal unity. The age-of-air ratios from tests with mixing fans within the CEC (23,33,38) are always within 0.11 of unity (see Table 3), with two exceptions. The exceptions, ratios of 1.13 and 1.15, are based on measurements of age in the jet of air exiting the TAM where imperfect mixing is definitly expected despite the use of mixing fans. Hence, we neglect these two ratios, and assume that an age-of-air ratio greater than 0.11 from unity is significant from the measurement-precision perspective.

We believe that at least three factors cause imprecision in the multiple (multi-point) measurements of age of air. First, there is a small bias between ages determined from: (a) numerical integration of real-time data, and (b) the bag and syringe samples. (We are investigating the cause of this bias.) Second, the air in the CEC was probably not perfectly mixed due to the internal partitions. Third, there is undoubtably some random error in the measured ages due to such factors as instrument imprecision. When we gain more experience and data, a statistical evaluation of measurement precision may become appropriate.

7.2 Unfurnished CEC

Age-of-air ratios from tests with no furnishings in the CEC are provided in Table 2. All ratios for tests with a high supply velocity (Tests 3, 7, and 8) are within 0.3 of unity; therefore, the deviation from uniform ventilation (actually, uniform age of air) during these tests is not large.

In Tests 3 and 7 (with CEC cooled, high supply flow rates, and air directed inward and upward), the age of air in the CEC return duct is lower than ages within the chamber, hence, there is some short circuiting of air from the TAM to the return. Surprisingly, the results indicate negligible short-circuiting in Test 8 which is similar except that the supply air is warmer than the CEC air (chamber is heated). Possibly, the indoor air is more completely mixed in Test 8 due to increased natural convection caused by the cold windows.

Table 2. Age-of-air ratios from tests with unfurnished CEC. Ratios in bold print are considered significantly different from unity from a perspective of measurement precision.

	Test #			
Ratio	3*	7	8	9
Return Duct / All B.L. Points	**0.84**	**0.87**	0.94	**1.30**
Return Duct / All CEC Points	**0.85**	0.92	0.97	**1.33**
A.L. of Central Ring / A.L. above TAM	1.11	**1.24**	**1.20**	**2.18**
B.L. of Outer Ring / B.L. of Central Ring	0.98	**1.30**	1.04	0.99

KEY: B.L. = Breathing Level (0.4 m above floor)
A.L. = All Levels (0.4 m, 1.3 m, and 2.1 m above floor)
Central Ring = 4 points, 1.2 m to 2.4.m from TAM
Outer Ring = 4 points, 2.2 m to 3.0 m from TAM
* missing data could have significantly affected ratios

In the single test with a low supply velocity (Test 9 with chamber cooled and air directed inward and upward), the ratios indicate a displacement flow pattern between TAM and return (i.e., a significantly higher age in the return). Ages also increase with height above floor. Evidently, there is less mixing of the indoor air during this test due to the low supply velocity. The measurements by Bauman et al.(4) and Arens et al. (5) are consistent -- they found considerable thermal stratification in tests with low supply velocities.

The third row of ratios in Table 2 indicate that the average age of air at locations above the TAM (in line with the jet of supply air) is significantly lower than the average age in a ring of points located 1.2 m to 2.4 m away from the TAM. These findings are consistent with expectations.

7.3 Age-of-Air Measurements in Furnished CEC

Table 3 provides age-of-air ratios from tests with the CEC furnished. A large majority of the ratios are within 0.2 of unity; therefore, in most tests, the deviation from uniform ventilation is not large.

During all tests (18, 19, and 26) with air supplied through a TAM located in work station number 2 (WS 2), the age of air in the return duct is significantly lower than the average age at the breathing level of the occupied workstation (WS 2), as illustrated in Figure 4, and also significantly lower than the average age at all levels within all workstations. We suspect that this short circuiting of air to the return is caused by the close proximity of the return grill (closer to WS 2 TAM than to any other TAM) and by the inward and upward direction of air supply.

In several tests, the age at the breathing level of unoccupied workstation(s) is significantly greater than the age at the breathing level of the occupied WS. In other words, the results of these tests indicate a significant, but generally modest, enhancement of ventilation at the occupant (i.e., true "task" ventilation). As illustrated in Figure 5, this efficient pattern of ventilation was evident in all tests with air directed toward the occupant (Tests 27, 32, 34, and 38D) and in two of three tests with air directed outward (35 and 36 but not 31) but in only two of 14 tests with air directed inward and upward (excluding Test 20 with mixing fans in the CEC). Possibly, the higher ages in unoccupied workstations during Tests 35 and 36 is caused by short circuiting of air from the TAM to the return grill. We have no explanation for the enhanced ventilation at the occupant during Test 30.

