#5905

Air Exchange Effectiveness of Conventional and Task Ventilation for Offices

W.J. Fisk D. Faulkner R. Prill

ABSTRACT

Air quality and comfort complaints within large buildings are often attributed to air distribution problems. We define three parameters for air exchange effectiveness related to air distribution. The first two indicate the indoor airflow pattern (i.e., the extent of short-circuiting, mixing, or displacement flow) for an entire building or region. The third parameter is most useful for assessments of the spatial variability of ventilation. We also define the air diffusion effectiveness, which indicates the airflow pattern within specific rooms or sections of buildings. The results of measurements of these parameters in U.S. office buildings by the authors and other researchers are reviewed. Almost all measurements indicate very limited short-circuiting or displacement flow between locations of air supply and removal. However, a moderate degree of short-circuiting is evident from a few measurements in rooms with heated supply air. The results of laboratory-based measurements by the authors are consistent with the field data. Our measurements in office buildings do indicate that ventilation rates can vary substantially between indoor locations, probably due to variation in air supply rates between locations rather than variation in the indoor airflow patterns. One possible method of improving air distribution is to employ task ventilation with air supplied closer to the occupant's breathing zone. We have evaluated two task ventilation systems in a laboratory setting. During most operating conditions, these systems did not provide a region of substantially increased ventilation where occupants breathe. However, both systems are capable of providing substantially enhanced ventilation at the breathing zone under some operating conditions. Therefore, task ventilation is a potential option for using ventilation air more effectively.

INTRODUCTION

There seems to be a fairly widespread belief among the ASHRAE membership that substantial short-circuiting of air between ceiling-level supply diffusers and ceiling-level return grilles is common, resulting in poor ventilation at the locations of occupants. Air exchange effectiveness (AEE), more commonly called "ventilation efficiency," is an indicator of the nature of the indoor airflow pattern between locations of air supply and removal within buildings or rooms. The indoor airflow pattern ranges between two hypothetical extreme cases. At one end of the scale, all supply air immediately short-circuits to the return or exhaust grilles. At the other end, a perfect displacement (piston-like) pattern of air flow occurs between the locations of air supply and removal. In between is the case of perfect instantaneous mixing of all indoor air. Several sources of air motion in real spaces, including natural convection plumes from internal heat sources, natural convection at warm or cool walls, the use of fans, and the motion of people, tend to mix the indoor air and prevent complete short-circuiting or perfect displacement flow. One of the objectives of this paper is to present and discuss data on indoor airflow patterns in office buildings.

The indoor airflow pattern has implications for indoor air quality (IAQ) and building energy use. A short-circuiting flow between ceiling-level supply diffusers and return grilles is generally inefficient in removing pollutants and heat generated in the occupied lower regions of rooms; hence, with short-circuiting, more outside air is required to maintain acceptable IAQ and more total supply air may be required to remove heat. However, when pollutant and heat sources are located in the path of the short-circuiting flow, this flow pattern may be efficient because the pollutants and heat also short-circuit to the exhaust. In contrast to short-circuiting, a displacement flow pattern in the floor-to-ceiling direction is generally more efficient in removing heat and pollutants generated in the occupied space than the "perfect mixing" pattern because the exiting air has a pollutant concentration above the building average and, in some cases, an above-average temperature.

The local AEE, as defined in the next section, has a different significance. This parameter is most useful for comparing the rate of ventilation (or age of air, as defined later) measured at different individual locations. In a large multi-room building, the local AEE is influenced by both the amount of air supplied locally (e.g., to the room in question) and by the indoor airflow pattern. Therefore, individual values of local AEE are not useful indicators of the extent of short-circuiting (an occasional point of confusion). The second objective of this paper is to discuss the spatial variability of ventilation as indicated by the local AEE and other parameters.

AEE parameters are useful for characterizing the ventilation performance of task ventilation systems. These systems, described in greater detail subsequently, permit individuals to adjust the rate and direction of a local air supply that serves their work space (primarily so occupants can fine-tune their thermal comfort).

William J. Fisk, David Faulkner, and **Richard Prill** are with the Indoor Environment Program, Applied Science Division, Lawrence Berkeley Laboratory, Berkeley, CA.

Ideally, these systems will provide a region of increased ventilation where the occupant normally breathes. The third and final major objective of this paper is to discuss the extent to which two task ventilation systems provide this enhanced ventilation.

