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ABSTRACT

We define two air exchange effectiveness parameters which indicate the extent of short circuiting, mixing, or displacement air flow in an entire building, the air diffusion effectiveness which indicates the air flow pattern locally, and the normalized local age of air. After describing two tracer gas procedures for measuring these parameters, we discuss assumptions inherent in the data analysis that are often violated in large office buildings. To obtain valuable data, careful selection of buildings for measurements and assessments to determine if operating conditions are reasonably consistent with the assumptions are necessary. Multiple factors, in addition to the air flow pattern in the occupied space, can affect measurement results, consequently, the interpretation of measurements is not straightforward. We summarize the results of measurements in several office buildings and in a research laboratory. Almost all measurements indicate that the extent of both short circuiting and displacement flow is small. A moderate amount of short circuiting is evident from a few measurements in rooms with heated supply air. Ages of air and their reciprocals (local ventilation rates) often vary substantially between rooms, probably because of room-to-room variation in the rate of air supply. For future research, we suggest assessments of measurement accuracy, development of measurement approaches that may be practically applied for a broader range of buildings, and a greater focus on pollutant removal efficiencies.

Key Words: office buildings, measurement, tracer gas, ventilation effectiveness

INTRODUCTION

To characterize indoor air and pollutant flow patterns in quantitative terms, a number of ventilation efficiency, ventilation effectiveness, and air exchange effectiveness parameters have been introduced by researchers. Despite the common dependence on indoor flow patterns, different parameters provide qualitatively different information.

The parameters in one class, frequently called ventilation efficiencies, are direct measures of the efficiency of pollutant removal by ventilation. We prefer the term "pollutant removal efficiency" for these parameters. An example is a ratio consisting of the steady state concentration of an indoor-generated pollutant in the air exhausted to outside divided by the steady state spatial average concentration of the same pollutant in the indoor air. An increase in this concentration ratio signifies more pollutant removal per unit volume of ventilation air. These parameters depend on the location of the pollutant source(s) and whether the pollutants are emitted passively (i.e., without momentum) or actively (e.g, in a plume of rising warm air).

A second class of parameters, often called air exchange effectiveness or ventilation effectiveness parameters, are measures of the extent of short circuiting or displacement (piston-like) air flow between the locations of air supply and removal. Perfect mixing of the indoor air is often used as a reference case. A continuum in the flow pattern with hypothetical complete short circuiting at one extreme (parameter equals zero) and hypothetical perfect displacement flow at the other extreme (parameter equals two) is envisioned. In between is perfect mixing of the indoor air, which is also hypothetical, with a parameter value of unity. These parameters have received more attention than pollutant removal efficiencies because they do not depend on the pollutant source characteristics. The presumption, largely unproven but plausible, is that high values of these parameters correspond to high pollutant removal efficiencies for most real pollutants of significance.

A third type of parameter, often called the local ventilation effectiveness or local air exchange effectiveness, is the ratio of the ventilation rate in a single location , e.g. a room, to the nominal ventilation rate of the entire building. (The nominal ventilation rate is the rate of supply of outside air per unit indoor air volume.) In multi-room buildings, the air within each individual room could be perfectly mixed but rooms with a below-average ventilation rate (which may be intentional) will have a low value of local air exchange effectiveness. Due to confusion about the meaning of parameters, low values of local air exchange effectiveness are often attributed to severe short-circuiting within room. To help prevent confusion, in the remainder of this paper we use the term "normalized local age of air" for this parameter (the age of air is defined in the next section).

The research issues or questions that are associated with these parameters include the following: (1) How can measurements of these parameters be made in large buildings? (2) What are typical values for these parameters in the existing building stock, particularly office buildings, and what are the important determinants? (3) How can these efficiency or effectiveness parameters be improved? In the remainder of this paper, we address the first two of these questions.

DEFINITIONS

We use the "age of air", τ, as the basis for defining air exchange effectiveness (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 age of air at a specific location within the occupied space, the age in various airstreams (such as the exhaust), and the spatial average age of all air within a building. The symbol τ_{BL} is used to represent an age of air measured at the typical breathing level of a seated person. Age of air is measured using tracer gas techniques described in the next section of this paper.

The nominal time constant, 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 nominal (building-wide) air exchange rate and is usually expressed in units of hours. τ_N equals the age of air exhausted to outside (Sandberg and Sjoberg 1983) and, therefore, can be determined from tracer gas measurements in the main return or exhaust airstreams.

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. The average of the measured local ages of air at breathing level is denoted $<\tau_{BL}>$.

We define two AEE parameters and the normalized local age of air (NLA) via the following equations:

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

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

$$\mathrm{NLA} = \tau_N / \tau_{BL} \tag{3}$$

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 potentially 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}. Both of these parameters are indicators of the extent of short circuiting or displacement flow as discussed in the introduction.