In several tests, the age of air at knee level in the occupied workstation is significantly greater than the age at breathing level -- with no evident correlation to test conditions. Our only possible explanation is that the knee level sampling point was in a protected location beneath the desk.

Some of the age-of-air ratios from Test 32 deviate very substantially from unity. In this test, there is a very significant enhancement of ventilation (reduced age of air) at the breathing level of the occupied workstations and age of air increases substantially with height, indicating a displacement flow, in both workstations with an operating TAM. The test was unique. Two TAMs were operating, the supply flow from each TAM was as low as possible, and air was directed toward the mannequin in WS3 and the chair to the desk of WS1. The finding of displacement flow when supply velocities are low is consistent with the results of Test 9 and with the results of complementary research on thermal comfort and temperature distributions.(4,5) Additional tests are required to further examine this general mode of operation.

Table 3. Age-of-air ratios from tests with furnished CEC. Ratios that are underlined are considered significantly different from unity from a perspective of measurement precision.

	Return	Return	Return	B.L. of UWS	C.L. of OWS	K.L. of OWS	C.L. of AWS	K.L. of AWS
Test #	B.L. of OWS	B.L. of AWS	AWS Loc.	B.L. of OWS	B.L. of OWS	B.L. of OWS	B.L. of AWS	B.L. of AWS
10	1.03	1.07	1.11	0.90	0.97	1.13	0.97	1.08
12	1.09	1.03	1.11	1.01	1.08	0.98	0.95	0.99
13	NA	NA	NA	NA	NA	NA	0.97	1.11
14	1.09	0.97	1.05	1.06	1.04	1.05	0.96	1.13
15	1.12	1.06	1.07	0.98	1.03	1.07	1.13	1.16
16	1.13	1.10	1.07	1.02	0.86	0.99	1.06	1.11
17	NA	1.06	1.08	NA	NA	NA	0.99	1.02
18	0.87	0.84	0.88	1.05	0.92	1.03	1.01	0.90
19	1.04	0.86	0.83	1.20	1.06	1.29	1.18	1.12
20*	1.06	1.03	1.00	1.05	1.06	1.10	1.05	1.07
20D	1.21	1.10	1.12	1.06	1.02	1.18	1.01	1.08
26	0.96	0.82	0.83	1.15	0.96	1.02	0.98	1.09
27	1.01	0.94	0.85	1.19	1.03	1.23	1.09	1.09
29	1.14	1.00	0.98	1.13	1.01	1.17	1.04	1.11
30	1.23	1.00	0.99	1.22	1.05	1.36	1.03	1.14
31	1.11	1.03	1.01	1.07	1.12	1.02	NA	1.17
32+	1.46	1.06	0.99	1.73	1.76	1.20	1.31	0.93
33*	1.09	1.00	0.92	1.13	1.11	1.15	1.10	1.11
34	1.06	0.89	0.93	1.19	0.90	1.13	0.92	1.06
35	1.07	0.91	0.91	1.17	1.02	1.23	1.07	1.06
36	1.13	1.00	0.89	1.17	1.18	1.24	1.13	1.17
37	1.00	1.00	0.96	0.98	0.93	1.20	1.02	1.18
38*	1.01	1.04	1.00	1.00	1.00	0.90	1.06	1.03
38D	1.17	0.93	0.90	1.33	1.24	1.07	1.07	1.00

KEY: Return = chamber return duct; B.L. = Breathing Level (1.1 m above floor); C.L. = Ceiling Level (2.1 m above floor); K.L. = Knee Level (0.4 m above floor); OWS = occupied work station (with mannequin); AWS = all work stations; UWS = unoccupied work station(s); Loc. = locations

