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Assessing Ventilation Effectiveness in Mechanically Ventilated Office Buildings

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ABSTRACT

Mechanical ventilation systems are designed and operated to bring outdoor air into buildings, distribute ventilation air within the occupied space, remove internally-generated contaminants and maintain thermal comfort. While standard measurement techniques exist to evaluate thermal comfort, air change rates and some aspects of ventilation air distribution in mechanically ventilated buildings, procedures to assess the uniformity of air distribution within a building and the degree of mixing within an occupied space are still being developed. This paper presents a general discussion of ventilation effectiveness in mechanically ventilated office buildings as the ability of the ventilation system to provide ventilation air in a manner consistent with the design goals of the system. The design and performance of air distribution systems are discussed on a range of scales, from the air handler to the individual workspace, as are the means for assessing ventilation effectiveness on each of these scales. Various approaches to the assessment of mixing within ventilated spaces, the most common conception of ventilation effectiveness, are presented and discussed in relation to their use in mechanically ventilated office buildings.

KEY WORDS air distribution, mechanical ventilation, ventilation, ventilation effectiveness

INTRODUCTION

Mechanical ventilation systems in commercial buildings are designed and operated to fulfill several functions: the maintenance of thermally acceptable conditions within the occupied space, the delivery of outdoor air to the occupants, and the removal of internally-generated contaminants. Ventilation systems have been employed to fulfill these functions for many years, and with increasing concerns about indoor air quality, their ability to do so is being discussed and assessed. Ventilation systems contain a large number of subsystems and components, and there are many factors to consider in evaluating their performance. The term ventilation effectiveness has been used to describe one such factor, i.e., the ability of the air distribution system to deliver ventilation air to the occupied space and to remove internally-generated contaminants. While most definitions of ventilation effectiveness have been developed to describe air distribution and mixing within an individual space, this paper discusses ventilation effectiveness in more general terms as the ability of the ventilation system to move and distribute ventilation air throughout a building in accordance with the system design.

Most discussions of ventilation effectiveness have been concerned with the distribution of ventilation air within a room and the characterization of the flow of air between the supply vents and the return or exhaust vents. This effort has been motivated by a concern that significant quantities of supply air may be flowing directly into the return or exhaust without reaching the occupied space, so-called "short-circuiting." While a significant amount of work has been done in the area of "workspace" ventilation effectiveness, the extent of short-circuiting within buildings has not been adequately assessed. Regardless of the extent of short-circuiting in office spaces, ventilation air distribution in mechanically ventilated buildings is an important aspect of ventilation system performance. The assessment of this aspect of air distribution performance needs to consider the range of scales over which these systems must perform, from the air handler to the individual workspace. Nonuniform air distribution, or distribution patterns that differ from design, can occur on all of these scales, and these nonuniformities impact the ability of the system to fulfill its functions.

This paper is specifically concerned with modern, mechanically ventilated office buildings typical of recent and current construction in the United States. Within this building type, most of the space requires cooling year round to remove internally-generated heat. Heating is required only in perimeter zones during certain periods of the year. The interior offices are equipped with supply air diffusers in the ceiling that are designed to induce room airflow, and return air exits the space through openings in the suspended ceiling into an unducted plenum. While other air distribution systems exist, and new approaches are being developed, the vast majority of modern office buildings employ these conventional systems, and it is these systems that are addressed within this paper.

PURPOSES OF VENTILATION

As stated above, ventilation systems are designed, installed and operated with three goals in mind: the maintenance of thermally acceptable conditions within the occupied space, the provision of adequate levels of outdoor air to the occupants, and the removal of internally-generated contaminants from the occupied space. The acceptability of the thermal environment within an occupied space is determined by the values of several parameters including air temperature, spatial variation in air temperature, relative humidity and air speed. In interior office spaces, a key issue in achieving thermal comfort is the removal of heat generated by lights, people and office equipment. In perimeter zones, heat must be removed or added depending on the season, the orientation of the exterior wall and the time of day. The heat generation rates in interior offices can cover a wide range from about 30 to 250 W/m^2 (10 to 80 Btu/hr-ft^2), depending on the lighting level, the occupant density and the amount of office equipment in the space (ASHRAE 1989a). The maintenance of comfortable interior temperatures within the space involves the removal of this heat by supplying cool air to the space with the ventilation system. The supply air in office building systems is generally at a temperature of about 12 °C (55 °F). Therefore, based on the above range of cooling loads, this supply air must be delivered to the space at a rate from about 2.5 to 20 L/s-m^2 (0.5 to 4 cfm/ft^2) to maintain the interior air temperature at about 22 °C (72 °F). Air supply rates of about 5 L/s-m^2 (1 cfm/ft^2) are fairly typical. It is of interest to consider these supply airflow rates in volumetric units. Assuming a floor area per person of 14 m^2 (150 ft^2) and a ceiling height of 3 m (10 ft) including the return air plenum, a supply airflow rate of 5 L/s-m^2 (1 cfm/ft^2) is equal to an airflow rate of 70 L/s (150 cfm) or 6 air changes per hour.

Two other keys determinants of thermal comfort are relative humidity and air speed. Thermally acceptable levels of relative humidity are discussed in ASHRAE (1989a) and are achieved by conditioning the supply air within the HVAC system. In general, humidity is removed during the cooling season and added under heating conditions. Acceptable levels of air speed are dependent on the air temperature, with higher air speeds being acceptable at higher air temperatures. Generally, air speeds in the range of 0.15 and 0.25 m/s (30 and 50 fpm) are considered acceptable. Maintaining acceptable air speeds in the occupied space is a function of how the supply air is introduced into the space. As discussed later in this paper, the Air Diffusion Performance Index (ADPI) is used to quantify the performance of an air diffuser in terms of providing acceptable conditions of temperature and air speed.

Mechanical ventilation systems are also intended to provide outdoor air to the occupied space for occupant comfort and contaminant control. Standards, guidelines and building codes specify minimum levels of outdoor air intake on a per person or per unit floor area basis. ASHRAE Standard 62-1989 (ASHRAE 1989b) contains minimum recommended levels of outdoor air intake per person or per m^2 (ft^2) of floor area for a variety of indoor spaces. In general office space, the recommended minimum level of outdoor air intake is 10 L/s (20 cfm) per person. Given the office space dimensions discussed above, this intake rate corresponds to 0.71 L/s-m^2 (0.13 cfm/ft^2) or 0.86 air changes per hour. Therefore, the amount of outdoor air required to meet ASHRAE Standard 62-1989 is a factor of seven below the total amount of ventilation air (outdoor air intake plus recirculated return air) required to maintain thermally acceptable conditions, i.e. to remove the heat generated within interior office space. Clearly, the relative magnitudes of the supply airflow rate and the outdoor air intake rate depend on the specifics of the space under consideration, but the outdoor air requirement is almost always well below the amount of supply air required to maintain thermal comfort. Furthermore, the thermal comfort requirement can be achieved without the provision of any outdoor air through the appropriate conditioning of recirculated return air, and the outdoor air requirement can be met or even significantly exceeded without maintaining thermally acceptable conditions. The distinction between ventilation air requirements for thermal comfort and outdoor air requirements for indoor air quality is important, though it is not always recognized.

