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TESTING OF LOCALIZED THERMAL DISTRIBUTION SYSTEMS
IN A NEW CONTROLLED ENVIRONMENT CHAMBER

E.A. ARENS, F.S. BAUMAN, L.P. JOHNSTON, and H. ZHANG

Center for Environmental Design Research
390 Wurster Hall, University of California
Berkeley, California 94720 USA

SYNOPSIS

This paper describes tests of thermal and ventilation performance of two relatively new occupant-controlled localized thermal distribution (also called task ventilation) systems. The first is a raised-floor distribution system providing air through grilles in the floor panels, and the second is a desk-mounted unit supplying conditioned air at desktop level. These systems have been tested in a mockup of a typical partitioned open-plan office, and the resulting temperature and air velocity distributions are reported for a variety of system and locally controlled conditions. Comfort model predictions are presented to describe the degree of control and range of occupant comfort levels produced in the local workstation. The results are also compared to those produced by a conventional ceiling supply system.

The tests were performed in a new controlled environment chamber (CEC) having unique capabilities for detailed studies of space conditioning and thermal comfort in office environments. The CEC closely resembles a contemporary office space 5.5 m x 5.5 m x 2.5 m in size, with exterior windows on two walls and reconfigurable HVAC and lighting systems. Air can be supplied and returned from floor or ceiling levels, the surface temperature of the windows controlled by air circulated through the triple-pane glazing, and two separately controlled air supplies can be provided to the space simultaneously.

The tests investigated the effects of supply volume, supply location, supply vent orientation, supply/return temperature difference, heat load density, and workstation size and layout. Temperature differences in the range of 1-2.5°C were observed between adjacent workstations, and local velocities in the vicinity of outlets could exceed 3 m/s. Such wide-ranging values could violate existing comfort standards, if strictly interpreted. However, since these systems put the local thermal conditions within the workstations under the direct control of their occupants, it is likely that the standards should grant exceptions to such systems.

1. INTRODUCTION

It has become increasingly difficult for conventional centralized HVAC systems to satisfy the environmental preferences of individual office workers. Offices today have large amounts of heat-generating equipment (computers, printers, etc.) whose loads vary considerably from workstation to workstation. The workstations are separated by partitions that divert the flow of air between ceiling-mounted supplies and returns so that the workstations themselves are not well ventilated. The workstations are also increasingly reconfigured to accommodate changing tenant needs, affecting the HVAC system's ability to meet the loads for which they were designed. Compounding this problem, there is a growing awareness of the importance of the comfort, health, and productivity of the individual office workers, giving rise to an increased demand among employers and employees for a high quality work environment.

Localized thermal distribution (LTD) systems distribute conditioned air through vents in the direct vicinity of the occupant. The vents can be located in the floor plane or in the office furniture, such as desks or workstation partitions. Such distribution systems have the potential to improve the ventilation efficiency at the breathing level and at the same time provide individual workers with the ability to adjust their local environments to their individual comfort preferences. They also appear to have energy-saving potential, particularly when occupancy sensors are

fitted to the local supply units to turn them off when their associated workstations are unoccupied. Localized thermal distribution systems are frequently combined with raised access floors installed to facilitate cable management and workstation reconfigurability.

In one of the earlier publications on occupant-controlled thermal distribution, David⁽¹⁾ describes several of the underfloor systems available at that time. The literature reports relatively few experimental studies of how such systems perform. Sodec⁽²⁾, Barker⁽³⁾, Barker et al.⁽⁴⁾, Tuddenham⁽⁵⁾, Rowlinson and Croome⁽⁶⁾, and Hanzawa et al.⁽⁷⁾ present data from test chamber studies of floor and desk-mounted supply vents. More recently, Spoormaker⁽⁸⁾ describes his experiences in South Africa with a floor supply system very similar to the one studied in the present investigation. Sodec and Craig⁽⁹⁾ describe the European experience with both floor and desk-level supply systems. Additional references are contained in a discussion by Bauman et al.⁽¹⁰⁾.

Under low supply velocity conditions, the performance of floor-based systems will resemble that of displacement ventilation systems, producing increased stratification while providing relatively uniform conditions at any given height within the occupied space. At higher rates of flow the supply air may form jets and produce nonuniform thermal conditions and localized drafts. Both of these could lead to local thermal discomfort even when whole-body comfort is acceptable. Research during recent years has studied the impact of turbulence intensity on the sensation of draft and concluded that further reductions in velocity limits contained in the present comfort standards may be necessary for airflows having higher levels of turbulence⁽¹¹⁾. Even with their present limits, the requirements of ASHRAE Standard 55-81⁽¹²⁾ and ISO Standard 7730⁽¹³⁾ are probably not met by many LTD's under normal operation because of high velocities in the vicinity of the supply vents and also because of temperature variations that may exist within the occupied zone.

On the other hand, there is some evidence that the variable climate they produce, when occupant controlled, may in fact be desirable for an office ventilation system. A recent survey of three installations of a floor-level LTD system found that two-thirds of the workers felt that an underfloor LTD system provided improved temperature and ventilation conditions compared with the overhead ventilation system in their previous buildings⁽¹⁴⁾. One might also look at this from the perspective of what appear to be inherent limitations to comfort standards. Both the ASHRAE and ISO comfort standards specify a zone of relatively uniform conditions within which no more than 20% of the occupants are to be dissatisfied. Although 20% is in itself a fairly large number, a recent field study in office buildings suggests that the dissatisfaction level for environments maintained within the comfort zone may in fact be higher⁽¹⁵⁾. In addition, this study and others^(16,17), have found that lack of air movement is one of the most common complaints in office environments, although the low air movement rates are permitted by the standard. Giving workers control over the temperature and ventilation in their local environment might be the only way to satisfy a larger percentage of people than is currently possible with traditional centralized control. If so, existing comfort standards will need to be reevaluated in terms of a broader definition of what are acceptable environmental conditions.

The authors are involved in a multiyear study to examine the performance of LTD systems, both in terms of the physical environments they produce and their effect on worker satisfaction. This paper describes some of the physical tests being made in our laboratory (the Controlled Environment Chamber) on two commercially available LTD systems.

2. DESCRIPTION OF SYSTEMS

2.1 Floor system

The floor system consists of self-powered supply modules that are components of a raised access floor system. Each module, measuring 0.6 m x 0.6 m, can be located at any position by exchanging it with a solid floor panel of equal size. Figure 1 shows a cutaway diagram of the floor supply module. A fan/motor assembly draws air from the sub-floor plenum and supplies it to the room through four 127 mm diameter discharge grilles. The grilles are molded of fire-resistant polycarbonate, and will support foot traffic and furniture. The individual vanes in the grilles are inclined 40° from vertical. A rotary speed control knob is recessed into one grille and each grille can be rotated through 360°, allowing office workers to control both the direction and quantity of air supplied from the module.

When the fan is switched on, the floor supply module can deliver between 40 and 90 L/s from a zero or very low pressure plenum. Over this same range of airflows the maximum outlet velocity measured at the grille varied between 2 and 6 m/s. The manufacturer's recommended operating procedures call for the four grilles to be turned inward toward the center of the module. At maximum air delivery, the four individual air jets converge at a height of 200-250 mm and produce a strong vertical turbulent jet and rapid vertical mixing with the room air. Under typical operation the Archimedes number (Ar) ranges between about 0.001 and 0.004, indicating that the force of inertia from the jet dominates the buoyancy forces in the room. (Ar is defined here as $Ar = g \cdot d_0 \cdot \Delta T_0 / (v_0^2 \cdot T_r)$, where g is the acceleration due to gravity (m/s^2), d_0 is the outlet diameter (m), v_0 is the outlet velocity (m/s), ΔT_0 is the temperature difference at jet entry (K), and T_r is the room temperature (K)).

The largest number of installations of this system occur in South Africa, although there are now nearly a dozen in North America.

2.2 Desk-mounted system

The desk-mounted system uses a self-powered mixing box (559 mm x 381 mm x 241 mm) that is hung in the back or corner of the knee space of the desk, and connected by flexible duct to two supply nozzles on the top of the desk (Figure 2). The supply vents may be rotated 360° in the horizontal plane and contain outlet vanes that are adjustable $\pm 30^\circ$ in the vertical plane. The mixing box uses a small variable-speed fan to pull supply air from a zero or very low pressure plenum either under the floor (as indicated) or from flexible ducts in the office partitions supplied from the ceiling. A second fan pulls air from the knee space. The unit has a desktop control panel containing sliders controlling: the speed of the air emerging from the vents, its temperature (produced by adjusting the ratio of supply to recirculated air, providing a design range of 10°C), the temperature of a 200 W radiant heating panel located in the knee space, the dimming of the occupant's task light, and a white noise generator in the unit that issues a rushing sound through the supply vents. The control panel also contains an infrared occupancy sensor that shuts the unit off when the workstation has been unoccupied for a few minutes.

Each workstation unit is capable of providing approximately 20-70 L/s of air.

