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Impact of Office Design and Layout on the Effectiveness of Ventilation Provided to Individual Workstations in Office Buildings

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ABSTRACT

Two methods, both developed to evaluate the effectiveness of ventilation provided to individual workstations under field conditions, give results comparable to those obtained in a test chamber using the age-of-air procedure. Trials conducted in a test chamber and in two office buildings have shown that the portion of outdoor air supplied to individual workstations can be greatly affected by the temperature of the air supplied, the type of diffuser used and its proximity to the return air inlets, the type of office (closed or open concept), the height of the partition used, the gap between the partition and the floor, and the orientation of the partitioned space and workstation with respect to the air supply and air return inlets. Recommendations are made to optimize the amount of outdoor air that is supplied to building occupants through careful office design and layout planning to ensure acceptable indoor air quality and to potentially reduce energy consumption.

INTRODUCTION

In January 1991, the ASHRAE Standard Project Committee (SPC 129) working on definitions and methods of measurement of ventilation effectiveness produced a working draft (129P) detailing four alternative procedures for measuring ventilation effectiveness (ASHRAE 1991). All the procedures are based on the method using the age of air in a given room (Liddament 1987). Our experience with this method and that of others (Persily 1985) has shown that it is rather difficult to apply in field environments and it is technically difficult to perform. A search for a possible alternative to this method has led to the development of two new methods that are readily conducted in actual building settings (Farant 1991).

These two methods have been validated by comparing the results obtained with those provided by the age-of-air method in the controlled environment of a test chamber. The new methods were also used in a test chamber and in two different building environments to assess the effect of various office design and layout factors—such as type of office space, type of partition used (height, gap at base), and type of air diffusers and air return inlet and their position with respect to each other—and ventilation system operational parameters—such as volumetric flow rate and supply air temperature—on ventilation effectiveness. The main objective of this study was to assess parameters that could have an impact on ventilation effectiveness and, concomitantly, on the work environment and energy consumption.

METHODOLOGY

Measurement of Ventilation Effectiveness

According to the proposed ASHRAE Standard 129P, measurements of ventilation effectiveness are referenced to the air delivery performance that would occur under perfectly mixed conditions. For the purpose of this study, ventilation effectiveness is defined as that portion of outdoor air delivered to a room that is supplied to its occupant(s). Three procedures were used to measure this parameter, either in a test chamber or in two office buildings.

Transitional Steady-State Method (TSS) This method is described in detail elsewhere (Farant 1991) and involves the release of a tracer gas, SF_6, at a constant rate into the outdoor air introduced into the building or into the air supplied to a test chamber. At steady state (Figure 1), the ratio of the concentration of the tracer gas, measured at breathing-zone level (1.1 m) at an individual workstation, to that found in the air supply at the ceiling diffuser serving the workstation is an estimate of the portion of outdoor air supplied to its occupant. That is, at steady state,

$$\text{Ventilation Effectiveness} = \frac{\text{Concentration of tracer gas at a workstation}}{\text{Concentration of tracer gas in supply air}}$$

Supply air temperature was measured before and after each test. The concentration of the tracer gas at the breathing zone in a workstation and in the air supplied by the diffuser serving it was monitored alternately at one-minute intervals for a period of 20 to 30 minutes with a multi-gas meter equipped with a filter specific for this gas. Once the transitional steady-state period was characterized (Figure 1), air samples were collected at other

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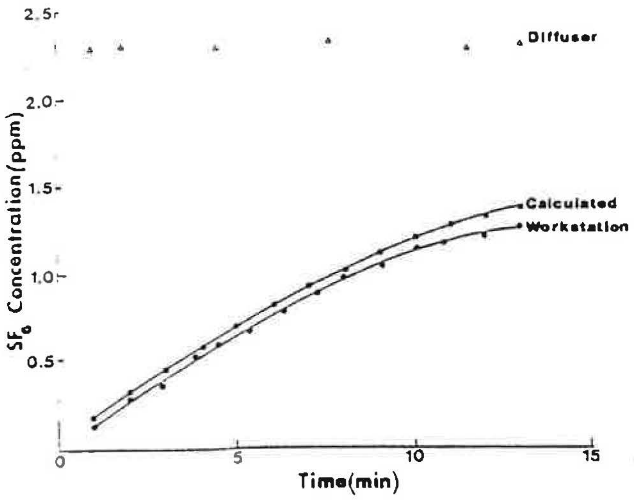

Figure 1 *Theoretical vs. actual changes in the concentration of the tracer gas SF_6 with time at a workstation (O = 0.075 outdoor air changes per minute)*

paired diffuser/workstation sites on a given floor in a building or in a test chamber.

