IN SITU MEASUREMENT OF AIR CLEANER VENTILATION EFFECTIVENESS

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ABSTRACT

A test room was used to evaluate the impact of airflow parameters on the effectiveness of an air cleaning system. The room's dimensions were nominally 11.2 m x 5.7 m x 2.7 m. The room has a drop-ceiling with space above for installation of above-ceiling air cleaning equipment and routing of ventilation ductwork. The HVAC system supplying the room could be turned on for constant flow (~349 l s^{-1}) or left off to independently evaluate the effectiveness of the air filtration system. Smoke was generated in the room by five smoking machines (8 cigarette ports) or eight human smokers situated throughout the room. A new type of air cleaning system (consisting of three-stage particulate filtration and a novel activated carbon filter panel) was tested and compared to commercial, off-the-shelf air cleaners. Different diffuser types and airflow patterns were evaluated to determine the most effective way to distribute air throughout the room.

Testing revealed that when careful attention is paid to ventilation airflow design, greater effective ventilation could be achieved than when mixing alone is used to distribute clean air and contaminants throughout a space.

INTRODUCTION

Air cleaning systems offer one effective solution for reducing the impact of cigarette smoking on indoor air. Many air cleaning systems rely on simple mixing to distribute clean air throughout a room and return contaminant-laden air to the unit. Ventilation strategies that maximize removal effectiveness by entraining contaminants in the air stream exhausted from a room have the potential to increase effective ventilation beyond the air supply rate [1]. Likewise, if smoke can be directed to the inlet of an air cleaner before it is fully dispersed throughout a room, the effective ventilation rate of the air cleaner can be increased beyond its rated airflow.

A new air cleaning system with the potential for highly efficient particulate removal, and the capability for its incorporation into a complete ventilation system design, was tested using the method described by Bohanon *et al.* [2]. The test method allowed *in situ* measurement of the effective ventilation rate (EVR) [2] of the air cleaner while it was installed in a test room configured to simulate a bar. (The EVR is equivalent to the effective amount of additional outside air that produces the measured average concentration in a well-mixed room.) EVR is calculated from the average smoke concentration in the room and incorporates terms to take smoke generation rate and smoking time-activity pattern into account. Different ventilation configurations were evaluated to determine which maximized the EVR of the filtration system. In addition, the new air cleaner was compared to two conventional ceiling mounted air cleaners which were installed in their typically encountered configuration. One was a flush mount unit with inlet and outlets in close proximity to each other and the other protruded below the ceiling with a central intake and outlet grilles along its sides.