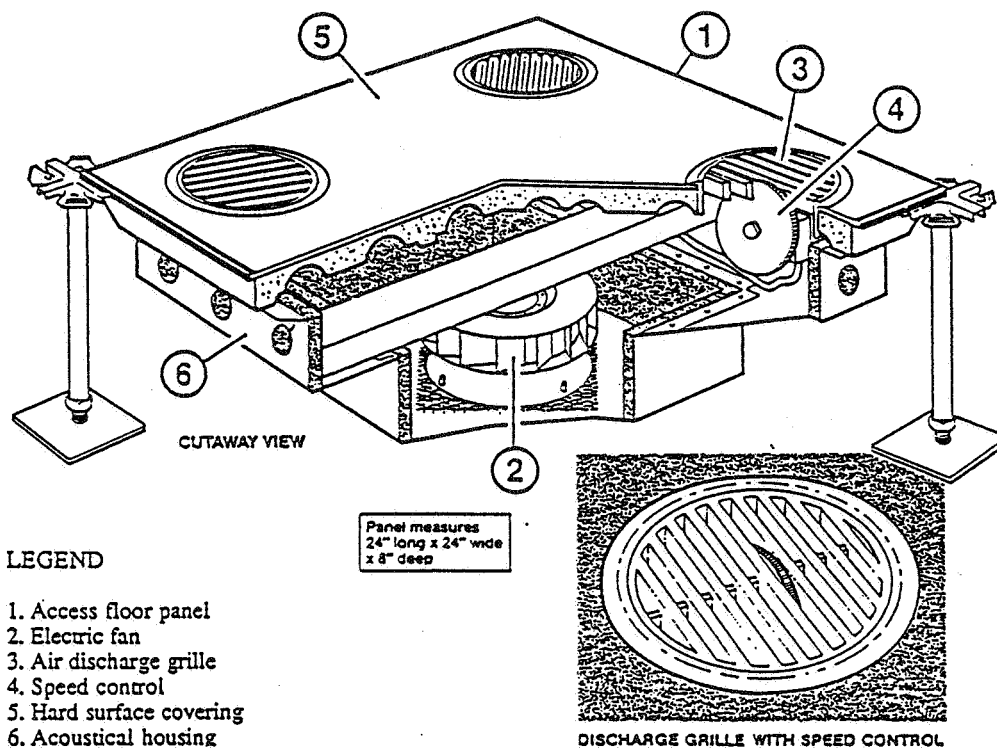


Figure 1. Floor Supply Module

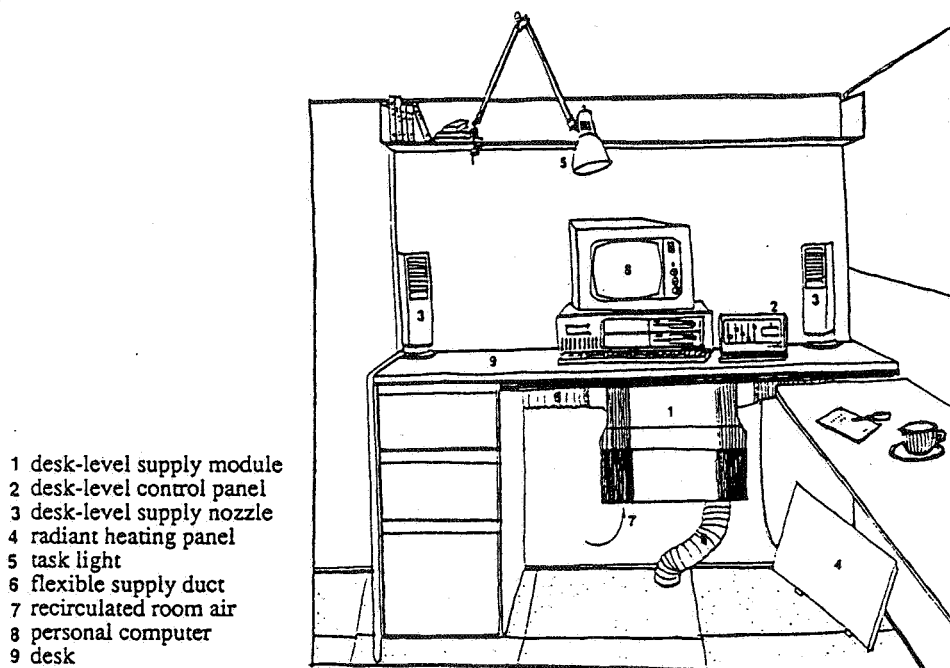


Figure 2. Desk-Mounted Supply System

Even when its internal fans are turned off, the system is designed to deliver 20 L/s to satisfy minimum ventilation requirements. The maximum outlet velocity measured at the face of the 58 x 100 mm supply vent varied between 2 and 7.5 m/s over the same range of airflows described above. In operation a design supply air temperature of 13°C is provided by a variable air volume HVAC system, with desk-level outlet temperatures in the range of 18°C. Under typical operating conditions, the Archimedes number for each outlet ranges between about $3.5\text{--}50 \times 10^{-4}$, where Ar is defined as above.

3. EXPERIMENTAL METHODS

3.1 Controlled environment chamber

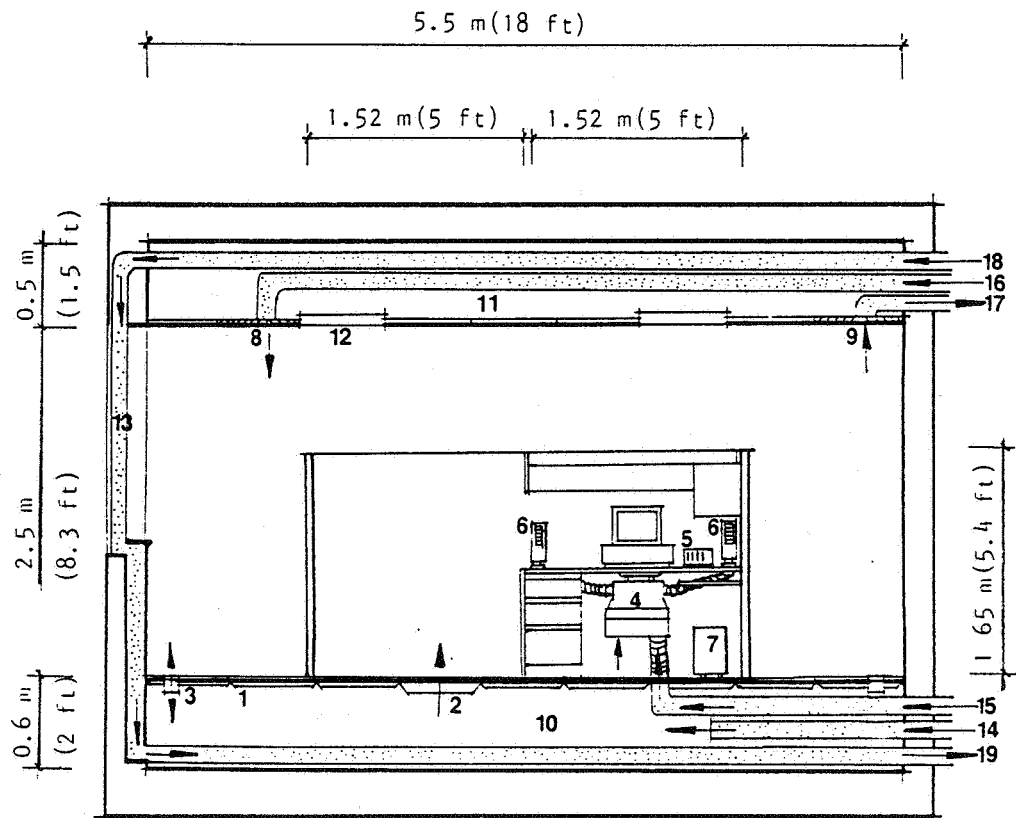
The two LTD systems have been tested in a controlled environment chamber (CEC) measuring 5.5 m x 5.5 m x 2.5 m, and located in a university laboratory. The CEC is designed to resemble a modern office space while still allowing a high degree of control over the test chamber's thermal environment⁽¹⁸⁾. The floor is fully covered with carpet tiles, finished gypboard walls are heavily insulated and painted white, triple-pane windows in the two exterior walls provide a view to the outside, the suspended ceiling contains acoustical tile with adjustable slots, and six 0.6 m square recessed dimmable lighting fixtures are mounted in the ceiling. As shown in Figure 3A, a raised access floor system provides a 0.6 m high sub-floor plenum, and the suspended ceiling provides a 0.5 m ceiling plenum.

A reconfigurable air distribution system permits ducted or plenum air to be supplied to and returned from the test chamber at any combination of ceiling and floor locations. Figure 3B shows the air flow configurations used during the tests reported here. All tests of the floor system used a sub-floor plenum supply. During these tests, a floor supply module was located within each of three modular workstations, as indicated in Figure 3B. For comparison with the floor system, a limited number of office tests were performed using a conventional ducted ceiling supply and return system. In this case a single perforated ceiling diffuser was used for supply air. To investigate the desk-mounted system, a separate supply line was ducted through the sub-floor plenum to the mixing box under the desk. The ducted ceiling supply diffuser was also used during some tests to control the average room temperature at the desired setpoint, while the supply air conditions at the desk could be varied to control the local workstation environment. During all LTD tests air was returned at the ceiling level through a single ducted perforated return grille (Figure 3A).

The CEC air distribution system also allows a separately controlled supply of air to be provided through the plenum-wall construction of the two exterior chamber walls. Air flow through this annular space was used to control the interior window surface temperature at a level equal to the average room air temperature.