DEFINITIONS

We use the age of air, usually denoted by the symbol τ, as the basis for defining AEE parameters. The age of a sample of air is the average amount of time that has elapsed since molecules in this sample entered the building. One can consider the local age of air at a specific location within the occupied space, the age in various airstreams (such as the exhaust), and the spatial mean age of all air within a building. We use the symbol τ_{BL} represent a local age of air measured at the typical breathing level of a seated person. Age of air is measured using tracer gas techniques described by numerous authors (Sandberg and Sjoberg 1983; Fisk et al. 1985, 1988, 1989; Persily 1985). For brevity, we do not repeat the descriptions of measurement techniques in this paper.

The nominal time constant, denoted τ_N, is used in the definitions of AEE parameters and equals the indoor volume divided by the flow rate of outside air supply. τ_N is the reciprocal of the air exchange rate and is usually expressed in units of hours. τ_N equals the local age of air exhausted to outside (Sandberg and Sjoberg 1983) and is determined from measurements in the main return or exhaust duct(s).

The spatial average age of air within the entire building, usually referred to as the mean age of air, is denoted by the symbol $<\tau>$ and is also determined from measurements of tracer gas concentrations in the exhaust airstreams. We also use the average of the measured local ages of air at breathing level, denoted $<\tau_{BL}>$ to calculate an AEE.

We define three AEE parameters via the following equations:

$$AEE_{GLOBAL} = AEE_G = \tau_N/<\tau> \quad (1)$$

$$AEE_{BREATHING\ LEVEL} = AEE_{BL} = \tau_N/<\tau_{BL}> \quad (2)$$

$$AEE_{LOCAL} = AEE_L = \tau_N/\tau_{BL} \quad (3)$$

AEE_G is representative of the entire building because both the numerator and denominator of this parameter are indicative of the entire building. The parameter AEE_{BL} is more relevant to human health because it is based on the average measured age of air at breathing level $<\tau_{BL}>$ rather than the spatial average indoor age $<\tau>$. However, multipoint measurements are required to obtain a representative average value of τ_{BL}. The local AEE is based on a comparison of the nominal time constant (a whole-building parameter) to the age at a single indoor location, and, as noted previously, the range of AEE_L is useful for assessing the spatial variability of ventilation.

The reference for all three AEE parameters (i.e., the case with AEE equal to unity) is perfectly mixed indoor air. The maximum possible value of AEE_G is 2.0 for a perfect displacement flow. There are no theoretical upper limits for the other two parameters. Values less than or greater than unity for AEE_G and AEE_{BL} indicate short-circuiting and displacement flow patterns, respectively. Larger deviations from unity indicate more pronounced short-circuiting or displacement flow.

We define another related parameter, the air diffusion effectiveness (ADE), which is a better indicator of the airflow pattern in a specific indoor region (e.g., a room).

$$ADE = \tau_{RG}/\tau_{BL} \quad (4)$$

where τ_{RG} is the age at a return grille located near the τ_{BL} measurement location. If low-age supply air short-circuits to the return grille, τ_{RG} should be significantly less than τ_{BL}; hence, the ADE will be less than unity. The converse is true with a displacement flow pattern. The advantages of ADE as an indicator of local short-circuiting or displacement flow are as follows: (1) both the numerator and denominator of the ADE are representative of the same general region (e.g., room) and (2) the residence time of air in return-air ceiling plenums and the leakage of supply air into return plenums will have a small effect on ADE but may substantially affect the other three parameters (thus, ADE is more indicative of the flow pattern in the room). The ADE will equal unity if the room is perfectly mixed. One could compute an ADE parameter based on an average of several measurements of both τ_{BL} and τ_{RG} in the same region; however, in this paper we use a single measured value of each parameter.

CONVENTIONAL AND TASK VENTILATION

Supply of air through ceiling-mounted diffusers or high wall supply grilles and removal of air through ceiling-level or high wall return grilles is conventional practice in U.S. office buildings. Air is supplied in high-velocity jets that entrain room air, promoting mixing. Complete mixing of the indoor air is the usual design goal. Indoor temperature control is achieved by regulating the supply temperature, supply flow rate, or both of these parameters. The regulation of supply temperature or flow is controlled by a thermostat. Generally, there are many more occupants than thermostats, and occupants are not able to adjust the thermostat setting.

