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Interrelations among Different Ventilation Parameters and Indoor Pollutants

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ABSTRACT

Measures of a number of ventilation parameters and of a number of pollutants from 21 locations furnished data for evaluating interrelations among commonly used descriptors of ventilation as well as their relation to frequently measured indoor gaseous and particulate pollutants (including carbon dioxide, carbon monoxide, particulates, and hydrocarbons). The analysis of the data is presented in three sections:

1. The intercomparison between different ventilation measures.
2. The relationship between ventilation and pollutant concentrations across buildings.
3. The relation of pollutants to ventilation measures in specific buildings.

The data show that:

1. Ventilation parameters based on estimated building use do not necessarily describe ventilation factors based on actual building use, so that ventilation requirements related to occupancy considerations alone may not adequately control indoor air quality.
2. Carbon dioxide concentrations respond quite differently to changes in ventilation than hydrocarbons, carbon monoxide, and particulates, which appear to depend mainly on outside levels.
3. Pollutant concentrations appear to approach asymptotic values with increasing ventilation. These asymptotes seem to be determined by the building and its environment and may be only marginally affected by increased ventilation.

INTRODUCTION

Existing ventilation standards are based on the need to maintain acceptable air quality in modern, tightly sealed buildings by the process of dilution with outside or makeup air. However, rising energy costs for heating and cooling makeup air have made the option of dilution increasingly costly (ASHRAE 1982). Reductions in both ventilation and energy use have been accompanied by increasing health and comfort complaints among occupants, often known as "Sick Building Syndrome." The cause is rarely definitely determined but often suspected to be related to components of the building or air supply system (NRC 1981; Sterling and Sterling 1983; Sterling et al. 1983).

Ventilating system design is determined by projections of the amount of air needed to provide risk-free and comfortable conditions to building occupants. Projections are based on building design and predictions of best estimates of heating, cooling and occupancy loads. The total amount of air, the amount of outdoor air, and the amount of recirculated air are specified to meet the projected requirements of a building, based to a large extent on estimated number of individuals expected to occupy the building—they are designed in. However, after completion and during its lifetime, actual loads may exceed or fall short of designed-in

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parameters. Ventilation parameters are usually given as overall measures that best express actual loads. The most commonly used overall criterion for actual load is human occupancy. Using the actual count of occupants as a base yields another set of parameters measuring ventilation capacity in terms of the total, the outdoor, and the recirculated amount of air supplied to each person actually occupying a building (on the average). Thus, there are two sets of ventilation parameters to consider—those that have been designed into the building based on estimates and those calculated from actual use.

For purposes of manipulating ventilation for controlling quality of air, it would appear to be of great importance to determine:

1. Are there discrepancies between different measures of ventilation, especially among the designed-in parameters and those affected by actual occupancy?
2. If there are such discrepancies, which are the most suitable or effective measures of ventilation for the purpose of air quality control?

Data to help make these determinations have now become available. A large number of office buildings have been studied during the last few years in order to determine the relationship of indoor pollutants either to health and comfort complaints of occupants or to building characteristics. (Most studies were done by NIOSH and CDC, but many of them also by university-based and private researchers.) Reports issued about most of these studies have been published. These reports contain a large amount of data about features, contents, and uses of the buildings, characteristics and reactions of occupants, detailed measurements on specifics of ventilation and the ambient environment, and other details. That information was coded (and clarified where needed, usually with the help of one of the original investigators) and stored in a specially developed Building Performance Database.* Among this coded information are data from 21 locations in which investigators provided information on ventilation characteristics of the buildings analyzed as well as levels of some key pollutants.** These data are analyzed here.

METHOD

Twenty-one different locations in the data base were extracted, which gave details about key ventilation characteristics including both the designed-in parameters and those calculated from actual use. Ventilation measures are stated as cubic feet per minute, as percent of total air supply, and as air changes per hour. Total, fresh, and recirculated air supplied per person was computed from the number of occupants actually counted. For each location it was then possible to determine:

1. Percent fresh makeup air
2. Percent recirculated air
3. CFM fresh makeup air
4. CFM recirculated air
5. CFM total supply air
6. CFM per person fresh makeup air
7. CFM per person recirculated air
8. CFM per person total supply air
9. Actual occupancy

In addition, information was available on a number of consistently measured indoor pollutants.