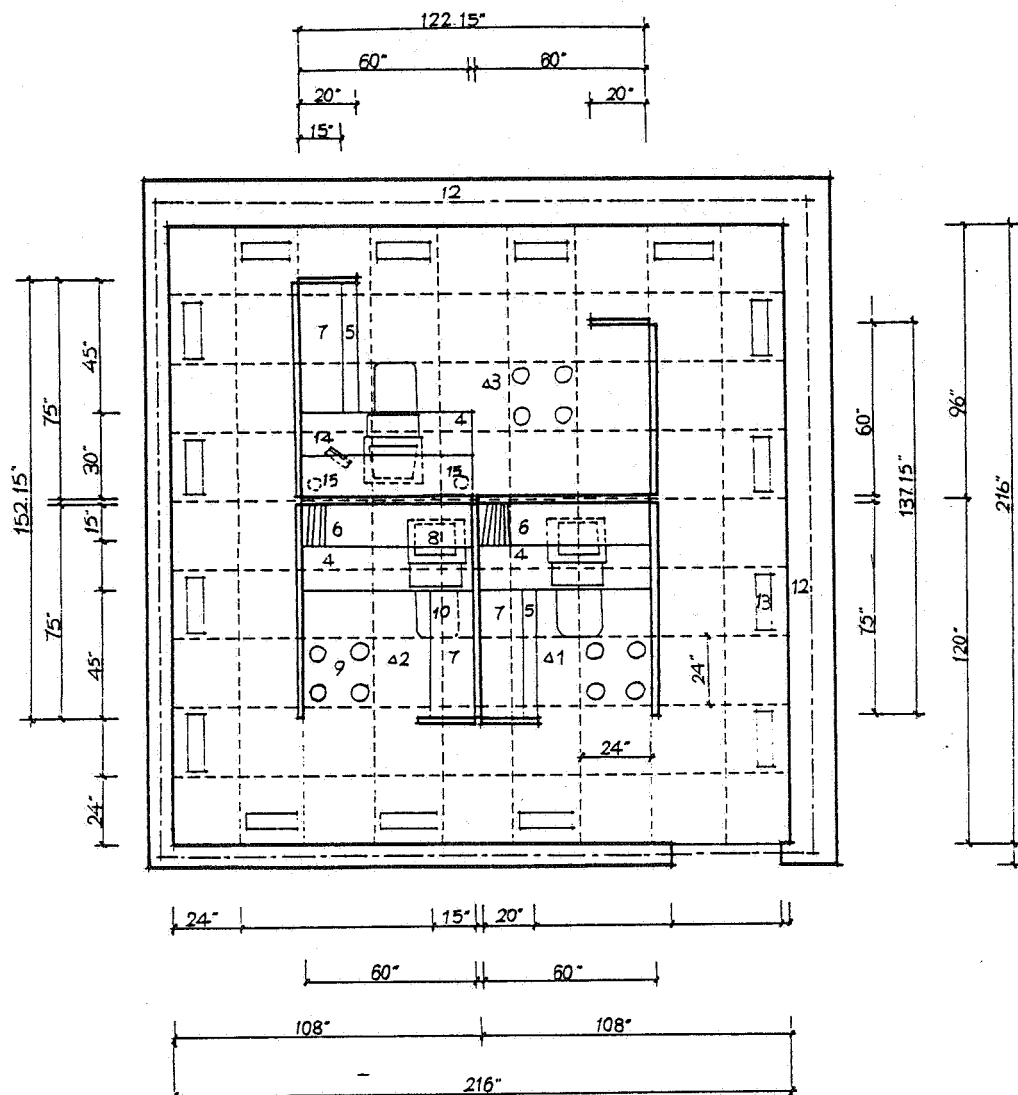
3.2 Instrumentation and equipment

Detailed air velocity and temperature measurements within the test room were accomplished by using a lightweight sensor rig fabricated out of aluminum tubing, that allowed a vertical array of sensors to be positioned at desired measurement heights and moved around the room to map out a grid of selected measurement lo-



- | | |
|----------------------------|-------------------------|
| 1 access floor system | 10 sub-floor plenum |
| 2 floor supply module | 11 ceiling plenum |
| 3 floor register | 12 ceiling luminaire |
| 4 desk-level supply module | 13 window plenum |
| 5 desk-level control panel | 14 floor-plenum supply |
| 6 desk-level supply nozzle | 15 desk-level supply |
| 7 radiant heating panel | 16 ceiling supply |
| 8 ceiling supply diffuser | 17 ceiling return |
| 9 ceiling return register | 18 annular space supply |
| | 19 annular space return |

Figure 3A. Section: Controlled Environment Chamber



- | | |
|---------------------|------------------------------|
| 1--workstation #1 | 8--computer |
| 2--workstation #2 | 9--floor supply module |
| 3--workstation #3 | 10--chair |
| 4--desk | 12--annular space |
| 5--sidetable | 13--floor register |
| 6--bookshelf | 14--desk-level control panel |
| 7--overhead storage | 15--desk-level supply nozzle |

Figure 3B. Chamber Plan 1:50

cations (Figure 4). By positioning the sensors within the space defined by the structural elements of the rig, protection was provided against damage from accidental encounters with office furniture and other obstacles. At each location in the room, air velocity and temperature were generally measured at six heights: 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.0 m, and 2.35 m. The 0.1 m, 0.6 m, and 1.1 m levels correspond to recommended measurement heights for seated subjects, and the 0.1 m, 1.1 m, and 1.7 m levels correspond to heights recommended for standing subjects, as specified by ASHRAE Standard 55-81. Velocities were measured with spherical-element omnidirectional anemometers having a range of 0-3.5 m/s, and temperatures were measured with shielded thermistor temperature probes. A portable computer-based data acquisition system was used to record the readings from the velocity and temperature sensors mounted on the aluminum sensor rig.

Supply and return air volumes were monitored by running the supply air through straight-lengths of small-diameter pipes with pitot tubes mounted to measure the fully-developed flow. The volume of supply air entering the test room through each floor supply module or ceiling diffuser was checked and balanced with a flowhood. The supply volume from the desk-level nozzles was checked with a precision portable thermal anemometer and revolving vane anemometer. Tests to measure the air velocity and turbulence intensity at a single point in the room were performed with an elliptical-element omnidirectional anemometer. This anemometer was used because of its relatively quick response time (0.2 sec for 90%) and associated signal conditioning and recording unit. Flow visualization of the room airflow patterns was performed with a helium-filled bubble generator.

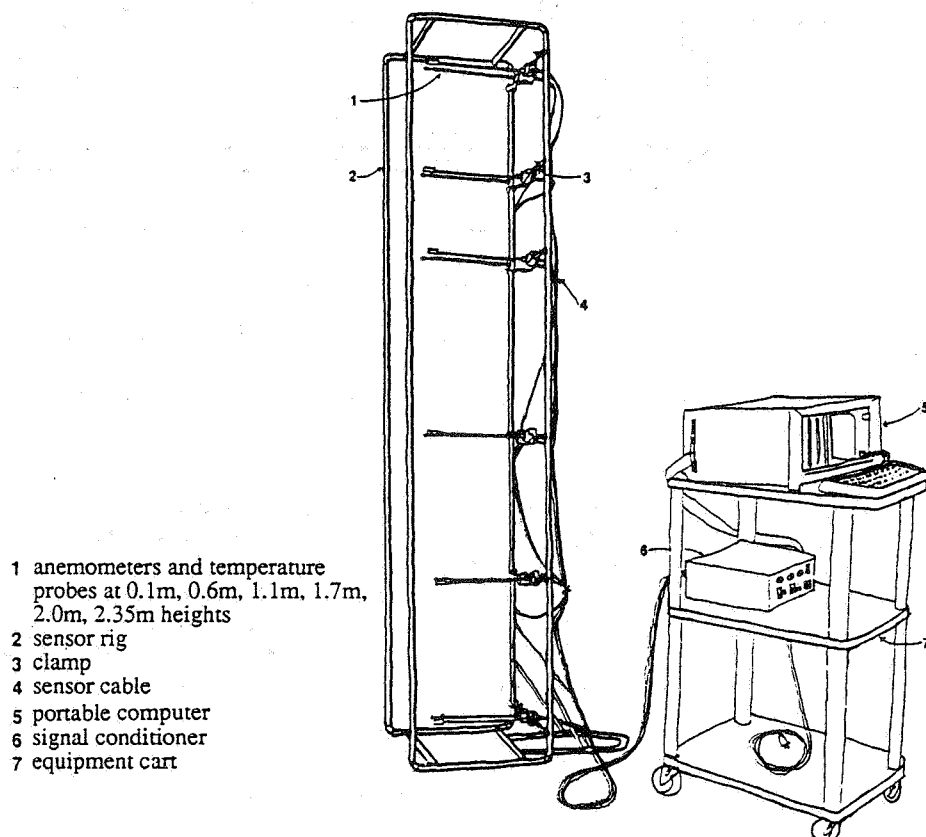


Figure 4. Sensor Rig and Data Acquisition System

Additional temperature measurements in the ducts and room were made with thermistor elements contained in duct immersion or wall-mounted units. These along with other test parameters were monitored and recorded through the direct digital control system for the CEC. Globe temperature was measured with a 38 mm diameter table tennis ball, as described by Benton et al.⁽¹⁹⁾. Room surface temperatures were checked by scanning with an infrared thermometer.

3.3 Test procedures

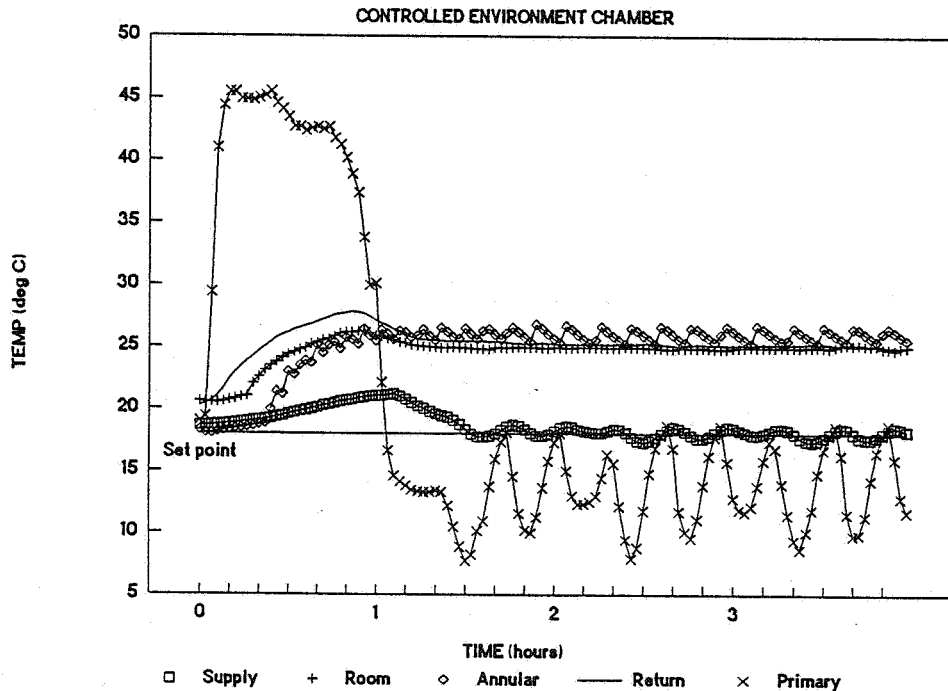
3.3.1 Office configuration with floor system

To study the performance of the floor supply module in an office environment, a modular workstation configuration shown in Figure 3B was installed in the test chamber. Solid partitions (1.65 m tall) were set up to produce two small 1.5 m x 1.9 m workstations and one double-sized 3.0 m x 1.9 m workstation. The arrangement of the furniture, including desks, side tables, and overhead storage bins, is also shown in the figure.

