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Comparison of Air Exchange Efficiency and Contaminant Removal Effectiveness as IAQ Indices

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ABSTRACT

Recently indoor air quality (IAQ) became an important issue and as a result researchers have developed a large number of different air quality indicators. This study focuses on air exchange efficiency (ε_a) and contaminant removal effectiveness (ε) as suitable indicators for use in design and on-site measurements. These two IAQ indicators were numerically studied and compared for five typical indoor spaces with different ventilation strategies and contaminant sources. Overall, more than fifty different simulations were performed. The results show that ε_a is appropriate for general evaluation of ventilation strategies for spaces with unknown contamination sources, while ε provides more informative results for removal of contaminants with known position and generation rates. Nevertheless, certain correlations between ε_a and ε exist. Based on the results of this study, designers could select an air quality indicator that is more appropriate for their particular application.

INTRODUCTION

Ventilation systems in buildings are designed and operated to accomplish two primary functions: (1) to deliver fresh air to occupants while removing internally generated contaminants and (2) to provide acceptable thermal comfort in the vicinity of occupants. During the operation of a ventilation system, occupants' focus is on the thermal comfort because perception of thermal comfort is immediate and thermal discomfort is intolerable. However, poor air quality is more difficult to notice and therefore, occupants' response takes longer periods of time. In addition, designers traditionally pay more attention to the thermal comfort than to the air quality because thermal comfort is better defined by standards. For example, ASHRAE Standard 62-2001 defines ventilation effectiveness (E_V) as an air quality indicator, but the standard does not provide practical information on how to evaluate or measure E_V. Furthermore, during the previous decades, researchers defined and evaluated more than a dozen different air quality indicators without comparative guidelines for ventilation designers, resulting in confusion to a certain degree. Nevertheless, the four most widely used indicators of indoor air quality are: number of air changes (n_{AC}), contaminant removal effectiveness (ε), ventilation effectiveness (E_v), and air exchange efficiency (ε_a).

The number of air changes in a space per unit of time (n_{AC}) is widely used to provide information about intensity of ventilation. This indicator can be defined for the total amount of supplied air or for the amount of fresh air. However, the n_{AC} value does not provide information on the quality of the fresh air distribution or contaminant removal from the space. Therefore, the number of air changes provides incomplete information on perceived air quality.

One of the first indicators that actually define a perceived air quality is the contaminant removal effectiveness ε (Yaglou and Witheridge 1937). This indicator is based on the room average contaminant concentration $\langle C \rangle$, the contaminant concentration at supply C_s, and the contaminant concentration at exhaust C_e:

$$\varepsilon = \frac{C_e - C_s}{\langle C \rangle - C_s} \tag{1}$$

Another perceived air quality indicator, the ventilation effectiveness (E_v), is based on a two-zone model that divides a space into two perfectly mixed zones separated by a horizontal plane at 1.8 m above the floor (Sandberg 1981; Janssen

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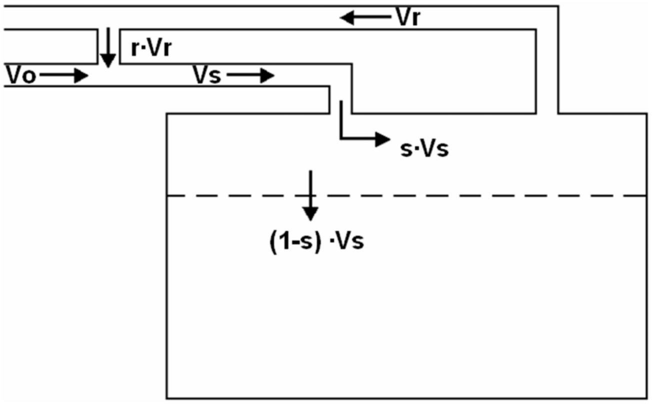

Figure 1 *The two-zone model used to define ventilation effectiveness* E_V *(ASHRAE 2001).*

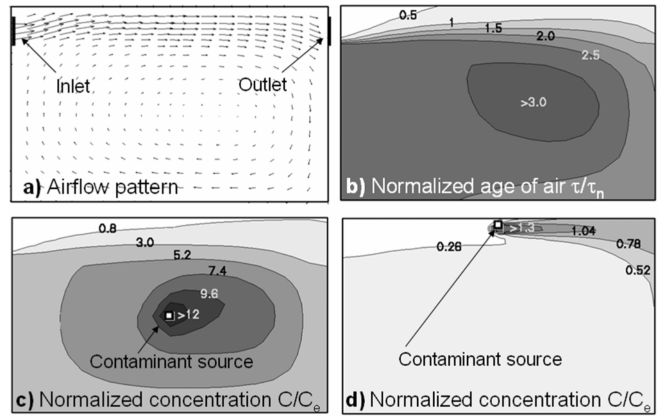

Figure 2 *Normalized local age of air and contaminant concentration distributions for the same airflow field and different positions of the contaminant source; (a) airflow pattern, (b)* $\varepsilon_a = 0.21$ *for this airflow pattern, (c)* $\varepsilon_a = 0.21$ *and* $\varepsilon = 0.19$ *for contaminant source at room center, (d)* $\varepsilon_a = 0.21$*, and* $\varepsilon = 2.20$ *for contaminant source in the supply air jet.*

1984). This assumption of the two well-mixed zones is not always correct even with mixing ventilation diffusers (Persily 1993). Furthermore, this model introduces a fraction of the supply air (s) that bypasses directly to the exhaust as defined in Appendix E of ASHRAE Standard 62-2001 (see Figure 1). However, the standard does not present a procedure for calculation or measurement of fraction s, which is a crucial value, together with the recirculation rate r, for determination of ventilation effectiveness:

$$E_V = \frac{(1-s)}{(1-r \cdot s)} \tag{2}$$

Based on a local value of age of air (τ), another perceived air quality indicator was developed in chemical engineering and then experimentally and theoretically evaluated for use in the indoor air quality field (Etheridge and Sandberg 1996). This indicator is the air exchange efficiency (ε_a) that represents the ratio between shortest possible time needed for replacing the air in the room (τ_n) and the average time for air exchange (τ_{exe}):

$$\varepsilon_a = \frac{\tau_n}{\tau_{exe}} = \frac{\tau_n}{2\langle\tau\rangle} \tag{3}$$

The average time for air exchange can be calculated as $\tau_{exe} = 2 \cdot \langle\tau\rangle$, where $\langle\tau\rangle$ represents the average of local values of age of air. The shortest possible time needed for replacing the air in the room (τ_n) is a reciprocal value of the number of air changes in the room ($\tau_n = 1/n_{AC}$). Table 1 presents the air exchange efficiency values for characteristic flow types.