Relationships among different measures of ventilation and between levels of ventilation and pollutant concentrations were intercorrelated across different locations using the familiar Pearson Product Moment Correlation Coefficient (usually given as "r"). The correlation between two continuous variables X_1 and X_2 are computed by:

$$r = b\, S_1/S_2$$

where b is the best fitting line of regression between the two continuous variables, X_1 and X_2, and S_1 and S_2 are their standard deviations.

*Access to the data base will be made available to building investigators through Simon Fraser University early next year when software to access through DATANET will be completed.

**The 21 studies used here are unpublished reports but are available on request from sponsoring agencies (mostly NIOSH and CDC). A detailed list of references will be made available on request.

The use of r to express a relationship is most convenient, because the sign of the correlation coefficient tells if a relationship is direct (i.e., "+") or inverse (i.e., "-"), while the magnitude of r, which takes on values between +1 and -1, can be used to evaluate if the positive or negative coincidence between two sets of measurements is greater than would be expected by chance (or statistically significant at a particular level of acceptable probability).

The results of the reanalysis of these data will be discussed in three sections: Part 1, the intercomparison between the different ventilation measures; Part 2: the relationship between ventilation and pollutant concentrations across buildings; Part 3: the relation of pollutants to ventilation measures in specific buildings.

RESULTS PART I: Intercomparison between Ventilation Measures

The relationship between ventilation parameters was assessed by intercorrelating different ways of measuring ventilation across the 21 locations. Results of intercorrelating all ventilation measures and actual occupancy are summarized in Table 1A. Table 1A gives an overview of all correlations that were statistically significant (with $p \leq .05$). Correlations that failed to reach a statistically acceptable level are not shown in Table A but appear on Tables 1B and 1C. (For instance, cfm recirculated air correlates positively and very substantially with cfm fresh makeup air ($r = +.87$), but it fails to correlate significantly with actual occupancy.)

It is immediately apparent that (1)designed-in ventilation parameters, cfm recirculated air, cfm total supply air, and cfm fresh makeup air are highly intercorrelated (total supply air is correlated with fresh air with $r = .89$; with recirculated air with $r = .99$; and recirculated air is correlated with fresh air with $r = .87$), and (2) ventilation parameters based on occupancy (cfm per person recirculated air, cfm per person total supply air, and cfm per person fresh makeup air) are also highly intercorrelated. Total supply air per person is correlated with fresh air per person with $r = .88$ and recirculated air per person with $r = .99$. Fresh air per person is correlated with recirculated air per person with $r = .84$.

Both of these clusters of intercorrelations are expected. The cluster of designed-in parameters ought to intercorrelate highly, because they all meet a common set of requirements and expectations. The cluster of parameters with respect to occupancy also ought to have a high intercorrelation, because not only were they designed to meet a common set of requirements about expected occupancy but they were modified by a possible relationship of expectation about occupancy with actual occupancy.

However, with one exception, the intercorrelations between the designed-in ventilation parameters and parameters based on occupancy are small and statistically not significant. The single exception is the correlation between fresh air per person and total fresh air with $r = .41$. All the correlation coefficients between these two sets of variables are shown in Table 1B. With one single exception then, designed-in ventilation parameters are poorly related to ventilation parameters that are based on actual use and occupancy. (The remaining intercorrelations are shown in Table 1C. They are small and not statistically significant with one exception.)

A further clue to the pattern of complex interrelationships between ventilation measures is the negative correlation shown in Table 1A between actual occupancy and fresh air per person. This correlation is statistically significant and negative ($r = -.37$, $p < .05$). This negative correlation is in stark contrast to the correlation between total fresh air and occupancy, which is highly significant and positive ($r = +.56$, $p < .01$).

Thus, as would be expected, as occupancy increases, the amount of fresh air provided to each person appears to decrease. This inverse relationship clearly appears in Figure 1, the scattergram between occupancy and fresh air per person.