For perfectly mixed conditions, the curve shown in Figure 1 can be represented by the equation

$$C_R = C_D (1 - e^{\theta t})$$

where C_R = room tracer gas concentration (ppb), C_D = diffuser air tracer gas concentration (ppb), θ = ventilation rate (air changes per minute), and t = time (minutes).

Volumetric Flow Rate Method (VFR) This method has been described in detail elsewhere. It is also based on the release of a tracer gas, SF_6, into the outdoor air introduced into a building or into the air supplied to a test chamber. However, in this instance, the decay of the tracer gas is measured following the attainment of equilibrium concentration in the space under investigation to obtain the ventilation rate (θ ACPS) at the breathing zone in individual workstations. The total amount of air supplied to the room (Q_T, m^3/s) is then measured with a bolometer, and the volumetric flow rate of outdoor air (Q_D, m^3/s) is estimated by correcting this amount using the percentage that is outdoor air (f_{OA}). Once the effective room volume is determined (85% of actual volume, V_E, m^3) the ventilation effectiveness (VE) is calculated using the following equation:

$$\text{Ventilation Effectiveness} = V_E\theta/Q_t f_{OA} = V_E\theta/Q_D$$

$$= \frac{\text{volumetric flow rate of OA at breathing zone}}{\text{volumetric flow rate of OA supplied to the room}}$$

Age-of-Air Method This method has been described elsewhere and will not be discussed here. The method detailed by Liddament (1987) was used.

Test Chamber

The test chamber is a 8.1 m by 4.6 m by 2.7 m windowless room equipped with an air delivery control system. Tempered, filtered air is supplied to the room by diffusers whose type and number can be varied. For this series of tests, air was supplied to the room by three two-way slot-type diffusers. The volumetric flow rate from each diffuser was set at 0.05 m^3/s. The air supplied to the room enters the ceiling plenum through slots on both sides of the room's six light fixtures and is exhausted to the outside. A single partitioned workspace was placed at the center of the room directly beneath one of the air diffusers (Figure 2). The height of the partitions and the gap at floor level could be varied. Heat load in the test chamber was provided by three 100 W light bulbs to simulate typical office load distributions and densities. The heat load density in the chamber was estimated to be 26.3 W/m^2.

All measurements were conducted under steady-state conditions chosen to represent the interior zone of an office building. These conditions were achieved by activating the electrical heat sources and mechanical systems in the morning to warm up the room to the temperature setpoint (22° to 26°C).

The tracer gas SF_6 was released at a known rate into the system's distribution box in the ceiling plenum.

Test Buildings

Two buildings located in downtown Montreal were selected for this study.

Building 1 Building 1 is a seven-story building whose floors are each equipped with dual HVAC systems. Outdoor air is delivered to the rooms housing each HVAC system, where it is mixed with return air from the floor. Tempered, filtered air is supplied at a constant rate to the floor by two-way slot diffusers. Return air enters the ceiling plenum through slots and is returned to the system. Air is exhausted from the floor via the washrooms. The floors in this building are subdivided into a large number of closed offices interspaced with relatively few open-concept office spaces.

Building 2 Building 2 is a 23-story building that has two identical variable-air-volume HVAC systems serving either the perimeter or the interior zone of each floor. The perimeter and interior zones' ventilation systems deliver tempered, filtered air to VAV boxes in the ceiling plenum. The perimeter zone VAV boxes route air primarily to closed office spaces through two-way slot-type diffusers, and the interior zone VAV boxes serve four-way ceiling diffusers that deliver air mainly to open office areas. The boxes can only close to a minimum 50%. Stale air passes into the ceiling void through "egg crate" grilles and is routed to the system where a portion of it is mixed with outdoor air.

