Korean J. Chem. Eng., **30**(2), 351-356 (2013)
DOI: 10.1007/s11814-012-0151-8

Removal characteristics and distribution of indoor tobacco smoke particles using a room air cleaner

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(*Received 21 December 2011 • accepted 2 September 2012*)

Abstract−The objective of this study is to analyze the removal characteristics and distribution of indoor air pollutants by a room air cleaner. A pollutant removal effect according to room volume and measurement point was evaluated in an indoor room. A series of filtration efficiency tests were performed on only the electrostatic precipitator of the room air cleaner. The measurements of filter efficiency and pressure drop across the electrostatic precipitator were made using an ASHRAE 52.1-1992 filter test system and an opacity meter to measure the particle concentration upstream and downstream of the test filter. Also the performance of the air cleaner in the room was evaluated by examining tobacco smoke particle concentration. The size distribution of the tobacco smoke particles was 1.27 μm in mass median diameter and a geometric standard deviation of 1.313 μm. The efficiency of the electrostatic filter was measured as 78.6% with dust particles of 1.96 μm in mass median diameter and 1.5 m/s face velocity. The tobacco smoke particle concentration as a function of time decayed exponentially. The contaminant removal effect was increased when increasing the effective clean air exchange rate ($\eta Q/V$), which is 0.0780 min^{-1} for 51 m^3 room and 0.0235 min^{-1} for 149 m^3 room. This study clearly shows that a room air cleaner with an electrostatic precipitator is effective in removing tobacco smoke particles. The removal characteristics and distribution of indoor air pollutants in other rooms is predicted based on empirical modeling.

Key words: Indoor Air Quality, Ventilation, Natural Decay, Electrostatic Precipitator, Tobacco Smoke, Effective Clear Air Rate

INTRODUCTION

Air cleaning is a form of pollution control widely applied to particulate matter, gases, and vapor generated by industrial sources. Room air cleaners have been used in indoor environments to remove radon progeny, tobacco smoke, and other air pollutants. Room air cleaners include an electrostatic precipitator unit, a pulsed discharge plasma combined with TiO_2 photocatalyst, and a fan. Air cleaners have been evaluated extensively for removal of radon progeny and have been found to be more effective than electronic systems [1-5]. Offermann et al. [6] evaluated eleven different types of portable air cleaners, including panel filters, electrostatic precipitators (ESPs), and ionizers for removing tobacco smoke in a well-controlled room. They concluded that ESPs are most effective in removing smoke particles, and the best units have effective cleaning rates ranging from 100 to 300 m^3/h. Many commercial room air cleaners are now available to remove biological aerosols, including pollens, fungal spores, and animal dander that can cause allergic reactions when inhaled. These aerosol particles are >5 μm, whereas radon progeny and tobacco smoke particles are submicrometer (<0.5 μm) in size. Usually, particles larger than 1 μm can be captured easily by inertial force and gravitational force, and very small particles smaller than 0.1 μm also can be captured by electrostatic force and diffusion force. However, the size range from 0.1-1 μm which is called MPPS (most penetrating particle size), has low collection efficiency. Those particles are too small to have enough inertial and gravitational forces, and too large to have electrostatic and diffusion forces. Mean size of tobacco smoke particles is about 0.5 μm. So they are not captured easily by air cleaner or filtration equipment.

The purpose of this paper is to investigate the performance of a room air cleaner for removal of tobacco smoke in an indoor room under realistic conditions for 30 minutes.

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INDOOR AIR MODEL

Aerosol dynamics in the test room are investigated to determine the factors that can influence the air cleaner and air exchange rate on concentrations of tobacco smoke. Fig. 1 shows a schematic diagram of the variation of indoor pollution concentration used in the mass balance of pollutants. The temporal changes in the indoor aerosol mass concentration, C (μg/m^3), can be described by the following Eq. (1).

$$\frac{dC}{dt}=\lambda_v C_{out}-\left(\lambda_v+\beta_w-S+\frac{\eta Q}{V}\right)C \quad (1)$$

where C_{out} is the outdoor mass concentration of tobacco smoke, λ_v is the air ventilation rate (as a fraction of room volume per hour),