A large number of new perceived air quality indicators were developed by Japanese researchers, who concentrated on details of airflow field. For example, ventilation efficiency indicators such as SVE1 and SVE2 take into account contaminant diffusion characteristics represented by spatial concentration and mean radius of diffusion, respectively (Kato and Murakami 1988). For spaces with multiple inlets and outlets, new air quality indicators quantify ventilation contributions from a particular inlet (SVE4) or outlet (SVE5) (Kato et al. 1993). These indicators are suitable only for spatial representation because they lose their meaning if they are averaged to obtain a representative single value.

TABLE 1
Air Exchange Efficiency for Characteristic Room Ventilation Flow Types

Flow pattern	Air exchange efficiency	Comparison with the average time of exchange
Unidirectional flow	0.5 - 1.0	$\tau_n < \tau_{exc} < 2\tau_n$
Perfect mixing	0.5	$\tau_{exc} = 2\tau_n$
Short Circuiting	0 - 0.5	$\tau_{exc} > 2\tau_n$

Each of these new indicators is useful for a certain type of ventilation system analysis. Nevertheless, the contaminant removal effectiveness (ε) and the air exchange efficiency (ε_a) appear to be the most suitable for use in design and standards because they are general and almost all other indicators are an extension of these two. Also, these two indicators are applicable to all types of ventilation systems (airflow patterns) and they can be more easily measured in the field or laboratories.

COMPARISON OF ε AND ε_a

For comparison of the contaminant removal effectiveness (ε) and the air exchange efficiency (ε_a), the main question is which one of these two perceived air quality indicators is more appropriate for general use, such as in design and standards, especially because these perceived air quality indicators can show conflicting values for indoor air quality in the same room, as illustrated in Figure 2. Figure 2a presents two-dimen-

TABLE 2
Limits for Air Exchange Efficiency and Contaminant Removal Effectiveness

Air exchange efficiency	Upper limit	$\varepsilon_a = 1$	Ideal piston flow
	Perfect mixing	$\varepsilon_a = 0.5$	Complete and instantaneous mixing
	Lower limit	$\varepsilon_a \rightarrow 0$	Bypass area and recirculation area are completely separated
Contaminant removal effectiveness	Upper limit	$\varepsilon \rightarrow \infty$	Contaminant source at the outlet Flow field does not have influence
	Perfect mixing	$\varepsilon = 1$	Complete and instantaneous mixing Position of contaminant does not have influence
	Lower limit	$\varepsilon \rightarrow 0$	Contaminant source is in the recirculation area, which is completely separated from the bypass area

sional airflow velocities with a bypass and a recirculation in the occupied zone. Figure 2b shows corresponding age of air normalized by the shortest time needed for the replacement of air (τ/τ_n). Figures 2c and 2d represent contaminant concentration normalized with the contaminant concentration at the exhaust (C/C_n) for two different positions of a contaminant source: in the room center (Figure 2c) and within the air jet (Figure 2d). The comparison of Figure 2b with 2c and 2d shows that, depending on the position of the contaminant source, the mean age of air and the contaminant concentration field might have a similar or completely different distribution. Consequently, the air exchange efficiency (ε_a) and the contaminant removal effectiveness (ε) can have the same or conflicting values for perceived indoor air quality in the same space.

The discrepancies in the concentration and age of air distribution patterns result in conflicting values of ε_a and ε with different positions of the contaminant source (see Figure 2). Different values of ε_a and ε are due to the different "nature" of these two indicators. The air exchange efficiency is an indicator of air distribution quality because it quantifies how good the airflow pattern is. This efficiency indicator accounts for the size and intensity of the recirculation in the room by comparing the room airflow pattern with the airflow pattern of the ideal piston flow. On the other hand, the contaminant removal effectiveness is the indicator of contamination level in a room. The effectiveness indicator depends not only on the airflow pattern but also on the intensity, area, and positions of contaminant sources relatively to this airflow pattern. Consequently, for well-known positions and intensities of contaminant sources, contaminant removal effectiveness provides good indication of air quality. However, in the spaces where contaminants are unknown, the air exchange efficiency is a more useful indicator because it provides general indication of air quality independently of contaminant source positions.

Equations 1 and 3 also demonstrate the different physical meanings of contaminant removal effectiveness and air exchange efficiency, rendering a direct comparison meaningless. The air exchange efficiency has values from 0 to 1, while the contaminant removal effectiveness takes values from 0 to infinity. Table 2 shows ventilation cases where ε and ε_a values approach their lower and upper limits.

The contaminant removal effectiveness depends not only on the position of the contaminant relative to the airflow pattern but also on the area of the source region. For example, a contaminant source might be released from a point source such as tobacco smoke or from a large area source such as pollutants from a floor finish. Furthermore, contaminant removal effectiveness depends on source properties such as contaminant density. Consequently, it is hard to expect a relationship between ε and ε_a (Sandberg and Sjoberg 1984; Skaret 1984) because the number of combinations of flow patterns and the type and positions of the contaminant sources are unlimited. However, for typical spaces usually found in buildings, there are a limited number of ventilation strategies with common types of contaminants and their positions. Therefore, the number of combinations in typical buildings is limited and certain correlations between the air exchange efficiency and the contaminant removal effectiveness may exist. The objective of this study is to establish for which types of space and ventilation strategies those correlations exist, quantify them, and detect the most important parameters that influence the intensity of the correlations.