* mixing fans in CEC

+ OWS includes both WS1 and WS3

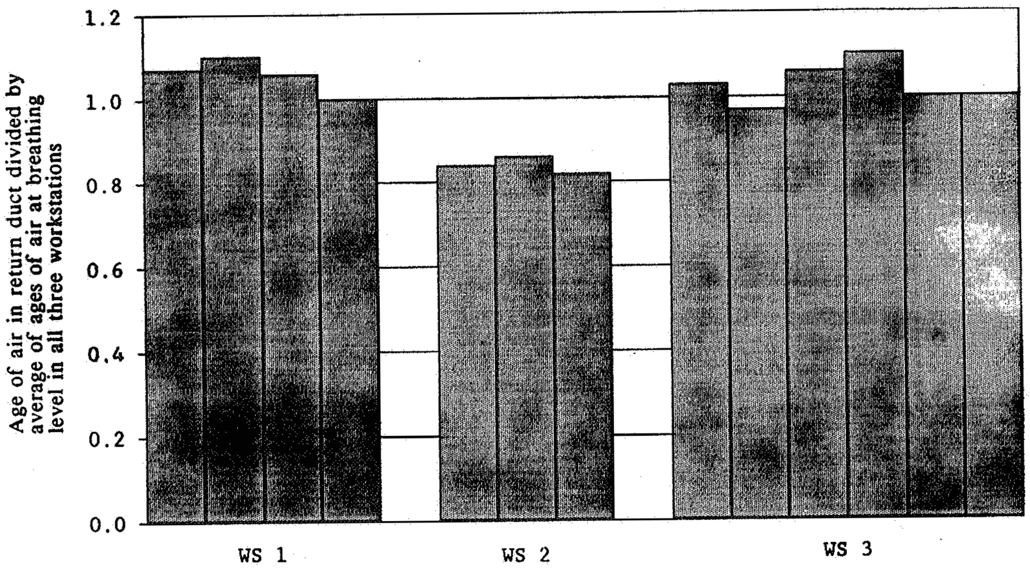

Figure 4. Age of air in return duct divided by average of ages of air at breathing level in all three workstations. Tests are divided into three groups depending on location of the operating TAM (WS1, WS2, or WS3). Tests with mixing fans in the CEC and Test 32 with two TAMS operating are not included.

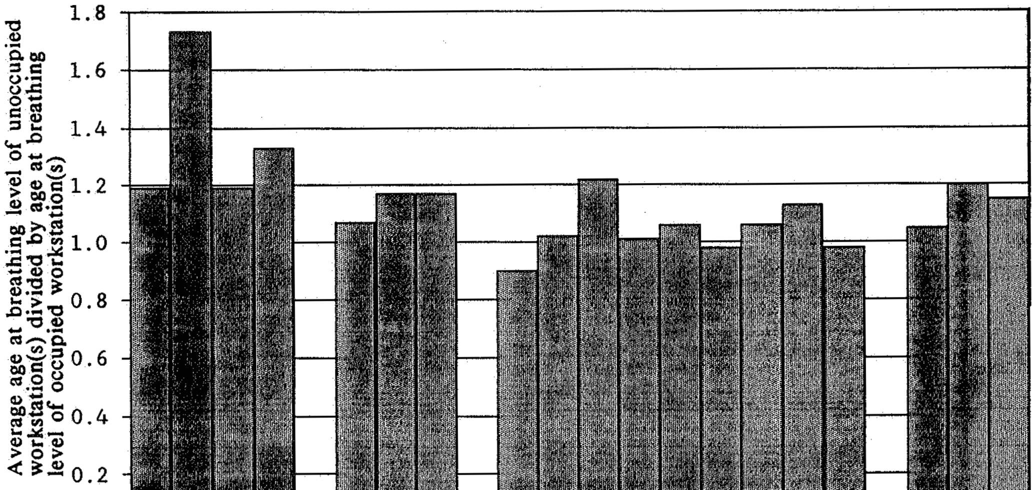

Figure 5. Average age of air at breathing level of unoccupied workstations divided by air of air at breathing level of occupied workstation(s). Only occupied wokrstations have an operating TAM. Tests with mixing fans in the CEC are not included. Tests are divided into groups depending on direction of air exiting TAM (toward occupant, outward, inward and upward). With air directed inward and upward, we separate tests with TAM operation in WS2 which was associated with short circuiting of supply air to the return grill.