Heat loads were provided to simulate typical office load distributions and densities. A personal computer and monitor (≈ 90 W total) were placed on each of the three desktops. Each workstation had a 75 W task light above the desk. A second 75 W light bulb was located at the 1.1 m level near the edge of the desk to simulate the sensible heat load from a typical office worker. The six overhead lighting fixtures had a total power rating of 600 W. Energy balance tests indicated that only a small fraction of the overhead lighting load contributed to the room load. During the test, the experimenter and computer-based data acquisition system added approximately 150 W to the total load. Two different office heat load densities were studied during the experiments. The heat sources described above generated a load density of approximately 35 W/m². A higher load density of 55 W/m² was produced by placing a 200 W electric radiant heater on the floor under each desk to represent larger computer processing units.

All experiments were carried out under steady-state conditions chosen to represent an interior zone of an office building. To achieve these conditions the electrical heat sources in the room and the mechanical system were turned on in the morning and allowed to warm up the room until the expected average room temperature for the upcoming experiment was reached (24-28°C during these tests). Figure 5 presents a time plot of temperature control provided by the mechanical system during the warm-up and subsequent steady-state test period for a typical experiment at 130 L/s supply volume. During the warm-up period primary air was provided directly to the test room through flexible ducts pulled up through open floor panels. This avoided heating up the sub-floor plenum and allowed the desired test conditions to be reached much more quickly. After completing the warm-up, the supply ducts were returned to the plenum, the access floor was closed up, the supply air volume and temperature were adjusted to their selected setpoints, and conditions in the room were allowed to further stabilize. Figure 5 shows that as the room temperature balance point is reached the cycling of the chiller is evidenced by the fluctuating temperature of the primary air supplied to the sub-floor plenum. These fluctuations are largely damped out by the time the air passes through the floor supply module. Typical control of the supply air temperature entering the room was 18°C \pm 0.5°C. Also shown is the return temperature of the annular space air-flow, demonstrating how it was controlled to a level close to the average room temperature. Room humidity levels were not controlled during the tests.

FIGURE 5. TEMPERATURE CONTROL



The supply air volume provided to the sub-floor plenum was balanced with the flow requirements of the floor supply modules, thus producing the desired low-pressure plenum. Pressure measurements across the access floor indicated pressure differentials between -0.25 and +0.25 Pa for the range of test conditions investigated. Transient load effects of heat storage in furniture, partitions, and room surfaces were also minimized by running the experiments under steady state conditions. Floor, wall, and ceiling surface temperatures were monitored with an infrared thermometer before and after each test period as a check of these storage effects.

The characteristics of the floor system tests can be seen in Table 1. Combinations of one, two, or three floor supply modules were investigated. The most common total supply air condition was 90 L/s at 18.0°C, supplied through one or split between two floor supply modules. The supply/return air temperature differentials ranged between 6 and 10°C, depending on load and flow conditions. As indicated the effects of grille position were studied for three orientations: (1) grilles turned inward, toward the center of the module; (2) all grilles turned toward the desk in the workstation; and (3) a combination of the above, usually with one or two grilles turned toward the desk and one or two turned inward or away.

Measurements using the sensor rig were made at two-foot intervals, with the vertical array of sensors centered over one of the access floor panels. Figure 6 shows the measurement locations used during most tests, which focussed on the thermal conditions within each of the three workstations. After positioning the sensor rig at the desired measurement location, all sensors were sampled over a one-minute measurement period. Preliminary tests had determined the length of this period as the minimum sampling time that still produced acceptable repeatability between consecutive measurements at the same position.

TABLE 1. FLOOR SYSTEM TEST CONDITIONS

Test Number	CHAMBER					WORKSTATIONS						
	Supply Air Volume (L/s)	Heat Load (W/sq.m)	Return Air Volume (L/s)	Supply Air Temp. (deg C)	Room Temp (deg C)	Return Air Temp. (deg C)	#1			#2		
							Air Volume (L/s)	Temp. (deg C)	Grille Position	Air Volume (L/s)	Temp. (deg C)	Grille Position
1A	92	55	66	17.9	25.7	26.4	0	-	-	0	-	-
1B	92	55	66	18.0	26.0	25.5	0	-	-	0	-	-
1C	91	55	66	18.0	26.2	25.9	0	-	-	0	-	-
2A	91	55	66	18.1	27.5	27.7	41	18.2	Toward	0	-	-
2B	91	55	66	18.0	27.7	27.8	41	18.2	Comb.	0	-	-
3	90	55	80	18.0	25.9	26.2	46	18.2	Comb.	44	17.7	Comb.
4	133	55	116	17.9	25.1	25.2	46	18.4	Comb.	44	17.8	Comb.
5A	64	55	49	18.1	27.3	27.6	0	-	-	0	-	-
5B	67	55	47	18.0	27.8	28.0	0	-	-	0	-	-
6A	89	35	66	18.0	23.9	23.5	0	-	-	0	-	-
6B	91	35	65	17.9	24.1	23.8	0	-	-	0	-	-
6C	91	35	68	18.0	24.6	24.4	0	-	-	0	-	-
7	91	35	67	17.9	24.8	25.2	45	18.1	Toward	0	-	-
8	91	35	67	18.0	24.5	24.6	45	18.2	Comb.	45	17.7	Toward
9	90	35	67	18.0	24.9	24.4	90	18.0	Comb.	0	-	-
10A	65	35	48	18.1	25.1	25.2	0	-	-	0	-	-
10B	65	35	48	18.1	25.4	25.4	0	-	-	0	-	-
11A	65	35	48	18.0	25.9	25.8	65	17.9	Inward	0	-	-
11B	65	35	48	18.0	25.7	25.8	65	18.0	Comb.	0	-	-

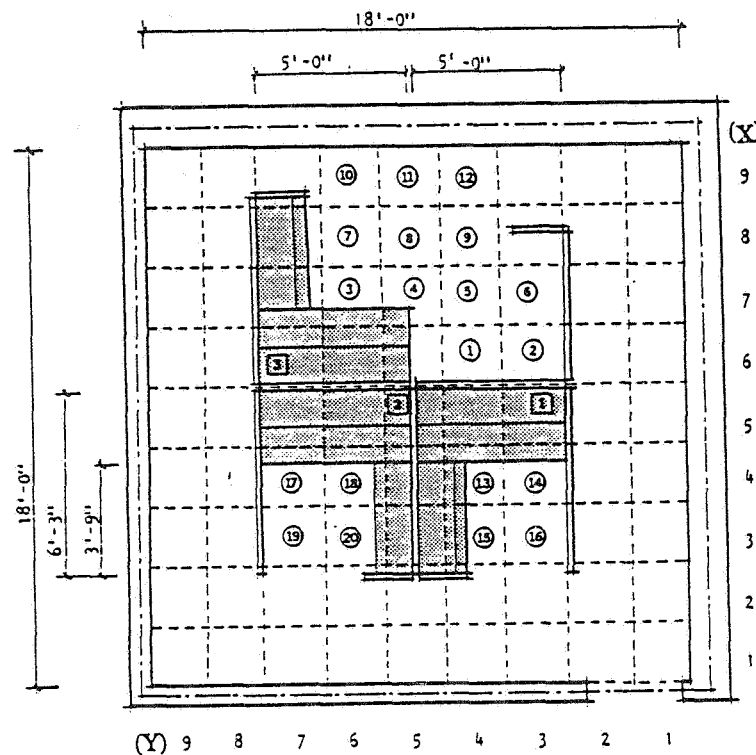


Figure 6. Test Position: Office Configuration

3.3.2 Office configuration with desk-mounted system

The desk-mounted system was installed in the larger Workstation #3, as indicated in Figures 2 and 3. During these tests, Workstations #1 and #2 had no local air supply. During some tests, supplemental space conditioning (beyond that provided by the desk-mounted system) was provided by a ceiling supply diffuser. For this purpose, the diffuser was positioned near one side of the room at (x=5, y=2), as defined by the nine by nine grid of 0.6 m by 0.6 m panels shown in Figure 6. The internal pattern deflectors of the diffuser were adjusted to produce a 3-way airflow pattern, away from the adjacent wall. The ceiling return register was located at (5,9) during all tests.

As with the floor system tests, experiments were performed under steady-state conditions. Testing of the desk-mounted system is still in progress, so only a limited number of preliminary results are presented here. Table 2 lists the conditions of the tests completed to date. All tests were made at the higher heat load density of 55 W/m², resulting in relatively high average room temperatures (26-28.5°C). Primary air supplied to the desk module was controlled at 13°C, resulting in desk-level supply air temperatures of 17-19°C. As indicated, different combinations of supply nozzle position and control panel settings for airflow and temperature were investigated. The nozzle positions studied included: (1) both nozzles turned toward the occupant with vanes level; (2) both nozzles turned toward the occupant with vanes up or down; (3) both nozzles turned to the left or right, away from the occupant; and (4) a combination of the above with one nozzle turned toward the occupant and one turned away. Velocity and temperature measurements with the sensor rig were made at the same locations shown in Figure 6.

