Effects of Different Ventilation Parameters on Indoor Pollutants

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ABSTRACT

For controlling and for setting ventilation standards to maintain acceptable indoor air quality, it would appear to be of greatest importance to determine the strength of relationships between contaminant concentrations on one hand and different rates of ventilation and how these rates are expressed on the other.

Important data to do just that are now available and are contained in a computer stored archive of building investigations of indoor air quality conducted in Canada and the U.S. This archive contains adequate ventilation information for 21 instances for comparing pollutant concentrations under various ventilation conditions.

Four observations emerge from the analysis of these data:

1. Some ventilation measures are more sensitive to occupancy requirements than are others.
2. Pollutants respond differently to ventilation. No one pollutant can serve as a predictor of overall indoor 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,
4. Current practice in ventilation system design may under-estimate actual occupancy loads.

INTRODUCTION

Existing ventilation standards are based on the need to maintain acceptable air quality in modern tightly sealed buildings. Until ten years ago, the most widely preferred strategy of reducing levels of indoor contaminants was by dilution with fresh (makeup) air from outdoors and, of course, ample use of filters. However, increased energy costs for heating and cooling makeup air have made the option of dilution less attractive. (ASHRAE, 1982) Reductions in both ventilation and energy use have been accompanied by increasing health and comfort complaints among occupants. An epidemic called Building Illness, or Office Building Syndrome, has been identified which refers to complaints of illness, including headache, burning eyes, irritation of the respiratory system, drowsiness and fatigue. The symptoms are generally experienced over an extended period of time and recur during occupancy in sealed buildings. The causes are rarely definitely determined, but suspected to be related to components of the building or air supply system. (Hicks, 1983; Sterling et al, 1983)

This relation is implicitly acknowledged by attempts to regulate the quality of indoor air, especially the concentration of pollutants by manipulating ventilation standards. But to do so requires more knowledge about (1) how different ventilation parameters (ways of measuring

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ventilation) are related to each other in practice, and (2) how different ventilation parameters are related to concentrations of gaseous and particulate components of indoor air.

Ventilation is expressed in a large variety of measurements. The most widely used measures are Air Changes per Hour (ACH) and Cubic Feet per Minute (CFM) or Litres per Second (L/S). ACH is the measure of total air exchange in an enclosed area based on time, while CFM (L/S) is a volumetric measurement of air movement. Requirements for ventilation of enclosures listed in Table 3 of the ASHRAE standard 62 - 1981 are calculated on the basis of occupant density (CFM/person, L/S.person), and in some cases based on other variables, such as floor space or number of beds in hospitals. The Total amount of air supplied or CFM (Total Supply Air) is a mixture of Recirculated air, or CFM (Recirculated Air), and Fresh outside air, or CFM (Fresh Makeup Air). However, it is not often known what the occupant load will be over the life of the building. For this reason, occupant load is often predicted on a square foot basis. The standard prediction factor is one person per 180 sq. ft. (Leaney, 1983)

As a consequence, a number of ventilation parameters are designed into the building to satisfy estimated ventilation requirements. The basic, designed-in parameter is CFM (Total Supply Air). The amount of CFM (Fresh Makeup Air) and CFM (Recirculated Air) are regulated by use of dampers, and at all times they are related as CFM (Total Supply Air) = CFM (Fresh Makeup Air) + CFM (Recirculated Air).

Designed-in CFM (Total Supply Air) will of course vary with the size of the building, its basic characteristics, number of occupants, its location, and other expectations of use and performance. In general, CFM (Total Supply Air) will be larger with larger buildings that will be expected to have greater use and occupancy than smaller buildings with less anticipated use and occupancy. However, any standard setting attempt needs to be aware of the degree to which these designed-in ventilation parameters correlate with each other and with parameters affected by actual use and occupancy.

