A METHOD FOR MEASURING AIR CLEANER EFFECTIVENESS

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ABSTRACT

Air cleaners are unitary devices that contain filtration media and fans. They are marketed for cleaning air in rooms. There is no current method for measuring the effectiveness of these devices in rooms of the size where they are typically installed. The proposed method provides engineers and manufacturers with a tool for evaluating and predicting applied air cleaner performance. Test results provide the effective ventilation rate of the device. This rate can be stated in terms of the whole room average, or for specific regions of concern, such as work areas, within the room. This method provides information about mixing or removal effectiveness, location optimization, and system performance efficiency.

INTRODUCTION

Current testing standards for air cleaners include a rating [1] based on decay in a small (28.5 m^3) test chamber resulting in a clean air delivery rate. Some components of air cleaners, such as fans [2,3] and particle filters [4], have test methods. The present method utilizes either real-time or integrated-average particulate measuring devices in a large room and may include multiple sources. The first step is to establish a generation rate from the sources under room test conditions. The next step is to run the test by locating the air-cleaning device in a pre-selected room location. Because particulate concentrations in a large room are typically nonuniform, different device locations should, in general, yield different results. The output is the measured concentration. This concentration is compared to the theoretical concentration under well-mixed conditions at a given airflow using a single compartment model.

METHODS

Equation 1 describes the relationship between a concentration of a substance with quantifiable source strength and ventilation/removal mechanisms in a well-mixed room [5].

$$C = C_{r0} e^{-(Q_{oa}+EQ_r)mt/V} + \frac{mC_o Q_{oa} + S}{m(Q_{oa} + EQ_r)}\left(1 - e^{-(Q_{oa}+EQ_r)mt/V}\right) \qquad \ldots(1)$$

where:

C	concentration of substance in room ($\mu g/m^3$)
C_O	concentration of substance in outdoor air ($\mu g/m^3$)
C_{r0}	concentration of substance in room at time 0 ($\mu g/m^3$)
E	filtration efficiency (dimensionless)
m	removal effectiveness (dimensionless)

Q_{oa} outside air ventilation rate (m^3/h)
Q_r volumetric rate of air recirculated through the filter (m^3/h)
S generation rate (µg/h)
t time (h)
V volume (m^3)

The average over a time period (from time x to time y) is given by equation 2.

$$\overline{C}_{xy} = \frac{1}{(y-x)} \int_x^y C(t)dt \qquad \ldots(2)$$

The objective is to determine the effective ventilation rate (EVR) provided by an air cleaning device in a large room. The average concentration during time period x to y must be measured. The EVR is the quantity described by the product mEQ_r in equation 1. The EVR is equivalent to the effective amount of additional outside air (more than Q_{oa}) that produces the measured average concentration in a well-mixed room.