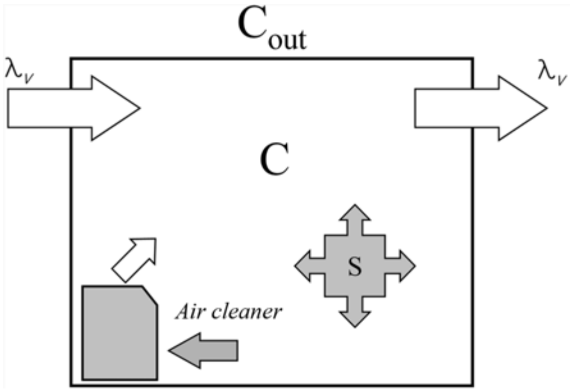


Fig. 1. Schematic diagram of variation of indoor pollution concentration used in mass balance of pollutants.

β_w is the natural decay rate of aerosol (min^{-1}), S is the pollutant emission rate (min^{-1}), η is the collection efficiency of the air cleaner, Q is the volumetric flow rate of the air cleaner (m^3/min), and V is the volume of the room (m^3), $\eta Q/V$ is the effective clean air rate (min^{-1}). The equation assumes perfect mixing of particle concentration in the room. Indoor particles are removed by three mechanisms: ventilation outside, particle deposition in the room, and filtration by the air cleaner. Eq. (1) can be solved with the initial condition that t=0, $C=C_0$, leading to the analytical solution [7].

$$C(t) = C_0 e^{-\lambda_\gamma t} + \lambda_v \frac{c_{out}(1-e^{-\lambda_\gamma t})}{\lambda_\gamma} \tag{2}$$

where $\lambda_\gamma = \lambda_v + \beta_w - S + \frac{\eta Q}{V}$

If the effects of the air ventilation rate through a leakage and the pollutant generation in a room are negligible, Eq. (2) is substituted for Eq. (3).

$$C(t) = C_0 e^{-\lambda t} \tag{3}$$

where $\lambda = \beta_w + \frac{\eta Q}{V}$

Here λ is the decay constant for particulate matter. The β_w is affected by particle characteristics and the $\eta Q/V$ is affected by air cleaner characteristics. Therefore, if we know the λ value then the removal characteristics and distribution of indoor air pollutants in other rooms can be predicted using the empirical modeling.

EXPERIMENTAL APPARATUS AND TEST PROCEDURE

1. Description of Air Cleaner

The air cleaner unit is a self-contained room air cleaner designed to reduce the levels of both airborne particulate matter and odors in a single room up to 66 m^2 in floor area. Fig. 2 shows a cutaway side view of the air cleaner. The room air cleaner is operated by circulating air through a prefilter, an electrostatic precipitator unit, and finally pulsed discharge plasma combined with TiO_2 photocatalyst. The fan assembly operated the unit at three speeds, with the highest (5.98 m^3/min) being used in these studies. The electrostatic precipitator unit is composed of the positive corona precharger upstream of the filter to precharge particles and the electrified filter collector coupled with external electrical field. The precharger unit consists of the discharge electrode of tungsten wire (0.1 mm in diameter) placed between grounded plates at a distance of 3.1 mm. The main function of the precharger in a gas filtration system is to impart the maximum possible charge to the dust particles in the gas stream. By passing through the first stage of the precharger with an applied voltage of 5.29 kV, the particles are positively charged. The DC voltage of 2.64 kV is applied between the upstream and downstream separators to produce electric field between the separators and media as well as across the media in a polarity so that most of the precharged particles are collected on the upstream filter collector. The corona-charging unit has been used to increase the natural charge on fine dust particles entering the air filter. Together with the air that flows through the filter, the dust particles will pass from the precharger to the second stage, which involves a scroll type collector. Here, the particles electrically charged in the precharger lie in an electric field that favors the arrest of the particles (due to the Coulomb force) on the separator.

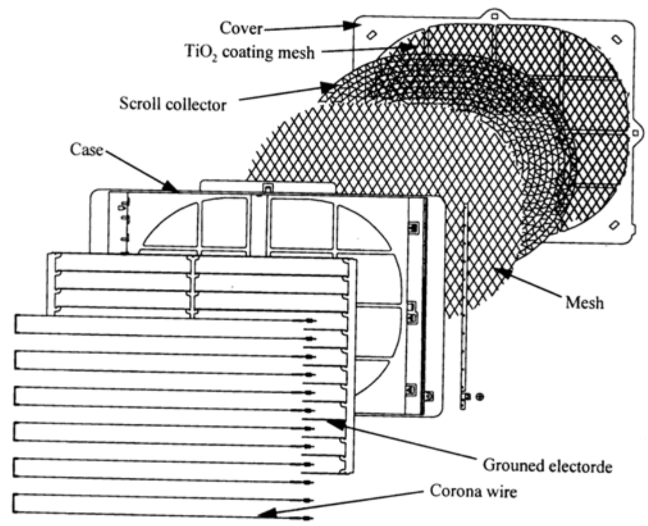


Fig. 2. Assembling plan of air cleaning apparatus.