Better knowledge about correlations between the air exchange efficiency and the contaminant removal effectiveness in typical room layouts enables decision when to apply the particular indicator. This is very important because the air exchange efficiency based on the tracer gas decay seems to be more appropriate for field and whole building applications (Persily et al. 1994) and, therefore, better suited for standards. On the other hand, for evaluation of air quality with particular contaminant sources, the contaminant removal effectiveness provides more informative results. Knowing the correlations between ε and ε_a, it may be possible to rely on results presented by only one of these two indicators. Finally, typical values of these two indicators for the usual space layouts and ventilation strategies should help designers to select an appropriate ventilation strategy for a particular space type.

ANALYZED CASES

The relationship between contaminant removal effectiveness (ε) and air exchange efficiency (ε_a) was analyzed for

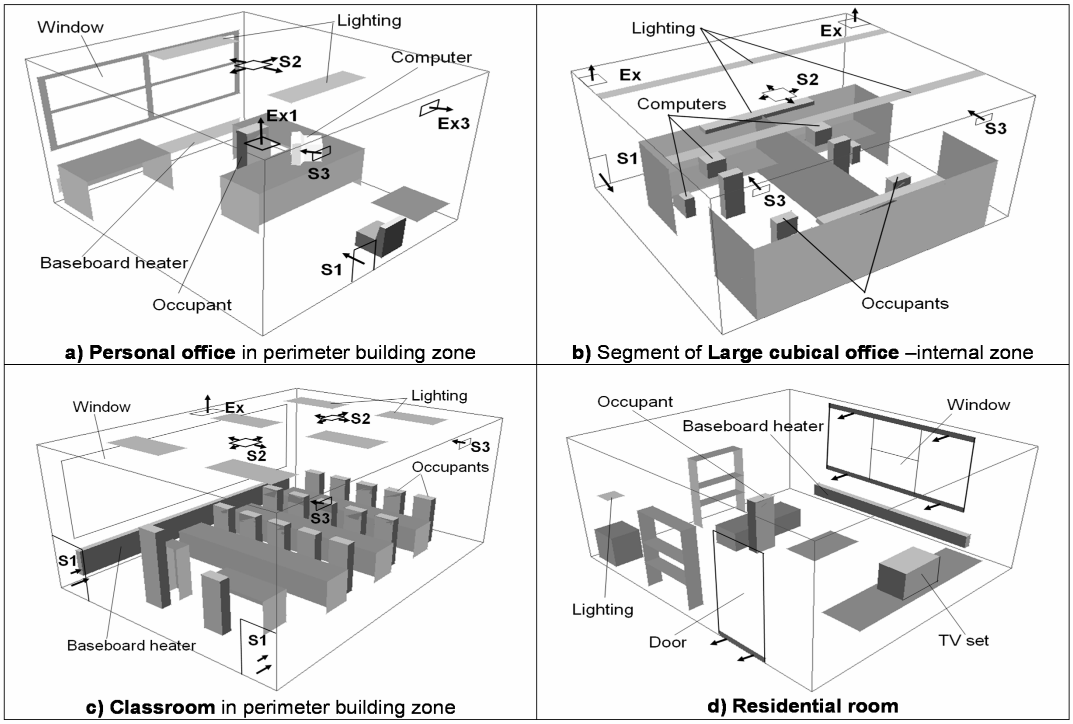

Figure 3 *Space layouts with supply and exhaust positions for the analyzed cases (S1 – displacement ventilation diffuser, S2 – ceiling mixing diffuser, S3 – grille diffuser, Ex – exhaust).*

several different spaces in typical buildings with typical ventilation strategies. The following space layouts were analyzed:

- a personal office, which is usually located in the perimeter zone in office buildings,
- a large cubical office, which is typical for internal zones in office buildings,
- a classroom, which also can represent a small conference room, and
- a residential space with a typical layout for a residential house or an apartment room.

Figure 3 shows space layouts with supply and exhaust positions for the studied spaces. In addition to spaces presented in Figure 3, one kitchen layout was also analyzed. Each of these five space types has its own characteristics related to room size, number of occupants per unit of floor, fresh air requirement, cooling or heating loads, and typical ventilation systems. A typical number of occupants per unit of floor for a specific space type was selected based on data in ASHRAE Standard 62-2001. The amount of supplied fresh air was selected according to the requirements for outdoor air in this standard.

The number of occupants determines the required amount of fresh air, which together with heating/cooling loads has considerable influence on selection of a ventilation system. For example, the personal office has a small occupancy rate and relatively high cooling loads per unit of floor area, which results in small flow rates of fresh air and large total airflow rates for all-air systems. On the other hand, in the cases where heating/cooling loads are treated with perimeter heater, fan coil, or chilled ceiling, only fresh air is supplied to save fan energy. The large cubical office has a large occupancy per unit of floor, but also very large cooling loads. Therefore, for this type of room and all-air systems, the amount of supply air is usually determined by cooling loads. In classrooms or small conference rooms, the number of occupants per unit of floor area is large and the amount of supply air is determined by the required amount of fresh air per occupant. Consequently, these type of spaces usually do not have recirculation. Finally, in the case of residential rooms, the occupancy is usually low and ventilation is usually accomplished by infiltration when the outdoor temperature is low or by open window when the outdoor climate and noise conditions are acceptable.

Based on the cooling or heating loads and the amount of supply air, several ventilation strategies were selected for each of the analyzed spaces. These ventilation strategies determined the position and type of supplies and exhausts (S1, S2, S3, and Ex in Figure 3). Analyzed ventilation strategies are: displacement ventilation (cases: A1, B1, C1), displacement ventilation combined with chilled ceiling (A2, B2), ceiling diffuser (A3, B3, C2), ceiling diffusers with the outlet at the floor level (A4), grille diffusers (A5, B4, C3), grille diffuser when the supply and exhaust are on the same side of the room