The NLA, which has a whole-building time constant in the numerator and a local age in the denominator, is useful for assessing the spatial variability of ventilation but is not an indicator of the extent of short circuiting in multi-room buildings. The reciprocal of the numerator equals the nominal ventilation or air exchange rate, i.e., the outside air flow rate divided by the indoor air volume. The reciprocal of the denominator may be considered an effective local ventilation rate at a breathing-level location. Hence, the ratio of these parameters is a ventilation rate at breathing level normalized by the nominal ventilation rate for the entire building.

All three of these parameters have a value of unity when the indoor air is perfectly mixed; however, perfect mixing is not the only condition that results in a value of unity. 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 air flow pattern in a specific indoor region (e.g., a room).

$$\mathrm{ADE} = \tau_{RG} / \tau_{BL} \tag{4}$$

where τ_{RG} is the age at a return grill located near the τ_{BL} measurement location. If supply air, which has a lower age than indoor air, short circuits to the return grill, 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 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 air is perfectly mixed.

MEASUREMENT TECHNIQUES

We describe the use of a tracer gas decay and a tracer gas stepup to measure the ages of air that are the basis of the aforementioned parameters. Derivations of the equations for calculating ages of air are provided by Sandberg and Sjoberg (1983).

Tracer Gas Decay

In a tracer gas decay, the indoor air is labeled uniformly with tracer gas (i.e., the initial tracer gas concentration must be spatially uniform) at some point in time and the time required to replace this "labeled" indoor air with tracer-free outdoor air is determined by monitoring of tracer gas concentrations over time. One method for labeling the indoor air uniformly with tracer gas is to rapidly inject a volume of tracer gas into the air while the outside air supply is temporarily stopped. Special fans can be operated to promote the initial mixing of tracer and indoor air. Another procedure is to inject tracer gas at a constant rate into the supply airstream without stopping the supply of outside air. If all outside air enters through the supply airstream and the rate of outside air supply is constant, the concentration of tracer gas in all of the indoor air must eventually equal the concentration of tracer gas in the supply airstream. After an acceptably-uniform initial tracer gas concentration is attained, the outside air supply is started or the tracer gas injection is stopped and a tracer gas decay (decrease in concentration with time) occurs. Tracer gas concentrations are monitored as a function of time, for example at fixed intervals, at various indoor locations and in the air streams of the ventilation system.

The age of air τ at a specific location is computed from the tracer gas data via the equation

$$\tau = \frac{1}{C(0)} \int_0^{t_{end}} C(t)\, dt \tag{5}$$

where the start of the decay corresponds to a time of zero, C(t) is the tracer gas concentration at time t , and t_{end} is the time at the end of the decay. Theoretically the integration, and consequently the tracer gas decay, should continue until time equals infinity, but terminating the decay (or tracer stepup as described subsequently) after three to five nominal time constants have elapsed yields acceptable results. For example, based on our analyses of data from laboratory tests with nominal time constants of 0.33 to 0.74 h, integrations with a t_{end} value equal to 3 nominal time constants resulted in ages of air approximately 5% smaller than the ages from integrations t_{end} equal to five to eight time constants. Sandberg et al. (1982) discuss a method for estimating the value of the integral between t_{end} and time equal to infinity.

The nominal time constant is determined by measuring the tracer concentration in the exhaust airstream and applying Equation 5. If the building has multiple exhaust airstreams, the nominal time constant is a weighted average of the ages in the exhaust airstreams with the exhaust flow rates used as the weighting factors.

Because the tracer concentration is usually only measured at discrete points in time, the integral of Equation 5 is evaluated numerically. However, measurements of tracer concentration as a function of time at large numbers of indoor locations is usually impractical because of the expensive instrumentation required. As an alternative, the age of air can be determined from measurements of the initial concentration, C(0), and the time average concentration, since the integral equals the product of t_{end} and the time average concentration between $t = 0$ and $t = t_{end}$. A grab sample can be collected and analyzed to determine the initial concentration. Manual collection of samples in syringes is a convenient method of collecting a grab sample. The time average concentration may be determined by directing a sample into a gas sample bag at a constant rate between $t=0$ and $t = t_{end}$ and measuring the resulting concentration in the bag.

Measurement of the spatial average indoor age of air $<\tau>$, requires that the time history of tracer gas concentration be measured in the exhaust airstreams. $<\tau>$ is calculated using the equation

$$<\tau> = \frac{1}{\tau_N} \frac{1}{C_e(0)} \int_0^{t_{end}} C_e(t)\, t\, dt \tag{6}$$

where $C_e(t)$ is the concentration in the exhaust airstream. If the building has multiple exhaust airstreams, $C_e(t)$ in Equation 6 should be a weighted average value, again with the exhaust air flow rates as the weighting factors.

By measuring the tracer gas concentration in both the exhaust and supply airstream and applying a mass balance, the percentage of outside air in the supply air (%OA) is determined

$$\%OA = 100\% \times [C_e(t) - C_s(t)] / C_e(t) \tag{7}$$

where $C_s(t)$ is the supply airstream concentration. The %OA is one of the factors that can influence air exchange effectiveness and the spatial variation in NLA.