The last aspect of ventilation system performance is the removal of internally-generated contaminants. The provision for contaminant removal from general office space is through the spill or exhaust of return air or via other buildings exhaust systems, e.g. toilets. The amount of outdoor air required to maintain indoor contaminants at an acceptable level depends on the source strength of the contaminant. The determination of the necessary rate of dilution also requires a target concentration for the contaminant in question based on health and comfort. Such target concentrations relevant to office environments currently exist for very few contaminants. ASHRAE Standard 62-1989 implies that the ventilation rate requirements in the standard are adequate to control contaminants in the absence of "...unusual indoor contaminants or sources...", but the standard does not define these unusual circumstances.

VENTILATION EFFECTIVENESS AND SYSTEM DESIGN

Rather than discuss the specific definitions of ventilation effectiveness that have been developed, it is useful to begin with a more general consideration of ventilation effectiveness in terms of the design and performance of the ventilation system. In a general terms, ventilation effectiveness can be thought of as the ability of a ventilation system to achieve the three goals discussed above: thermal comfort, outdoor air delivery and contaminant removal. The ability of a ventilation system to achieve these goals depends on several factors including the amount of supply air and outdoor air, the psychometric properties of the supply air, the distribution of the supply air throughout the building, and the mixing of the supply air within the occupied space. In most discussions of ventilation effectiveness, it is only the last aspect of performance that is addressed. Employing a more general concept of ventilation effectiveness, it is useful to consider the various scales within a ventilation system, ranging from the air handler to the air distribution ductwork to the ventilated space. There are design goals at each scale in the system, and ventilation effectiveness can be thought of as the success of the system in attaining the desired performance at each scale.

The first scale at which to consider ventilation effectiveness is the air handler itself. Figure 1 contains a schematic diagram of a conventional air handling system for a commercial building. The airflow rates of interest shown in the schematic include the outdoor air intake, the supply air to the occupied space, the return air from the occupied space, the spill or exhaust air, and the recirculation air. The ability to provide thermal comfort is a function of the supply air temperature and relative humidity and the supply airflow rate. Adequate outdoor air delivery and effective contaminant removal depend on the outdoor air intake rate at the air handler. In order to achieve these and other design objectives, the ventilation system design specifies several key parameters including the minimum outdoor air intake rate, the supply and return fan capacities, the supply air temperature and relative humidity under various operating conditions, and the airflow rate control through the modulation of dampers and perhaps fan speed. Ventilation effectiveness at the air handler involves the correspondence between the actual and specified values of these parameters. The assessment of ventilation effectiveness involves the measurement of airflow rates and supply air properties under a range of weather and internal loads. ASHRAE Standard 111-1988 provides the procedures required to conduct such an assessment. Situations of poor "air handler ventilation effectiveness" include low outdoor air intake rates, imbalances between the supply and return airflow rates, incorrect modulation of the outdoor air intake and supply airflow rates in response to weather and loads, and differences between the values of the supply air temperature and relative humidity and their setpoints. When these situations occur in the field, they can result in unacceptable conditions within the occupied space regardless of the performance at other scales within the ventilation system. Poor ventilation effectiveness at the air handler can also lead to increased energy consumption. Good ventilation effectiveness at the air handler is achieved through the proper installation of the air handling equipment and the associated control system, the application of balancing procedures at installation and periodically thereafter, and good maintenance of the air handling equipment and the control system.

The next scale of ventilation effectiveness involves the ductwork that distributes the supply air from the ventilation system to the various floors and zones within the building. In addition to good performance at the air handler, the ability to provide acceptable thermal comfort, outdoor air delivery and contaminant removal requires that the distribution of the supply air within the building is consistent with the thermal loads and outdoor air requirements of the individual zones. Figure 2 is a schematic showing an example of design specifications for supply air distribution ductwork. The schematic, a so-called "riser diagram," shows the design supply airflow rate for each floor of the building. In constant volume systems, these airflow rates should be achieved whenever the system is in operation. In variable air volume systems, these airflow rates are supply airflow rate capacities and are relevant to the system performance under full load. Under part load conditions, the supply airflow rates will be lower, depending on the thermal load on each floor. Achieving the specified supply air distribution to individual floors of a building, or other large sections depending on how the building is zoned, requires that the supply airflow rate at the air handler itself is at its design value. In addition, dampers, terminal units and diffusers throughout the building must be operating properly. Otherwise, entire floors or other large portions of the building may not be receiving the proper amounts of supply airflow, even if they are at the correct level at the air handler. Situations have been identified where fire dampers on the return side were closed and never reopened, cutting off a portion of the building from the return air system and thereby significantly reducing the supply airflow rate to that space. Cases of poor supply air distribution can result in the inability to maintain thermally acceptable conditions and the delivery of inadequate amounts of outdoor air to large portions of the building.

Figure 3 shows the supply air distribution system on a portion of a floor, showing the supply air ductwork and the terminal units. The airflow rate at each terminal unit is specified, either as a design capacity in a VAV system or as the design airflow rate in a constant volume system. In addition to the design information contained in such a drawing, additional specifications exist for the airflow rate out of each supply air diffuser. The terminal units provide the ventilation air, and outdoor air, to each zone on the floor, and the diffusers provide the ventilation air to the individual workspaces. Maintaining these airflow rates at their design levels is critical to providing thermal comfort and adequate outdoor air to the individual workspaces. Depending on the system type, the performance requirements for the terminal units include modulating the supply airflow rate in response to thermal loads, inducing the correct fraction of plenum air into the supply air, or mixing air from a cold and hot deck in proper proportions. Ventilation effectiveness within the supply air distribution ductwork on a floor involves the correspondence of the actual airflow rates within the ductwork, terminal units and diffusers to their design values. Ventilation effectiveness assessment of the air distribution system on a floor involves the measurement of these airflow rates under a range of weather and internal loads. Again, ASHRAE Standard 111-1988 contains the procedures for assessing ventilation effectiveness on this scale. Situations of poor "supply air ductwork ventilation effectiveness" include significant deviations between the specified and actual airflow rates, and can compromise both thermal comfort and outdoor air delivery. Good ventilation effectiveness at this scale is achieved through good ventilation effectiveness at the air handler and the application of balancing procedures within the supply air distribution system, at installation and periodically thereafter. A good maintenance program that addresses the ductwork, dampers, terminal boxes and diffusers is also required.

The final scale of ventilation effectiveness is the ventilated space in which the ventilation air is actually providing thermal comfort, outdoor air and contaminant removal. In the systems generally employed in modern commercial buildings, a ceiling diffuser is used to provide the ventilation air to the space. These diffusers discharge the supply air horizontally at much higher velocities than would be acceptable in the occupied space. In interior zones, the supply air is at a temperature about 10 °C (20 °F) below the average air temperature within the ventilated space. These diffusers are designed to entrain room air into the primary airstream discharging from the diffuser, such that the air velocity is reduced and the air temperature increased before this air enters the occupied portion of the space. Diffusers performance is dependent on the supply air temperature, the discharge velocity from the diffuser and the direction of the discharge, and diffuser design and performance have been studied for many years (ASHRAE 1989a, Nevins 1976).