In both instances, the tracer gas SF_6 was released at a constant known rate into the HVAC system's outdoor air/return air mixing plenum chamber.

RESULTS AND DISCUSSION

Test Chamber

The objective of these tests was to determine the effects of the number, height, and gap at floor level of partitions that

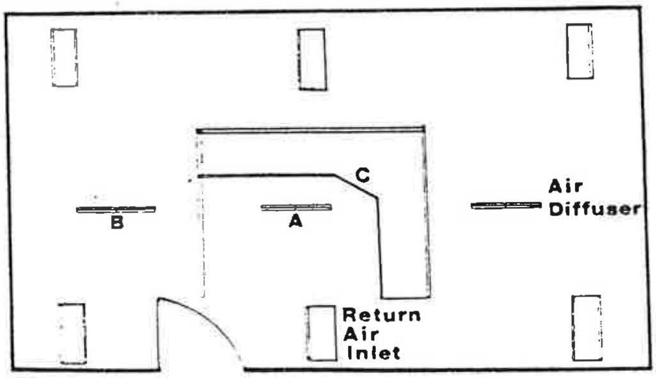

Figure 2 *Schematic of the environmental test chamber*

TABLE 1
Effectiveness of Ventilation Provided to a Partitioned Workspace in a Test Chamber

Partition Height (m)	Partition Gap (m)	Volumetric Flow Rate (L/s)	Air Supply Temperature (°C)	Ventilation Effectiveness: Site A TSS*	Site A VFR	Site B TSS	Site B VFR	Site C TSS	Site C VFR	Room Mean Age of Air
1.7	0	142	19.0	0.68±0.06	0.55	0.67±0.07	0.57	0.53±0.06	0.52	0.57
1.2	0	142	19.0	0.68±0.03	0.65	0.71±0.04	0.64	0.67±0.03	0.62	0.64
1.0	0	142	19.0	0.67±0.04		0.70±0.02				0.58
1.7	0.23	142	19.0	0.53±0.05	0.54	0.60±0.05	0.55	0.60±0.05	0.55	0.52
1.7	0.32	142	19.0	0.55±0.05	0.63	0.62±0.03	0.67	0.56±0.03	0.66	0.63
1.7	0.40	142	17.0	0.59±0.05	0.61	0.61±0.04	0.55	0.54±0.04	0.59	0.56
1.0	0.08	142	19.0	0.68±0.04	0.65	0.71±0.02	0.52	0.68±0.03	0.58	0.61
1.0	0.40	142	17.0	0.60±0.02	0.51	0.64±0.06	0.58	0.55±0.02	0.58	0.56
1.7	0.08	142	24.0	0.42±0.03	0.51	0.44±0.01	0.48	0.39±0.01	0.48	0.53
1.7	0.16	142	24.5	0.41±0.02		0.46±0.01		0.43±0.02		

*Average of four values.

TABLE 2
Effect of Changes in the Volumetric Flow Rate of Supply Air on Ventilation Effectiveness*

Total Volumetric Flow Rate (L/s)	Air Supply Temperature (°C)	Ventilation Effectiveness: TSS Method	Ventilation Effectiveness: Age-of-Air Method
94.4	16	0.27	
94.4	16	0.24	
70.8	16	0.29	
70.8	16	0.26	
23.6	15	0.32	0.36
Average:		0.28±0.03	

*Measured 1.1 m above floor level at workstation separated by a 1.8 m partition extending to floor level from two-way slot-type diffuser.