2. ASHRAE Filter Test System

Fig. 3 is a schematic drawing of the ASHRAE 52.1-1992 filter test system which consists of a cross sectional area duct of 610 mm× 610 mm, dust feeder (part #1), filter sampler (part #2), test filter (part #3), perforated plate (part #4), fan (part #5), pressure gauges (part #6), and orifices (part #7) [8]. In the test duct, the main blower is downstream of the test device. The duct, which is composed of five parts, is made of a galvanized iron to protect static electricity, and each part is connected by flanges. One of the two orifices (#7) is a mixing orifice of dust and air and the other is an orifice of 305 mm in diameter for measurement of flow rate. A perforated plate (#4) that has 40% open area and diameter of 152 mm is installed in the inlet to distribute the mixed air with the dust and to ensure a uniform flow. The filter sampler (#2) should have a flow rate of 944±9 cm^3/s without target paper, and a flow rate of 710 cm^3/s with target paper. The critical orifice is installed to get a constant flow rate. The dust concentrations upstream and downstream of the samplers are measured by the ASHRAE dust spot opacity meter (AFTL, Inc.) which is based on the percentage decrease in the relative light transmission of a dust-spot sampling target resulting from dust buildup on the target [8]. The flow rate in this study is 0.5 m/s, 1.0 m/s, 1.5

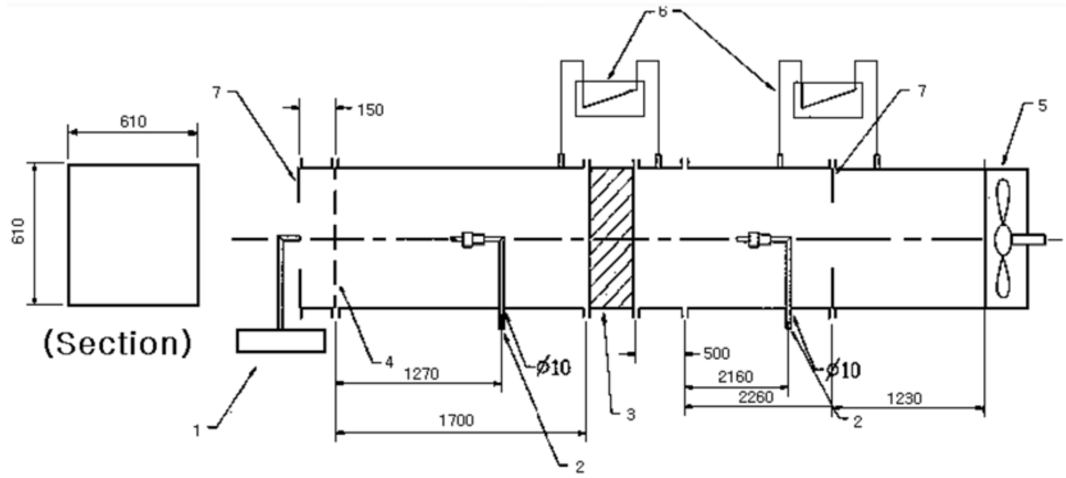


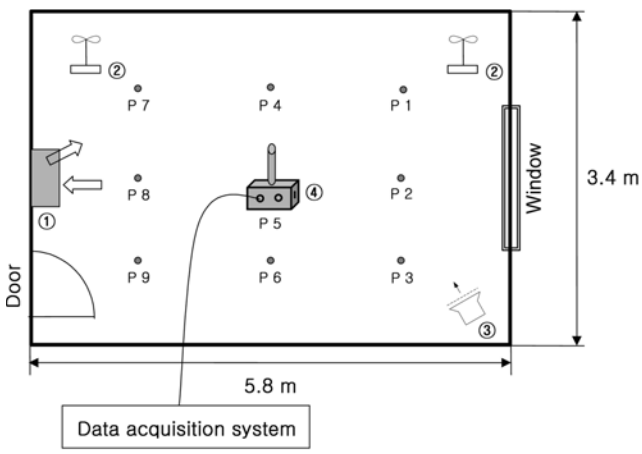
Fig. 3. Schematic diagram of the ASHRAE air cleaner test system (ASHRAE, 1992).