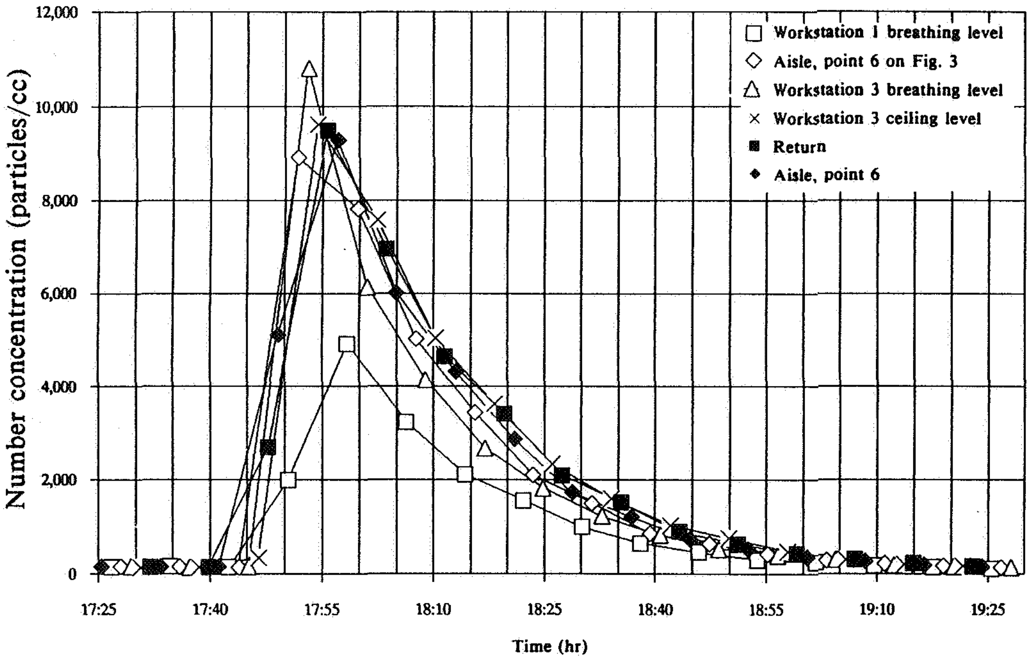

Figure 6. Total (for all size bins) particle number concentration versus time for Test 32. A cigarette was smoked in workstation 3 between 17:45 and 17:55 and TAMs operated in both WS1 and WS3.

Table 4. Total (for all size bins) time-average particle number concentrations (particles/cm^3), minus the background concentrations before and long after cigarette smoking

	Location								
Test #	B.L. of WS1	B.L. of WS2	B.L. of WS3*	B.L.m of WS3+	C.L. of WS2	C.L. of WS3	Return Grill	Supply Duct	Aisle#
31	1099	1116	1331	1265	---	---	1236	62	---
32	986	---	1693	---	---	1926	1939	---	1930
33†	1127	---	1091	---	---	1168	1175	---	1112
34	---	1525	1549	---	1514	1639	1693	208	---
35	---	1718	1496	---	1709	1633	1800	703	---
36	---	1913	1838	---	1944	1964	2047	233	---
37	---	1643	1765	---	1560	1620	1582	292	---
38U†	---	2292	2041	---	2242	2020	1869	333	---
39D	---	1876	1672	---	1902	1934	2071	275	---

Key: B.L. = Breathing Level (1.1 m above floor); C.L. = Ceiling Level (2.1 m above floor); WS1 = Work Station #1; WS2 = Work Station #2; WS3 = Work Station #3

* near mannequin (Point 3 in Figure 3)
\+ second B.L. location in WS3 (Point 4 in Figure 3)
\# point 6 on Figure 3
† mixing fans in CEC

Several test variables did not seem to significantly influence the spatial pattern of age of air. There is only a slight hint of short circuiting of air from supply to return in Test 34 with heating; this is consistent with the results of the Test 8 with heating and an unfurnished CEC. Turning off the computers, which contain small cooling fans, did not noticeably affect results. The magnitude of internal heat load did not seem to influence results for the range of loads studied. Recirculation of air by the air handler (Test 35) also had no apparent effect on results. The insignificant impact of computer fans, increased heat sources, and recirculation is probably a consequence of the relatively thorough mixing within the chamber even without these factors.

7.4 Particle Removal Experiments

Table 4 contains the time-average particle number concentrations from all tests with tobacco smoking and Figure 6 provides an example of concentration versus time for one test. During Tests 33 and 38, the air within the chamber was mixed with fans. The ratio of maximum to minimum measured particle concentration for these two tests was 1.20 and 1.23, respectively, which compares to an ideal ratio of unity in a perfectly mixed chamber if there is no measurement imprecision. Therefore, we assume differences in particle concentrations greater than approximately 20 percent are real, i.e., not caused by measurement imprecision.