TABLE 3
Simulation Parameters for the Studied Cases

Room Type	Case	Ventilation strategy	Air changes	Recirculation rate	Total convective load		Air load		Δt supply	
			[h^{-1}]	[-]	[W/m^2]	[$Btu/h \cdot ft^2$]	[W/m^2]	[$Btu/h \cdot ft^2$]	[°C]	[°F]
A) Personal office	A1	DV	4.4	3/4	35	11	35	11	6	11
Space area: A = 14 m^2 (156 ft^2)	A2	DV/CC	1.1	0	21	7	6	2	7	13
	A3	CD	4.4	3/4	35	11	35	11	10	18
Space volume: V = 33.6 m^3 (1244 ft^3)	A4	CD-lo	4.4	3/4	35	11	35	11	10	18
	A5	GD	4.4	3/4	35	11	35	11	10	18
Outdoor air per person: OA=10 L/s (20 cfm)	A6	DV/BH	1.1	0	-45	-14	4	1	3	5
	A7	CD/BH	2.2	1/2	-45	-14	7	2	4	7
	A8	CD-w	4.4	3/4	-45	-14	-30	-10	-11	-20
B) Large box office	B1	DV	6.4	3/4	65	21	65	21	6	11
A = 31.2 m^2 (347 ft^2)	B2	DV/CC	1.6	0	36	11	7	2	7	13
V = 93.6 m^3 (3467 ft^3)	B3	CD	6.4	3/4	65	21	65	21	10	18
OA=10 L/s (20 cfm)	B4	GD	6.4	3/4	65	21	65	21	10	18
	B5	GD-s	6.4	3/4	65	21	65	21	10	18
C) Classroom	C1	DV	6	0	50	16	50	16	4	7
A = 34 m^2 (378 ft^2)	C2	CD	6	0	50	16	50	16	9	16
V = 102 m^3 (3778 ft^3)	C3	GD	6	0	50	16	50	16	9	16
OA=7.5 L/s (15 cfm)	C4	DV/BH	6	0	-30	-10	18	6	2	4
	C5	CD/BH	6	0	-30	-10	18	6	3	5
D) Residential room A = 22.5 m^2 (250 ft^2)	D1	OW	4	0	15	5	15	5	5	9
V = 54 m^3 (2000 ft^3)	D2	INF/BH	0.5	0	-38	-12	5	2	30	54
OA=7.5 L/s (15 cfm)*	D3	INF/AH	3	5/6	-38	-12	5	2	30	54

DV – displacement ventilation, DV/CC – displacement ventilation combined with cold ceiling, CD – ceiling diffuser,
CD-lo – ceiling diffuser with low outlet, GD – grille diffuser, GD-s – grille diffuser with outlet on same side of room,
DV/BH – displacement ventilation combined with baseboard heater, CD/BH – ceiling diffuser combined with baseboard heater,
OW – open window, INF/BH – infiltration combined with baseboard heater, INF/AH – infiltration combined with air heating,
* For case D1 with open window, outdoor air per person (OA) is 60 L/s (120 cfm).

(B5), displacement diffuse combined with baseboard heater (A6, C4), ceiling diffuser combined with baseboard heater (A7, C5), ceiling diffuser for all-air heating (A8), natural ventilation with open window (D1), natural ventilation with infiltration and heating by baseboard heater (D2), and natural ventilation with infiltration and air heating supply below the window (D3). Table 3 lists the important parameters for all of these cases. In some cases, the total convective load differs from the air load due to the installed chilled ceiling or baseboard heater or in cases with an all-air heating system due to the internal heat sources. In Table 3, the "Total convective load" indicates the intensity of buoyancy-driven flow in the room, while the "Air load" indicates a fraction of the total convective load removed by air. Negative values for total convective loads indicate that heating in the room is needed, while negative values for air loads show that the supply air has higher temperature than the exhaust air. The last column in Table 3 contains temperature difference between the supply air and the average room temperature (Δ*t* supply), which is an important parameter that influences airflow pattern.

The ε and ε_a for active and passive contaminant sources were calculated for all cases. To study active types of pollutants that are associated with heat sources, the distribution of contaminant released in the vicinity of an occupant's head was analyzed. This contaminant may represent CO_2, tobacco smoke, or any human bioeffluent. Passive pollutants are not directly moved with thermal plumes of heat sources because of their position relative to the heat sources or size of the source area. To evaluate transport of passive pollutants, the distribution of contaminants released from a carpet was analyzed. Moreover, carpets often present primary sources of VOCs and other types of pollutants such as dust and bio-

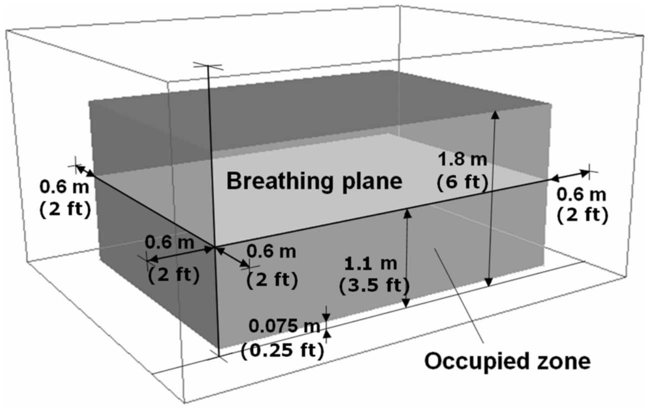

Figure 4 *Position of the occupied zone and breathing plane.*

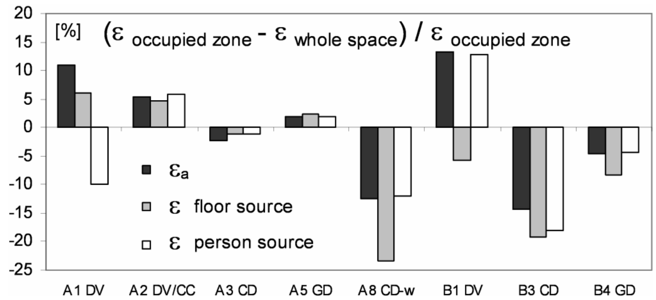

Figure 5 *Differences in air exchange efficiency (ε_a) and contaminant removal effectiveness defined for the occupied zone ($\varepsilon_{\text{occupied zone}}$) and the entire space ($\varepsilon_{\text{whole space}}$).*

organisms. Additional details on passive pollutant distribution was obtained by analysis of contaminants released from walls and partition dividers in the cubical office.