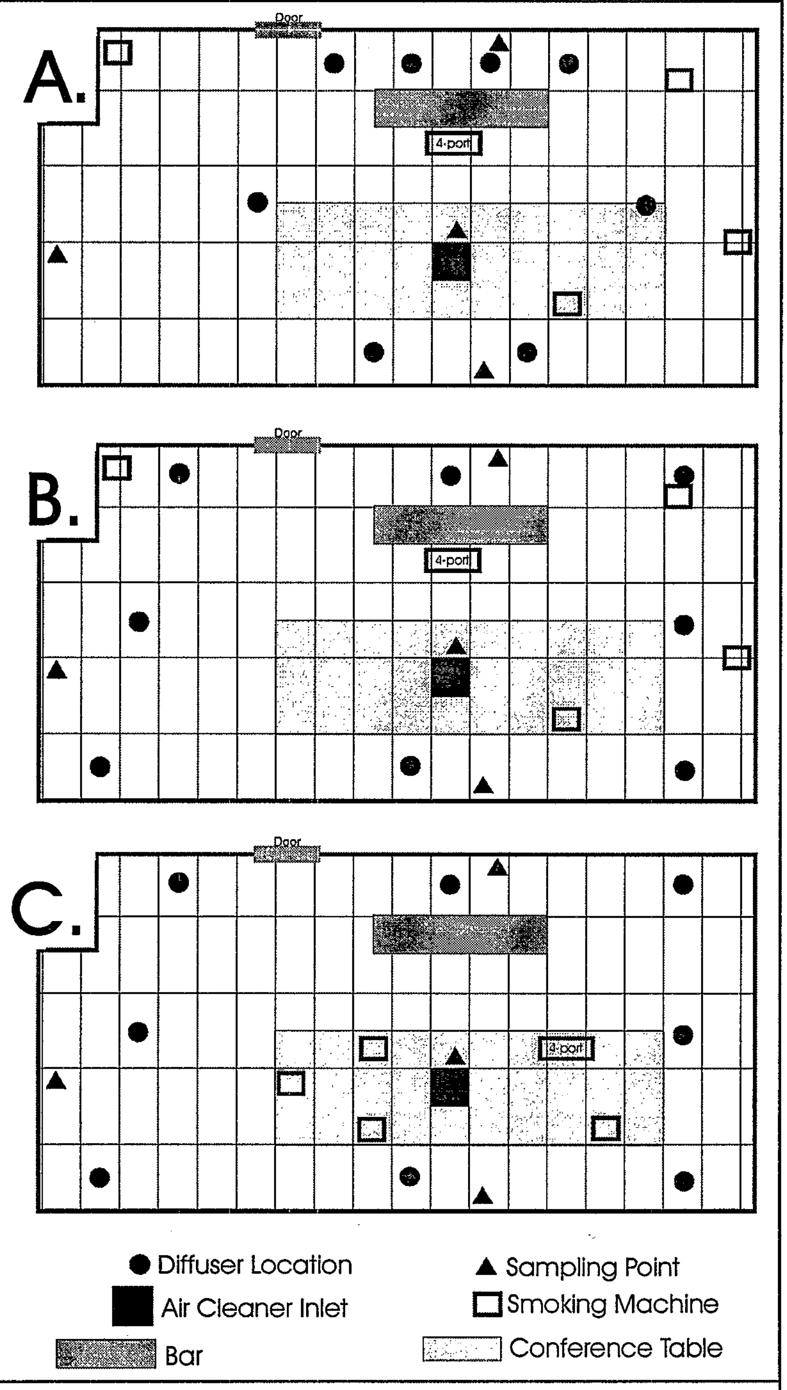

Figure 1. Test room diagram showing placement of key components. A shows the ventilation configuration with 50% of the air distributed behind the bar. In B and C, air was evenly distributed around the room perimeter. To determine whether human or machine smoking of cigarettes influenced test results, smoking machines were positioned as shown in C. The grid corresponds to t-bar placement of the suspended ceiling.

METHODS

Test room. The air cleaner effectiveness test took place in a 171.5 m^3 (11.2 m x 5.7 m x 2.7 m) conference room that was modified for this test. (Product of room dimensions does not equal room volume due to inset corner.) The room's HVAC system could be controlled separately from that of the overall building. When the air cleaners were tested, ventilation to the room was turned off. For these tests, the room was configured as a "bar" (smoking distributed throughout room, but concentrated in front of a mock bar). The test room's configuration is diagrammed in Figure 1.

Ventilation configuration. The first test performed was an evaluation of the effect of ventilation configuration on the ability of an air cleaner to remove environmental tobacco smoke (ETS) from the air. Five ventilation factors were tested in each of two "positions." The factors evaluated were: diffuser type - spot / 2x2 lay-in; air velocity - high / low; diffuser placement - evenly distributed / concentrated behind bar; airflow direction - down / angled; bar upflow device - on / off. The placement of the diffusers is illustrated in

Figure 1A and 1B for the configurations where ventilation was concentrated behind the bar, and was evenly distributed, respectively.

Thirty-two combinations of the above factors are possible. To reduce testing demands, a statistical test design was employed which led to the testing of 16 configurations in triplicate and allowed the determination of direct effects and first-order interactions among the variables. The 16 test configurations are summarized in Appendix 1.

Air filtration. For the ventilation configuration testing and true ETS evaluation, a new air cleaner that incorporates three stages of particulate filtration was used. The first stage is a washable metal mesh filter, which removes large particulate material. The second stage includes a two-stage electronic air cleaner, which collects and/or agglomerates the ETS particulate matter. The final collection stage of particulate filtration is a 95% dust spot efficiency filter, measured by ASHRAE 52.1. The air cleaner also incorporates a proprietary blend of impregnated carbons in HMZD (High Mass, Zero Dust) carbon panels. The unit operated at 472 l s^{-1}.

For the comparison of air filtration equipment, two additional air filtration units were employed. Both of the tested units were flush-mounted above the suspended ceiling. The first unit contained an electrostatic cell and delivered 382 l s^{-1} to the room. The second unit relied on mechanical filtration and delivered ~472 l s^{-1} to the room.