TABLE 2. DESK-MOUNTED SYSTEM TEST CONDITIONS

Test Number	CHAMBER					
	Ceiling Sup. Air Volume (L/s)	Heat Load (W/sq.m)	Return Air Volume (L/s)	Ceiling Sup. Air Temp. (deg C)	Room Temp. (deg C)	Return Air Temp. (deg C)
1A	37	55	60	14.3	26.8	27.6
1B	37	55	59	14.2	26.9	27.8
2A	52	55	67	12.0	26.2	26.0
2B	52	55	68	11.9	26.3	26.3
3A	0	55	43	-	28.5	29.0
3B	0	55	39	-	28.0	28.4
4A	40	55	67	13.4	26.5	26.9
4B	37	55	58	13.8	26.8	27.5

WORKSTATION #3						
Test Number	Supply Air Volume (L/s)	Supply Air Temp. (deg C)	Temp. Setting	Air Flow Setting	Nozzle Position	
					Left	Right
1A	23	18.9	Min.	Min.	Toward, Level	Toward, Level
1B	24	18.5	Min.	Min.	Right, Level	Straight, Level
2A	66	17.3	Min.	Max.	Toward, Level	Toward, Level
2B	66	17.5	Min.	Max.	Right, Level	Straight, Level
3A	43	18.0	Min.	Max.	Toward, Down	Toward, Up
3B	48	17.8	Min.	Max.	Toward, Level	Toward, Level
4A	Variable	Variable	Variable	Variable	Variable	Variable
4B	Variable	Variable	Variable	Variable	Variable	Variable

3.3.3 Office configuration with overhead supply system

For comparison with the floor system, a limited number of tests were performed with a conventional overhead ducted supply and return system, positioned at the same ceiling locations as described in 3.3.2. For consistency, the supply air volume was controlled at 90 L/s, equal to the volume used during most of the floor supply tests. For this airflow rate, the throw of the diffuser was slightly below the minimum level recommended by the manufacturer to achieve acceptable room air diffusion. Supply air temperature was controlled at 13°C, a typical value for overhead supply systems. Tests were performed only for the higher heat load density (55 W/m²).

3.3.4 Tests of controllability and comfort

To investigate the degree of control and range of comfort conditions that an office worker could produce in the local workstation, a series of short-term adjustments were made to the LTD systems installed in Workstation #3, and the resulting thermal conditions were monitored at the nearby desk. Each system was studied separately. The controllability tests studied changes in fan speed and grille position for the floor system, and changes in nozzle position and airflow and temperature settings for the desk-mounted system.

As with previously described test procedures, the room was allowed to warm up and stabilize until the room temperature balance point was reached. For the floor system test, a constant volume of 90 L/s primary air was supplied to the sub-floor plenum throughout the test and its temperature was controlled to maintain an 18.0°C supply air temperature, as averaged between the three floor supply modules. Initially the floor supply module in Workstation #3 was turned off; the 90 L/s supply air volume was split equally between Workstations #1 and #2, by adjusting the fan speed to its minimum flow setting in each of the two floor supply modules. Since floor modules #1 and #2 maintained their constant air volumes throughout the test, when floor module #3 was turned on, a flow imbalance existed between the primary air supply and the three floor modules. In this case, rectangular floor grilles, located around the perimeter of the chamber, were opened to allowed the air supply requirements of the floor modules to be made up with room air (see Figure 2A).

Throughout the desk-mounted system test, a fairly constant supply of air was provided through the ceiling diffuser to maintain the desired average room air temperature ($\approx 27^{\circ}\text{C}$). The desk unit was initially turned off, although as previously described, some minimum air supply ($\approx 20\text{ L/s}$) was still provided under these conditions.

The sensor rig was placed directly in front of the desk at the normal working position (measurement location #3 in Figure 6). Globe temperature was also monitored at the 1.1 m height to allow the calculation of mean radiant temperature. Sensor readings were recorded at exactly two-minute intervals throughout the tests.

After recording the initial conditions, the system was turned on and the airflow and temperature controls, and grilles/nozzles were adjusted to their desired positions. These settings were maintained for 16 minutes, after which a second adjustment was made to the system. This procedure was repeated for a total of eight different control settings for the floor system (see Table 3), and nine settings for the desk-mounted system (see Table 4). The tests were performed at the higher office heat load density of 55 W/m².

**Table 3. Floor System Controllability Test:
Control Settings**

No.	Airflow	Grille Position
1	OFF	---
2	maximum	toward
3	maximum	inward
4	minimum	inward
5	minimum	toward
6	50%	toward
7	50%	combination
8	OFF	---

**Table 4. Desk-Mounted System Controllability Test:
Control Settings**

No.	Control Panel		Nozzle Position	
	Airflow	Temperature	Left	Right
1	OFF	---	away	away
2	maximum	minimum	toward, level	toward, level
3	maximum	maximum	toward, level	toward, level
4	maximum	maximum	toward, up	toward, up
5	maximum	minimum	toward, up	toward, up
6	maximum	minimum	left, level	left, level
7	50%	minimum	left, level	toward, level
8	minimum	minimum	toward, level	toward, level
9	OFF	---	away	away

4. RESULTS

4.1 Floor system

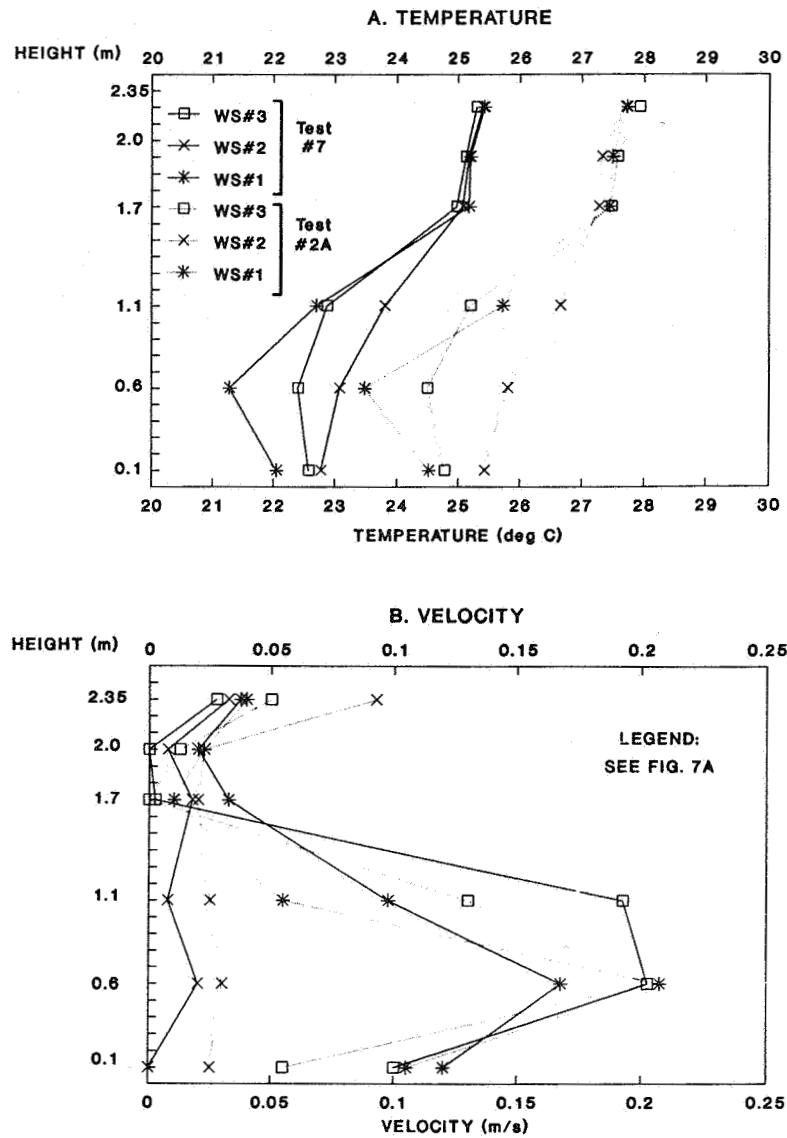
4.1.1 Heat load effects

Due to the large amount of experimental data, a limited number of tests have been selected from the lists shown in Tables 1 and 2 for presentation and discussion. A more complete data set is contained in Bauman et al.⁽²⁰⁾. The emphasis of the data presented here is on the local thermal conditions within each workstation. Results of concurrent ventilation efficiency experiments performed on the floor system in the same test facility are described by Fisk et al.⁽²¹⁾. For brevity, average conditions at a given height in a workstation are defined below and in subsequent sections of the paper as the velocity or temperature calculated by averaging the measured values obtained from the four locations directly in front of the desk. Referring to Figure 6, average conditions in Workstation #1 (WS#1) are based on points 13, 14, 15, and 16, those in Workstation #2 (WS#2) are based on points 17, 18, 19, and 20, and those in Workstation #3 (WS#3) are based on points 3, 4, 7, and 8.

Figures 7A and 7B present the average velocity and temperature results for Tests 2A and 7. Test conditions are identical for both tests (minimum flow setting in both WS#1 and WS#3), except 2A has the higher heat load. The observations are as follows:

1. The effect of higher heat loads is clearly visible as all temperatures are increased by 2-3°C between tests. The relative shape of the vertical temperature profiles, however, are quite similar.
2. For these conditions, a temperature difference in the range of 1-2.5°C can be maintained at the 0.6 m level between adjacent workstations. As expected, the warmer temperature always occurs in WS#2, where the floor supply module is turned off.
3. Under minimum flow conditions, the supply air jets do not reach the 1.7 m level, as evidenced by the minimal velocities above this height. Instead, the cool supply air remains near the floor, producing conditions similar to displacement ventilation. The vertical temperature profiles indicate that the characteristic stationary front separating the cool lower zone and warm upper zone occurs between the 1.1 m and 1.7 m heights, in agreement with other experimental results⁽²²⁾.
4. The stratification produced in WS#1 and WS#3 exceeds the comfort limits for vertical temperature difference of 3°C between the 0.1 m and 1.7 m levels⁽¹²⁾. In fact, due to the angle of the supply jet, a larger temperature difference exists between the 0.6 m and 1.7 m levels.
5. Under similar supply air conditions, WS#1, the smaller workstation, is always cooler than WS#3. This suggests that floor supply modules should not be located in small workstations, such as WS#1, where the supply jet enters directly into a regularly occupied space. The larger WS#3 allows the module to be positioned further away at a location that is only occasionally occupied.
6. The higher average velocities in the occupied zone of WS#1 and WS#3, compared to WS#2, where no floor supply is provided, is clearly visible in Figure 7B.