METHODOLOGY

To obtain perceived indoor air quality indicators, computational fluid dynamics (CFD) was used to calculate distributions of contaminant concentration and local age of air for all analyzed spaces. The contaminant concentration distributions were calculated for passive and active contaminant sources within a room. The age of air distributions were obtained from the concentration distribution for a homogeneous contaminant source uniformly distributed in the entire room and generated at a constant rate (Sandberg 1981).

Several assumptions were introduced to obtain age of air and concentration distributions. First, all results were obtained for steady-state airflows, which is the case for spaces where cooling/heating loads do not change rapidly. Influence of infiltration was neglected, under assumption that the flow rate of the supplied fresh air through the inlet is much larger than the flow rate caused by infiltration. This assumption of negligible infiltration also implies that there was no contaminant inflow or outflow from adjacent spaces. The final assumption is that contaminant distributions are not influenced by different densities of the contaminants and supplied air, which is correct for most of the contaminants that exist in indoor spaces.

To obtain typical values of the age of air and contaminant distributions, more than 50 simulations of different flow fields were performed. Several validation procedures were used to evaluate these numerical results. First, the grid independent and convergent results were obtained. For diffuser jet simulations, which provide crucial boundary conditions for CFD simulations, the box and momentum methods were used. These methods have been extensively validated for indoor airflow simulations (Nielsen 1997; Srebric and Chen 2001). Finally, for a space with displacement ventilation, contaminant removal effectiveness (ε) based on experimental measurements (provided by Chen et al. 1998) was compared with numerically calculated ε in the occupied zone. Although few spatial values of measured and calculated contaminant concentrations differed more than 50%, calculated ε differed less than 10% from measured ε. Therefore, CFD was used as a reliable tool to calculate ε_a and ε.

RESULTS

Difference in ε_a and ε Defined for Whole Space, Occupied Zone, and Breathing Plane

Because the occupants are the focus of ventilation design, it is important to evaluate ε_a and ε in the occupied zone. Figure 4 shows the occupied zone definition available in ASHRAE Standard 62. For all analyzed cases, ε_a and ε were calculated for the whole space and for the occupied zone. The difference between the calculated ε_a and ε for the whole space and for the occupied zone depends on the space type, ventilation strategy, and position of contaminant sources. Figure 5 shows these differences for several ventilation strategies in personal and cubicle offices.

Air exchange efficiency (ε_a) has a greater value in the occupied zones than in the whole space for all cases with displacement ventilation (cases A1, A2, and B1 on Figure 5). In cases with grille and ceiling diffusers (mixing ventilation), the difference between these two values mostly depends on room height and temperature of supply air. For spaces with greater room height and supply at the ceiling level (B3 and B4) or spaces with warm supply air (A8), ε_a has smaller values in the occupied zones than the ones in the whole room. However, for spaces with room height slightly greater than in the occupied zone such as a personal office (A3 and A5), the difference in calculated ε_a for the occupied zone and whole space is small.

Differences in contaminant removal effectiveness (ε) defined for the occupied zone and the whole space are similar to the differences in ε_a, except for displacement ventilation where the position of the contaminant source has much larger influence than with mixing ventilation. For example, in the personal office with displacement ventilation, the concentration of contaminant released by the occupant is larger in the occupied zone (“ε person source” in case A1, Figure 5) because of the small size of the occupied zone that surrounds the contaminant source released at the center of this zone. For contaminant released from a carpet, ε defined for the occupied zone is the same or even lower than ε defined for the whole room ("ε floor source" in case B1, Figure 5) because of the airflow pattern at the floor level with displacement ventilation.

In general, for displacement ventilation and contaminants released by occupants, ε_a and ε are smaller in the occupied zone than in the whole space; while for contaminants released at the floor level, ε values in the occupied zone are similar to the ones in the whole room. On the other hand, with mixing ventilation, ε_a and ε in the occupied zone are the same or worse than in the whole space. Also, ε_a and ε mostly depend on room height and supply air temperature for mixing ventilation.

Figure 4 also shows the breathing plane defined for this analysis as a plane in the occupied zone at the breathing level of a sitting person. Numerical results show that ε_a defined for the breathing plane and occupied zone differs less than 10% for cases with displacement ventilation and less than 5% for cases with mixing ventilation. For contaminant sources released at the floor level, ε values defined for the breathing plane and the occupied zone differ even less than for ε_a. Exceptions are cases with all-air heating systems, such as case A8, where a recirculation zone at the floor level creates a large stratification of the carpet contaminant in the lower part of the occupied zone. In this case ε calculated for the breathing plane is considerably larger than ε for the occupied zone. For contaminant sources released by occupants, ε defined for the breathing plane is the same or slightly higher than for the occupied zone regardless of the ventilation strategies. This overlapping of ε_a and ε defined for the breathing plane and occupied zone is very beneficial for on-site measurements when the number of measuring points is limited.

It is important to point out that for contaminants released by still occupants, the spatial contaminant concentrations in the breathing plane differ considerably depending on the distance from the source. However, in practice, the occupants are not still, and, according to experiments with moving occupants (Sandburg 1993; Nielsen 1993), the concentrations in the vicinity and further away from occupants have similar values for the breathing plane. The concentrations with the moving occupants are in the range of the spatial concentration values obtained for still occupants. Therefore, use of the average contaminant concentration in the breathing plane for calculation of the contaminant removal effectiveness has justification. Consequently, ε_a and ε values measured in the breathing plane could represent ε_a and ε in the occupied zone for practical applications.

Correlations Between ε_a and ε

Numerical values of ε_a and ε for three different contaminant sources that usually appear in the ventilated spaces are listed in the first part of Table 4. Based on calculated ε_a and ε values, Figure 6 presents correlations between ε_a and ε for different ventilation strategies.

For cooling cases with lower jet temperature than the air room temperature and mixing ventilation (GD and CD cases in Tables 3 and 4), ε_a is between 0.42 and 0.53. The correlation between ε_a and ε is strong for all of the analyzed types of sources for cooling with mixing ventilation (Figure 6). Generally, with ceiling diffusers, ε_a and ε have smaller values than with the perfect mixing ventilation because of bypass flow in the upper part of a room. The bypass flow with mixing ventilation increases in the cubical office where partition walls prevent appropriate mixing. In the case where the outlet is moved to the lower part of the room, bypassing is reduced and values for both ε_a and ε become slightly closer to the values for the perfect mixing (compare cases A3 and A4 in Tables 3 and 4).