demarcate a workstation on the effectiveness of the ventilation provided to its occupant. This series of tests was conducted with a workspace having partitions on three of its sides whose height varied from 1.0 to 1.2 to 1.7 m and whose gap at floor level varied from 0, 0.08, 0.15, 0.23, and 0.30 to 0.40 m. This workspace was served by three two-way slot-type diffusers, one of which was located directly above it. The other two diffusers flanked the workspace. Measurements of ventilation effectiveness (VE) were made at paired sites A and B (Figure 2) located directly beneath two diffusers to determine the extent of VE perturbation attributable to the enclosure. Measurements were made using the TSS method at 0.1, 1.1, 1.2, and 1.7 m above floor level to assess stratification of outdoor air supplied. Site C was located at the occupant's workstation and measurements were made at 1.1, 1.2, and 1.7 m above floor level. All measurements were made simultaneously when the transitional steady-state period was attained (two samples per site, one minute apart) using the sampling device described elsewhere. Measurements were made concomitantly at 1.1 m at sites A and B using the VFR method. Difficulties were experienced in obtaining VE values at these sites with the age-of-air method, since it requires measurements of the decay rate of the tracer gas in the return air. This room does not have a ducted air return, and this allowed only the determination of a mean VE value for the room. This is a common problem for this technique and seriously limits its applicability.

The results obtained in the test chamber are given in Table 1. Comparison of sites A and B results indicates that the partitions caused a marginal decrease in ventilation effectiveness. An increase in the gap between the partition and floor similarly had little or no effect on the ventilation effectiveness for this workspace configuration. It is notable that the differences between the results obtained with all three methods were not significant ($p < 0.001$). The differences in the VE values measured at sites A, B, and C (< 10%) indicated that there was little or no stratification in the air supplied to these sites. However, an increase in the temperature of the air supplied from 19°C to 24.5°C resulted in a significant decrease in ventilation effectiveness.

The effect of changes in the volumetric flow rate at the diffuser serving a workstation was then studied using a different configuration. This involved a workstation partially shielded from the two-way slot-type diffuser serving it by a 1.8-m-high partition extending to floor level. The results obtained by varying this diffuser's volumetric flow rate are shown in Table 2. It indicates that the effectiveness of the ventilation at the workstation is not affected by these changes and essentially remains constant. The effect of placing a 1.8-m partition extending to floor level between the workstation and its main air diffuser is considerable.

Test Buildings

Our initial intent had been to use all three methods to measure ventilation effectiveness at 60 workstations in building 1. Unfortunately, all attempts to use the age-of-air procedure in this building were unsuccessful for a variety of reasons (Persily 1985). The VFR method could only be used in closed office areas, where the ventilation rate (θ), effective volume (V_E), and supply air volumetric flow rate (Q_T) could be measured with certainty. Thus, VE was measured with both the TSS and VFR methods in closed offices and only with the TSS method in open-concept areas. A representative number of values obtained is shown in Table 3. A number of factors apparently had a direct effect on the VE measured in these closed offices. These include the size (area) and proximity of air return slots to the diffusers and the temperature of the air supplied. The effect of the area of the return air slots on VE was clearly demonstrated by sealing all of these in room 4-264 except for 310 cm^2. The VE value increased 2.4-fold. It is notable that the policy in this building at the time of the study was to maintain the temperature of the air supply to peripheral zones at a relatively high temperature, 20 °C to 24 °C (most of the office areas included in Table 3), and the inner zone air supply at 13 °C to 17 °C.

According to the definition of ventilation effectiveness adopted for this study, this parameter is directly related to the amount of outdoor air supplied to the workstation's occupant, and the results in Table 3 clearly support this fact. For example, the increase in VE found in room 4-264 following modification is reflected in the 2.4-fold increase in ventilation rate. It should be noted that VE is not affected by the volumetric flow rate of outdoor air, while the ventilation rate is. Some of the rooms investigated benefited from an oversupply of outdoor air (> 10 L/s per person) while others were significantly deprived. This situation could be corrected by a combination of an optimal return air slot area (< 500 cm^2), adequate air supply temperature (13 °C to 16 °C), an appropriate outdoor air volumetric flow rate, and a ventilation effectiveness > 0.80.

The results in Table 3 also show that the two methods used to measure VE in closed offices afford similar values ($r = 0.71$). It should also be noted that both methods can be used when the ventilation systems are operating at high levels of recirculation.