Tracer Gas Stepup

A tracer gas stepup is the inverse of a tracer gas decay. The incoming outside air is labeled uniformly with tracer gas by injection of tracer gas into the airstream at a constant rate. The tracer gas must mix thoroughly in the outside airstream (or in the associated supply airstream) upstream of any point where tracer concentrations are measured or a point where the airstream splits into two or more components. Multipoint measurements are essential to confirm this mixing. Tracer gas concentrations are measured indoors and in airstreams during the time period of increasing tracer gas concentration. If the building has more than one stream of outside air, each must be labeled with the same concentration of tracer gas (which is generally impractical) or more complex multi-tracer techniques can be used (Fisk et al. 1985, 1988, 1989). In many buildings, there is no defined stream of outside air because the outside air passes through dampers and immediately mixes with recirculated indoor air. In these cases, the tracer gas can be injected into the supply airstream (i.e., the mixture of outside air and recirculated air); however, multipoint measurements of tracer gas concentration are required to confirm that the outside and supply air mix thoroughly. The equations for calculating age of air, the spatial average indoor age of air, and the %OA are

$$\tau = \frac{1}{C(t_{end})} \int_0^{t_{end}} [C(t_{end}) - C(t)]\, dt\,, \tag{8}$$

$$<\tau> = \frac{1}{\tau_N} \frac{1}{C_e(t_{end})} \int_0^{t_{end}} [C_e(t_{end}) - C_e(t)]\, t\, dt\,, \text{ and} \tag{9}$$

$$\%OA = [\, C_e(t) - C_s(t)\,] \,/\, [\, C_e(t) - C_0(t)\,] \;\; x\ 100\% \tag{10}$$

where $C_s(t)$ and $C_0(t)$ are the tracer gas concentration in the supply airstream and outside airstream, respectively. Equation 10 is based on an assumption that tracer gas is injected into the outside airstream and that the concentration in this airstream can be measured. If the tracer gas is injected into the supply airstream, the %OA is calculated as described by Fisk et al (1988). Bag sampling techniques (or other methods of sampling that yield the time-average concentration), plus analyses of grab samples collected from the same location at the end of the stepup, can be used to determine the age of air. In this case, the age is computed using the equation

$$\tau = t_{end} \;[\, 1 - C_{bag} \,/\, C(t_{end}\,)\,] \tag{11}$$

where C_{bag} is the time-average concentration during the tracer gas stepup.

MEASUREMENT AND INTERPRETATION ISSUES

The operating conditions of many large buildings are inconsistent with the assumptions inherent in the use of age distribution theory (the basis for Equations 5, 6, 8, 9, and 11) to calculate ages of air and the associated air exchange effectiveness parameters. Implementation of the tracer gas procedures is often impractical and the interpretation of measurement results is not straight forward. In this section, we discuss these issues and point out the need for new measurement approaches.

Assumptions

The age of air equations are based on steady-state mass balances. Consequently, the rate of outside air supply and the indoor air flow patterns must be stable during the tracer gas decay or stepup. In fact, one significant advantage of a tracer gas stepup, relative to a decay, is that measurements of tracer gas concentrations versus time in the outside or supply air and in the exhaust airstream at the end of the stepup provide information on the stability of the ventilation process. In conflict with this stability requirement, the outside air flow rates are often highly variable in large buildings. For example, economizer control systems intentionally regulate outside air flow rates. When economizers are deactivated outside air flow rates can still vary due to variations in the pressure difference across the outside air dampers associated with the modulation of the flow rates in variable air volume systems or changes in wind. The rates of air leakage into buildings or air entry through windows can also be highly variable for the same reasons. Even when outside air flow rates are relatively stable, we have seen evidence of shifts in indoor air flow patterns during a test. (This evidence is from multi-tracer tests which indicate that the direction of air flow between zones can change during a test.) We are unsure of the causes but suspect that opening or closing of doors, variation in fan speeds, and changes in flow rates and air temperatures may be causes. The impact of these temporal variations on measurement accuracy are not known.

The equations and measurement procedures also do not properly account for air infiltration and exfiltration which usually occur at a significant rate, even in buildings with closed or sealed windows (Persily 1985, Fisk et al. 1988, 1989). Air flow through open windows may be considered an extreme case of infiltration and exfiltration in this context. Infiltrating air is not labeled with tracer gas in a stepup. Measurement of the concentration of tracer gas in exfiltrating air is not practical during either a stepup or a decay. Consequently, when air exfiltrates the building, the true average exhaust-air tracer gas concentration is not used in calculations of the nominal time constant or the spatial average indoor age of air. The associated errors are not known but presumably increase when air infiltration and exfiltration rates are high or the indoor air is not well mixed.