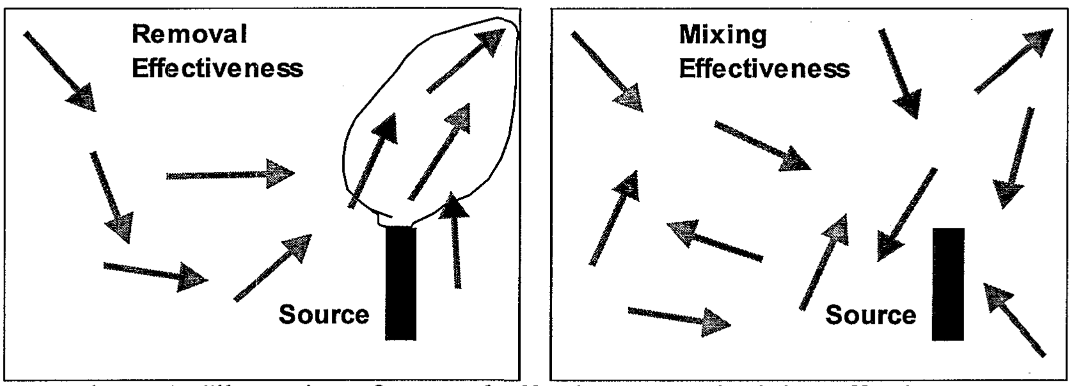

Figure 1. Illustration of removal effectiveness and mixing effectiveness

The term m is often used as mixing effectiveness; however, in this application, the more appropriate term is removal effectiveness[6,7]. Figure 1 illustrates both concepts where with good removal effectiveness the source emission is captured in the air-stream and removed before mixing. With good mixing effectiveness the emission is uniformly mixed before removal from the room. This dynamic test quantifies the effect of the removal effectiveness term m. This effect cannot be observed in a test that begins with a well mixed condition and measures decay. A system designed for good removal effectiveness prevents buildup of the substance. To obtain the desired quantity (mEQ_r), equation 1 must be integrated. The terms C_{ro} and V are constant. For a test setup, Q_{oa} should be held constant and should be small compared to E^*Q_r. In almost all cases, m, E, and Q_r will be constant in time. C_o, the concentration in the outdoor air, is usually constant. If C_o is small and Q_{oa} is small then the product $m^*C_o^*Q_{oa}$ may be assumed negligible. If the generation rate (S) is known and controlled, then the equation can be integrated and the effective ventilation rate can be determined by running a test from time x to time y and measuring the average concentration.

RESULTS

This method can be applied to evaluate air-cleaning systems marketed for removing environmental tobacco smoke in bars and restaurants. A nominal volumetric capacity for this equipment is 500 l/s. A preliminary calculation indicates that smoking eight standard cigarettes twice will produce a measurable quantity of smoke in a 200 m^3 room and that outside air concentrations will be relatively small. With a room this size, there may be different locations of interest. The air need not be well mixed and the concentrations may vary within the occupied area. The system may be designed to minimize concentration in a specific area. Thus, one may focus on specific area concentrations (e.g. a nonsmoking area, behind a bar) or on an overall room average concentration.

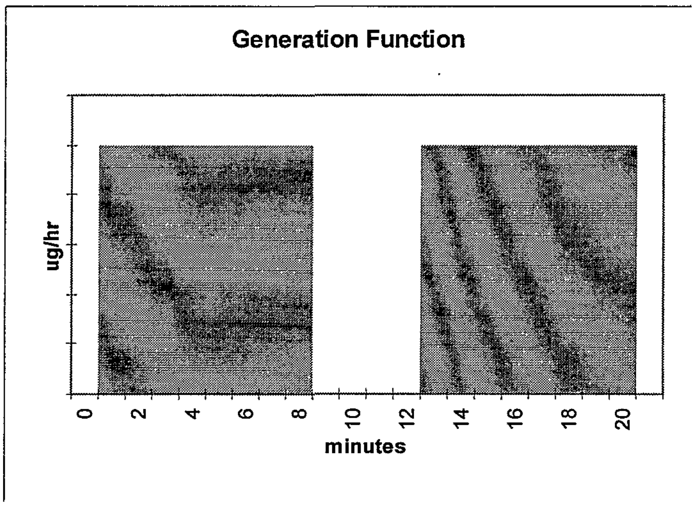

Figure 2. Generation function

For the cigarette smoking regimen, the generation function is best approximated by the four-part step function shown in figure 2. This function represents two smoking cycles. The use of smoking machines for generation of smoke makes the generation more uniform and repeatable. Cigarettes take about 8 minutes to be consumed in a smoking machine set to take one 35 cc puff of 2 s duration per minute. The (no generation) time in the middle is spent loading new cigarettes into the machines after the cigarettes of the first cycle are extinguished and before the cigarettes of the second cycle are lit.

The exact times of the edges of the step functions are determined by the average start and stop times for the cigarettes in each cycle. Since there are eight cigarettes to light one at a time, the beginning time is approximated as the average time of lighting the eight cigarettes. The same approximation is made for extinguishing the cigarettes. The area of each box represents the mass of particles generated by smoking the eight cigarettes in the machines.

There are four distinct time steps over approximately 22 minutes: eight minutes of smoking, four minutes of no smoke generation while reloading, eight minutes of smoking and two minutes of no smoking. The fourth time step comes about because of the variation in smoking cessation time following the second cycle. For consistency in computation, the time period extending out to 22 minutes is used in the calculation.