Insofar as the designed-in supply of fresh air is based on an estimate of the number of people anticipated to occupy the premises, one would expect a positive and significant correlation between fresh air per person and number of people actually present. However, the correlation between the calculated value of fresh air per person and occupancy actually present is negative. This negative correlation indicates that while it may be true that the amount of fresh air supplied to a space increases with increases in estimated occupancy, the increase is not proportionate to the actual amount of individuals who occupy that space once the building is built. In other words, the number of individuals who actually occupy a space tend to be consistently larger than the number of individuals who were expected to occupy that space. One important consequence is that the amount of fresh air supplied per person actually decreases as the number of people occupying a space increases.

Discussion - Part I

Not all ventilation parameters, then, measure the same aspect of ventilation. Total fresh air and fresh air per person may be very different measures of ventilation. Total fresh air is the additive, predicted fresh air requirement based on certain assumptions regulating heating, cooling and air quality for a building of a given size, expected use, and occupancy. These factors are building-dependent and do not necessarily increase with an increase in the population using the premises. One reason for the low interrelation between some ventilation parameters appears to be a systematic underestimate of future occupancy. That underestimate appears to increase with increase in estimated building use at the time when the building is designed.

RESULTS PART II: Relations between Ventilation Parameters and Pollutant Concentrations

Next we explored the relation between the different ventilation parameters and concentrations of pollutants measured in tightly sealed buildings. Table 2 shows the correlation between (1) the total amount of air provided and (2) the amount of air provided per person with levels of carbon dioxide, carbon monoxide, particulates, and hydrocarbons measured inside tightly sealed buildings. (In a previous ASHRAE publication, the authors reported on the average concentrations of these pollutants measured [Sterling et al. 1983]. For carbon dioxide, the average level measured in 23 buildings was 369 ppm; for carbon monoxide, the average level measured in 53 buildings was 2.25 ppm; for particulates, the average level measured in 16 buildings was .028 mg/m; and for hydrocarbons, in 57 buildings only trace levels were found.) The correlation between total air and carbon dioxide is negative and significant ($r = -.85$, $p = < .01$). This result is expected. Carbon dioxide is primarily an indoor source generated by occupants. As total air supply increases, carbon dioxide decreases. However, the correlation between total air and hydrocarbons is positive and significant ($r = .85$, $p < .01$). As total air supplied increases, hydrocarbon concentrations also increase. Hydrocarbons thus are primarily an outdoor source. Neither carbon monoxide nor particulate levels appear to be related to total air measurements. The results are similar for the relation between the amount of air provided per person with levels of carbon dioxide, carbon monoxide, particulates, and hydrocarbons measured in tightly sealed buildings. Total air per person shows significant negative correlation with carbon dioxide ($r = -.62$, $p < .05$), and no correlation with particulates, carbon monoxide, or hydrocarbons.

Discussion - Part II

Carbon dioxide concentrations are often used to predict the level of acceptability of indoor air quality, which implies acceptability of indoor contaminant levels. However, observations from actual buildings show that carbon dioxide levels respond differently to changes in the amount of air provided for ventilation (total air and total air per person) than other consistently measured indoor pollutants, specifically hydrocarbons, carbon monoxide, and particulates.

Particulates are not related to total air and total air per person. However, concentrations of hydrocarbons, which in a way may also be thought of as primarily introduced from outdoors, increase significantly with the total amount of air supplied. The increase in concentration of very small particles could be accounted for by torn or poorly maintained filters, which fail to remove smaller particles from the supply air.

The relationships between ventilation and both carbon monoxide and carbon dioxide are of considerable interest. Both are gaseous air constituents. If the major sources of each are indoors, then they should both show significant and substantial reductions with increased ventilation. This is not the case. Carbon dioxide is reduced by increased ventilation but carbon monoxide is not. The major proportions of carbon monoxide found indoors appear to infiltrate the building fabric from outdoors. Thus a high level of carbon monoxide measured outside a building would indicate that the indoor level is also elevated. Measurement data from 143 buildings presented by Sterling et al. (1983) at the ASHRAE Washington, DC, meeting lends support to this explanation. These findings also agree with reviews and studies in the published literature, which show carbon monoxide measured indoors consistently similar to the ambient outdoor level (Sterling et al. 1982; Yocum 1982).