FIGURE 7. FLOOR SYSTEM HEAT LOAD EFFECTS

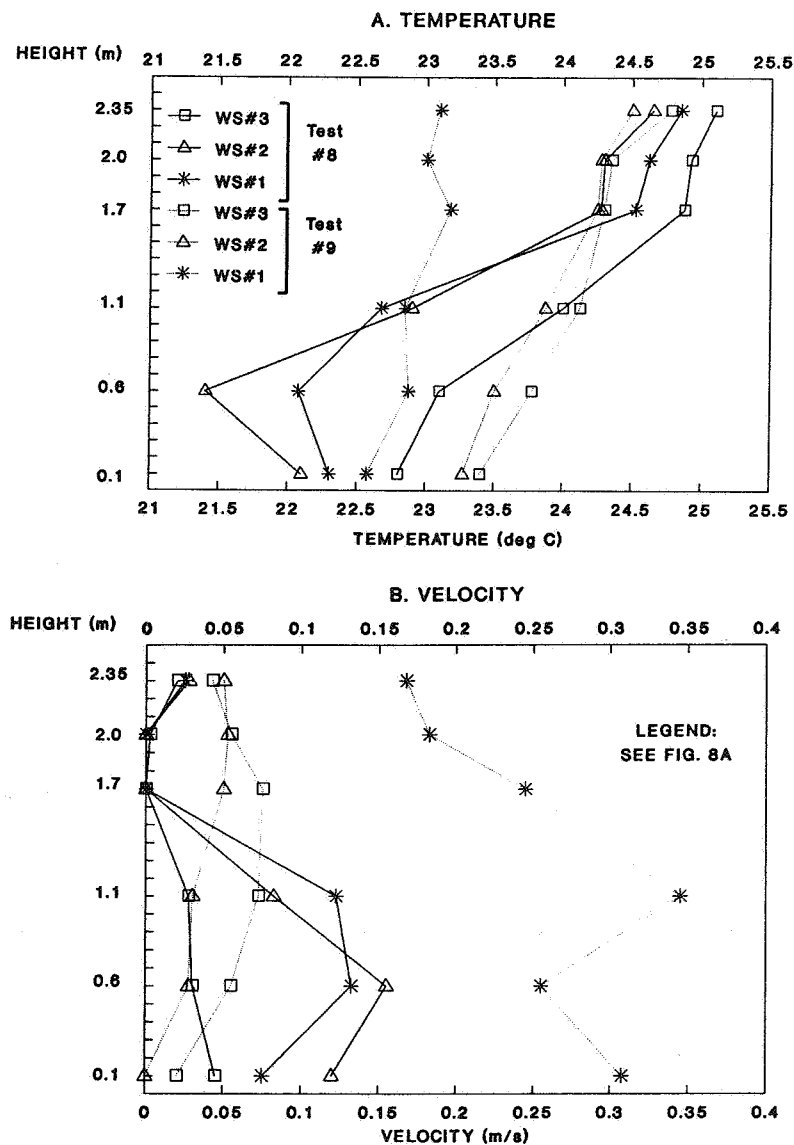


4.1.2 Local supply volume effects

Figures 8A and 8B present the average temperature and velocity results for Tests 8 and 9. In these tests, performed at the lower heat load level, the total supply volume to the chamber remains the same. The local supply characteristics vary, however, as WS#1 and WS#2 are set at minimum flow in Test 8, and in Test 9, the total air volume is supplied in WS#1, set at maximum flow. The observations are as follows:

1. As in Tests 2A and 7, the conditions of Test 8 resemble displacement ventilation performance. Due to the lower heat load level, the 3°C vertical temperature difference limit is not exceeded in any workstation.
2. In Test 9, when the air is supplied in a strong vertical jet, the degree of stratification is reduced at all locations in the room, despite the existence of flow obstacles (partitions and furniture) in the room. This effect is very visible in WS#3, which has no local supply air in either test.
3. Due to the reduced mixing of the low speed supply jets in Test 8, temperatures near the floor are actually cooler than those obtained in Test 9. This occurs in all three workstations.
4. Temperatures profiles above the partition height (1.65 m) are all quite similar, and exhibit only slight stratification, except those above WS#1 in Test 9. At these same levels, velocities are higher in Test 9 compared to the negligible values found in Test 8.

FIGURE 8. FLOOR SYSTEM LOCAL SUPPLY VOLUME EFFECTS



4.1.3 Controllability and comfort

Potentially the most significant performance characteristic of LTD systems are their controllability by individual office workers. A test was performed to determine the range of thermal conditions which could be achieved in a relatively short length of time (16 min) by simply adjusting the fan speed and grille positions of the floor supply module.

Figure 9 presents plots of temperature and velocity versus time for a series of adjustments made to the floor supply module. The circled numbers along the top of each plot refer to the flow control settings listed in Table 3. The observations are as follows:

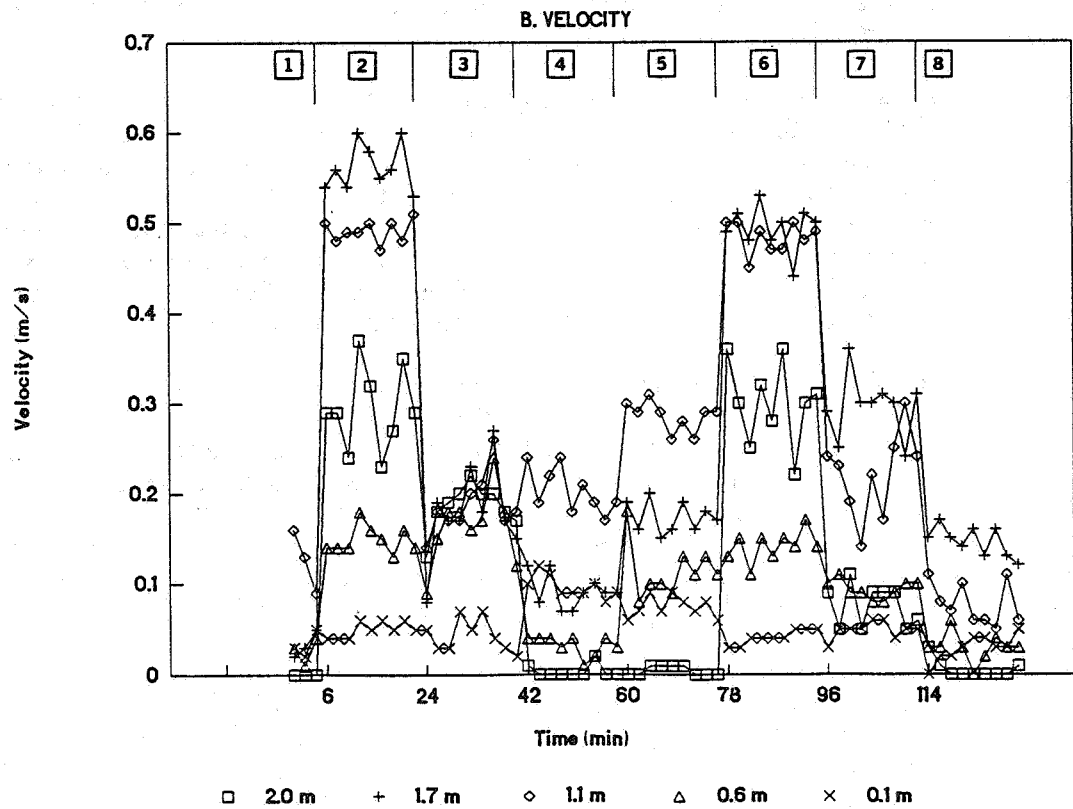
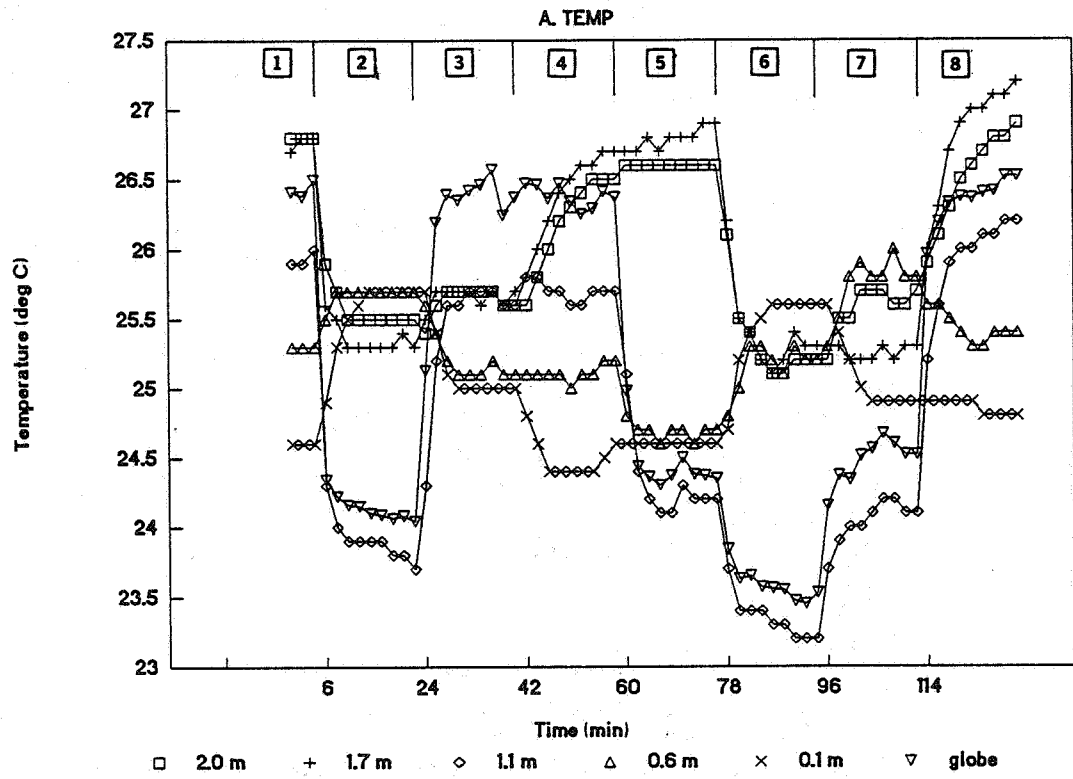
1. Initially, with the supply turned off, the workstation experiences warm, stratified low-velocity conditions.
2. When the flow is set to 100% and the grilles are turned toward the desk, the stratification disappears and maximum velocities reach 0.6 m/s.
3. When the grilles are turned inward, only small stratification persists and the globe and air temperatures at the 1.1 m level rise because they are no longer in line with the supply jet. Velocities in the occupied zone do not exceed about 0.25 m/s.
4. When the flow is reduced to its minimum level, stratification reappears as the temperatures at the upper levels increase and those near the floor decrease. Velocities in the upper region approach zero.
5. When the grilles are turned toward the desk, the temperatures are reduced and velocities increased at the lower levels.
6. When the flow is increased to 50% of maximum, the conditions are quite similar to those achieved with maximum flow for the same grille position.
7. A combined grille position with two toward and two inward produces an improved temperature distribution with velocities no greater than 0.3 m/s.
8. Finally, conditions return to their initial levels when the floor supply module is turned off.