There are of course a number of ventilation parameters that can be defined by expressing total, fresh and recirculated air with respect to actual occupancy and activities in the building. Perhaps the most important are ventilation parameters related to actual occupancy. These can be expressed as an operational CFM/PERSON (Total Supply Air) CFM/PERSON (Fresh Makeup Air) and CFM/PERSON (Recirculated Air), where CFM/PERSON (Total Supply Air) equals to CFM (Total Supply Air) divided by the actual number of occupants and CFM/PERSON (Fresh Makeup Air) and CFM/PERSON (Recirculated Air) are calculated in like manner.

The current ventilation standard (ASHRAE 62-1981), as its predecessor (ASHRAE 62-73), is based primarily on chamber studies such as those conducted in the 1930's by Yaglou et al (1936) or more recently by Cain et al (1983). Results were reported in CFM/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. For controlling and setting ventilation standards to maintain acceptable indoor air quality, it would appear to be of greatest importance now to determine:

1. the strength of relationships between ventilation and contaminant concentrations, and
2. the most effective measure of ventilation for the purpose of air quality control.

In 21 cases where adequate data exist for ventilation and air quality we examine relationships among different ways of measuring ventilaton and between these possible measures of ventilation and observed concentrations of gaseous and particulate air contaminants.

METHOD

A large number of office buildings have been investigated 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. At the time of this report, 143 such studies had been reviewed and information contained in them placed in a computer based Building Performance Information System (BPIS). Contained in this data base are 21 instances in which investigators provided information on ventilation characteristics of the buildings analyzed as well as levels of some key pollutants. That information was extracted from BPIS and prepared for further analysis.

Ventilation characteristics were obtained either as they were stated in or calculated from information in each report. Measured characteristics include: percent of fresh air, percent of 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 Air Supply), Total Air Changes per Hour (TACH), Fresh Air Changes per Hour (FACH), and number of individuals occupying a space (Population).

An adequate number of these studies also measured the same pollutants so that their analysis could be included. These were carbon dioxide, carbon monoxide, particulates, and hydrocarbons.

The results of analysis of these data are presented in three sections. First, the intercomparison between the different ventilation measures; second, the relationship between ventilation and pollutant concentrations across buildings and third, the relation of pollutants to ventilation measures in specific buildings.

Results Part I: Intercomparison Between Ventilation Measures

Table 1 summarizes results of correlating major ventilation parameters across buildings for which these measures can be computed (using Pearson Product Moment Correlation Coefficients). It is immediately apparent that designed-in parameters CFM (Total Supply Air), CFM (Fresh Makeup Air), and CFM (Recirculated Air) are highly intercorrelated as would be expected. After all, they are determined by the same requirements dictating the properties of ventilation systems. On the other hand, intercorrelations fail to be significant between most designed-in parameters and parameters relating to actual use. However, these latter are again highly intercorrelated.

CFM (Total Supply Air) is significantly and highly correlated to both CFM (Fresh Makeup Air) ($r = .89$) and CFM (Recirculated Air)($r = .99$). That is, as CFM (Total Supply Air) increases, so does CFM (Recirculated Air) and CFM (Fresh Makeup Air). While CFM (Fresh Makeup Air) is correlated with CFM/PERSON (Fresh Makeup Air) ($r = .41$) and Population ($r = .56$), it is not significantly related to CFM/PERSON (Total Supply Air) or CFM/PERSON (Recirculated Air). This lack of correlation, by itself, is an interesting finding. Among the determinants of CFM (Total Supply Air) (and with it CFM (Fresh Makeup Air)) is the expected use of the building, especially the anticipated number of occupants. Thus one would expect calculated CFM/PERSON (Fresh Makeup Air) and estimated, that is, designed-in CFM (Fresh Makeup Air) to correlate highly. Although that correlation is positive and statistically significant, it is relatively small ($r = .41$, $p = .05$). Further the correlation between CFM (Fresh Makeup Air) and CFM/PERSON (Total Supply Air) is small and not significant ($r = .31$, $p = .2$). A further clue for the complexity of these inter-relationships is offered by the negative correlation between actual occupancy and CFM/PERSON (Fresh Makeup Air). This correlation is statistically significant and negative ($r = -.37$, $p = .05$). (See Figures 1 and 2.)