Figure 4 is an example of the airflow pattern induced by a ceiling diffuser as calculated with a three-dimensional finite difference program (Fang and Persily 1991). The airflow pattern shown in the figure is for a cubicle within an open office space with a bi-directional linear slot diffuser located in the upper left and a return vent located in the upper right. A heat source is located directly below the supply diffuser. The calculated velocity profile shows the horizontal jet at the ceiling, entraining air from the room. The flow deflects downward under the return vent, where it meets an opposing flow from the diffuser to the right of this cubicle. The air then flows horizontally to the heat source, and vertically at the supply air diffuser. This recirculating flow structure is fairly typical for a conventional ventilation system configuration. The velocities and air temperatures calculated within the space were used to determine the ADPI (discussed below), and the result was 90% or better when the input parameters reflected proper operation of the system. The calculated velocities were also used to conduct a computer simulation of a tracer gas measurement of ventilation effectiveness based on the age-of-air approach (discussed below). The results of the ventilation effectiveness calculations were indicative of good mixing within the space.

Ventilation effectiveness within the ventilated space involves two issues, thermal comfort and mixing of the ventilation air within the space. In order to provide thermal comfort, the air diffuser needs to supply the ventilation air such that the variations in temperature within the room, the fluctuations in temperature over time and the air speeds within the room are not excessive. The effective draft temperature has been defined to describe thermal comfort in terms of the magnitude and uniformity of the air temperature and the air speed within the occupied zone. The effective draft temperature θ at a specific location is defined as:

$$\theta = (t_x - t_c) - 8.0\ (V_x - 0.15). \tag{1}$$

t_x is the local dry-bulb temperature in °C, t_c is the average room temperature, and V_x is the local air speed in m/s. The thermal comfort performance of an air diffuser is evaluated by determining the effective draft temperature throughout the occupied zone, defined to be from the floor to 1.8 m (6 ft) above the floor. The percentage of points with effective draft temperatures between -1.7 °C and 1.1 °C (-3 °F and 2 °F) and local air speeds less than 0.35 m/s (70 fpm) is referred to as the Air Diffusion Performance Index or ADPI (ASHRAE 1989a, Nevins 1976). A great deal of work has been done to relate the value of ADPI to the cooling load within the space, the type of diffuser outlet, the distance between outlets and the throw of the diffuser. The throw is the distance from the outlet at which the air speed is reduced to a reference speed, for example 0.25 m/s (50 fpm). ADPI has proven to be very useful for characterizing the ability of an air diffuser to provide thermal comfort in the occupied space. Based on many years of experience with air diffusion equipment, designers are able to provide good thermal comfort with this equipment. ASHRAE Standard 113-1990 contains the procedures the assessing air diffusion performance in the field.

The other performance aspect of an air diffuser is the ability to deliver the ventilation air to the occupied space and to purge the space of internally-generated contaminants. While conventional air diffusers are designed to mix the supply air with the room air for good thermal comfort, attempts to quantify the mass transfer aspect of their performance are a more recent development. Most discussions of ventilation effectiveness have concerned just this issue, i.e., the mixing of the ventilation air on the scale of a room. Figure 5 contains three idealized representations of airflow patterns within rooms that are used in discussions of ventilation effectiveness. The first case is referred to as "perfect mixing," in which the supply air is completely and instantaneously mixed with the room air. Although perfect mixing is an idealization, conventional air diffusion equipment is designed to achieve this goal. "Piston flow" describes an airflow pattern in which supply air displaces room air without mixing, sweeping internally-generated contaminants to the return or exhaust vent. Again an idealization, piston flow is the design principal behind so-called displacement ventilation systems in which the supply air is provided at floor level and the room air is exhausted from high in the room. Piston flow can result in very good ventilation effectiveness in terms of both providing supply air to the occupants and removing internally-generated contaminants. The last schematic represents a situation in which a significant portion of the supply air short-circuits to the return vent, bypassing the occupied zone of the room. Short-circuiting is undesirable in that only a portion of the outdoor air reaches the occupants and the removal of contaminants generated within the bypassed zone is not particularly effective. The following section describes the various measures of ventilation effectiveness that have been proposed to quantify the mixing of ventilation air, and in some cases the removal of internally-generated contaminants, within a ventilated space.

VENTILATION EFFECTIVENESS MEASURES

This section presents ventilation effectiveness definitions that are currently being proposed and applied in mechanically ventilated office buildings. These definitions have generally been developed to address mixing within the occupied zone, but some are also applicable to larger scales within the air distribution system. The following review covers ventilation effectiveness definitions based on concentration ratios between the occupied space and the exhaust air, two-zone approaches including that presented in ASHRAE Standard 62-1989, a recently developed approach based on a "quasi-equilibrium" analysis, and the age-of-air approach being considered by ASHRAE SPC129P. A review of ventilation effectiveness definitions conducted seven years ago (Persily 1985) included essentially the same approaches, except for the quasi-equilibrium method.

In presenting these definitions of ventilation effectiveness, this discussion also considers the tracer gas procedures used in their determination and the applicability of these procedures in the field. In these procedures, tracer gas is used to either tag the outdoor air or to simulate a contaminant source within the space. In the former case, the tracer gas is injected into the supply airstream; in the latter case the tracer gas is injected into the space itself. When the tracer gas is used to simulate a contaminant source within the space, the value of the ventilation effectiveness will in general depend on the where within the room the tracer gas is released. The application of most of these measures of ventilation effectiveness and the associated tracer gas procedures for their determination are straightforward in experimental test rooms. The following discussion specifically addresses their use in the field to study ventilated spaces within larger buildings and to test whole buildings. In many situations one would like to access the ventilation rate and the ventilation effectiveness of a single room, in isolation from the rest of the building. However, the interactions between a single room and the rest of a building, both through the ventilation system and other airflow paths, are generally too extensive to allow such a separation. In the following discussion, a clear distinction is maintained between the application of measurement procedures to a single room or ventilated space and the application to an entire building.

Concentration Ratios

Measures of ventilation effectiveness have been developed that are based on simple relationships between tracer gas concentrations in a room. One such measure is based on the steady-state concentrations of a tracer gas generated at a constant rate within the room. This steady-state ventilation effectiveness is defined by

$$\varepsilon_x = (C_e - C_s)/(C_x - C_s) \tag{2}$$

where C_e is the concentration in the exhaust air, C_s is the concentration in the supply air, and C_s is the concentration at a point in the space (Sandberg 1981). ε_x can be used to assess the ability of the ventilation system to remove an internally-generated contaminant and how this ability varies within a room. C_s can be replaced by the average concentration in the room $\overline{C}$ to determine a room average steady-state ventilation effectiveness $\overline{\varepsilon}$.

In the idealized case of perfect mixing, the concentrations are uniform throughout the space and equal to the exhaust concentration, thus the steady-state ventilation effectiveness is equal to one. In the case of piston flow, the value of ε_x depends on the location of the tracer gas source relative to the measurement point. If the tracer gas is generated downstream from the measurement point, then C_x will equal C_s, and the steady-state ventilation effectiveness is infinite. If the tracer gas source is upstream of the measurement point, then C_x will equal C_e, and ε_x is equal to one. If there is short-circuiting of the supply air to the exhaust, and the tracer gas is generated in the portion of the space that is bypassed by the supply air, C_x will be greater than C_e. The steady-state ventilation effectiveness is therefore less than one, a generally undesirable situation.