Implementation of Tracer Gas Procedures

Obtaining the required mixing of tracer and air is often difficult. Based on our experience, tracer gas injected into an airstream often does not mix thoroughly with the air in the airstream, even when the airstream passes through a fan. Multipoint injection of tracer gas into the airstream is frequently necessary and multipoint measurements from different locations within the airstream are essential to confirm mixing. In a laboratory setting, we install mixing fans inside the supply duct but this option is not practical in large buildings. In some buildings, for example with one outside airstream directed to numerous supply fans, we have been unsuccessful in obtaining adequate mixing despite several days of effort. In tracer gas decays within large multi-room buildings that may have several ventilation systems, obtaining the initial mixing between the tracer gas and the indoor air poses a similar challenge.

Interpretation of Measurement Results

The complex features of many large buildings can complicate the interpretation of measurement results. We provide three examples. First consider the leakage of supply air, which includes the outside air, into a return air plenum above a suspended ceiling. This air will enter the exhaust airstream reducing its age. This leakage is a form of short circuiting and will reduce the measured values of AEE_G and AEE_{BL}. However, these parameters do not allow one to distinguish between supply-duct leakage to return plenums and short circuiting within the occupied space. Second, consider that return air plenums divide the ventilated space into two zones and that the volume of the plenum can be a significant fraction of the volume of the occupied space. In theory, the presence of two zones will generally increase AEE parameters but the effectiveness of the ventilation process in the important occupied zone is not increased by having a return plenum or making the plenum larger. Third, one should recognize that the indoor air flow patterns could vary throughout a building. Short circuiting in some rooms could counteract displacement flow in other rooms and result in AEE values close to unity for the entire building. Consequently, a value of unity for AEE_G does not necessarily indicate an acceptable indoor air flow pattern throughout the entire building.

Recommendations

Based on this discussion of measurement issues and before summarizing measurement results, we provide a conclusion and some recommendations. We conclude that the tracer gas procedures described above and data analyses based on age of air equations are impractical or inappropriate for many large complex buildings. In order to obtain valuable data, we recommend careful selection of buildings for these measurements, assessments to determine if operating conditions are reasonably consistent with the assumptions inherent in age distribution theory, and checks of the mixing between tracer and air. Also, measurement results should be interpreted with caution because multiple factors can influence the AEE parameters. In particular, low values of AEE parameters should not be automatically attributed to short circuiting within the occupied space. With regard to research needs, we have three suggestions. First, research is required to determine the accuracy of measurements of age of air and AEE parameters. Experiments in chambers with well mixed air and known ventilation rates and comparisons of simultaneous field measurements by different investigators are two potential approaches for gaining information on measurement accuracy. Second, research is required to develop more convenient measurement techniques that can be applied in a wider range of buildings, including those with airflow conditions that are inconsistent with the assumptions of age distribution theory. New parameters for characterizing indoor air flow patterns will probably have to accompany new measurement approaches. Finally, we suggest that more emphasis be placed on measurement of pollutant removal efficiencies because the efficiencies of pollutant removal may not correlate well with the AEE parameters. In addition, measurements of pollutant removal efficiencies do not depend on steady air flow rates and, therefore, may be more practical to implement than measurements of the AEE parameters.

RESULTS OF MEASUREMENTS IN OFFICES

Buildings

The authors have measured the two AEE parameters, the ADE, and the NLA in several office buildings located in the San Francisco area. The buildings had sealed windows or windows maintained closed. Economizer systems were deactivated during experiments. Most of the data have been presented previously (Fisk et al. 1988, 1989, 1991). Brief descriptions of the buildings and ventilation equipment are provided in Table 1 which also provides measurement results, the %OA during measurements, and the rates of outside air supply per occupant. All of the buildings used conventional methods of air supply and return, i.e., none had a displacement ventilation system or occupant-controlled task ventilation with air supplied from the floor or at desk top. Supply air temperatures were lower than indoor temperatures. In most buildings, we completed measurements with both minimum and maximum %OA (i.e., maximum and minimum recirculation of air by the air handler). The measurement method was a multi-tracer stepup (see Fisk et al. 1988, 1989, 1991 for details on measurement and data analysis procedures).

We have also completed measurements in a more ideal setting (Bauman et al. 1991) -- a laboratory called the Controlled Environment Chamber (CEC) which has dimensions of 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 work stations separated by partitions. Each work station contained typical office furniture (desks, side tables, chairs, book cases). The chamber also contained sources of heat and air motion typical of real offices including overhead lights, task lights, and personal computers with 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 work stations. Air was supplied through a single perforated diffuser mounted in the ceiling either centrally or at the edge of the ceiling near the center of one wall. Air exited through a ceiling-level return grill.

Global AEE

The results of field measurements of AEE_G, plus the results of measurements by Persily (1986) in a three story office building, are illustrated in Figure 1. 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. We believe that the uncertainty in our measured values of AEE_G are comparable to our estimates of the uncertainties in measured values of AEE_{BL} as discussed subsequently. Thus, we have included 95% confidence limits of ±20% on the figure. These 95% confidence limits and the confidence limits presented subsequently for other parameters are rough estimates and do not account for many of the potential sources of error, such as the error resulting from temporal variability in outside air flow rates. Within these confidence limits, 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 suggest minimal short circuiting or displacement flow, on average, for the entire building.