Figure 1 is a scattergram of CFM (Fresh Makeup Air) by Population. Figure 2 is a similar plot with CFM/PERSON (Fresh Makeup Air) by Population. From visual inspection it can be seen that as Population increases so does CFM (Fresh Makeup Air). But a negative relation exists between CFM/PERSON (Fresh Makeup Air) and Population.

Insofar as CFM (Fresh Makeup Air) is based on an estimate of the number of people anticipated to occupy the premises, one would expect the correlation between CFM/PERSON (Fresh Makeup Air) and number of people actually present to be positive. That is, the more people are present, the larger would be CFM (Fresh Makeup Air). Now that is true in part because the correlation between CFM (Fresh Makeup Air) and Population is indeed positive ($r = .56$, $p = .01$) (See Figure 2) However, the correlation between the calculated value of CFM/PERSON (Fresh Makeup Air) and Population actually present is negative. This negative correlation indicates that while it may be true that as the number of persons expected to occupy a space increases, the amount of CFM (Fresh Makeup Air) supplied to this space also increases, yet that increase fails to be proportionate to the actual number of individuals who occupy that space once the building is built. Or, stated another way, 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. Thus the observed correlation between CFM/PERSON (Fresh Makeup Air) and population is negative. As one important consequence, the amount of fresh air per person appears to be constantly and, what may be more important, progressively underestimated.

Conclusion, Part I

Not all ventilation parameters measure the same aspect of ventilation. CFM (Fresh Makeup Air) and CFM/PERSON (Fresh Makeup Air) may be very different measures of ventilation. CFM (Fresh Makeup Air) is the additive, predicted fresh air requirement for a total building based on certain assumptions--heat gain from lighting, solar exposure and equipment as well as the number of occupants expected. Although heat gain increases somewhat with population, other major sources of heat are lighting, solar radiation and working equipment. These factors do not necessarily increase with an increase in population. Ventilation engineers concerned with provision of acceptable air quality should select the most appropriate measure of ventilation as the basis for systems design. At present, CFM (Fresh Makeup Air) and CFM/PERSON (Fresh Makeup Air) are not proportionally related. Attempts at developing new standards need to take these factors into consideration.

Results Part II - Relations between Ventilation Parameters and Pollutant Concentrations

Ventilation is the primary mechanism used in modern office buildings for achieving acceptable air quality. CFM (Total Supply Air) and CFM/PERSON (Total Supply Air) are the most widely used measures of ventilation. Table 2 shows the correlation between these ventilation measures, CFM (Total Supply Air) and CFM/PERSON (Total Supply Air) with, levels of carbon dioxide , carbon monoxide, particulates and hydrocarbons. The correlation between CFM (Total Supply Air) and carbon dioxide is negative and significant ($r = -.85$, $p \leq .01$). As total air supply increases, carbon dioxide decreases. However, the correlation between CFM (Total Supply Air) and hydrocarbons is positive and significant ($4 = .85$, $p \leq .01$). As CFM (Total Supply Air) increases, hydrocarbons also increase. Neither carbon monoxide nor particulate levels appear to be related to CFM (Total Supply Air) measures. CFM/PERSON (Total Supply Air), shows significant negative correlation with carbon dioxide ($r = -.62$, $p \leq .05$), as does CFM (Total Supply Air). However, correlations with hydrocarbons, particulates and carbon monoxide are small and statistically not significant.

Conclusion Part II

Carbon dioxide concentrations are often used to predict the level of acceptability of indoor air. However, the existing data shows that carbon dioxide levels respond differently to changes in ventilation than do hydrocarbons, carbon monoxide and particulates (specifically to changes in CFM (Total Supply Air) and CFM/PERSON (Total Supply Air)).