In contrast to conventional ventilation, we define task ventilation (TV) as a method of ventilation that permits the occupants to adjust some local air supply parameter, such as supply flow rate, temperature, or direction. 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 TV. Improved indoor air quality is another potential benefit because the supply air can be delivered more directly to the region around the occupant. TV systems may also, in some situations, result in a displacement (pistonlike) airflow 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 can result in lower pollutant concentrations at the breathing level and higher concentrations in the ceiling-level exhaust air (see, for example, Holmberg et al. 1990).

We consider two task ventilation systems that are being introduced in the U.S. We call the first system the "floor supply system." Air supply modules are installed in an raised panel floor. Each module contains a fan that draws air from the subfloor supply-air plenum and discharges this air into the room through slots (inclined 40° from vertical) in four plastic grilles each 0.13 m in diameter. Using a recessed thumb wheel, the fan speed and, thus, airflow 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 the air supply can be changed by rotating any or all of the four grilles. Occupants cannot control the supply air temperature, which, to reduce the potential for cold drafts, is typically about 18°C or 5°F higher than the supply temperature of many conventional U.S. ventilation systems. Air is typically withdrawn from the occupied spaces through ceiling-level return grilles.

We refer to the second task ventilation system as the "desk-supply system." Air from either a subfloor supply plenum or from supply ducts is drawn into one opening of a fan/control unit that fits under a desk. Air is also drawn directly into another opening of the fan/control unit from the room. A mixture of the air from both sources is supplied to the room through a pair of nozzles with movable vanes located at the desktop. The nozzles may be rotated

360° in a horizontal plane, and the vanes may be angled ±30° in a vertical plane. The temperature of air supplied through the nozzles is a function of the ratio of recirculated room air versus supply air in the air exiting the nozzles, which, in turn, is determined by the position of two dampers in the fan/control unit. Damper positions are controlled by the air temperature setting on a desktop control panel. The control panel also gives the occupant the ability to set the air supply rate (via adjustment of fan speeds) and to control operation of a radiant heating panel, a task light, and a white noise generator. The control panel also contains an occupant sensor that will turn off power to the fans, heater, light, and noise generator if no occupant is detected for 10 minutes. When an occupant is detected, the system resumes operation at the previously set conditions. The maximum flow rate of supply air with fans operating is approximately 70 L/s. With no power to the propeller fans and 25 Pa positive static pressure provided by the main air handler, approximately 10 L/s will flow through each nozzle.

MEASUREMENT RESULTS

Field Measurements with Conventional Ventilation

The authors have measured the three AEE parameters and the ADE in several office buildings located in the San Francisco area. All of the buildings used conventional methods of air supply and return. Supply air temperatures were lower than indoor temperatures. In most buildings, we completed measurements with both minimum and maximum percent outside air supply (i.e., maximum and minimum recirculation of air by the air handler). The measurement method involves labeling each stream of outside air with a unique tracer gas via constant tracer gas injection and monitoring tracer gas concentrations in major airstreams and also at multiple locations within the occupied spaces (see Fisk et al. 1988, 1989, 1991 for details on measurement and data analysis procedures). Table 1 provides the key results (some have been published previously).

First consider the AEE_G. The majority of measured values are within the range 1.0 to 1.2 and three of the four values outside of this range are equal to 1.3. Based on an evaluation of measurement precision in a laboratory setting (Fisk et al. 1991) and our estimate of the magnitude of additional errors in field settings, the 95% confidence limits for measurements of AEE_G are at least ±20%. Within this confidence limit, most of the AEE_G values are indistinguishable from the value obtained with complete mixing. However, because we use different tracer gases to simultaneously label the outside air entering buildings through each air handler, we know that the indoor air throughout these large buildings is often not perfectly mixed (Fisk et al. 1988, 1989). Thus, our measurement of an AEE_G value close to 1.0 does not indicate perfect mixing throughout a building but does indicate minimal short-circuiting or displacement flow, on average, for the entire building. (In theory, displacement flow in some locations could counteract short-circuiting elsewhere, resulting in a value of 1.0 for AEE_G.)

With three exceptions, the values of AEE_{BL} in Table 1 are also indistinguishable (i.e., within 0.2) from 1.0. We suspect that values of 1.4 and 1.3 for both the fifth and sixth floors of Building No. 1 are due to a primarily one-way flow between the office regions (where air was supplied) and the bathroom/janitorial regions that contained the only exhaust grilles (see Fisk et al. [1988] for details). The elevated value of 1.4 in one test of Building No. 5 may have resulted from the very large spatial variation in age of air during this test, leading to an inaccurate determination of the true average age at breathing level.