RESULTS PART III: Relation of Pollutants to Ventilation Measures in Specific Buildings

Is ventilation an effective means of reducing levels of pollutants in sealed buildings? The answer appears to be yes and no.

Carbon dioxide generated indoors can be reduced by ventilation; however, none of the other pollutants consistently measured in tightly sealed buildings responds significantly to ventilation. Three of the studies supplying data for this analysis monitored pollutant levels simultaneously with manipulation of ventilation rates. Pollutants measured include carbon dioxide, carbon monoxide, particulates and hydrocarbons.

Table 3 presents consolidated results of these three studies. Here the relation of pollutant levels with variations of ventilation rates can be seen within the same building. The table presents ventilation measures as they could be determined from the reports obtained from the investigators. Turiel et al. (1981) at the Lawrence Berkeley Laboratory measured indoor levels of pollutants in a new San Francisco office building under 15% and 100% fresh air conditions. Berk et al. (1979), also at the Lawrence Berkeley Laboratory, measured pollutants in a new high school under 5.1%, 8.4%, and 45% fresh air conditions. Salisbury et al. (1980) measured pollutants on six different floors of a 36-story new office building in Atlanta. Ventilation conditions varied from 13.2% to 29.5% fresh air. For Berk and Salisbury, only lowest and highest fresh air conditions are shown for purposes of comparison.

In all three cases, carbon dioxide was the only pollutant to decrease significantly with increased fresh air ventilation. Carbon monoxide, hydrocarbons, and particulates appear to maintain a steady level within each building. Carbon monoxide appeared to reflect outdoor levels at all times. Hydrocarbons decrease slightly in the Turiel study but remain constant and appear to be partly an outdoor source in the Salisbury study. Particulates increase slightly in the Salisbury study and decrease slightly in the Turiel study.

Discussion - Part III

An asymptotic relation very likely exists for contaminants found in modern buildings. Buildings maintain base levels of commonly measured pollutants. Contaminant levels measured tend to be building-dependent. Increased ventilation reduces the level of carbon dioxide. However, other contaminants including carbon monoxide and particulates, respond more to outdoor levels than to indoor sources. In specific buildings with large occupancy levels and small volumes, increased ventilation may be an effective means of reducing carbon dioxide and other indoor-generated contaminants to acceptable levels. However, a better means for controlling carbon monoxide and particulates would be by control or filtration of outdoor air.

CONCLUSIONS

The current ventilation standard, ASHRAE 62-1981 (ASHRAE 1981), as its predecessor ASHRAE 62-73 (ASHRAE 1973), is based primarily on chamber studies such as those conducted in the 1930s by Yaglou et al. (1936). Results were based on occupancy and reported in cfm per person of fresh air ventilation needed to provide "odor free" environments (Woods 1979). In the 50 years since the Yaglou studies, significant advances have occurred in both air quality and ventilation measurement technology. Also in the past 10 years, both ventilation and air quality have been measured simultaneously in investigative studies of many modern sealed buildings (Berglund et al. 1984). For the purpose of setting ventilation standards to maintain acceptable indoor air quality, it would appear to be of greatest importance now to review actual building ventilation system performance as the basis for a new consensus ventilation standard. We have seen that:

1. Some ventilation measures, such as the level of carbon dioxide, are more sensitive to occupancy requirements than are others. Also, and more importantly, current practice in ventilating system design may underestimate actual occupancy loads.
2. Pollutants respond differently to ventilation. No one pollutant can serve as a predictor of total air quality.
3. Air quality may be largely building-dependent. Buildings maintain an ambient level of contaminants based on configuration, location, indoor activities, occupancy, materials, equipment, and maintenance. Once a building is operational, manipulation of ventilation may have only a small impact on the base level of indoor pollutants.