The steady-state ventilation effectiveness based on concentration ratios has been used in laboratory test rooms to study the performance of different types of ventilation systems and the impact of system parameters on ventilation effectiveness (Helenius et al. 1987, Kim and Homma 1992). The use of this technique to assess ventilation system performance in the field is more problematic. The first question is whether the technique is applied to an individual space or to a whole building. If the measurement is made in an individual space, then one must select either a point source tracer gas injection or a homogeneous injection throughout the occupied zone. The results will differ depending on which option is employed, and in the case of a point injection, where the point is located. A more important issue relevant to measurements in a single space is the existence of airflows between the space and other portions of the building and the outdoors. These interzone airflows will affect the steady-state tracer gas concentrations, and therefore the steady-state ventilation effectiveness, and these effects can not be accounted for without knowing the values of the airflow rates. The interzone airflow problem, though not the envelope leakage issue, is avoided to a degree by conducting a whole building test. However, it is impractical to inject tracer gas throughout the occupied zones of an entire building of any significant size. Therefore, the steady-state ventilation effectiveness based on concentration ratios is not particularly useful in the field, although it is useful in laboratory test rooms.

Two-Zone Models

Ventilation effectiveness definitions exist that are based on two-zone models of the ventilated space, in which the space under consideration is divided horizontally into two perfectly mixed zones (Sandberg 1981, Janssen 1984). Figure 6 shows a schematic of the simple two-zone model from Sandberg (1981) and the two-zone model presented in Appendix F of ASHRAE Standard 62-1989. The diagrams are only intended to show that the supply and exhaust vents are located in the ceiling, not the number of vents or their specific locations within the zone. One problem with two-zone models is that their use requires one to determine the volumes of the two zones, and no general means of identifying these volumes has been proposed. A more basic issue is whether a two-zone model is an appropriate description of the airflow within a room. In general, the airflow patterns within a room are more complex than two perfectly mixed zones, as seen in Figure 4.

In the Sandberg model, Q is the airflow into and out of the space and βQ is the airflow rate between the two zones, where β is a dimensionless parameter ranging from zero to infinity. A value of β equal to zero corresponds to no mixing, while β equal to infinity corresponds to complete mixing within the space. Sandberg presents analysis showing how ventilation effectiveness is affected by the value of β, using concentration ratio definitions as in Equation (2) for both steady-state and transient conditions. He also applies tracer gas techniques to measure ventilation effectiveness based on this two-zone model in a laboratory test room. While the work of Sandberg and others have demonstrated the usefulness of these measurement techniques in the laboratory, their use in the field is subject to the same complications regarding injection location and interzone airflows as the ventilation effectiveness measures based on concentration ratio described above. In a single zone test, the results obtained depend on the injection location and are affected by air exchange with other zones and the outdoors. In whole building tests, it is not practical to inject tracer gas throughout the occupied zone of the building.

A two-zone approach to ventilation effectiveness is also presented in Appendix F of ASHRAE Standard 62 (ASHRAE 1989b, Janssen 1984). In this model, depicted schematically in Figure 6, s is the fraction of the supply air delivered to a zone that bypasses the occupied portion of that zone. Based on the definition of the occupied zone in the standard, the horizontal line dividing the space into the occupied zone and the upper zone is 1.8 m (6 ft) off the floor. With V_s equal to the supply airflow rate to the zone, $(1\text{-s})V_s$ is the fraction of the supply air that reaches the occupied zone. V_o is the outdoor air intake rate, V_r is the return airflow rate, and r is the fraction of the return air that is recirculated. $(1\text{-s})V_s$ is not the actual airflow rate from the upper zone to the occupied zone (βQ in the two-zone approach discussed above), it is just that portion of the supply air that eventually gets into the lower zone. With ceiling supplies and returns, the maximum value of s is equal to one, corresponding to all of the supply air short-circuiting the occupied zone. The minimum value of s in this vent configuration corresponds to perfect mixing of the supply air within the zone, in which case some of the supply air still bypasses the occupied zone. In this case, s is given by the following expression

$$s = (H - 1.8)/H \tag{3}$$

where H is the height of the room in meters.

If the return vent is located in the occupied zone, then the supply air will always enter the occupied zone and s will always equal zero. Similarly, if the supply vent is in the occupied zone, as in a displacement ventilation system, s will again always be equal to zero. Therefore, s is not a very useful concept for characterizing mixing in these configurations.

The ventilation effectiveness in Standard 62 is defined as the amount of the outdoor air from the ventilation system that flows into the occupied zone divided by the amount of outdoor air intake by the ventilation system, and is given by the following expression

$$E_v = (1 - s)/(1 - rs). \tag{4}$$

This definition does not account for outdoor airflow from other rooms or the outdoors, but it does account for recirculation. When the supplies and returns are located in the ceiling, for a given value of r the minimum value of E_v is zero, corresponding to total stratification (s=1). In the text of the standard, it is stated that E_v is equal to 100% under conditions of perfect mixing. In fact, with ceiling supplies and returns, the maximum value of E_v is somewhat less than 100%, based on the value of s given in Equation (3). When the return or supply vent is located in the occupied zone, E_v is always equal to 100%.

While Standard 62 does not describe a test procedure for determining E_v, a tracer gas procedure has been described elsewhere (Janssen 1984). This procedure employs a tracer gas decay in the zone being tested to determine the ventilation effectiveness based on an initial and final tracer gas decay rate. There are several concerns regarding the use of this procedure in the field. First, the determination of the initial and final decay rates are generally associated with significant measurement errors. Also, this procedure considers the zone in question in isolation and does not account for interzone airflow or infiltration. When monitoring the tracer gas decay within a single ventilated space, the decay is impacted by both outdoor airflow through the ventilation system and from other portions of the building, and the effects of these two factors on the decay can not be distinguished. As with all two-zone approaches, the use of the model is only justified when it is appropriate to model the ventilation of the space as two well-mixed zones. Otherwise, the test procedure and the associated analysis will not provide useful results. Given the airflow patterns typical of office space employing conventional air diffusers, the use of a two-zone model is questionable.

Quasi-Equilibrium Approach

A recently proposed approach to ventilation effectiveness, referred to here as quasi-equilibrium, is based on a constant injection of tracer gas into the outdoor air intake of a building (Farant 1991). When the tracer gas concentration attains steady-state, the tracer gas concentration within the occupied zone is divided by the concentration in the supply air to calculate the so-called outdoor air supply index (OASI). The OASI is claimed to provide an estimate of the portion of the outdoor air that is delivered to the occupied space. In fact, at steady-state the tracer gas concentration within the room will be uniform and equal to the supply air concentration, unless there is airflow to the space from zones with a tracer gas concentration less than that in the supply air, e.g. the outdoors. Therefore this ratio provides no information on the extent of mixing in the space, but is only a measure of the amount of outdoor airflow into the zone from other than the ventilation system, i.e., from other zones and envelope leakage. In the reference that describes this approach (Farant 1991), the OASI ratio is actually calculated before the tracer gas concentrations attain equilibrium, referred to as "transient steady-state." While these values of OASI obtained prior to steady-state are interpreted as being indicative of poor delivery of outdoor air to the occupied zone, their actual meaning is not clear. Because the results of this procedure at steady state are not affected by mixing within the space, and because the reported results were obtained prior to equilibrium conditions, the value of this procedure is questionable.