Three-minute turbulence intensity measurements at the 1.1 m height found a range of 35-45% for the conditions of the above test. All conditions produced a value of 45% except the maximum flow setting with grilles positioned toward the desk. These turbulence levels are in agreement with representative measurements reported by Hanzawa et al.⁽²³⁾ However, if more restrictive velocity limits are applied in relation to increasing turbulence levels, as suggested by Fanger et al.⁽¹¹⁾, almost all flow fields in the vicinity of an operating floor supply module would experience some excessive velocities in the occupied zone.

The Fobelets and Gagge⁽²⁴⁾ two-node comfort model was used to predict the characteristic comfort indices for each of the flow control settings studied. Measurements recorded at the end of each 16-minute test period were used as input to the model along with assumed values of 50% relative humidity, 0.5 clo, and 1.2 met. The model was run for two sets of data for each test condition: (1) data recorded at the 1.1 m level, representing the head/neck region of a seated person, and recognized as the most sensitive area to draft discomfort; and (2) data averaged for the 0.1, 0.6, and 1.1 m levels, representing a whole-body average for a seated person.

The comfort model predictions for ET*, DISC, and PMV are listed in Table 5. The two control settings producing the most comfortable conditions are: (1) minimum flow setting (≈ 40 L/s) with grilles turned toward the desk, and (2) 50% flow setting (≈ 65 L/s) with grilles in a combined position. As previously discussed the

FIGURE 9. FLOOR SYSTEM CONTROLLABILITY



**Table 5. Floor System Controllability Test:
Comfort Model Results (RH = 50%, 0.5 clo, 1.2 met)**

Control Setting No. [†]	Data Set	ET* (°C)	DISC	PMV
1	1.1 m	26.5	0.58	0.59
1	avg	26.4	0.53	0.57
2	1.1 m	24.2	-0.05	-0.28
2	avg	23.6	-0.01	-0.15
3	1.1 m	26.6	0.62	0.61
3	avg	26.5	0.57	0.59
4	1.1 m	26.6	0.63	0.60
4	avg	26.5	0.56	0.58
5	1.1 m	24.4	-0.01	-0.07
5	avg	24.3	0.05	0.05
6	1.1 m	23.7	-0.09	-0.32
6	avg	23.0	-0.03	-0.26
7	1.1 m	24.7	0.08	0.08
7	avg	24.4	0.08	0.08
8	1.1 m	26.5	0.55	0.58
8	avg	26.4	0.52	0.57

[†] see Table 3

3°C limit for vertical temperature difference is often exceeded under minimum flow conditions. In all probability the second, intermediate setting represents the most comfortable control setting tested.

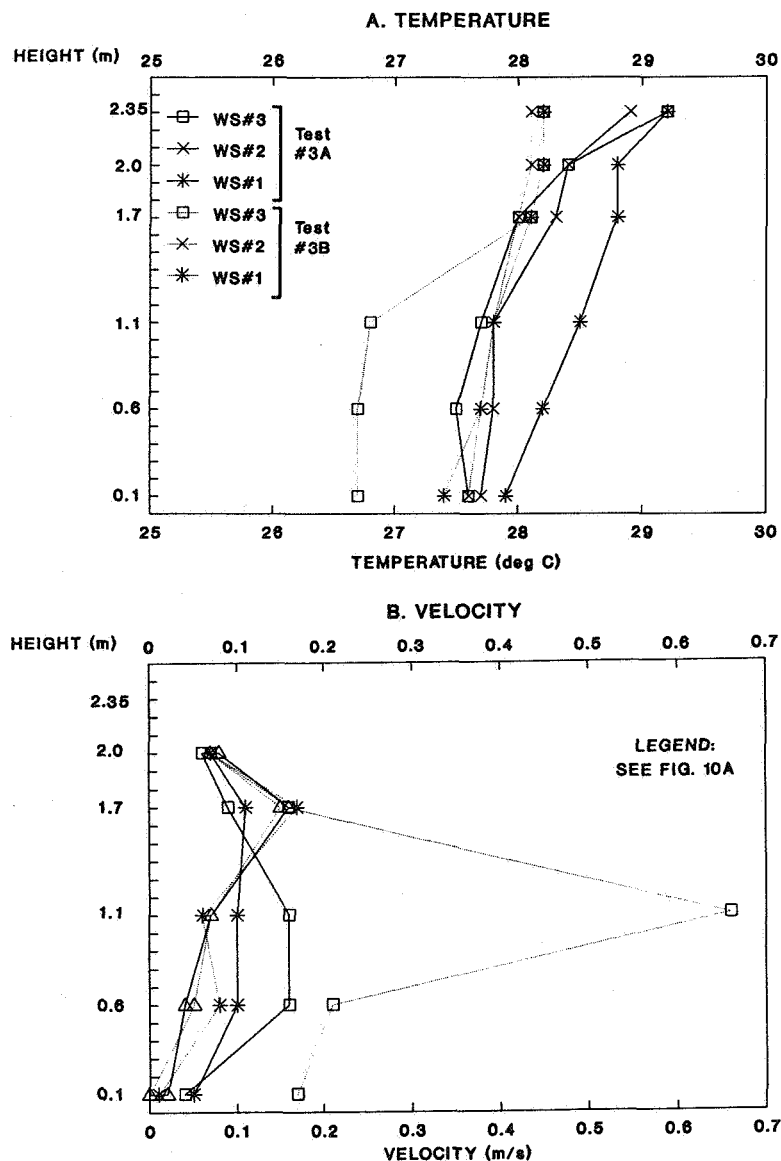
4.2 Desk-mounted system

4.2.1 Local supply volume effects

Figures 10A and 10B present the average temperature and velocity results for Tests 3A and 3B (Table 2). During these tests air was supplied to the room only through the desk-mounted nozzles at a relatively high airflow rate. Conditions were very similar during both tests with the exception of the nozzle positions. In Test 3A, both nozzles were turned toward the normal working location in front of the desk (measurement point #3) with the left vanes turned down and right vanes turned up. In Test 3B, the vanes of both nozzles were adjusted to a level orientation while still pointing toward the work location. The observations are as follows:

1. The lowest temperatures and highest velocities are obtained in WS#3 with both nozzles level and pointed toward the head level (1.1 m) of the work location (Test 3B). For these test conditions, which were quite warm, a temperature difference in the range of 1-1.5°C could be maintained at all heights up to 1.1 m between WS#3 and both WS#1 and WS#2.
2. As expected, in Test 3B a maximum velocity occurs at the 1.1 m level. The velocity recorded at point #3 was greater than 2 m/s.
3. The horizontal injection of supply air during Test 3B maintains lower temperatures and increased air motion at and below the 1.1 m level over a larger floor area of WS#3.
4. During Test 3A with nozzle vanes turned up and down, temperatures in WS#3 are about 1°C warmer than they were in Test 3B, and velocities are only slightly higher than those found in WS#1 and WS#2.
5. Floor-to-ceiling stratification was no greater than 1.5°C in all workstations except WS #3 during Test 3B. For this ventilation system, air supply at the desk height did not produce the same evidence of displacement ventilation found in the floor system tests.