The great flexibility and ease of performance of the transitional steady-state method made it an ideal choice for the study of the effects of the type of diffuser, office, and partition and return air inlet and their position relative to each other on the amount of outdoor air provided to individual occupants in building 2. The results obtained on one of the floors investigated in this building illustrate well the effect of the aforementioned parameters on the amount of outdoor air that actually reaches a workstation occupant. The values found on part of this floor are depicted in Figure 3. Similar values were obtained on the remainder of the floor. This floor is characterized by 1.6-m-high partitions extending to floor level and few peripheral closed offices. The two closed offices both have dual slot-type diffusers and small "egg crate" air return inlets, and the VE values obtained were 0.71 and 0.81. All other peripheral offices are partitioned areas served by two-way slot-type diffusers whose airflow is directed toward the windows. The VE values for these offices ranged from 0.42 to 0.67 and averaged 0.53 ± 0.08. These values agree remarkably with those obtained for a similar partitioned workspace in the test chamber. The VE values obtained for the inner zone's partitioned offices ranged from 0.10 to 0.43 and averaged 0.29 ± 0.12. These workspaces are

TABLE 3
Ventilation Effectiveness Measured in Building 1

Site	Room Volume V (m^3)	Total Air Supplied Q_T (L/s)	Outdoor Air Fraction f_{OA}	Air Supply Temperature (°C)	Ventilation Rate θ (L/s/person)	Ventilation Effectiveness TSS	Ventilation Effectiveness VFR	Return Air Slot Area (cm^2)
5-256	33.9	70.8 (2)*	0.10	18.7	3.74	0.53	0.53	1240
6-293	34.5	70.8 (2)	0.12	20.1	4.08	0.51	0.48	1240
3-311	35.0	56.6 (1)	0.10	22.2	4.38	0.78	0.75	620
4-273	34.6	68.4 (1)	0.23	21.6	6.58	0.38	0.42	620
3-293	31.8	21.2 (1)	0.10	23.1	0.83	0.38	0.39	620
6-262	28.0	40.1 (1)	0.19	20.0	2.44	0.37	0.32	930
6-274	31.1	125 (2)	0.10	23.0	5.86	0.55	0.47	620
4-264	44.9	21.2 (1)	0.23	22.5	0.88	0.18		1240
4-264 (**)	44.9	21.2 (1)	0.19	22.0	2.15	0.44		310
7-295	34.8	40.1 (1)	0.43	17.9	8.35	0.43	0.48	620
1-277	28.0	191 (3)	0.33	23.7	32.1	0.51		930
1-250	34.8	68.4 (2)	0.50	15.6	13.3	0.34	0.39	1240

*Number of air supply diffusers.
**Most air return slots blocked.