Next consider the ADE. Based on multipoint measurements in a well-mixed room, we have calculated 95% confidence limits for an ADE measurement of 12% to 20% (confidence limits varied with test conditions; we assume 20% for the subsequent discussion). Forty-two measured values of ADE are provided in Table 1. None is below 0.8, i.e., none is significantly below unity with 95% confidence. Only six measured values exceed 1.2. Thus, the ADE data also indicate that there is minimal short-circuiting or displacement flow at the majority of measurement locations within these buildings. The average of the 42 measured values is 1.1, which is significantly greater than unity. (The 95% confidence limit for the average of 42 measurements is ±0.03.) Thus, these measurements indicate a very slight tendency toward displacement flow.

The local air exchange effectiveness values frequently deviate substantially from unity. Because of the evidence of minimal short-circuiting or displacement flow, the large deviations from unity must result from variable air supply rates throughout the buildings. The relative standard deviations (RSD) in the age of air at breathing level within these buildings must also reflect these variations in air supply rates. The RSD is typically 0.1 to 0.2 in tests with minimum percent outside air (maximum recirculation) but is as high as 0.5 in tests with maximum percent outside air.

The final column of Table 1 provides the outside air supply rate per occupant during these tests. In Building No. 1, the 10 L/s per occupant supply rates are equal to the minimum rates specified for offices in *ASHRAE Standard 62-1989* (ASHRAE 1989). In other tests with minimum percent outside air, the outside air supply ranged from 16 to 45 L/s per occupant—substantially above the minimum value specified in this standard. Thus, if a moderate degree of short-circuiting did occur in these buildings, the "effective" outside air supply rate (e.g., product of actual outside air supply rate and AEE) would generally still exceed the value prescribed in the ASHRAE standard. However, rooms with a very low local air exchange effectiveness could be underventilated relative to the rate prescribed in the ASHRAE standard.

There are only a few additional measurements in U.S. office buildings. Our general findings of limited short-circuiting or displacement flow are consistent with results of tests in a three-story office building by Persily (1986). In three tests, the global air exchange effectiveness ranged from 1.04 to 1.12 and the averages of several measurements of local air exchange effectiveness during each test (the average is similar to AEE_{BL}) ranged from 0.73 to 1.02.

Persily and Dols (1990) also completed nine tests in a large office/library building, and the averages of seven to eight measurements of local air exchange effectiveness during each test ranged from 0.92 to 1.05.

Offermann (1988) completed two tests within an isolated room in an office building with conventional ceiling diffusers and a ceiling-level return grille. The room was heated with the supply air during these tests. The breathing-level air exchange effectiveness was 0.66 and 0.73, respectively; thus, these two tests do indicate significant short-circuiting. Possibly the elevated supply air temperatures were a reason for the short-circuiting.

Rask and Sun (1989) describe results from three spaces; however, they use a different definition of air exchange effectiveness that precludes comparison of their results to ours. Their definition results in an air exchange effectiveness less than unity even in a room with perfectly mixed air if the room volume exceeds the volume of the occupied zone as defined by ASHRAE. (*ASHRAE Standard 62-1989* defines the occupied zone as the region between 0.075 and 1.8 m [3 and 72 in.] above the floor and greater than 0.6 m [2 ft] from walls.) The largest volume of published data (that we identified) from field measurements outside the U.S. is based on measurements in 23 offices within Finland (Seppanen 1986). The global air exchange effectiveness always exceeded 0.82 and was typically near 1.0 except in office buildings with air supplied to the hallway and exhausted from the office area. With this ventilation configuration, which is unusual in the U.S., the global air exchange effectiveness ranged from 0.72 to 1.0.

Laboratory Measurements with Conventional Ventilation

The authors have also measured air exchange effectiveness (see Bauman et al. 1991a) in a laboratory called the Controlled Environment Chamber (CEC), which is 5.5 m by 5.5 m by 2.5 m high. Although a flexible research laboratory, the CEC closely resembles a modern office space. For the tests described in this paper, the CEC was subdivided into three workstations separated by partitions. Each workstation contained typical office furniture (desks, side tables, chairs, bookcases). The chamber also contained sources of heat and air motion typical of real offices, including overhead lights, task lights, and personal computers with a small cooling fans plus monitors. A seated mannequin that released heat in a manner similar to a real person was located in one or two of the workstations. Airflow in the cavities of the exterior walls and between window panes maintained wall and window temperatures close to the indoor temperature during tests with the CEC cooled. Consequently, these exterior walls and windows were not a source of strong natural convection but affected indoor air movement like interior walls. During tests with the CEC heated, the exterior walls and windows were cooled (to create a heat sink); thus, during heating tests these surfaces were a stronger source of natural convection airflow. Air was supplied through a single perforated diffuser mounted in the ceiling either centrally or near the center of one wall. Air exited through a ceiling-level return grille.