In the heating cases, where the air ceiling jet has a higher supply temperature than the room average, such as with an all-air heating system with the exhaust at the ceiling level, a short circuiting occurs (case A8 in Tables 3 and 4). In this case, ε_a and ε for all of the analyzed types of contaminants have considerably lower values than with the perfect mixing (Figure 6). Fortunately, this type of bypassing is always followed by temperature stratification, and, therefore, it is easy to detect it.

In cases where displacement ventilation is used, ε_a is in the range of 0.55 and 0.92. Lower values are obtained for cases of displacement ventilation combined with cooled ceiling or baseboard heater. These additional water systems eliminate a major part of the sensible cooling or heating loads, causing larger air mixing than with air displacement ventilation alone. For cases where displacement ventilation supplies a large amount of supply air, the airflow pattern is more similar to the unidirectional flow and ε_a has values above 0.7 (Figure 6). Correlations between ε_a and ε for displacement ventilation are weaker than for mixing ventilation because the influence of contaminant source position on ε is significant for displace-

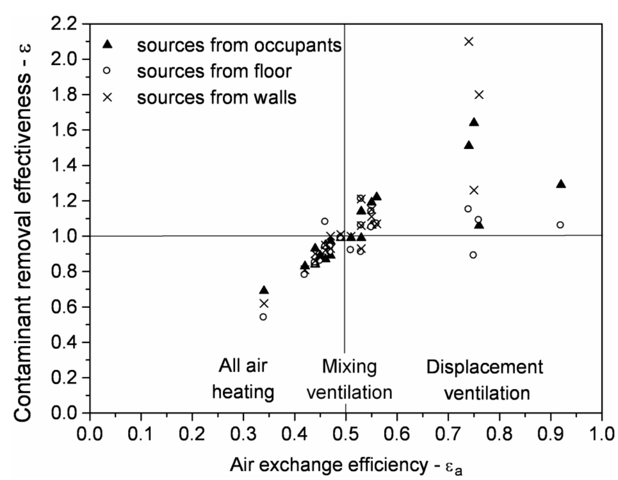

Figure 6 *The correlation between air exchange efficiency and contaminant removal effectiveness.*

TABLE 4
Contaminant Removal Effectiveness ε and Air Exchange Efficiency ε_a for the Occupied Zone

Room Type	Case	Ventilation strategy	First part: For space with all fresh air				Second part: For whole system				
			ε occupant	ε floor	ε walls	ε_a	ε occupant	ε floor	ε walls	$2 \cdot \varepsilon_a \cdot OA$ [L/s]	$2 \cdot \varepsilon_a \cdot OA$ [cfm]
A) Personal office	A1	DV	1.51	1.15	2.10	0.74	1.09	1.03	1.15	14.8	31.1
	A2	DV/CC	1.19	1.05	1.11	0.55	1.19	1.05	1.11	11.0	23.1
	A3	CD	0.89	0.86	0.88	0.45	0.97	0.96	0.97	9.0	18.9
	A4	CD-lo	0.97	0.94	1.00	0.47	0.99	0.98	1.00	9.4	19.7
	A5	GD	0.99	1.21	1.21	0.53	1.00	1.05	1.05	10.6	22.3
	A6	DV/BH	1.14	1.06	1.06	0.53	1.14	1.06	1.06	10.6	22.3
	A7	CD/BH	0.95	0.94	0.92	0.46	0.97	0.97	0.96	9.2	19.3
	A8	CD-w	0.69	0.54	0.62	0.34	0.90	0.82	0.87	6.8	14.3
B) Large cubicle office	B1	DV	1.64	0.89	1.26	0.75	1.11	0.97	1.05	15.0	31.5
	B2	DV/CC	1.22	1.07	1.07	0.56	1.22	1.07	1.07	11.2	23.5
	B3	CD	0.83	0.78	0.81	0.42	0.95	0.93	0.94	8.4	17.6
	B4	GD	0.93	0.84	0.86	0.44	0.98	0.95	0.96	8.8	18.5
	B5	GD-s	0.89	0.91	0.93	0.47	0.97	0.98	0.98	9.4	19.7
C) Classroom	C1	DV	1.29	1.06	2.72	0.92	1.29	1.06	2.72	13.8	29.0
	C2	CD	0.89	0.85	0.90	0.44	0.89	0.85	0.90	6.6	13.9
	C3	GD	0.99	0.92	1.00	0.51	0.99	0.92	1.00	7.7	16.2
	C4	DV/BH	1.14	0.91	0.93	0.53	1.14	0.91	0.93	8.0	16.8
	C5	CD/BH	0.87	1.08	0.95	0.46	0.87	1.08	0.95	6.9	14.5
D) Residential room	D1	OW	1.06	1.09	1.80	0.76	1.06	1.09	1.80	91.2	191.5
	D2	INF/BH	1.06	1.14	1.15	0.55	1.06	1.14	1.15	8.3	17.4
	D3	INF/AH	0.99	0.99	1.01	0.49	1.00	1.00	1.00	7.4	15.5

ment ventilation. Figure 7 illustrates dependency of this correlation on contaminant source type.

For contaminants released by occupants, increase of ε_a above the value for the perfect mixing ventilation (0.5) is, in most cases, followed by increase of ε (Figure 7a). On the other hand, increase of ε_a above 0.5 with displacement ventilation does not result in increase of ε for contaminants released from a carpet (Figure 7b).The reason for this is the "fact" that supply air, which is delivered at the floor level, transports passive contaminants through the whole room regardless of the flow in the upper part of the room. Figure 7 also illustrates that room type does not affect ε_a because all four types of spaces have wide ranges of values for ε_a and ε that mostly depend on ventilation strategy.