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TABLE 1A

All Intercorrelations Between Ventilation Parameters That Are Statistically Significant With $p \leq .05$

	% Fresh Makeup Air	% Recirculated Air	CFM Fresh Makeup Air	CFM Recirculated Air	CFM Total Supply Air	CFM/Person Fresh Makeup Air	CFM/Person Recirculated Air	CFM/Person Total Supply Air	Occupancy
% Fresh Makeup Air	1.0								
% Recirculated Air	−.99+	1.0							
CFM Fresh Makeup Air			1.0						
CFM Recirculated Air			.87+	1.0					
CFM Total Supply Air			.89+	.99+	1.0				
CFM/Person Fresh Makeup Air			.41*			1.0			
CFM/Person Recirculated Air						.84+	1.0		
CFM/Person Total Supply Air						.88+	.99+	1.0	
Occupancy			.56+			−.37*			1.0

* $p < 0.05$

+ $p < 0.01$

TABLE 1B

All Intercorrelations Between Designed-In Ventilation Parameters (CFM Fresh, Recirculated and Total Air) and Ventilation Parameters Based on Actual Occupancy (CFM Fresh, Recirculated and Total Air Per Actual Number of Persons Using Premises). Relevant Variables are Unshaded.

	CFM Fresh Makeup Air	CFM Recirculated Air	CFM Total Supply Air
CFM/Person Fresh Makeup Air	+.41*	−.01	+.02
CFM/Person Recirculated Air	+.32	+.20	+.22
CFM/Person Total Supply Air	+.31	+.17	+.20

* $p < 0.05$

TABLE 1C
Remaining Intercorrelations Not Shown in Tables 1A and 1B.
Relevant Variables are Unshaded.

	% FRESH MAKEUP AIR	% RECIRCULATED AIR	CFM FRESH MAKEUP AIR	CFM RECIRCULATED AIR	CFM TOTAL SUPPLY AIR	CFM/PERSON FRESH MAKEUP AIR	CFM/PERSON RECIRCULATED AIR	CFM/PERSON TOTAL SUPPLY AIR	OCCUPANCY
% FRESH MAKEUP AIR	1.0								
% RECIRCULATED AIR	-.99*	1.0							
CFM FRESH MAKEUP AIR	+.09	+.02	1.0						
CFM RECIRCULATED AIR	-.22	+.22		1.0					
CFM TOTAL SUPPLY AIR	-.23	+.20			1.0				
CFM/PERSON FRESH MAKEUP AIR	+.17	-.32				1.0			
CFM/PERSON RECIRCULATED AIR	-.20	-.01					1.0		
CFM/PERSON TOTAL SUPPLY AIR	-.18	-.07						1.0	
OCCUPANCY	-.16	+.30			+.24	+.21	-.31	-.17	1.0

* $p < 0.01$

TABLE 2
Product Moment Correlations of Total CFM and Total CFM/Person
with Levels of Commonly Measured Indoor Air Pollutants from 21 Case Studies

POLLUTANT	CFM (TOTAL)		CFM/PERSON* (TOTAL)	
	r	p	r	p
CARBON DIOXIDE	-.85	<.01	-.62	<.05
CARBON MONOXIDE	-.07	x	-.13	x
PARTICULATES	+.06	x	+.28	x
HYDROCARBONS	+.85	<.01	+.31	x

x not significant

TABLE 3
Comparison of Pollutant Levels with Ventilation Measures in Three Building Air Quality Investigations

VENTILATION PARAMETERS	TURIEL et al		BERK et al		SALISBURY et al	
	A	B	A	B	A	B
% FRESH AIR	15	100	5.1	45	13.2	25.9
% RECIRCULATED AIR	85	0	94.9	55	86.8	74.1
CFM/PERSON (FRESH)	4 - 6	20 - 33	1.5	13.3	25	78
CFM/PERSON (RECIRCULATED)	22.7 - 34	0	28.1	16.3	165	222
CFM/PERSON (TOTAL)	26.7 - 40	20 - 33	29.6	29.6	190	300
AIR CHANGES/HOUR (TOTAL)	3.12 - 4.8	2.4 - 3.96				
AIR CHANGES/HOUR (FRESH)	0.49 - 0.72	2.4 - 3.96				
POLLUTION MEASURES						
CARBON DIOXIDE ppm	1160	660	1275	875	700	600
CARBON MONOXIDE ppm	<4	4	3.4	3.4	4.75	3.25
HYDROCARBONS mg/m^3	13	6			4.0	3.55
PARTICULATES mg/m^3	31	21			23.1	24.15