Seppanen (1986) measured the AEE_G in 23 offices within Finland. AEE_G 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 .

Breathing Level AEE

Figure 2 illustrates the results of our field measurements of AEE_{BL} plus the results of nine measurements by Persily and Dols (1990) in a single building and two measurements by Offermann (1988) in an isolated office within a larger building. We include only two of the measurements by Offermann (1988) because his other measurements involved unusual test conditions. Based on our evaluations of measurement precision in the CEC during tests with the indoor air vigorously mixed (Fisk et al. 1991), the 95% confidence limits for measurements of AEE_{BL} are estimated to be ± 20%. Most of the measured values of AEE_{BL} are indistinguishable (i.e., within 0.2) from unity. We suspect that values of 1.4 and 1.3 for both the fifth and sixth floor 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 which contained the only exhaust grills (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. The values of 0.66 and 0.73 measured by Offermann (1988) are the only results that indicate significant short circuiting. The room was heated with the supply air during these two tests, and short circuiting may be due to the buoyancy of the supply air.

The measured values of AEE_{BL} in the CEC are shown in Figure 3. The estimated 95% confidence limits are slightly smaller for these laboratory measurements. Only two out 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 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. Bauman et al. (1991) provide a more detailed description of the results of these measurements in the CEC and show that the partitions that separate the workstations did not cause low air velocities or low ventilation rates within the workstations.

Air Diffusion Effectiveness

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). The results of forty two measurements of ADE within six office buildings are illustrated in Figure 4. 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. As described previously, the ADE is a better indicator of air flow patterns within rooms than AEE_G or AEE_{BL}. 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 within the ventilated rooms; however, the tendency is too small to be of practical significance.

Normalized Local Age of Air

The maximum and minimum measured values of NLA in seven office buildings are included in Table 1. Values frequently deviate substantially from unity. Because of the evidence of minimal short circuiting or displacement flow, we suspect that the large deviations from unity result from variable air supply rates throughout the buildings. Some of the spatial variation in NLA may be intentional. For example, rooms with a low occupant density would typically have lower supply flow rates leading to lower values of NLA. Thus, the considerable spatial variation in this parameter is not necessarily indicative of any problem in air distribution. The NLA should be considered in conjunction with information on occupant density and information on the strength of local pollutant emissions from sources other than occupants.

SUMMARY AND CONCLUSIONS

We have defined two air exchange effectiveness parameters which indicate the nature of the indoor air flow pattern in an entire building, the air diffusion effectiveness which indicates the extent of short circuiting, mixing, or displacement flow in a room, and the normalized local age of air which compares the ventilation rate locally to the building-average ventilation rate. The tracer gas decay and tracer gas stepup procedures for measuring these parameters are described. Several measurement issues and difficulties are discussed and the results of measurements in office buildings and office spaces are summarized.

With regard to measurement issues, we conclude that the tracer gas decay and stepup procedures, with data analyses based on age distribution theory, are impractical or inappropriate for many large complex buildings. Valuable data can only be obtained from buildings with operating conditions that are reasonably consistent with the assumptions inherent in age distribution theory. Measurement results must be interpreted with caution because multiple factors, such as supply duct leakage, can influence the air exchange effectiveness parameters. Low values of air exchange effectiveness parameters should not be automatically attributed to short circuiting within the occupied space.

The large majority of measurements indicate very limited short circuiting or displacement flow within office buildings. A moderate degree of short circuiting is suggested by a few measurements in rooms with heated air supplied at the ceiling and return grills also located in the ceiling. The available data are too sparse for general conclusions but suggest strongly that short circuiting is not the severe and pervasive problem assumed by many engineers and indoor air quality specialists. The authors' data does indicate that the ventilation rate within U.S. office buildings varies substantially with location. The normalized local age of air measured by the authors, which equal the ventilation rate at a breathing level location divided by the nominal ventilation rate for the entire building, range from 0.3 to 3.6. This spatial variation is probably caused primarily by spatial variation in air supply rates.

We consider the air diffusion effectiveness (ADE) and the normalized local age of air (NLA) to be the more useful than the AEE parameters for practitioners who seek to evaluate ventilation within a building. Regions of the building with short-circuiting air flow or low or excessive ventilation can be identified by multipoint measurements of the ADE and NLA.

With regard to research needs, we include three suggestions. First, research is required to determine the accuracy of measurements of age of air and the associated parameters. Second, research is required to develop more convenient measurement techniques that can be applied in a wider range of buildings. Finally, we suggest that more research emphasis be placed on measurement of pollutant removal efficiencies.

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DISCUSSION

Question of Jianshun Zhang, National Research Council of Canada:

Assuming that you measured two ventilation systems and found system A had 20% higher air change efficiency than system B, would you say that system A is better than system B, considering the uncertainties involved in the tracer gas technique?