1. Dust feeder
2. Sampler
3. Test filter
4. Perforated diffusion plate
5. Fan
6. Pressure gage
7. Orifice

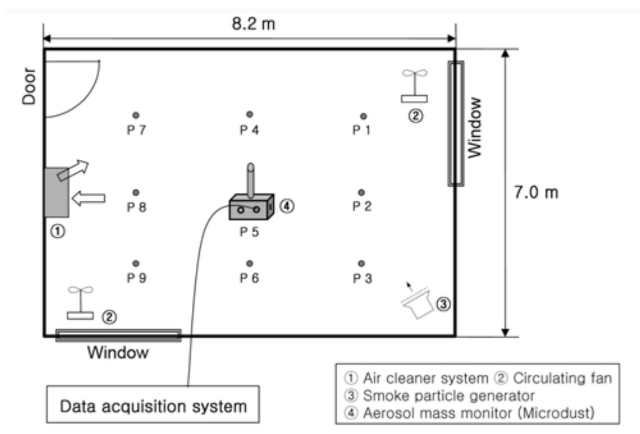
m/s face velocity being a representative face velocity in industrial ventilation for removing particulate matter.

3. Test Room Description and Test Protocol

Fig. 4 is a schematic diagram of the test room for the removal characteristics and distribution of the room air cleaner using tobacco smoke. The room has two types of volume: 5.8 m×3.4 m×2.6 m (Case 1, 51 m^3) and 8.2 m×7.0 m×2.6 m (Case 2, 149 m^3). The room air cleaner is positioned in the center of one side wall. The tobacco is used and generated inside the test room with a device combining the vacuum pump and the vacuum transducer. The Microdust 880 nm Aerosol Monitoring System (CASELLA) and the FE-80 (Hiac/Royco) are used to measure the tobacco smoke concentration in real time. The Microdust system is a particle counter using the principle of light scattering, and uses a modulated beam of infra-red light projected forward into a measurement chamber. The Fe-80 can measure the particle size from 0.5-30 μm based on the light scattering principle using a laser optic system. The Microdust can measure particle mass concentration; however, the FE-80 gives particle number concentration based on the particle size. The output is sent to an RS-232 serial port and is recorded on a computer. The test procedure requires a natural decay measurement and a particle removal measurement. Both measurements are performed after the room is filled with tobacco smoke. Natural decay is defined as the decay of the tobacco smoke in the room with the air cleaner off. The test protocol of particle removal measurement is described below. The circulating fans are switched on and the room is filled with tobacco smoke to a suitable concentration level. After a period of mixing, the circulating fans are switched off and the test starts. Variations of the tobacco smoke concentration as a function of time are measured at nine locations in the room and 130 cm height from the floor, which is the center of the room. The particle removal measurement is defined as the decay while the air cleaner is running. The decay constants for the tobacco smoke with and without the air cleaner operating are calculated.



(a) Case 1 (volume of room, V=51 m^3)



(b) Case 2 (volume of room, V=149 m^3)

Fig. 4. Schematic diagram of the air handling chamber system.

RESULTS AND DISCUSSION

1. Filter Efficiency Measurements

Filter efficiency measurements are performed in a single flow using Arizona road dust particles and the ASHRAE 52.1-1992 filter test system. The dust-spot efficiency of the filter is used as a repre-

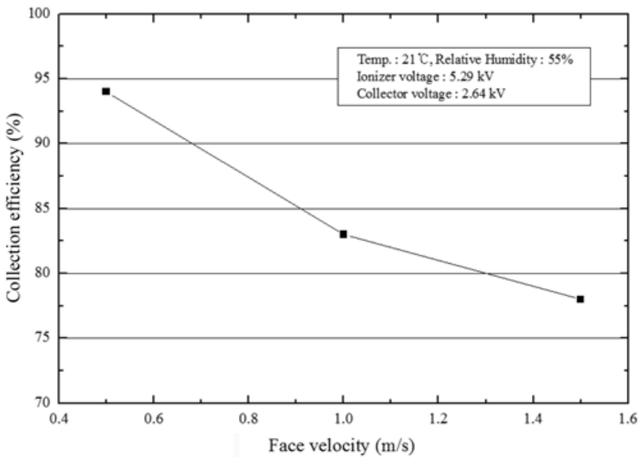


Fig. 5. Variation of collection efficiency with face velocity.