Table 2 provides the primary results of AEE measurements in the CEC. Only two of ten values of AEE_{BL} are significantly different from unity with 95% confidence. In all seven tests with the CEC cooled, the AEE_{BL} is greater than unity, but only one deviation from unity is significant. In all three tests with the CEC heated, AEE_{BL} is less than unity, but again, the difference is significant in only one case. The results of these laboratory measurements are very consistent with the previously discussed results of measurements in actual buildings. In general, the air exchange effectiveness is close to unity. The data indicate a very slight tendency toward displacement flow when the CEC is cooled and a slight tendency toward short-circuiting when the CEC is heated. At least during these tests, the partitions do not interrupt the airflow (a commonly expressed concern) and cause significant short-circuiting. In addition, the data in Table 2 on age of air vs. height (and the individual measurements that are not included in the table) indicate that the ventilation within and above the partitions is nearly identical; hence, the partitions do not create "dead spaces" with poor ventilation. Thermal comfort and air velocity measurements by Bauman et al. (1991a) lead to the same conclusion.

Laboratory Measurements with Task Ventilation

The air exchange effectiveness of the two previously described task ventilation systems has also been measured via laboratory experiments in the furnished CEC. Some results were reported in Arens et al. (1991), Bauman et al. (1991b), and Fisk et al. (1991). Twenty tests have been completed with the floor supply system operating. Test variables have included the direction of air supply (e.g., toward the occupant or toward the center of the floor supply module), location of the floor supply module, rate of air supply, and supply temperature (cooling or heating of the CEC), with and without recirculation by the main air handler (100% outside air was supplied during most tests). In general, AEE_{BL} was within 0.15 of unity. (The 95% confidence limits for this series of tests is $\pm 15\%$.) Consequently, the system did not usually provide a region of significantly enhanced ventilation where occupants breathe. Directing the air from the floor supply toward the occupant's breathing zone resulted in slightly (e.g., 15%) lower ages of air in the breathing zone than at the return grille. However, the results of one unique test are promising. We have completed only one test with minimum supply flow rates and two floor supply modules operating simultaneously. In that test, AEE_{BL} was approximately 1.5. The multipoint measurements indicate a significant increase in age of air with height, which is indicative of a displacement flow pattern. Therefore, with a low air supply rate, this system can provide highly effective ventilation.

We have completed only five tests with the desk-supply system operating; thus conclusions regarding the air exchange effectiveness of this system are only tentative. With the air supply nozzles supplied by the manufacturer, the supply flow rate at each workstation was maintained below approximately 20 L/s and the air was directed toward the occupant's breathing zone. Under these conditions, the measured AEE_{BL} ranged from 1.1 to 1.3. The value of 1.3 is a significant but still moderate enhancement compared to the case of complete mixing. To permit higher supply flow rates without high velocities at the occupant's face, we fabricated a set of larger air supply nozzles that reduced exit velocities by approximately a factor of three. In a single test with 42 L/s supplied at each of two workstations, AEE_{BL} was 1.6. Hence, this system can also provide highly effective ventilation.

CONCLUSIONS AND DISCUSSION

The number of measurements of air exchange effectiveness in U.S. office buildings or realistic laboratory mock-ups of offices is limited. The large majority of available data from conventionally ventilated spaces indicate very limited short-circuiting and limited displacement flow between the locations of air supply and removal. We suspect that these results are due to the mixing of indoor air caused by both high-velocity jets of supply air and natural convection. We do not claim that short-circuiting is minimal in all or a very high percentage of U.S. office buildings—the available data are too sparse for such a claim. In fact, some data indicate a moderate degree of short-circuiting of supply air to return grilles when the supply air is heated. We believe that additional measurements are required. However, based on the available information, short-circuiting is not the pervasive problem assumed by many engineers and indoor air quality specialists.