Age of Air

The age-of-air approach to ventilation effectiveness is one of the most promising approaches for assessing ventilation effectiveness in the field (Sandberg 1983, Sandberg and Sjoberg 1983, Seppanen 1986). In fact, the age-of-air approach is being considered by ASHRAE SPC 129P in its attempt to develop a standard test method for ventilation effectiveness. In this approach, tracer gas techniques are used to measure the age-of-air at several key locations in the building. The average age-of-air at a specific location is defined as the amount of time that has elapsed since the air at that location entered the building. The local age of air is denoted by τ_i, and the age of air averaged over a particular space is denoted by $\langle\tau\rangle$. The inverse of the building air change rate is referred to as the nominal time constant of the building τ_n. There are several definitions of ventilation effectiveness based on comparisons of τ_i, $\langle\tau\rangle$, and τ_n. The local air exchange effectiveness ε_i characterizes the ventilation effectiveness at a specific location and is defined as

$$\varepsilon_i = \tau_n/\tau_i. \tag{5}$$

The mean air exchange effectiveness of a building or a space η is a measure of the overall air distribution pattern for the building or space and is given by

$$\eta = \tau_n/\langle\tau\rangle. \tag{6}$$

The tracer gas techniques used to measure the age of air are described in detail elsewhere (Sandberg 1983, Sandberg and Sjoberg 1983). One procedure involves injecting tracer gas at a constant rate into the building supply airstream and monitoring the tracer gas concentration build-up in the space and the exhaust. The injection continues until the concentrations have attained steady-state. The concentration data is then analyzed to determine the age-of-air at each space location and in the exhaust air. An alternate procedure exists in which one starts with a uniform tracer gas concentration in the space, and then monitors the decay in tracer gas concentration within the space and the exhaust air. The concentration data during the decay are then analyzed to determine the age-of-air at each space location and in the exhaust air. The decay procedure, as opposed to build-up, is generally employed in field measurements.

If the air within a space is perfectly mixed, then the local age of air τ_i will be the same throughout the space and equal to the inverse of the air change rate, i.e., τ_n. The value of $\langle\tau\rangle$ will also equal τ_n. The local air exchange effectiveness ε_i at all locations within the space and the mean air exchange effectiveness η for the space will equal one. In the idealized case of pure piston flow through the space, τ_i will be minimized near the supply and maximized near the return. The mean age of air for the space $\langle\tau\rangle$ will be exactly equal to $\tau_n/2$, and therefore η will equal 2, its maximum possible value. The local air exchange effectiveness ε_i will be below one near the return and above one near the supply. If there is non-uniform air distribution within a space, those locations with poor ventilation air distribution will have local ages of air that are higher than the space average. Locations in the so-called "stagnant" regions will have values of τ_i that are relatively large and values of ε_i significantly less than one, a generally undesirable situation. The existence of significant stagnation in a space will result in a value of η for the space that is well below one.

The assessment of ventilation effectiveness based on the age-of-air approach is straightforward in laboratory test rooms. A significant amount of work has been done in such test rooms, advancing the understanding of ventilation system performance (Fisk et al. 1991a, Sandberg 1983, Seppanen 1986). The application of these techniques in the field, however, are more complicated and research is currently underway to investigate the applicability of this approach in the field (Fisk et al. 1991b, Persily and Dols 1991). One issue is whether the test involves tracer gas injection and concentration monitoring in a single room or over an entire building. As discussed earlier, a single room test is complicated because the decay in tracer gas concentration within a room is affected by both outdoor air ventilation and interzone airflow. Therefore, single room tests are not generally reliable, unless the room is well isolated from the rest of the building, and this isolation can be demonstrated. A measurement involving tracer gas injection into an entire building, even if the concentration measurements are primarily in a single room, avoids the interzone airflow problem. In a whole building test, one can not separate the outdoor airflow into a room due to the ventilation system from the outdoor air provided via other spaces, but the test results do unambiguously account for all of the outdoor airflow. Age-of-air measurements in the field generally employ the tracer gas decay procedure, which requires initial conditions of a uniform tracer gas concentration throughout the building. Achieving these initial conditions can be quite difficult in the field, given the wide variety and complexity of office building layouts, ventilation system configurations and system operation schedules. One strategy for achieving a uniform concentration in the building is to inject tracer gas at a constant rate into each air intake until equilibrium conditions have been attained. In general, many hours are required to reach equilibrium, during which the tracer gas injection rates into the air handlers will probably need to be adjusted. This process can be quite involved and time consuming, and it is possible that a sufficiently uniform tracer gas concentration will not be achievable in some buildings. However, it is not yet clear how uniform the concentrations within the building must be in order to obtain reliable results. Additional field testing is required to develop practical strategies for achieving the desired initial conditions and to determine the degree of concentration uniformity that is required and achievable.

When measuring the local age of air at a particular location, the results are influenced by both the air mixing within the space and the uniformity of the distribution of supply air to that space. As pointed out by Fisk (1991b), comparing the value of τ_i to the nominal time constant of the building as in the definition of ε_i in Equation (5), does not enable one to distinguish between the effects of mixing and distribution. In order to assess the within-space mixing, Fisk proposes comparing the value of τ_i to the age-of-air measured at the return vent(s) serving the space. The values of the return vent age-of-air throughout the building can also be used to evaluate the uniformity of ventilation air distribution within the building.

Even with the experimental complexity of conducting age-of-air measurements in the field, this approach to assessing ventilation effectiveness holds a great deal of promise. Before this approach is generally applicable in the field, additional tests are needed to develop experience with its use and to assess its feasibility over a range of buildings and ventilation system types. Conducting these tests will enable the development of estimates of the experimental errors, including the repeatability of the test results. A study by Persily and Dols (1991) provides some indication of the repeatability of the test results. In this study, the local age of air was measured at a single location eight times during one week and three times at twenty-two additional locations. The standard deviation of the measurement results at the single location tested eight times was about 5% of the mean value. For the twenty-two locations tested three times each, the standard deviation of the age of air ranged from 2% to 11% of the mean, with an average value of 8%. Additional demonstrations in the field will improve the ability to estimate measurement errors and to deal with the realities of complex building and ventilation system configurations and operating schedules as they impact issues of tracer gas injection, achieving uniform a uniform concentration within the building and air sampling.

The limited field measurements of age-of-air conducted to date in U.S. office buildings have been indicative of good mixing of the ventilation air within ventilated spaces (Fisk et al. 1991b, Persily and Dols 1991). These measurements have concentrated on cooling situations, and additional study of heating situations and larger numbers of buildings are required to enable any generalizations about the extent of the short-circuiting in office buildings. While the measurements to date have not identified serious problems of short-circuiting, they have noted problems of air distribution on larger scales within buildings. In addition, other tracer gas studies and airflow measurements in buildings have identified problems in which ventilation air distribution to whole floors or other large portions of buildings have deviated significantly from design (Grot 1982, Persily et al. 1989). Again, additional measurements are required before any generalizations are possible, but it may turn out that large scale air distribution is a more significant problem than within room mixing.