Smoke generation. During the first phase of testing, machine-generated aged and diluted sidestream smoke (ADSS) [3] was used as a surrogate for ETS. Smoke was generated in the room by five smoking machines - a Borgwaldt RM4-CS 4-port smoking machine and four single port Filamatic smoking machines. The smoking machines each took one 35 cc puff of two seconds duration per minute to a line 3 mm from the overwrap during the smoking periods. During a second phase of testing, eight smokers were present in the room and they smoked their cigarettes *ad libitum*. A popular commercial full flavor low "tar" cigarette was used throughout the tests.

The smoking pattern described in the companion paper [2] was used during each test. Each test session lasted 35 min. During the first 5 min of each test, no cigarettes were smoked so that background RSP concentrations could be determined. At 5 min, eight cigarettes were lit at pre-determined intervals during the ADSS tests, and all eight smokers lit cigarettes during the ETS tests. Cigarette lighting and extinguishing times were recorded for each cigarette. At 16 min, a second round of cigarettes repeated the protocol. Data collection continued for ~10 min after smoking ended so that RSP decay curves could be analyzed.

Smoke measurement. Respirable suspended particle (RSP) concentrations were simultaneously measured at four points in the room using DustTrak respirable aerosol monitors. Because the particle size of the ETS aerosol is very different from the factory calibration test dust, it was necessary to calibrate the response of each monitor to ETS. The response factors to ADSS were determined separately in a environmental chamber. On average, the factory calibration overestimated the true smoke concentration by a factor of ~4.

RESULTS AND DISCUSSION

Ventilation configuration tests. For the tests performed, an effective ventilation of 472 l s^{-1} would be expected for a 100% efficient cleaner and a mixing factor of unity in the room. EVR values less than 472 mean that the unit is effectively providing less than 472 l s^{-1} of particle free air to the space. Values greater than 472 indicate that some fraction of the smoke is being captured by the air cleaner before it is distributed throughout the room. In effect, this corresponds to a removal effectiveness greater than one. That is, the combination of air distribution patterns and air filtration device efficiency enhances the unit's effect beyond its actual airflow. As speculated prior to the test, type and placement of air distribution components had a significant impact on the effectiveness of the air filtration system. Figure 2 shows the distribution of calculated effective ventilation across each of the 16 tests performed. As can be seen in the figure, EVRs could vary widely among the tested configurations, and it was possible to obtain a removal effectiveness greater than 1.

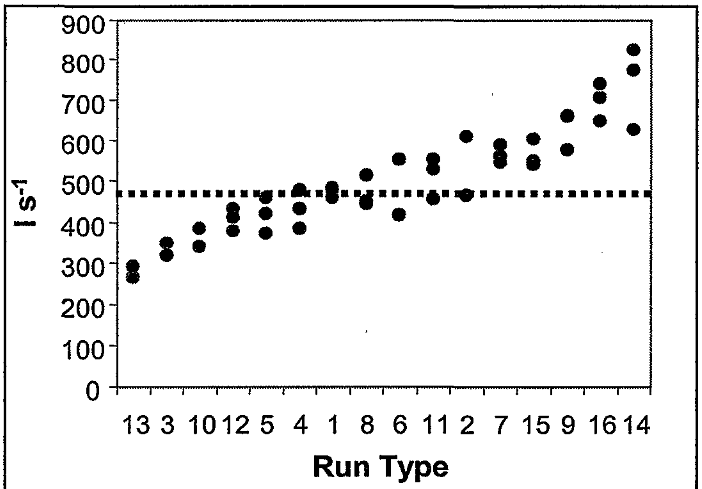

Figure 2. Range of calculated EVRs for air filtration system operated in different ventilation configurations. Dotted line represents EVR of 472 l s^{-1} which corresponds to a mixing efficiency of 1.

The test revealed that interactions between the tested factors were significant. Unfortunately, this makes scale-up from the model bar to the real-world difficult. However, the test method does allow direct comparisons between different air distribution arrangements; and general features of the results can likely be extrapolated to typical design situations.

One test design parameter was the addition of a bar upflow device to the back of the bar. In principle, the device creates an air curtain directed up and away from a bartender to reduce his/her exposure to patrons' smoke. Although this device helped to reduce ETS concentration behind the bar, it's overall effect was not great enough to warrant further development of the idea. If one design goal of a bar ventilation system is to minimize a bartender's exposure to ETS, then ventilation configurations that direct air behind the bar may be useful.

Another hypothesis held before the test was that directing a jet of air toward the floor would result in a general upward displacement of air that would drive smoke toward the ceiling and the intake of the air cleaner. However, by itself, a direct downward deflection of the air at either a high or low velocity did not result in great improvements in the particulate removal.