FIGURE 10. DESK SYSTEM LOCAL SUPPLY VOLUME EFFECTS

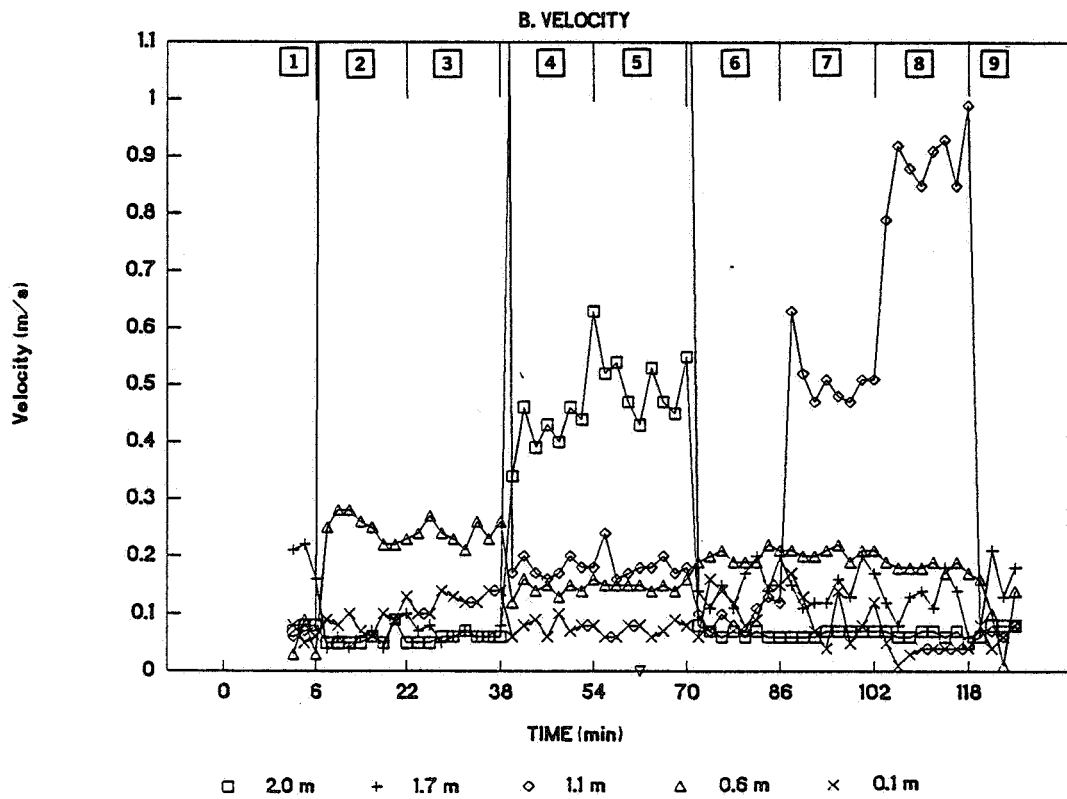
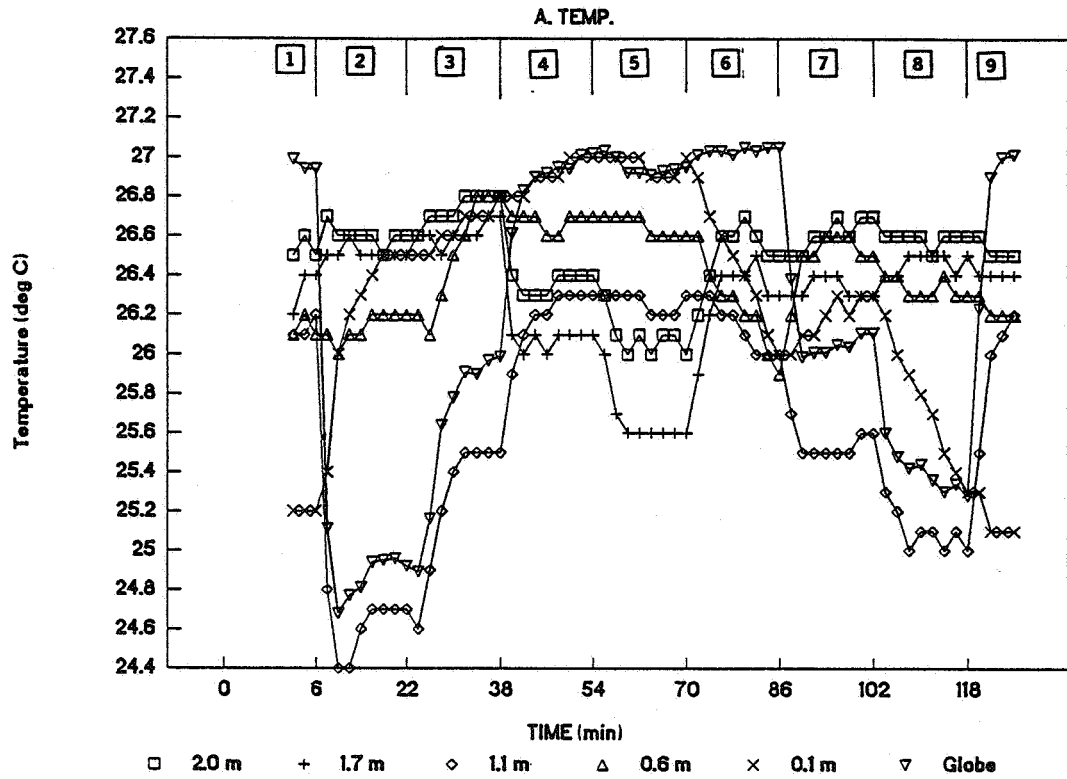


4.2.2 Controllability and comfort

Figure 11 presents plots of temperature and velocity versus time for the series of adjustments made to the desk-mounted system control panel and supply nozzle positions. The circled numbers along the top of each plot refer to the control settings listed in Table 4. Comfort model predictions for ET*, DISC, and PMV for the nine combinations of control settings are listed in Table 6. The model predictions were made using the same methodology described previously for the floor system. The observations are as follows:

1. From the initial warm, stratified and low-velocity conditions, velocities and temperatures below the 1.7 m level change dramatically when the airflow is set to maximum and the nozzles are turned toward the measurement location. At the 1.1 m level a velocity greater than 3 m/s is obtained at a temperature that is 1-2°C cooler than those found at all other heights (for purposes of showing greater detail in the velocity results, only velocities up to 1 m/s are displayed in Figure 11B). Not surprisingly, the greatest degree of cold discomfort is obtained from the comfort model predictions for these conditions.
2. When the control panel setting for temperature is changed from minimum to maximum, about a 1°C increase in air and globe temperature at the 1.1 m level is obtained.
3. When the vanes of both nozzles are turned upward, velocities approaching 2 m/s are found at the 1.7 m level, and greater than 0.5 m/s at the 2.0 m level. These same heights also experience the lowest temperatures as stratification is reversed. Lowering the temperature control setting to a minimum produces only a 0.5°C decrease at these same locations.
4. Turning the nozzles to the left in an attempt to provide a circular air motion within the partitioned workstation produces air velocities in the 0.1-0.2 m/s range within the occupied zone (0.1-1.7 m), but is unable to provide adequate cooling. The comfort model predicted the highest degree of warm discomfort for this control setting.
5. A 50% airflow setting with only one nozzle pointed toward the measurement location provides velocities around 0.5 m/s at the 1.1 m level and improves conditions considerably compared to the previous warm conditions.
6. At the minimum airflow setting with both nozzles level and toward the measurement location, air velocities up to 1 m/s are obtained at the 1.1 m level, and temperatures at the 0.1 and 1.1 m levels decrease significantly. Comfort model runs predict the most comfortable conditions for this test. This demonstrates the large effect of the airflow control when compared to the rather cool conditions that existed for control setting #2, having maximum airflow with both nozzles toward the work location.
7. The results indicate that office workers using the desk-mounted system are capable of controlling their comfort levels over a range of values for ET*, DISC, and PMV corresponding to the full range of the ASHRAE-specified summer comfort zone⁽¹²⁾.

FIGURE 11. DESK SYSTEM CONTROLLABILITY



**Table 6. Desk-Mounted System Controllability Test:
Comfort Model Results (RH = 50%, 0.5 clo, 1.2 met)**

Control Setting No. [†]	Data Set	ET* (°C)	DISC	PMV
1	1.1 m	27.0	0.67	0.70
1	avg	26.9	0.62	0.68
2	1.1 m	25.1	-0.27	-0.46
2	avg	24.3	-0.20	-0.42
3	1.1 m	26.4	-0.13	-0.33
3	avg	25.7	-0.07	-0.29
4	1.1 m	27.3	0.81	0.78
4	avg	27.1	0.75	0.73
5	1.1 m	27.2	0.78	0.76
5	avg	27.0	0.73	0.71
6	1.1 m	27.2	0.77	0.78
6	avg	27.3	0.81	0.80
7	1.1 m	26.4	0.18	0.21
7	avg	26.1	0.38	0.37
8	1.1 m	25.5	-0.04	-0.27
8	avg	25.1	0.00	-0.02
9	1.1 m	27.1	0.70	0.73
9	avg	27.1	0.73	0.75

[†] see Table 4

4.3 Overhead supply system

Available velocity and temperature data from the overhead supply test were limited to WS#1 and WS#2, plus four points outside of these two workstations. Data collected within the occupied zone (0.1 m - 1.7 m) at these same 12 measurement locations for Test 3 of the floor system were used to make the comparison. The ASHRAE-specified ADPI method⁽²⁵⁾ was used to evaluate and compare the air diffusion performance of the two systems.

The calculated ADPI for the overhead system was 90% compared to 52% for the floor system. This demonstrates that overhead systems can perform quite adequately in a partitioned office under the right conditions. The rather poor performance of the floor-based system is not surprising since the use of floor supply modules in small workstations is not optimal, as previously noted. ADPI may not be the most appropriate method to evaluate floor-based or desk-mounted system performance, since it does not allow velocities to exceed 0.35 m/s within the occupied zone. This is a very strict requirement for any ventilation system supplying air directly to the occupied zone, except low-velocity displacement systems.

5. CONCLUSIONS

Measurements have been made of the thermal performance of two occupant-controlled localized ventilation systems. The experiments were performed in a controlled environment chamber configured to resemble a modern office space with modular partitioned workstations. Tests were conducted to investigate the effects of supply volume, supply location, supply direction, supply/return temperature difference, heat load density, and workstation size and layout. The major conclusions are as follows:

1. The jet supply characteristics of the floor supply module produced high velocity air in the vicinity of the module. The risk of draft discomfort did exist in this region. However, under certain conditions, within short distances (less than 1 m) of the module, the velocities reduced to more acceptable levels.
2. Under minimum flow conditions from a floor module, significant stratification was produced, which, depending on heat load levels and total supply volume, exceeded the 3°C vertical temperature difference limit specified by ASHRAE Standard 55-81. This stratification in the surrounding office space was greatly reduced at maximum flow conditions. For all tests of the desk-mounted system, no excessive stratification was observed, presumably due to the higher supply location in the room.
3. Under minimum flow from a floor module, the overall ventilation performance of the room resembled that of displacement ventilation systems.
4. The primarily horizontal injection of air from the desk-mounted system distributed supply air to a larger area of the office, providing both cooler temperatures and increased air motion in the occupied zone.
5. Using existing ASHRAE test methods, an overhead supply system received a significantly higher performance rating compared to that of the floor system. However, the ADPI method may not be appropriate for evaluating such occupant-controlled systems.
6. Short-term tests indicated that the LTD systems could be controlled over a wide range, giving workers the opportunity to fine-tune the local environment to their individual preferences.
7. The perceived comfort benefits of having personal control over the local environment are not accounted for in existing comfort and performance standards.

Future work on occupant-controlled ventilation systems is needed to address the following issues.

1. Performance testing of other occupant-controlled ventilation systems.
2. Optimization of comfort control with human subject studies in laboratories.
3. Occupant comfort field surveys of operational systems.
4. Investigation of energy and productivity issues related to these systems.
5. Investigation of mechanical system control requirements for occupant-controlled systems.
6. Evaluation of compatibility of existing comfort and performance standards with occupant-controlled systems.

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Discussion

Paper 6

W. Raatschen (Dornier GmbH, Germany)

Aren't these systems with a fan in the subfloor or below the desk very noisy?

E Arens (LBL, USA)

No, they seem quite silent. We have not measured sound levels. It does appear to reduce air noise, but I have no experience with this.