Author's Answer:

Good question! We certainly need to develop better estimates of the uncertainties of tracer gas measurements of air change effectiveness in different situations. I have estimated the precision of our age-of-air measurements in a well-mixed room and estimated the associated uncertainties in air change effectiveness. Based on these estimates, a difference of 20% between two measured values of air change effectiveness is probably real (not due to measurement error) if the measurements are completed in a fairly ideal situation (constant flow rates, minimal air infiltration, etc.). A difference of 10% is likely to be the result of measurement errors. I recommend repeating all measurements, rather than basing conclusions on a single measurement. If measurements are performed in buildings with conditions that deviate substantially from the assumed conditions, the measurements will be of limited value.

Question of K. Kimara, Waseda University:

You explained two parameters: ventilation effectiveness and age of air, besides classical air change rate. If they are convertible to each other, different definitions may lead to confusion to beginner scientists. Are there clear distinctions among them?

Author's Answer:

The parameters are clearly different. Traditional ventilation rates include outside air supply rates per occupant, per unit volume, or per unit floor area. These traditional parameters are unaffected by indoor air flow patterns. The age of air at a particular location is the time elapsed since the air entered the building. In one particular case, uniformly-mixed indoor air and no infiltration, the age of air equals the reciprocal of the rate of outside air supply per unit indoor air volume. Many different air change effectiveness parameters have been defined -- the different parameters are a source of confusion. My paper and other papers presented at this conference should answer your questions in more detail.

Comment of Dan Int-Hout, United Technologies-Carrier, USA:

The heating tests with low effectiveness were, in fact, not installed per ASHRAE recommendations for heating applications, so the stratification, both ventilation and comfort, was not surprising.

Author's Response:

The comment refers to the heating tests performed by F.J. Offermann and described in my paper. I agree with the comment.

Table 1 **Results of field measurements of air exchange effectiveness, air diffusion effectiveness, and normalized local ventilation rate by authors and colleagues.**

Reference, Bldg. #	Building or Space Description	Test #	% Outside Air	Air Exchange Effectiveness		Air Diffusion Effectiveness	Normalized Local Age of Air Min. - Max.
				AEE_G	AEE_{BL}		
Fisk et al 1988, Bldg #1	5th fl. office area, 430 m^2, CV, induction units supply at 1 m height at perimeter, small AHUin plenum supplies through ceiling SD in core, all return & exhaust grills at one end of floor	-	constant supply of 100% outside air to induction units	-	1.4	1.2	1.2-1.5
Fisk et al 1988, Bldg #1	6th fl., otherwise same as above	-	same as above	-	1.3	-	1.1-1.6
Fisk et al 1988, Bldg. B2 & B3	two interconnected office bldgs. served by same VAV AHU, 4400 m^2, ceiling SD & RG	1	17 (min)	1.4	1.1	-	1.0-1.4
		2	29 (min)	1.1	1.0	-	0.8-1.3
		3	31 (min)	1.2	0.9	1.0	0.8-1.1
Fisk et al 1988, Bldg B4	Office bldg connected to B2 & B3, 2400 m^2, one VAV AHU, ceiling SD & RG	1	22 (min)	1.0	0.9	-	0.9-1.0
		2	24 (min)	1.3	1.1	-	0.9-1.1
		3	24 (min)	1.3	1.0	-	0.9-1.1
Fisk et al 1991, Bldg 3	University office bldg, 7200 m^2, CV with 15 supply fans, ceiling SD & RG	3	min +	-	-	-	-
		5	min +	-	-	-	-
Fisk et al 1991, Bldg 5	Office area of science center, 3600 m^2, CV, ceiling & high-wall SD &RG	3	87 (max)	1.3	1.4	-	0.8-3.6
		5	36 (min)	-	0.9	-	0.6-1.1
		7	38 (min)	-	-	1.0,1.6,1.4,1.2	0.7-1.0
Fisk et al 1989, Bldg 6	Office bldg, 4100 m^2, two VAV AHU with common return shaft, ceiling SD & RG	1	23,24 (min)	1.1	1.2	1.1,1.0,1.0	1.1-1.7
		2	25,24 (min)	1.2	1.0	1.1,1.1,1.0,1.0	0.6-1.3
		7	86, 80 (max)	1.1	1.0	1.5,1.1,1.3,1.1,1.2	0.5-1.8
Fisk et al 1991, Bldg 7	Office bldg, 2000 m^2, three VAV AHU, ceiling SD & RG	1	63,33,71 (max)	-	1.1	1.2,1.2	0.8-2.4
		2	61,30,70 (max)	1.0	0.8	1.0,0.8,1.4,1.0	0.3-1.4
		3	10,13,16 (min)	-	-	0.9,0.9,1.1,1.0	-
Fisk et al 1991, Bldg 8	Office bldg, 950 m^2 office area, one VAV AHU, ceiling & high wall SG, ceiling RG, high infiltration, some supply air vented into return plenum	1	min +	-	-	1.2,1.0,0.8,1.3,1.1	-
		2	min +	-	-	1.2,1.1,1.2,1.1	-
		3	max +	-	-	1.1,1.0,1.0,1.1,1.0	-

Abbreviations: Bldg=Building; RG=return grill; SD=supply diffuser; min=minimum; max=maximum; occ=occupant; CV=constant volume; VAV=variable air volume; AHU=air handling unit.