sentative test method and usually expressed as follows:

$$\text{Dust spot efficiency} = 100 \times \left(1 - \frac{Z_d}{Z_u}\right) \quad (4)$$

where Z_u and Z_d are the opacity index corresponding to the opacity of the upstream target and downstream target, respectively. The particle opacity index of target filters is measured in terms of light transmission upstream and downstream of the electrostatic precipitator by the ASHRAE dust-spot opacity meter.

The pressure drops across the electrostatic precipitator are 0.3 mmH_2O, 0.8 mmH_2O, and 1.6 mmH_2O at the face velocity of 0.5 m/s, 1.0 m/s, and 1.5 m/s, respectively. Fig. 5 shows the collection efficiency of the air cleaner with face velocity, showing 94%, 83%, and 78% collection efficiency. The collection efficiency of the electrostatic precipitator increased with a decrease in the face velocity across the electrostatic precipitator.

2. Tobacco Smoke Removal in the Occupied Spaces

Fig. 6 represents variation of particle removal characteristics with each test point, and the natural decay is measured at the center of the room. Without the air cleaner operation, 30% concentration decay is shown in 30 minutes. This means that pollutants occupying the space are removed due to wall attachment through diffusion effect, gravitational sedimentation and clearance ventilation [1,7]. At the nine measuring points, room air concentration is decreased by 90% compared to initial value for 30 minutes when the air cleaner is in operation.

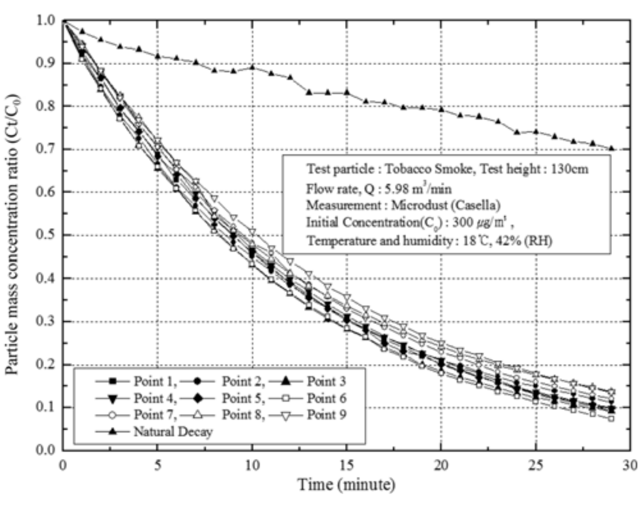


Fig. 6. Variation of particle concentration with each test point in case 1 (volume of room, V=51 m^3, circulating rate=0.117 min^{-1}).

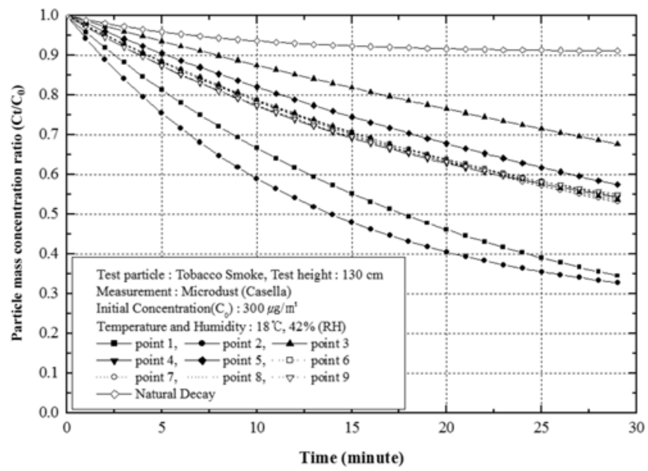


Fig. 7. Variation of particle concentration with each test point in case 2 (volume of room, V=149 m^3, circulating rate=0.040 min^{-1}).