Concentrations of particulates appear not to be related to CFM (Total Supply Air) and CFM/PERSON (Total Supply Air). However, concentrations of hydrocarbons (very small particles) increase significantly with CFM (Total Supply Air). 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 air supply once they are entrapped inside the building structure.

Carbon monoxide levels are unrelated to changes in ventilation parameters. Carbon monoxide and carbon dioxide are both gaseous air constituents. If major sources of both are located indoors, such as human metabolism for carbon dioxide or tobacco smoke for carbon monoxide, then they should respond similarly to all measures of ventilation. This is not the case. Carbon dioxide is reduced by increased ventilation but carbon monoxide is not. The most logical explanation is that although sources exist inside some buildings, the major proportion of carbon monoxide found indoors infiltrates the building fabric from outdoors. Measurement data from 143 buildings presented at the ASHRAE, Washington, DC, meeting (Sterling et al, 1983) lends support to this explanation. Levels of carbon monoxide are uniformly small, irregardless if smoking is prohibited, restricted or permitted. These findings also agree with reviews and studies in the published literature. (Sterling et al, 1982,1983) Carbon monoxide levels measured indoors primarily reflect outdoor not indoor sources. (also shown in Yocum, 1982)

Results Part III - Relation of Pollutants to Ventilation Measures in Specific Buildings

Three studies in the sample monitored pollutant levels simultaneous with manipulation of ventilation rates. Pollutants that have been consistently measured include carbon dioxide, carbon monoxide, particulates and hydrocarbons.

Table 3 presents consolidated results of three such studies. Here the relation of pollutant levels with variations of ventilation rates can be seen within the same building. Table 3 presents ventilation measures as they could be determined from the reports obtained from the investigators. Turiel et al (1981) measured indoor levels of carbon dioxide, hydrocarbons, particulates, and carbon monoxide in a new San Francisco office building under both 15% and 100% fresh air conditions. Berk et al (1979) measured carbon dioxide and carbon monoxide in a new high school under 5.1%, 8.4% and 45% fresh air conditions. Salisbury et al (1979) measured carbon dioxide, carbon monoxide and particulates 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 et al and Salisbury et al Table 3 only includes lowest and highest fresh air conditions for purposes of comparison.

In all three cases, with increased fresh air ventilation, the only significant reduction in pollutant levels occurred for carbon dioxide. The carbon dioxide level decreased when percent of fresh air increased. All other contaminants maintained a steady level within each building. Carbon monoxide reflected outdoor levels at all times. Both findings are consistent with results of Part II where relation of measured pollution levels with ventilation increases were compared across buildings.

Conclusion Part III

These data indicate that an asymtotic relation very likely exists for contaminants found in modern buildings. Contaminant levels measured tend to be building dependent. Buildings maintain base levels of commonly measured pollutants. Increased ventilation reduces the level of carbon dioxide slightly and may have a similar effect on other indoor generated contaminants. On the other hand, other contaminants measured, 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 appear to be filtration of outdoor air.

CONCLUSIONS

These data are only the beginning of a review of actual building ventilation system performance which must be undertaken as basis for a new consensus ventilation standard. We have seen that:

1. Some ventilation measures are more sensitive to occupancy requirements than are others.
2. Pollutants respond differently to ventilation, no one pollutant can serve as a predictor of overall indoor 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.
4. Current practice in ventilation system design may under-estimate actual occupancy loads.