CONCLUSIONS

The basic purpose of ventilation effectiveness assessment should be to evaluate the performance of the ventilation system relative to the system design objectives: outdoor air intake, ventilation air distribution, contaminant removal and thermal comfort. Furthermore, ventilation effectiveness assessment protocols should involve measurements that compare the actual performance of the system to the design specifications on all scales of the system. Therefore, the assessment protocols should involve airflow rate, temperature and relative humidity measurements at the air handler, airflow rate measurements in the ductwork and at the diffusers, and thermal comfort and air mixing measurements in the occupied space. The last performance parameter, mixing within the occupied space, has been the focus of most discussions of ventilation effectiveness to date. Of the various measures of ventilation effectiveness that have been proposed, the age-of-air approach based on tracer gas decay appears to be the most promising for field application. While much work remains in the area of protocol development, this technique will probably be useful for assessing ventilation effectiveness in terms of mixing within rooms and distribution throughout buildings. Based on the limited number of measurements to date, mixing within rooms in cooling situations appears to be good, i.e., short-circuiting has not been identified as a prevalent problem. On the other hand, ventilation effectiveness problems do exist in buildings and these include differences between system airflow rates and their design values, deviations between supply air temperatures and relative humidities and their setpoints, and nonuniform ventilation air distribution. Procedures exist to assess these aspects of ventilation effectiveness, and they should be used to assess these critical aspects of ventilation system performance.

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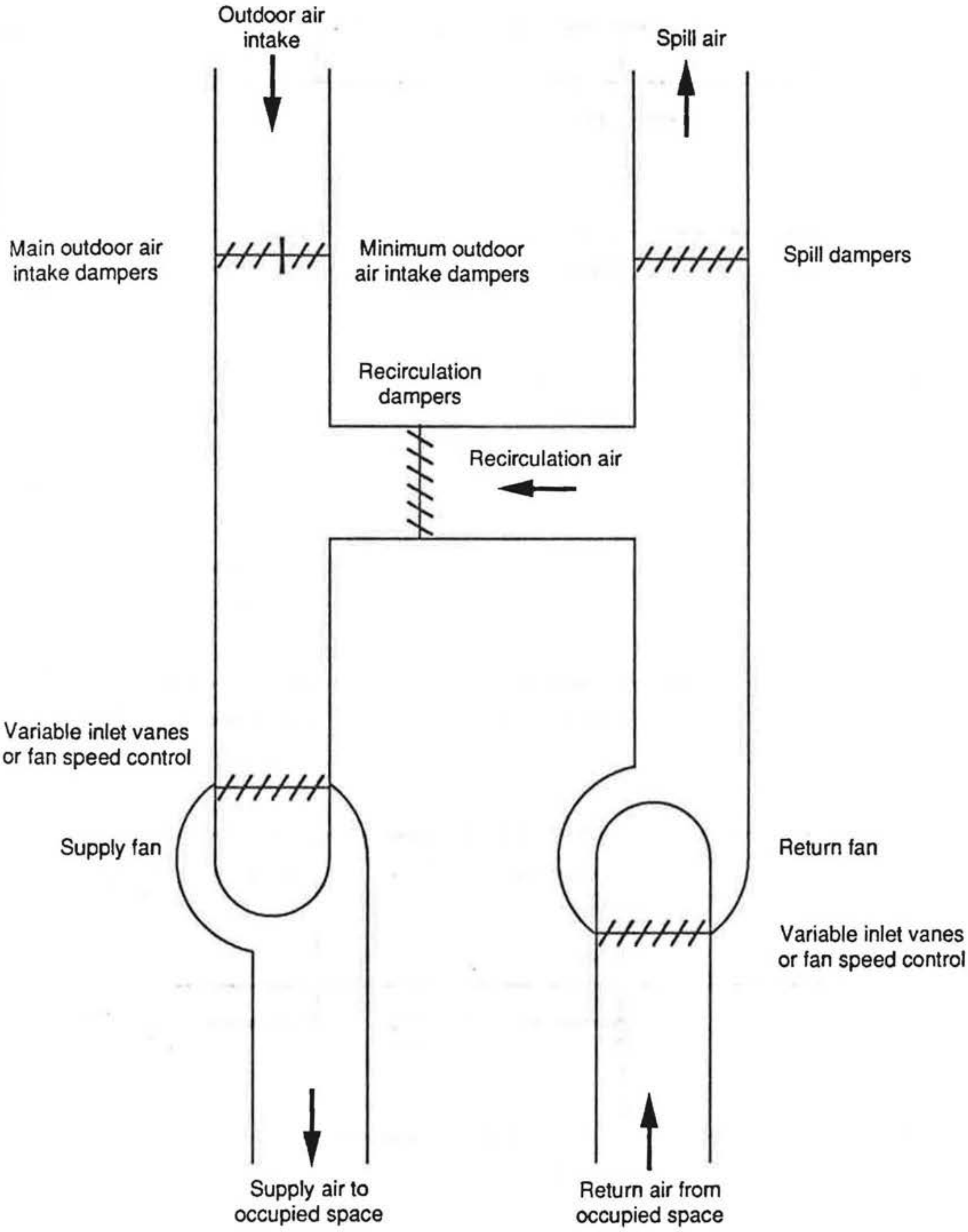