Correlations presented in Figures 6 and 7 are for design numbers of occupants and design cooling loads. For off-design conditions (reduced cooling load), the supply temperature increases with the constant air volume (CAV) cooling systems or jet momentum decreases with the variable air

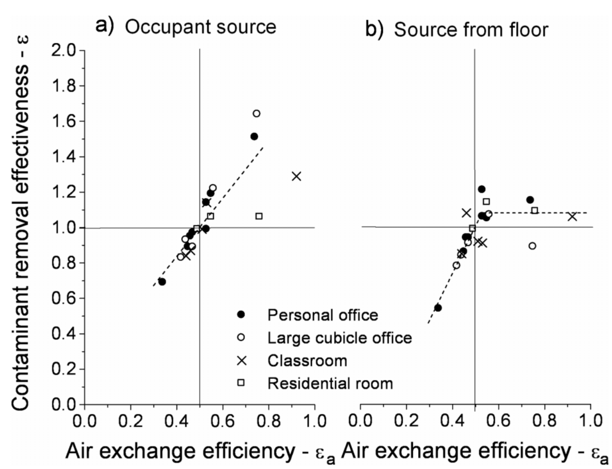

Figure 7 *Influence of different contaminant sources on correlations between ε_a and ε.*

volume (VAV) system. With a mixing ventilation system, both of these changes increase possibility for short circuiting and, as a result, ε_a decreases. To analyze correlations between ε_a and ε for off-design conditions, an additional "set" of cases is simulated for a classroom with ceiling diffuser supply system (case C2). By reducing the number of occupants, cooling load is reduced up to 40% of design load, resulting in an increase of jet temperature with the CAV system or in reduction of supply air volume flow rate with the VAV system. The reduction in supply airflow rate with the VAV system causes only small changes of ε_a and ε compared to the values for design conditions (differences less than 10%). With a CAV system, increase in supply temperature results in decrease of ε_a and ε for all types of pollutants. Therefore, for off-design conditions, the correlations between ε_a and ε presented in Figures 6 and 7 are still valid.

Based on the presented results, for typical spaces and contaminant sources, certain correlations between ε_a and ε exist. These correlations are not strong enough to be expressed by equations. Yet, the general result is that good/bad air exchange efficiency in most cases results in good/bad contaminant removal effectiveness.

ε_a and ε with Ventilation Systems That Use Air Recirculation

Numerical values of ε_a and ε for all cases in Table 3 are presented in Table 4. In the first part of this table, values for contaminant removal effectiveness ($\varepsilon_{occupant}$, ε_{floor}, ε_{walls}) for different cases are not directly comparable because they do not account for recirculation. For example, direct comparison of $\varepsilon_{occupant}$ for cases A1 and A2 (Table 4) are not relevant even though the same amount of fresh air is provided in both of the cases (Table 3). Case A1 has a larger total amount of supplied air because of recirculation. In this case, the contaminant concentration at the inlet is larger than in case A2 where the only fresh amount of air is supplied without recirculation (Table 3). A direct comparison of air quality in two cases by comparing ε is possible only in the situation where both cases have the same inlet and outlet contaminant concentrations. To be able to compare contaminant removal effectiveness for spaces with different recirculation rates, it is necessary to calculate contaminant removal effectiveness including the whole ventilation system. For a one-zone system, where the contaminant concentration in recirculated air is the same as the outlet concentration, Equation 2 can be used for calculation of contaminant removal effectiveness for the entire system. It is only necessary to substitute (1-s) with ε that was calculated for the space with all fresh air supply (values in first part of Table 4).

The second part of Table 4 presents values of contaminant removal effectiveness (ε) for a system with one zone where the recirculation flow rate percentage is given in Table 3. Results show that with the increase of recirculation rate, ε approaches the value for perfect mixing. Values of ε larger than 1 decrease while values smaller than 1 increase.

Usually, one ventilation system serves more than one space and in this case contaminant concentration in recirculated air does not have to overlap with the concentration at the outlet. With CAV systems, this is the case in situations where various spaces have different outlet contaminant concentrations. The reasons for these different outlet contaminant concentrations are unequal outdoor air requirements and/or dynamic contaminant generation rates. With VAV systems, which serve more than one space, a minimal amount of fresh air is supplied only in the critical space (ASHRAE Standard 62-2001). Because of the different amounts of fresh air supplied in other spaces, the contaminant concentration at outlets differs from space to space. To use contaminant removal effectiveness for comparison of the multiple spaces ventilation systems with recirculation, contaminant concentration in the return air of the considered space should be taken into account.

Values for ε defined for spaces that include performance of the whole system (second part of Table 4) are good for qualitative comparison of contaminant removal with different ventilation systems. For qualitative and quantitative comparisons, it is necessary to calculate the average contaminant concentration in the occupied zone by multiplying ε defined for the whole system with the concentration in the return air. This concentration in the return air is a function of the volume flow rate of fresh air and intensity of contaminant sources. The other way to obtain the average contaminant concentration in the occupied zone is to use the equations in Appendix D of ASHRAE Standard 62-2001. These equations, for different configurations of a system with recirculation, express the contaminant concentration in the spaces as a function of ventilation effectiveness (E_v). It is only necessary to substitute E_v with contaminant removal effectiveness (ε) defined for a particular contaminant in the space with all fresh air supply (values in first part of Table 4).

For qualitative and quantitative comparison of air quality with different ventilation systems, $2{\cdot}\varepsilon_a$ is sometimes multiplied by the volume flow rate that is provided per occupant. The last column in Table 4 provides these values for the analyzed cases. The physical meaning of this value is similar to the amount of fresh air per occupant that reaches the occupied zone. The double value of air exchange efficiency is called air-change effectiveness $E = 2{\cdot}\varepsilon_a$ (ASHRAE Standard 129-1997). This value can be used for calculation of the average contaminant concentration with equations in Appendix D of ASHRAE Standard 62-2001 for contaminants with known generation rate. This use of E, which is based on average age of air, for calculation of space contaminant concentration has justification in cases where positions of the contaminant sources are unknown and assumption of a homogeneous source that is uniformly distributed in the space is valid. The reason for this is the "fact" that with uniformly distributed sources, air-change efficiency (E) and contaminant removal effectiveness (ε) have the same values.