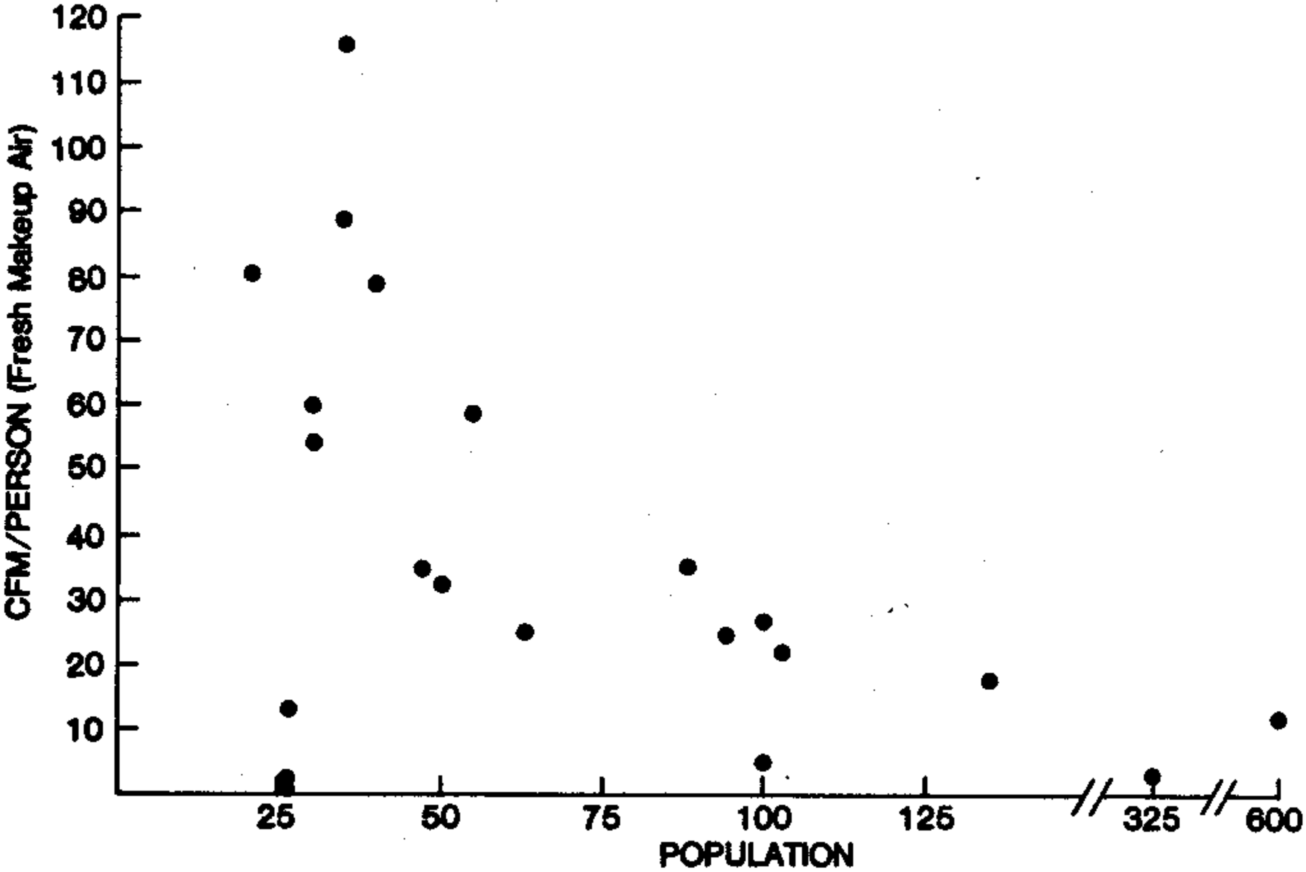

Figure 1. Scattergram showing the inverse relationship between CFM/person fresh makeup air and actual counted occupancy in 21 instances