***Air filter comparison*.** The comparison among air cleaners illustrated the efficacy gain that could be realized by combining an effective air cleaner with good ventilation design. During the air cleaner comparison, the only air movement in the room was provided by the air cleaners themselves. The two commercial air cleaners were tested as they were designed to be used. As tested, the EVR for the electronic air cleaner was 143 l s^{-1}. The mechanical air cleaner's EVR was 105 l s^{-1}. By comparison, the EVR of the new air filtration system ranged from 277-741 l s^{-1} (see Figure 2).

These results illustrate a number of important points. To maximize the effectiveness of an air filtration system, it is important to consider the air distribution system. Ideally, the air should be distributed in such a way that smoke, or any other contaminant of interest, will be pass through the air filtration system before it has an opportunity to be distributed throughout a room. It is also obvious that there can be considerable differences among air cleaners with similar volumetric flowrates. The best systems combine high efficiency with large volumetric air movement and high removal effectiveness.

Human vs. machine generated smoke. A series of tests was carried out to determine if human-generated, true ETS would give different test results than machine generated ADSS. Two test set ups, predicted to be highly effective by a model developed from the 16 test runs, were compared.

Eight smokers participated in each test session. They were not instructed where to sit in the room, and they were allowed to freely move about if desired. The smokers tended to space themselves around a conference table in the center of the room. As a result, the location of smoke sources differed from locations used during the smoking machine tests.

For the first tested configuration, an overall EVR of 741 l s^{-1} was calculated for machine-generated smoke and 605 l s^{-1} for the human smokers. The second test configuration resulted in an EVRs of 566 l s^{-1} and 460 l s^{-1} for machine and human generated smoke, respectively. Clearly, there were differences in the effective ventilation rates determined for machine and human generated smoke. Although the EVRs calculated when smokers were present corresponded to removal effectiveness of ~1 to 1.2, they were not as great as expected.

One possible explanation for the difference in calculated EVRs was the different location of the smokers and smoking machines. To test the hypothesis that smoking position may have an influence on the effectiveness of the air cleaning system, an additional experiment was performed in which the smoking machines were distributed around the table at positions roughly correlating to the human smokers' positions (see Fig. 1C). The EVR calculated for the smoking machines distributed around the table was 438 l s^{-1}. That value was lower than the EVR of 741 l s^{-1} determined when the smoking machines were in their original position. This result indicates that there can be a strong interaction between the location of smoke source and the overall effectiveness of the air filtration system.

CONCLUSIONS

Experimental results show that the combination of an efficient air cleaner with a well designed air distribution system can result in effective ventilation rates greater than the rated capacity of the air cleaner alone. In order to achieve an relative effectiveness greater than 1, ETS, or any other contaminant of interest, should be captured by the filtration system before it has an opportunity to disperse throughout a space.

Alternatively, poor air distribution, as was seen with the two flush-mount commercial air cleaners, can result in low overall effectiveness for an air cleaner. Even at the configuration with the lowest effectiveness, the new air filtration system cleaned the air much more effectively than the flush-mounted units. Although filtration/ventilation systems may be more expensive to install than typical drop-in systems, their increased effectiveness can offset the increased cost.

Smoke generation patterns also appear to significantly influence the effectiveness of air filtration systems. The unexpected differences in effectiveness observed with smoking machine placement in this study illustrate the importance of testing multiple smoking configurations in test room evaluations of air filtration systems.

Despite less than perfect results, *in situ* testing combined with a model to predict air cleaner performance [2], proved useful for characterizing the effect of air distribution patterns on filtration system effectiveness, and for comparing the effectiveness of commercial air cleaners under environmental conditions that approximate real-world spaces.

REFERENCES

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APPENDIX 1

Factors for 16 run types in ventilation configuration test.

Run	vel	flow	dir	config	aux
1	-	-	-	-	+
2	+	-	-	-	-
3	-	+	-	-	-
4	+	+	-	-	+
5	-	-	+	-	-
6	+	-	+	-	+
7	-	+	+	-	+
8	+	+	+	-	-
9	-	-	-	+	-
10	+	-	-	+	+
11	-	+	-	+	+
12	+	+	-	+	-
13	-	-	+	+	+
14	+	-	+	+	-
15	-	+	+	+	-
16	+	+	+	+	+

Explanation of terms:

vel:	air velocity	+ = high	- = low
flow:	diffuser type	+ = jet	- = diffused
dir:	direction	+ = angled	- = down
config:	configuration	+ = ½ air behind bar	- = distributed air
aux:	bar up flow device	+ = on	- = off