To illustrate calculations for the four steps assume that the start/stop times in minutes are as follows:

Average smoking begin time cycle 1 = 0 minutes
Average smoking cessation time cycle 1 = 8 minutes
Average smoking begin time cycle 2 = 12 minutes
Average smoking cesation time cycle 2 = 20 minutes
End of process = 22 minutes

The total removal measured in the tests of the systems is Q.

$$Q = m(Q_{oa} + EQ_r). \quad ...(3)$$

The ventilation/removal rate Q is assumed constant. The product of outdoor concentration and outdoor ventilation rate (C_oQ_{oa}) from equation 1 is assumed to be negligible. There are four different generation rates illustrated in figure 2. For the first and third period, the generation rate S is determined from the baseline test described later in this paper. For the second and fourth period $S = 0$. For this illustration, the time-weighted average concentration over the four periods is calculated by equation 4 (where subscripts represent time in minutes).

$$\overline{C}_{0-22} = \frac{8*\overline{C}_{0-8} + 4*\overline{C}_{8-12} + 8*\overline{C}_{12-20} + 2*\overline{C}_{20-22}}{22} \quad ...(4)$$

The average concentration for time period 1 is computed by:

$$\overline{C}_{0-8} = \left(\frac{C_{r0} - \frac{S}{Q}}{\frac{Q}{V}T} \right) \left(1 - e^{-\frac{Q}{V}T} \right) + \frac{S}{Q} \quad ...(5)$$

where C_{r0} is the beginning concentration in the room at the start of the test; in this case at time = 0. T = 8 minutes corresponds to T = 0.133 h.

For time period 2 the beginning concentration at time=8 minutes is calculated by

$$C_8 = C_{r0} e^{-\frac{Q}{V}t} + \frac{S}{Q}\left(1 - e^{-\frac{Q}{V}t} \right) \quad ...(6)$$

where t = 8 minutes = 0.133 h.

The average concentration for time period 2 is computed by:

$$\overline{C}_{8-12} = \left(\frac{C_{r8}}{\frac{Q}{V}T} \right) \left(1 - e^{-\frac{Q}{V}T} \right) \quad ...(7)$$

where C_{r8} is the beginning concentration in the room at time = 8 minutes; S = 0; T = 4 minutes = 0.0667 h.

For time period 3 the beginning concentration at time=12 minutes is calculated by:

$$C_{12} = C_{r8} e^{-\frac{Q}{V}t} \qquad \ldots(8)$$

where t = 4 minutes = 0.0667 h.

The average concentration for time period 3 is computed by:

$$\overline{C}_{12-20} = \left(\frac{C_{r12} - \frac{S}{Q}}{\frac{Q}{V}T} \right) \left(1 - e^{-\frac{Q}{V}T} \right) + \frac{S}{Q} \qquad \ldots(9)$$

where C_{r12} is the beginning concentration in the room at time = 12 minutes; T = 8 minutes = 0.133 h.

For time period 4 the beginning concentration at time=20 minutes is calculated by

$$C_{20} = C_{r12} e^{-\frac{Q}{V}t} + \frac{S}{Q}\left(1 - e^{-\frac{Q}{V}t} \right) \qquad \ldots(10)$$

where t = 8 minutes = 0.133 h.

The average concentration for time period 4 is computed by:

$$\overline{C}_{20-22} = \left(\frac{C_{r20}}{\frac{Q}{V}T} \right) \left(1 - e^{-\frac{Q}{V}T} \right) \qquad \ldots(11)$$

where C_{r20} is the beginning concentration in the room at time = 20 minutes; S = 0; T = 2 minutes = 0.0333 h.

The average concentration over the period 0-22 minutes is measured. The generation rate S is determined from the baseline tests. Substituting these experimental values into eqn. 4 then allows us to solve for the unknown, Q. The computation should be adjusted to reflect the actual start/stop times of each test run. For example, if the average end of the burn time for the first run of cigarettes is 8 minutes 15 seconds from the average start time, then that time value should be used instead of 8 min. in the example calculation. The value of S (μg/h) should be adjusted such that the mass of particles generated per cigarette remains constant.

Baseline tests use the same source in the room with no filtration/ventilation under well-mixed conditions to establish values for the cigarette emission rate in μg/cigarette and for Q_{oa} the background removal rate. In the baseline test Q_r is zero so the total removal is Q_{oa}. The value of Q_{oa} is determined from the decay after the generation has ended in the baseline test. S is determined by the average room concentration (C_{0-22}) in the baseline tests. Equations 4-11 are solved with the average room concentration and the system ventilation rate (Q_{oa}) as measured parameters and S as the unknown. With the times and the number of cigarettes known, S (µg/h) can be converted to the cigarette emission rate in µg/cigarette.

DISCUSSION

Tests with cigarettes were run using particles as the ETS marker. The results of the tests are discussed in a companion paper [8]. Gas phase markers could be used and other sources could be used. The effective ventilation rate output from this process describes potential results from air-cleaning system application in a room more completely than other measures.

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