In tests without mixing fans, excluding Test 32, there is little spatial variability in the time-average particle concentration based on the limited number of measurement locations. In fact, the ratio of maximum to minimum concentration during these tests is always below 1.25. During Test 32 (with large spatial differences in age of air as noted previously), the particle concentration at one indoor measurement location is approximately 50 percent of the other measured concentrations (see Figure 6). The low concentration was measured at breathing level in WS 1 which has an operating TAM directing air at low velocity toward the occupant. Apparently the partitions separating WS 1 from WS 3 (the cigarette was smoked in WS 3) and the direct supply of air in WS 1, were sufficient to substantially reduce particle transport to the breathing location in WS 1. We would not expect this region of low particle concentration if the ventilation were provided in the typical manner through ceiling-mounted air supply diffusers; however, additional experiments are required to confirm this expectation.

8.0 SUMMARY OF MAJOR FINDINGS

1. Except in tests with the minimum possible rate of air supply through the TAMs, age-of-air ratios were almost always within 0.3 of unity indicating that deviations from uniform ventilation were not large. We hypothesize that entrainment of room air in the high velocity supply jets was a major cause of mixing of the indoor air.

2. With the minimum possible rate of air supplied through TAMs, there was a significant displacement flow pattern in the CEC. More tests with low supply velocities are required.

3. In almost all tests with air directed toward the occupant or in an outward direction, but very few tests with air directed inward, the age of air at breathing level of the occupant was significantly (but, in general, only moderately) lower than the age of air at other indoor locations.

4. Directing air inward and upward toward a return grill was associated with a slight amount of short circuiting between the floor-mounted TAM and the ceiling-mounted return.

5. Increased internal heat load, operation of computers containing small cooling fans, and recirculation of air by the main air-handling unit had no discernible impact on the spatial pattern of age of air, probably due to relatively thorough mixing without these factors.

6. With workstations separated by partitions, using the task ventilation system to directly supply air toward the occupant's breathing location appears to inhibit the transport of tobacco smoke particles to that location from an adjacent workstation.

9.0 ACKNOWLEDGMENTS

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Discussion

Paper 5

W.Raatschen (Dornier GmbH, Germany)

Is the ratio of the exit age vs. local mean age an appropriate value to characterise a displacement flow system?

W.Fisk (LBL, USA)

An increase in the age of air with height above the floor is a proper indication of displacement flow in the floor-to-ceiling direction. This trend was indicated by measurements at three heights within the chamber plus measurements at the ceiling-level return grille. Comparing the exit age (age at return grille) to a single local age (e.g. at breathing level) is a less certain indication of displacement flow.

M.Masoero (Politecnico di Torino, Italy)

According to some system manufacturers, subfloor air distribution is beneficial to IAQ because the raised floor can be raised and cleaning performed. Other people agree that subfloor space contains plastic electric cables that can themselves be sources of pollution. Can you comment on this? See comment by Mike Holmes.

W.Fisk (LBL, USA)

My response to the question by M J Holmes applies to this question. I also note that many return-air plenums contain electrical cable and that we have many plastics, adhesives, caulks, etc., within the occupied spaces of our buildings. I am not aware of data indicating that electrical cables are an important source of indoor pollutants.

M.J.Holmes (Ove Arup, London)

There are two types of underfloor systems, neutral and pressurized floors. The neutal pressure floor can be achieved by either ducting recirculation air and using fans to overcome the terminal resistance, or a non ducted system with a terminal fan. Floor pollution is obvious in the latter case, in the form debris falling into the system could cause a problem. Pressurized floors also have a contamination problem and they leak. Have you any comments?

W.Fisk (LBL, USA)

Our primary interest is task (i.e. occupant controlled) ventilation which does not necessarily require the use of a subfloor supply air plenum. We have no practical experience with accumulation of dirt in these plenums. However, avoiding a subfloor plenum does not eliminate problems of dirt accumulation on surfaces in contact with air supplied to occupants. Dirt can accumulate inside supply ducts (this problem may be increased when ducts are lined with a porous insulation) and also in return-air plenums.

Bas Knoll (TNO, Netherlands)

How does compartmentation by the separations affect or improve displacement flow?

W. Fisk (LBL, USA)

Displacement flow doesn't seem majorly affected by it.