The available data do indicate that the ventilation rate within U.S. office buildings can vary substantially with location. Based on measurements by the authors, the relative standard deviation in the age of air at breathing level was typically 0.1 to 0.2 when minimum outside air was supplied and as high as 0.5 with maximum percent outside air supplied. Local air exchange effectiveness values reported here ranged from 0.3 to 3.6 (i.e., local ages of air at the breathing level were 30% to 330% of the nominal time constant for the entire building). We suspect that this variation is caused primarily by spatial variations in air supply rates.

Based on a preliminary examination of the performance of two task ventilation systems, we conclude that these systems do not produce a region of substantially (i.e., more than 25%) increased ventilation where occupants breathe for most of the operating conditions considered. However, under certain operating conditions, both task ventilation systems are capable of producing an age of air in the occupant's breathing zone that is approximately 65% of the age of air at the return grille. Thus, task ventilation is one potential option for using ventilation air more effectively that deserves further study.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy (DOE) under Contract No. DE-AC03-76SF00098. The research reported here was also funded in part by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. We thank Ed Arens and Fred Bauman from the U.C. Berkeley Department of Architecture for permitting us to conduct experiments in their Controlled Environment Chamber and also David Pih and Pleasant J. McNeel IV for their assistance in performance of experiments.

REFERENCES

Arens, E.A., F.S. Bauman, L.P. Johnston, and H. Zhang. 1991. Tests of localized ventilation systems in a new controlled-environment chamber. To be published in *Indoor Air.*

ASHRAE. 1989. *ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Bauman, F.S., D. Faulkner, E.A. Arens, W.J. Fisk, L.P. Johnston, P.J. NcNeel, D. Pih, and H. Zhang. 1991a. Air movement, comfort, and ventilation in workstations. Lawrence Berkeley Laboratory, LBL-30574, Berkeley, CA.

Bauman, F.S., L.P. Johnston, H. Zhang, and E.A. Arens. 1991b. Performance testing of a floor-based, occupant-controlled office ventilation system. *ASHRAE Transactions* 97(1).

Fisk, W.J., J. Binenboym, H. Kaboli, D. Grimsrud, A.W. Robb, and B. Weber. 1985. A multi-tracer system for measuring ventilation rates and ventilation efficiencies in large mechanically-ventilated buildings. *Proceedings of the 6th AIVC Conference, Ventilation Strategies and Measurement Techniques.* Coventry, UK: Air Infiltration and Ventilation Centre.

Fisk, W.J., R.J. Prill, and O. Seppanen. 1988. Commercial building ventilation measurements using multiple tracer gases. *Proceedings of the 9th AIVC Conference, Effective Ventilation.* Coventry, UK: Air Infiltration and Ventilation Centre.

Fisk, W.J., R.J. Prill, and O. Seppanen. 1989. A multi-tracer technique for studying rates of ventilation, air distribution patterns, and air exchange efficiencies. *Building Systems: Room Air and Air Contaminant Distribution.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Fisk, W.J., D. Faulkner, F.S. Bauman, E.A. Arens, D. Pih, and P.J. McNeel. 1991. Indoor airflow and pollutant removal in a room with task ventilation. To be published in *Indoor Air.*

Holmberg, R.B., L. Eliasson, O. Folkesson, and O. Strindehag. 1990. Inhalation-zone air quality provided by displacement ventilation. *Proceedings of Room Vent '90,* June 13-15, Oslo, Norway. Oslo: Norsk VVS.

Offermann, F.J. 1988. Ventilation effectiveness and ADPI measurements of a forced air heating system. *ASHRAE Transactions* 94(1): 694-704.

Persily, A.K. 1985. Ventilation effectiveness in mechanically ventilated office buildings. NBSIR 85-3208. Gaithersburg, MD: National Institute of Standards and Technology.

Persily, A.K. 1986. Ventilation effectiveness measurements in an office building. *Proceedings of IAQ '86, Managing Indoor Air for Health and Energy Conservation.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Persily, A.K., and W.S. Dols. 1990. Field measurements of ventilation and ventilation effectiveness in a library building. *Proceedings of the 11th AIVC Conference, Ventilation System Performance.* Vol. 2. Coventry, UK: Air Infiltration and Ventilation Centre.

Rask, D.R., and J. Sun. 1989. A ventilation efficiency model. Golden Valley, MN: Honeywell Indoor Air Quality Diagnostics.

Sandberg, M., and M. Sjoberg. 1983. The use of moments for assessing air quality in ventilated rooms. *Buildings and Environment* 18: 181-197.

Seppanen, O. 1986. Ventilation efficiency in practice. *Proceedings of IAQ '86, Managing Indoor Air for Health and Energy Conservation.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.