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Table 1: Statistically Significant Ventilation Variable Intercorrelations

	% 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	POPULATION
% 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	
POPULATION	–	–	.56•	–	–	–.37•	–	–	1.0

– CORRELATION NOT SIGNIFICANT
• p < 0.05
• 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	-	-.13	-
PARTICULATES	+.06	-	-.20	-
HYDROCARBONS	+.85	<.01	+.31	-

- 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
POLLUTION MEASURES						
CARBON DIOXIDE ppm	976.0	645.8	1275	850	650	600
CARBON MONOXIDE ppm	≤4	≤4	4.5	4.5	4.75	3.25
HYDROCARBONS ppm	2.5	0.56	-	-	3.55	3.31
PARTICULATES mg/m^3	.031	.021	-	-	.023	.024

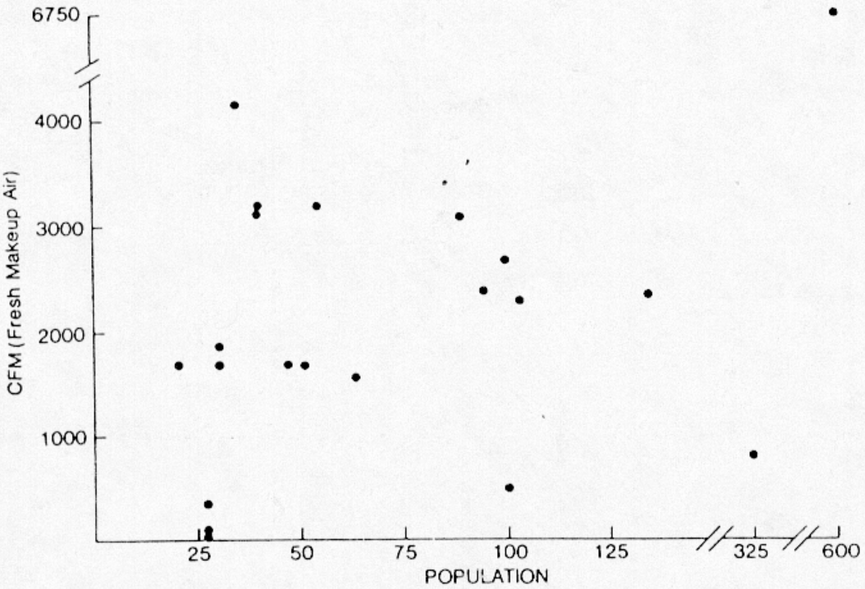

Figure 1. Scattergram of CFM (fresh makeup air) by population

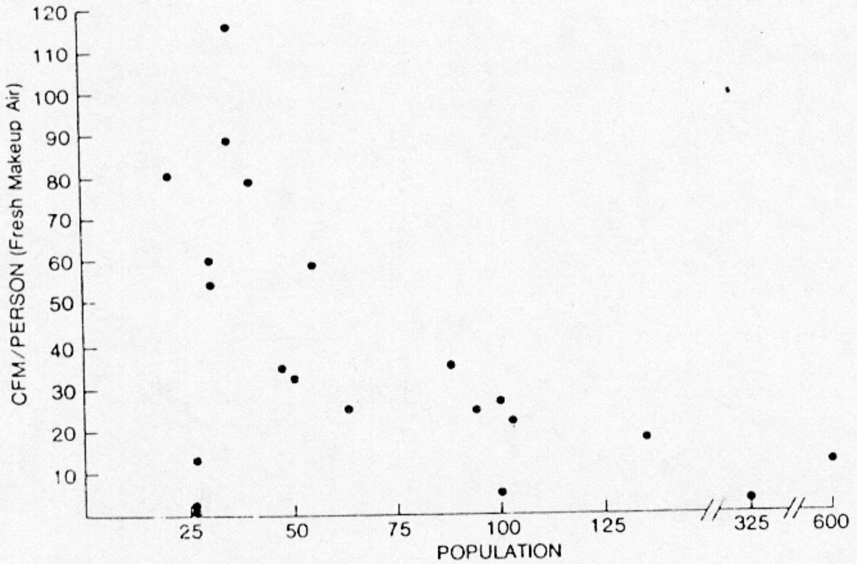

Figure 2. Scattergram of CFM/Person (fresh makeup air) by populations