Figure 1 Air Handler Schematic

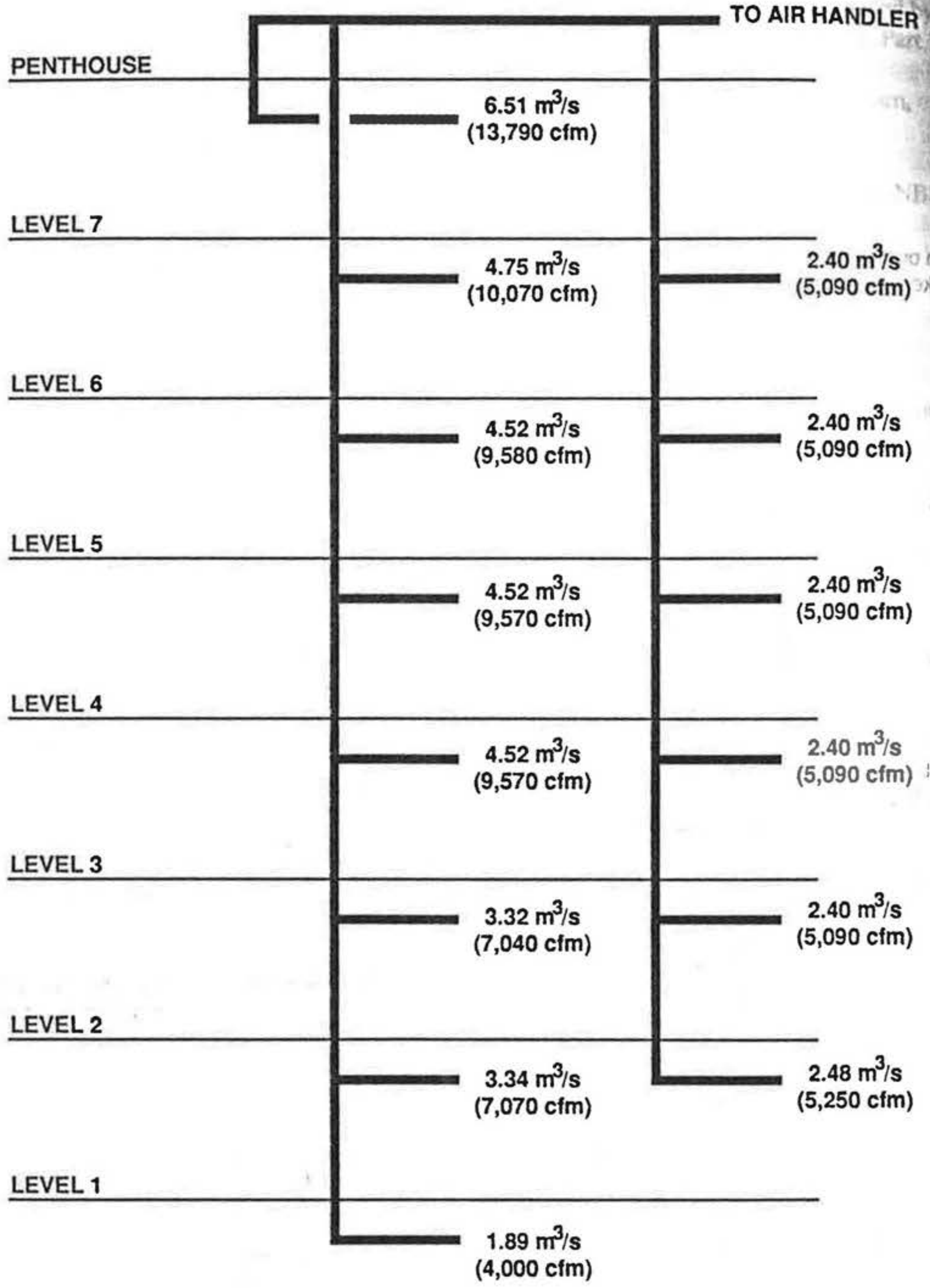

Figure 2 Air Riser Diagram

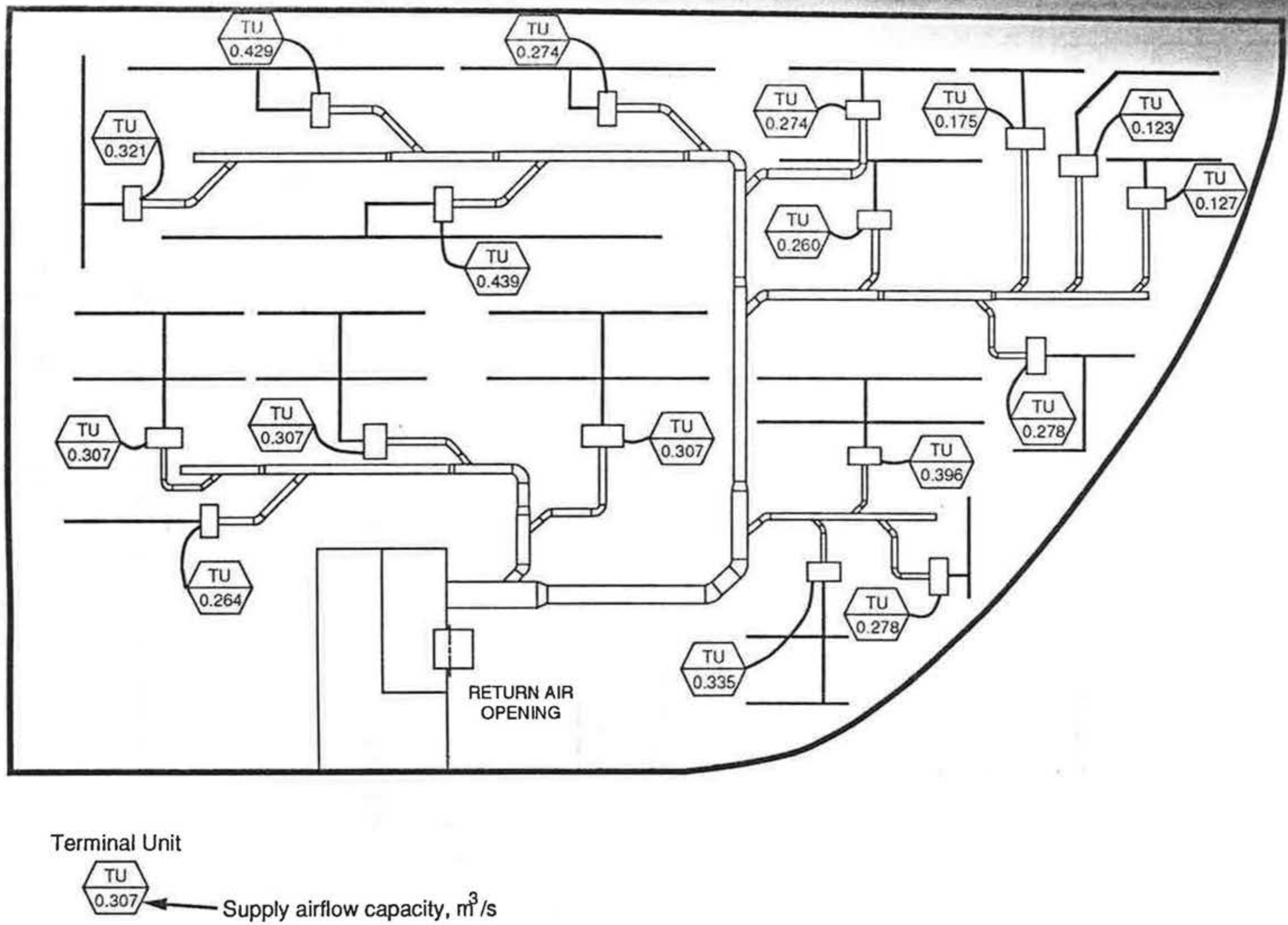

Figure 3 Air Distribution Schematic on Floor

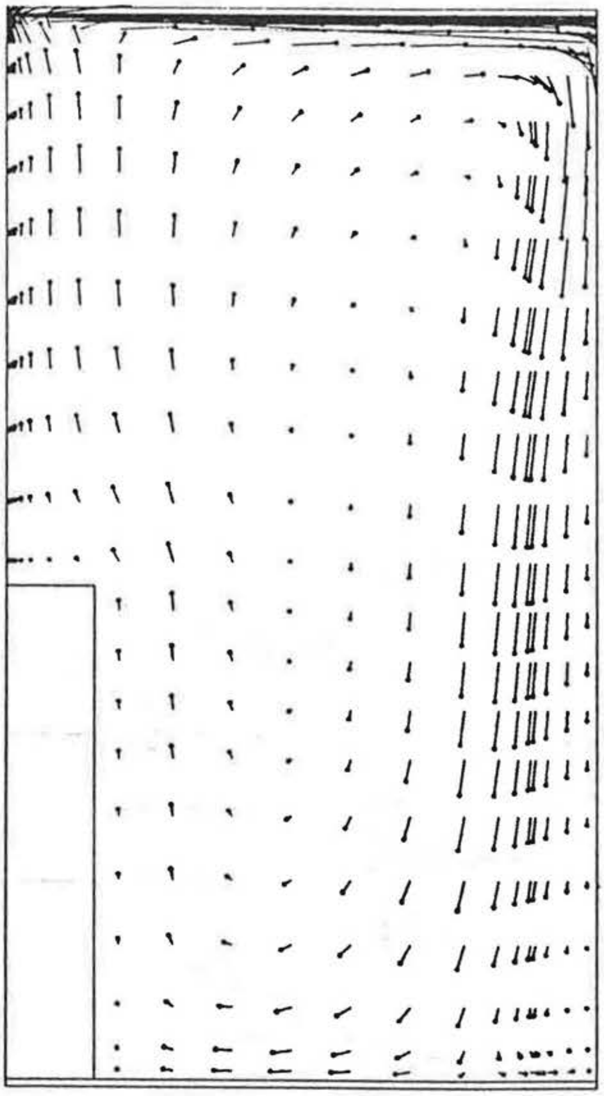