Fig. 7 shows the variation of particle concentration with each test point (volume of room, V=149 m^3, circulating rate=0.040 min^{-1}), showing that without air cleaner operation, the tobacco smoke concentration ratio decreases to 10% of initial value for 30 minutes when it is measured at the center of the room. The difference between Fig. 6 and Fig. 7 is that each test room has its own clearance ventilation effect and surface area. A large variation occurs in collection efficiency from one point to another point. Point 2 is the maximum decreasing point and 70% of pollutants are removed for 30 minutes with air cleaner operation. Point 3 is the minimum decreasing point and 35% of pollutants are removed for 30 minutes. Other points have about 45% of collection efficiency compared to the initial value.

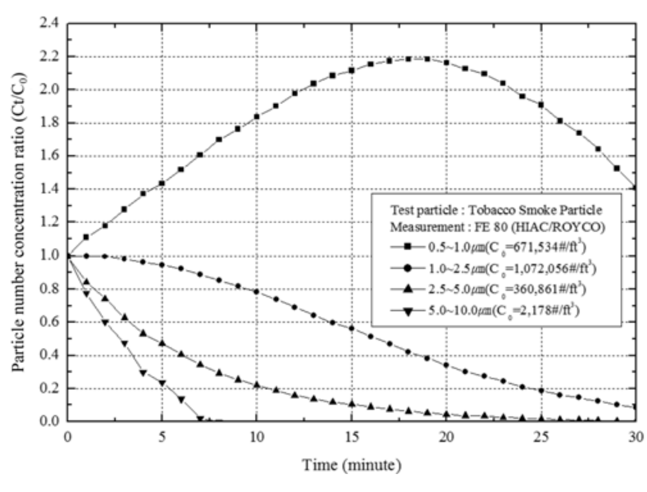


Fig. 8. Variation of particle concentration with particle size in case 1 (volume of room, V=51 m^3, circulating rate=0.117 min^{-1}).

This test result shows that the air change rate per hour of 2.4 is not efficient enough for this room to remove pollutants. The ventilation in collection efficiency results from the differences in air distribution velocity from the centrifugal fan. Point 2 has relatively higher velocity and point 3 is a dead zone.

Fig. 8 shows the decay characteristics of tobacco smoke particles according to the particle diameters in the room with air circulation of 0.117 min^{-1}. Particles of 0.5-1.0 μm, 1.0-2.5 μm, 2.5-5.0 μm and 5.0-10.0 μm diameters are respiratory, and these bands of diameter are set to be measured. Except for the particles of 0.5-1.0 μm, the concentration of tobacco smoke decreases with time. Especially, particles of 5.0-10.0 μm diameter accounting for a significant part of the mass concentration are removed fully within 8 minutes and particles of 2.5-5.0 μm diameter are all removed within 20 minutes. The concentration of 0.5-1.0 μm diameter particles increases up to double initial value before decreasing, which occurs because the tobacco smoke particles that originated at an initial low concentration of 450 $\mu g/m^3$ proved to become smaller in size by the evaporation phenomenon [1,9].

Fig. 9 shows a comparison of experimental results and the theoretical result of particle decay at the center point and mean value of the decay constant for particulate matter at each test point in Case 1 (volume of room, V=51 m^3, circulating rate=0.117 min^{-1}). From the result of the experiment, the natural decay rate of aerosol β_ω is 0.0120 min^{-1} and the effective clean air rate is 0.0780 min^{-1}. Compared with the theoretical decay constant of 0.1080 min^{-1}, this slightly differs; however, it can be useful for predicting the particle removal performance in practical use.

Fig. 10 shows a comparison of experimental results and the calculated result at point 2, which shows minimum particle removal, and at point 5 which is the center of the room, in Case 2 (volume of room, V=149 m^3, circulating rate=0.040 min^{-1}). The natural decay rate of aerosol β_ω is 0.0026 min^{-1}, and the effective clean air rate is 0.0235 min^{-1}. The theoretical decay constant for particulate matter is 0.0341 min^{-1}.

The particle collection efficiency is increased with increasing the effective clean air rate ($\eta Q/V$), which is 0.0780 min^{-1} for 51 m^3 and 0.0235 min^{-1} for 149 m^3 room. The particle removal characteristics and concentration of indoor air pollutants in other rooms can be predicted using the empirical modeling.