Footnotes: +not measured.

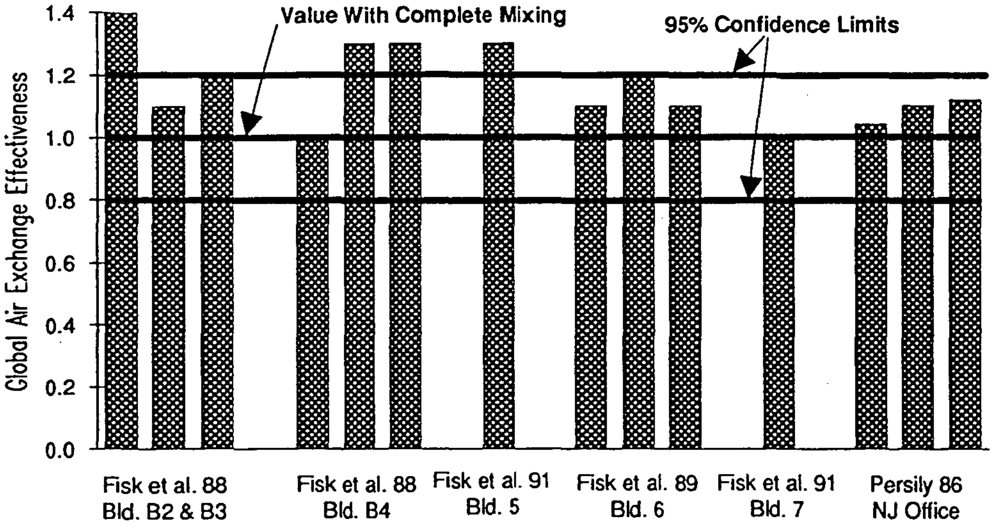

Figure 1. Results of field measurements of the global air exchange effectiveness. The 95% confidence limits are illustrated for a measurement with a value of 1.0.

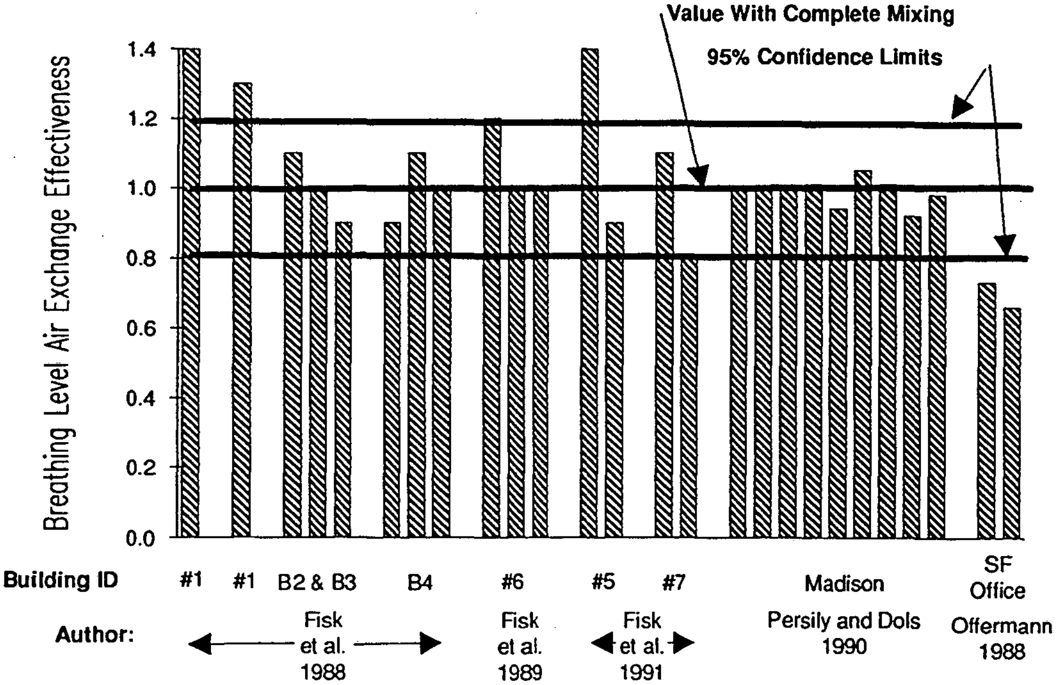

Figure 2. Results of field measurements of breathing level air exchange effectiveness. The 95% confidence limits are illustrated for a measurement with a value of 1.0.