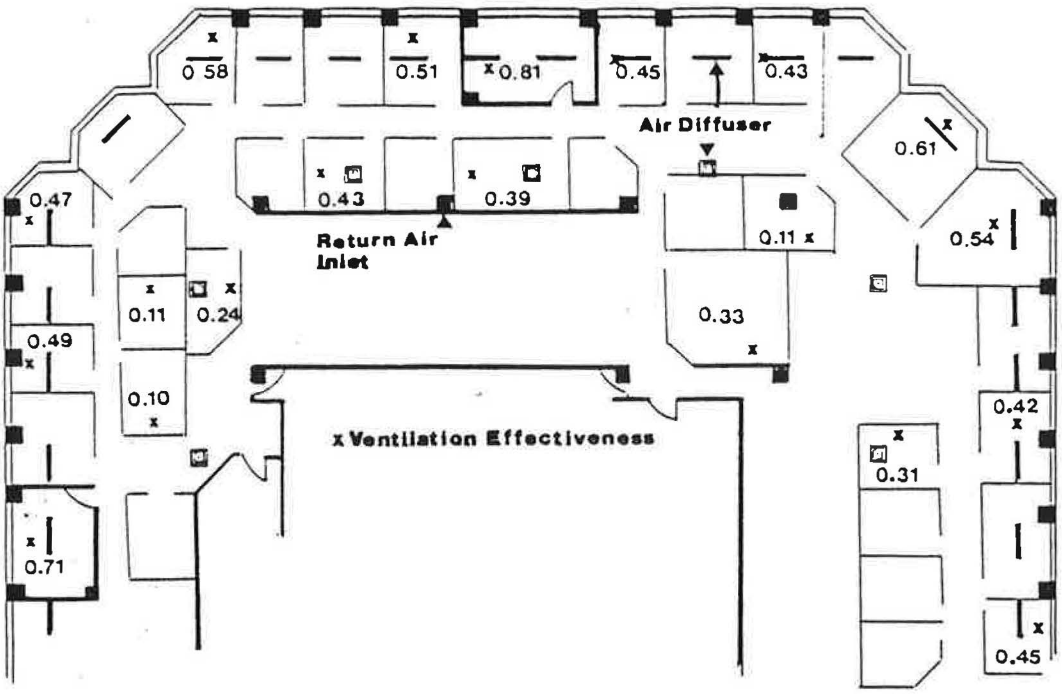

Figure 3 Ventilation effectiveness measured at various workstations on a floor in building 2

served by equidistant four-way conical air diffusers that are within 3 m of large air returns. The worst workstations on this floor are characterized by a ceiling diffuser located at their periphery in close proximity to an air return. The environment within these enclosures is best described as "stuffy." The best workstation (> 0.40) in this zone benefited from a proximity to a wall that acted as a deflector for the air supplied by the diffuser. It should be noted that the two HVAC systems serving this floor delivered similar amounts of air, and that the temperature of this air never exceeded 16 °C.

CONCLUSIONS

Of the two methods developed, the transitional steady-state method proved to be the most flexible, most easily performed, and least time-consuming procedure for evaluating the effectiveness of the ventilation afforded to building occupants. The other method, the volumetric flow rate method, yielded very similar results. However, its application was limited to closed office areas (or test chambers) where volumetric flow rate can be most readily measured. Both methods afforded ventilation effectiveness values similar to those obtained with the more currently accepted age-of-air method in the controlled environment of a test chamber. We were not successful in using this latter procedure in a field environment.

Studies conducted in a test chamber and in two buildings have shown conclusively that the amount of outdoor air that a person receives in an office building can be affected by the temperature of the air supplied to the room, the type of diffuser, and the type, size, and proximity of the air return inlet to the latter. The type of office selected, its design and layout, could also have a marked effect. The occupants of closed offices, for instance, usually receive a larger portion of the outdoor air delivered to their workspaces than their counterparts in open-concept areas. This may, in part, explain the fact that most IAQ complaints originate from occupants in the latter type of workspaces. In these areas, the type of partition selected, its height and gap at floor level, and the partitioned workspace's orientation with respect to the air diffuser and air return inlet are crucial considerations.

A relatively high value for the portion of outdoor air delivered to a building occupant does not necessarily imply that the latter is receiving an adequate amount of outdoor air. The converse is also true. A combination of an adequate supply of outdoor air delivered to a room with an appropriate ventilation effectiveness (VE > 0.80) would ensure that at least 10 L/s per person would be supplied to its occupant(s) as recommended by ASHRAE (*ASHRAE Standard 62-1989*). It would also ensure that a relatively high portion of the outdoor air that is tempered, filtered, and treated would accomplish its designated task in an economical fashion.

The current definition of ventilation effectiveness (Liddament 1987) in essence refers to the performance of mechanical ventilation and air distribution systems. The values obtained during this study apparently reflect more than the effects of these parameters and take into consideration factors that are related to office layout and design. For these reasons, it is suggested that the values obtained with either the TSS or VFR method are indicative of the portion of outdoor air supplied that is actually delivered to the occupant, and these values would be more accurately termed "outdoor air supply indices" (OASI).

RECOMMENDATIONS

Architects and office design specialists would benefit greatly from testing proposed office designs and layouts in the controlled environment of a test chamber to determine which combination and configuration of selected partitions, air diffusers, and air return inlets would ensure an optimal supply of outdoor air to future building occupants. Once the optimal office design and layout has been characterized and installed in the renovated or new building, the amount of outdoor air supplied to the building occupants should be verified by conducting tests with a method such as TSS. All that would be needed to ensure that the building occupants benefit from an acceptable ventilation rate and, concomitantly, from an acceptable work environment, would be to ascertain that an appropriate amount of outdoor air is delivered to the workspaces at an adequate temperature (13 °C to 16 °C). Existing facilities could be submitted to similar tests and the shortcomings identified and corrected.

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