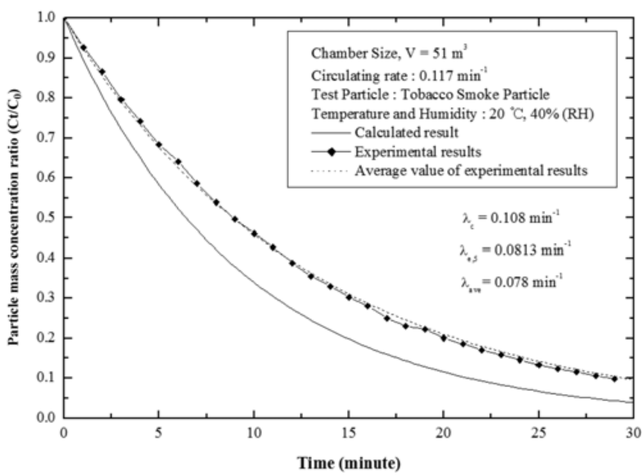


Fig. 9. Comparison of experimental results and calculated result in case 1 (volume of room, V=51 m^3, circulating rate=0.117 min^{-1}).

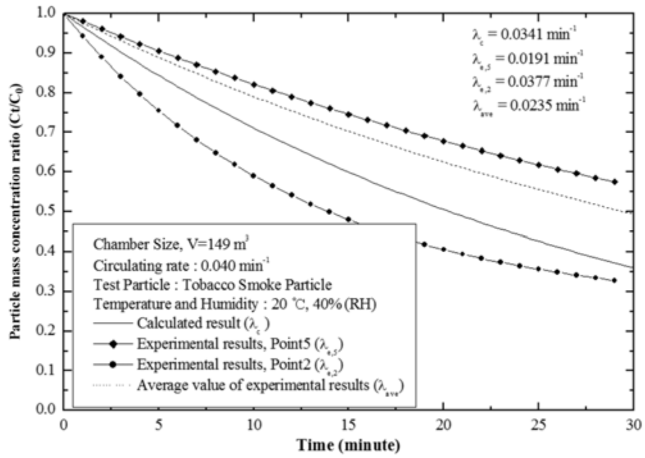


Fig. 10. Comparison of experimental results and calculated result in case 2 (volume of room, V=149 m^3, circulating rate=0.040 min^{-1}).

CONCLUSIONS

The performance of a commercial air cleaner is evaluated in an occupied space by examining tobacco smoke concentration. This study clearly shows that the room air cleaner is effective in removing the tobacco smoke.

1) The electric precipitator for the room air cleaner is found to provide a removal efficiency of 78% by the ANSI/ASHRAE 52.1-1992 test method with a high fan speed.

2) At a room volume of 51 m^3 (circulating rate=0.117 min^{-1}) without air cleaner operation, the tobacco smoke concentration ratio decreases to 30% of initial concentration C_0=450 $\mu g/m^3$ by natural decay within 30 minutes and with air cleaner operation, it decreases to 90% of the initial value.

At a room volume of 149 m^3 (circulating rate=0.040 min^{-1}) without air cleaner operation, the tobacco smoke concentration ratio decreases to 10% of initial concentration C_0=450 $\mu g/m^3$ by natural decay within 30 minutes and with air cleaner operation, it decreases to 50% of the initial value.

3) At a room volume of 51 m^3 (circulating rate=0.117 min^{-1}), the overall removal efficiency of the air cleaner is about 80% within 20 minutes. The concentration of 0.5-1.0 μm particulate matters increases by two-times compared to initial value and then decreases. This is the reason why tobacco smoke particles are originated at a low concentration of 450 $\mu g/m^3$ and the surface evaporation phenomenon makes each particle smaller in size.

4) The theoretical model of the particle removal can be used for the prediction of the performance of air cleaners in other rooms.

NOMENCLATURE

C : concentration [$\mu g/m^3$]
C_c : cunningham correction factor
C_o : initial concentration [$\mu g/m^3$]

d_p : particle diameter [μm]
Q : flow rate of air through the room air cleaner [m^3/min]
S : pollutant emission rate [min^{-1}]
V : volume of room [m^3]
t : time [sec, min, hour]
β_w : natural decay rate [min^{-1}]
η : efficiency of air cleaner
λ : decay constant [min^{-1}]
λ_v : air ventilation rate [min^{-1}]

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