Figure 4 Calculated Room Airflow Pattern

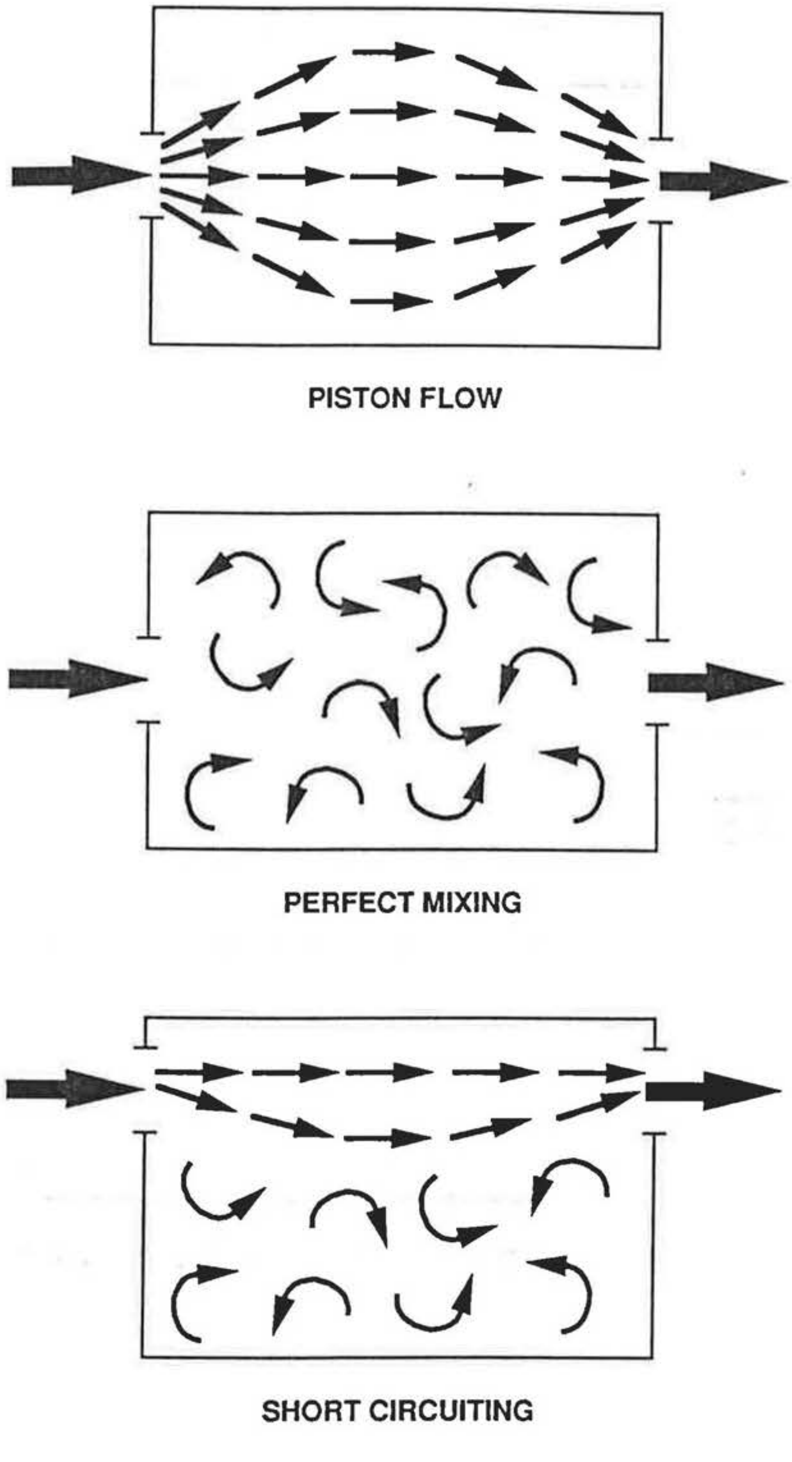

Figure 5 Idealized Room Airflow Patterns

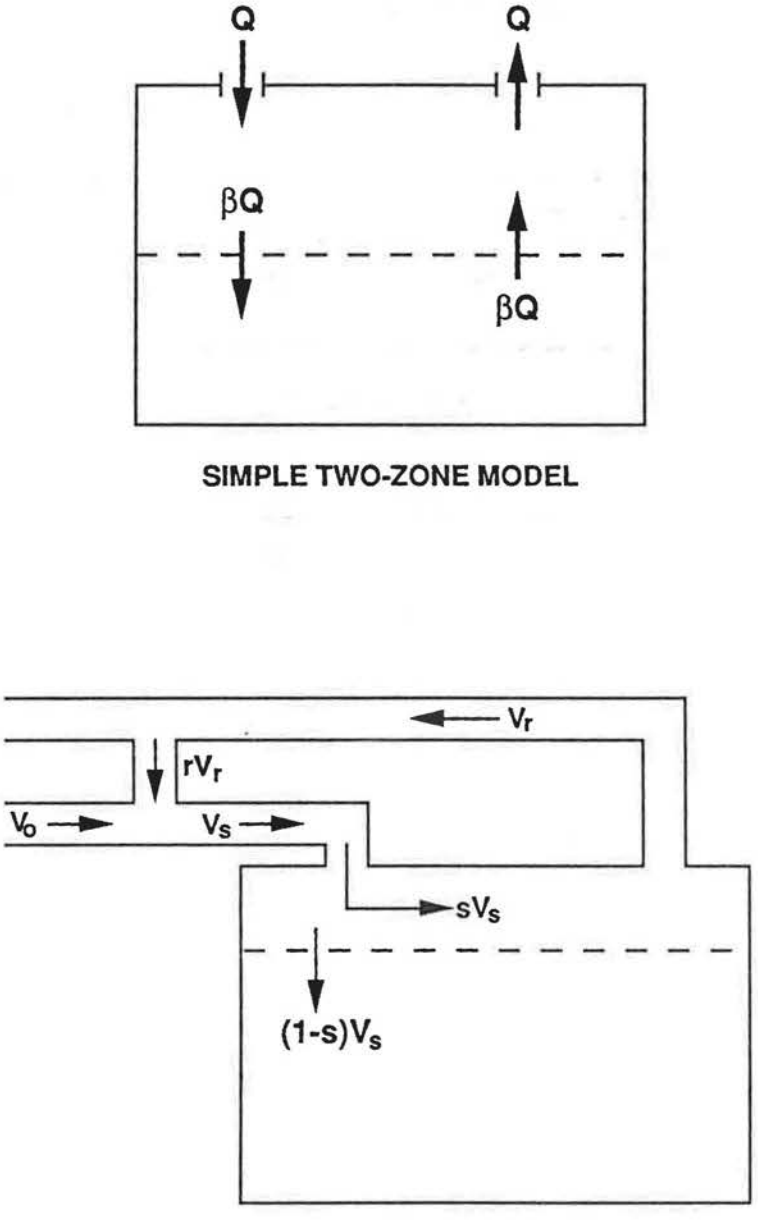

Figure 6 Two-Zone Models of Ventilation Effectiveness