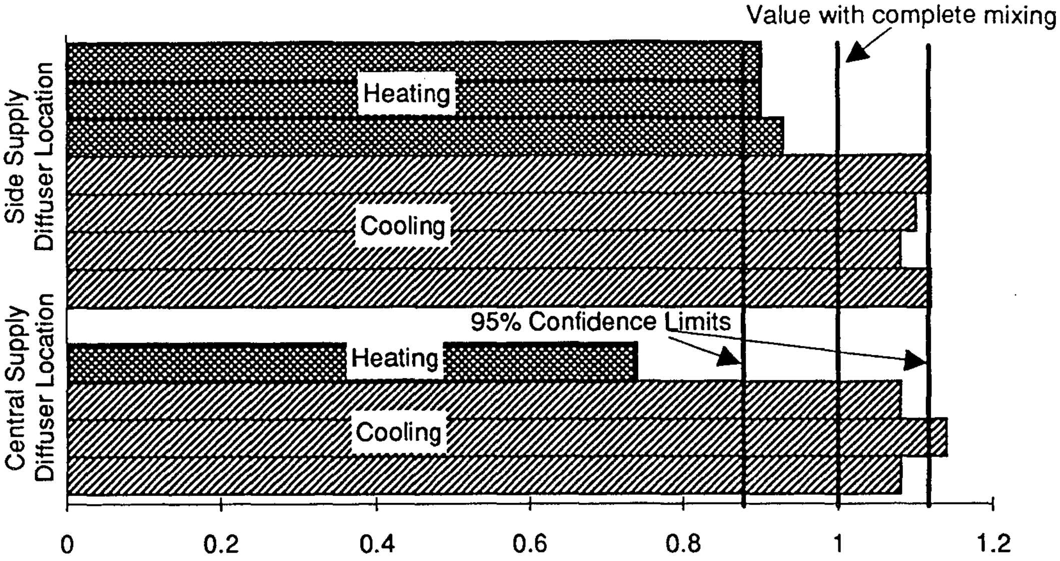

Figure 3. Results of measurement of breathing level air exchange effectiveness in the controlled environment chamber. The 95% confidence limits are illustrated for a measurement with a value of 1.0

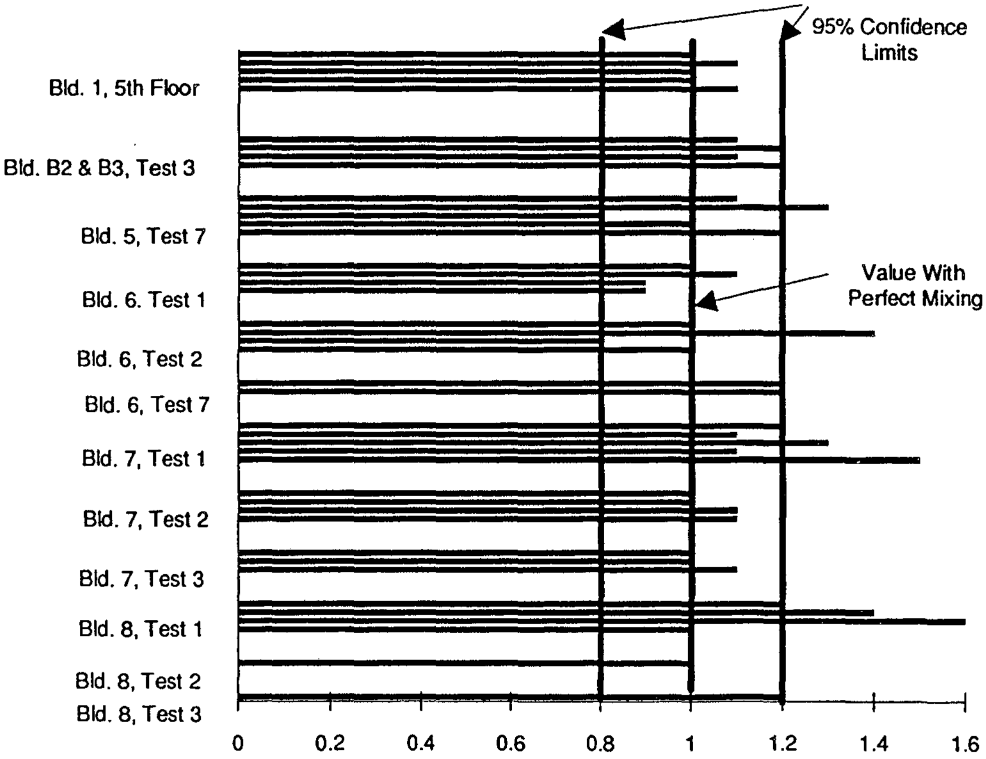

Figure 4. Results of field measurements of air diffusion effectiveness by the authors and colleagues (Fisk et al. 1988, 1989, 1991). The 95% confidence limits are illustrated for a measurement with a value of 1.0.

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