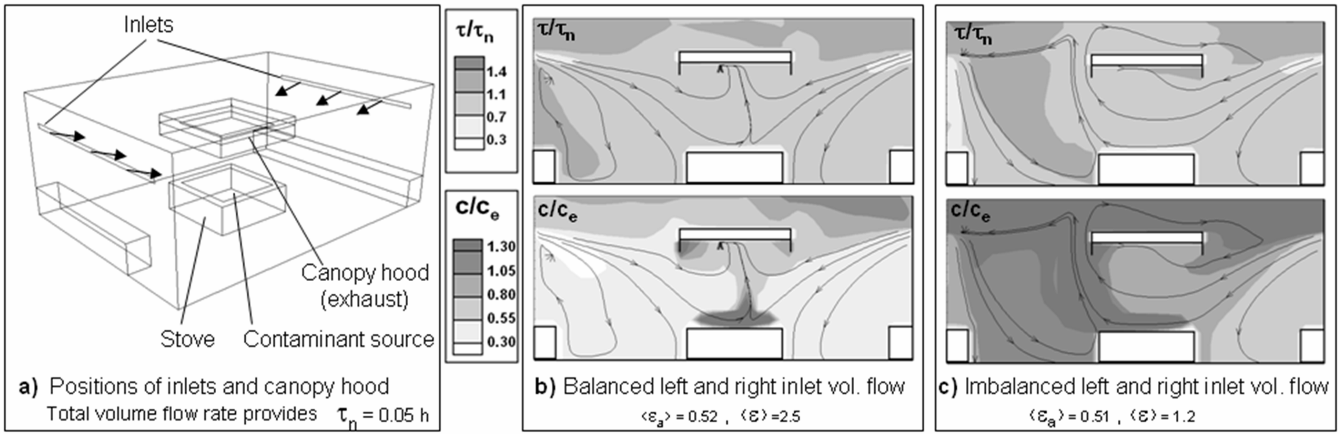

Figure 8 *Air exchange efficiency (ε_a) and contaminant removal effectiveness (ε) in the kitchen for: balanced flow —left and right inlet volume flow rate are the same; imbalanced flow—left inlet volume flow rate is one-third of right.*

APPLICATION OF ε AND ε_a

For practical use of any air quality indicator, it is very important to have relatively simple and reliable measurement methods for on-site applications. Several tracer gas methods exist for the measurement of age-of-air distribution that is necessary for calculation of air exchange efficiency (Etheridge and Sandburg 1996). Depending on the required accuracy (accounting or not for infiltration) more or less complex methods are applied to a single space or a whole building. With the tracer gas method, it is also possible to measure contaminant removal effectiveness for particular sources by continuous injection of tracer gas instead of analyzed contaminant. This method is very suitable for laboratory applications. However, for building analysis, it is impractical to inject tracer gas instead of real contaminant in a whole building (Persily 1993). Therefore, for practical use on sites, air exchange effectiveness is more suitable.

The feasibility of air exchange efficiency (ε_a) for on-site applications and its correlation with contaminant removal effectiveness (ε) for typical contaminant sources does not mean that ε_a may always be used instead of ε. This is especially true for applications where a particular contaminant with known position is to be removed and/or task ventilation is applied. Figure 8 shows ventilation in a kitchen with a canopy hood to illustrate the importance of ε. The contaminant source is on the top of the stove below the canopy hood (Figure 8a). Figure 8b presents normalized age of air τ/τ_n and contaminant concentration C/C_e when both inlets supply the same amount of air. In this case, a very small amount of contaminant "escapes" from the hood. In the case with imbalanced left and right jets (Figure 8b), the amount of contaminant that "escapes" from the hood is considerably larger, resulting in decrease of contaminant removal effectiveness (ε) from 2.5 to 1.2. On the other hand, air exchange efficiency (ε_a) indicates only negligible change of air quality by decrease from 0.52 to 0.51. Therefore, in cases such as this one, it is more important to analyze contaminant removal effectiveness than air exchange efficiency.

For large spaces such as atria and workshops, which do not have a typical ventilation strategy, numerical simulations of air quality are usually performed. In this type of analysis, contaminant removal effectiveness provides more informative results when particular sources are considered. On the other hand, in the cases with unknown contaminant sources air exchange efficiency as an air quality indicator is more appropriate. Overall, with numerical simulations, it is easy to use both air quality indicators because the calculation of an additional concentration field is not too expensive.

CONCLUSIONS

The air quality in the occupant's vicinity is the focus of ventilation design, and, therefore, it is important to evaluate air quality in the occupied zone. Depending on the ventilation strategy, contaminant source, and room size, perceived air quality indicators in the occupied zone differ more or less from perceived air quality indicators in the whole room. Generally, results show that with a displacement ventilation system, air quality indicators calculated for the occupied zone suggest better air quality than indicators calculated for the whole space. On the other hand, with mixing ventilation, air quality indicators calculated for the occupied zone are usually the same or worse than indicators calculated for the whole space. Also, results show that perceived air quality indicators defined for the occupied zone and breathing plane have very similar values. This overlapping of quality indicators for the occupied zone and breathing plane reduces the number of necessary measuring points with the experimental evaluation of air quality, which is very important for on-site measurements where the number of measuring points is limited.

Comparison of air exchange efficiency (ε_a) and contaminant removal effectiveness (ε) for typical ventilation systems and contaminant sources showed that certain correlations exist between these two perceived air quality indicators. The intensity of these correlations mostly depends on ventilation strategy. With mixing ventilation systems, the correlation is strong and it does not depend on contaminant sources. With displacement ventilation, correlation is weaker because of the significant influence of the contaminant source position. For the contaminants released by occupants, the correlation between ε_a and ε still exists, while for the contaminants released from a floor finish, the correlation is considerably weaker.

It is easier to measure ε_a than ε. Therefore, ε_a is more suitable for practical on-site applications. Furthermore, the existence of correlations between ε_a and ε justify use of air-change efficiency ($E = 2 \cdot \varepsilon_a$) for calculation of the average contaminant concentration. This average value can be calculated based on the equations in Appendix D of ASHRAE Standard 62-2001 for the spaces with known contaminant generation rates. However, in the spaces where a particular contaminant with known position is investigated, ε should be used because it provides more informative results. Therefore, designers could select which air quality indicator is more appropriate for their application based on the recommendations given in this study.

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