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# Efficient test method for evaluating gas removal performance of room air cleaners using FTIR measurement and CADR calculation

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A B S T R A C T

We have developed a new test method for differentiating the gas-removal performance of indoor air cleaners by using Fourier-transfer infrared measurements and a clean-air-delivery-rate (CADR) calculation method in a closed test chamber (4 $m^3$). Eighteen air cleaners were evaluated using both the new method and the current Korean and Japanese test methods, using ammonia, acetic acid, acetaldehyde, and toluene as test gases. The Association of Home Appliance Manufacturers' statistical method for calculating regression line slopes of test chamber gas concentrations during air cleaner operation was used. The standard deviations of CADRs for ammonia, acetic acid, and toluene, gases that were easily removed by the air cleaners in the test chamber, were 3.2, 751.3, and 13.4 times higher, respectively, than the gas-removal efficiencies determined using the current arithmetic calculation method, which uses the ratio of concentrations after 0 and 30 min of air cleaner operation. The new test method clearly differentiated the gas-removal performances of various air cleaners, especially for gases that are quickly removed by indoor air cleaners. Also, the single-pass removal efficiency of the air cleaners was obtained with a simple calculation: CADR/flow rate/0.83.



## 1. Introduction

Indoor air quality (IAQ) is a top environmental priority of environmental agencies such as the US Environmental Protection Agency (US EPA) and the European Environment Agency (EEA). IAQ is a global problem because people now spend much of their time indoors, and exposure to toxic gas pollutants such as $NO_2$, CO, VOCs from fuel/tobacco combustion, construction and furnishing materials can be an issue in the workplace or home, or both [1,2]. Airborne indoor pollutants include particulates, allergens, and organic and inorganic gaseous pollutants [3]. In particular, some buildings, including new construction, contain such high concentrations of gas-phase pollutants that they are qualified as "sick" because exposure to the inside of buildings results in multiple sickness symptoms, such as headache, fatigue, skin and eye irritation, or respiratory illness, commonly described as "sick-building syndrome" (SBS) [4]. Solutions recommended by the US EPA to improve IAQ include combinations of actions such as removing pollutant sources such as dust and harmful gases, increasing ventilation rates and improving air distribution, and cleaning indoor air [5,6]. The most efficient method of cleaning indoor air is the use of air cleaners, which remove airborne contaminants relatively quickly by several different processes of varying effectiveness, such as filtration, activated carbon, ionization, and photocatalytic oxidation [7–10]. US EPA explains that usually the best way to address this risk is to control or eliminate the sources of pollutants, and to ventilate a home with clean outdoor air. The ventilation method may, however, be limited by weather conditions or undesirable levels of contaminants contained in outdoor air. If these measures are insufficient, an air cleaning device may be useful [11]. In particular, to remove gas-phase pollutants, most air cleaners use an adsorption mechanism; activated carbon filters have been commonly used because they have a high adsorption capacity of gas-phase pollutants due to their highly developed porous structure and large specific surface area [12].

Many countries, including the US, Japan, and Korea, evaluate the performance of room air cleaners using their own standard test methods [13–15]. Brief descriptions of the methods commonly used in these countries to test air cleaner performance are listed in Table 1. For particle removal performance, all methods measure the clean air delivery rate (CADR; $m^3$/min), which describes the equivalent volume of clean air provided to the space by an air cleaner. This is a universal and efficient metric for estimating the particle removal performance of air-cleaning devices in rooms of

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**Table 1**
Details of Korean, American, and Japanese test methods for evaluating particle and gas removal performance of household air cleaners.

| Test method | Experimental conditions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Particle removal | | | | Gas removal | | | |
| | Type of test particle | Initial particle concentration (#/m$^3$) | Size range (μm) | Measurement | Type of test gas | Size of test chamber (m$^3$) | Measurement time (min) | Measurement |
| KACA | KCl | $10^8$–$10^{10}$ | 0.3 | CADR | Ammonia, Acetic acid, Acetaldehyde (10–13 ppm) | 4 | 30 | Removal efficiency |
| JEMA | Smoke Dust | $7.07 \times 10^{10}$–$3.54 \times 10^{11}$ | 0.3 | CADR | Ammonia, Acetic acid, Acetaldehyde from five tobaccos | 1 | 30 | Removal efficiency |
| AHAM | Cigarette Smoke<br>Arizona Dust<br>Pollen | $2.4$–$3.5 \times 10^{10}$<br>$2.0$–$4.0 \times 10^8$<br>$4.0$–$6.0 \times 10^6$ | 0.1–1.0<br>0.5–3.0<br>5–11 | CADR | – | – | – | – |

various sizes or in comparing air cleaning with ventilation as an IAQ control technique [16,17]. The only difference among the three performance tests listed above for particle removal is the experimental conditions of the test particles. EPA had explained that although AHAM uses the CADR concept to evaluate the performance of portable air cleaners in reducing particulate matter concentrations, the CADR can be applied equally to the removal of gases pollutants.

The gas-removal efficiencies of 126 room air cleaners for ammonia, acetaldehydes, and acetic acid, evaluated using the Korean test standard, SPS-KACA-002-132, for 5 years, from 2005 to 2009, are shown in Fig. 1. The average removal efficiencies for ammonia, acetaldehyde, and acetic acid were 86.5%, 69.8%, and 98.1%, and the efficiencies for ammonia and acetaldehyde ranged from 20 to 100% with relative deviations of 17.8% and 23.8%, while those for acetic acid were mostly 100% with a deviation of only 3.5%. These results indicate that the test method for evaluating gas-removal performance has a technical limitation, namely an inability to differentiate among the time-dependent gas-removal performances of various air cleaners and test gases, especially gases that are easily removed by air cleaners, because removal performance is evaluated using only the gas concentrations at specific times (0 and 30 min) according to Korean and Japanese standards.

To evaluate the time-dependent gas-removal performances of air-cleaning devices more efficiently, several research groups have developed test protocols that have not been standardized [12,18–23]. Chen et al. [19] developed a full-scale test method with a 54-m$^3$ test chamber, gas chromatography/mass spectrometry

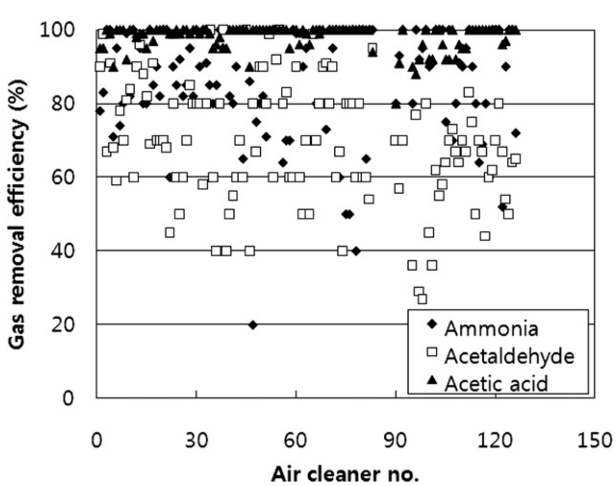


**Fig. 1.** Gas-removal efficiencies of 126 room air cleaners for ammonia, acetaldehyde, and acetic acid, determined using the Korean standard test method.

(GC/MS) measurements, and 17 volatile organic compounds (VOCs). They measured the CADRs of 15 air cleaners, but due to the scale of the test chamber and the measurement method, approximately 12 h were needed to obtain a single test result. Howard-Reed et al. [21,22] also developed a field test protocol with test houses of 85 and 340 m$^3$ to compensate for the technical limitations of CADR evaluation in the field, given dynamic mass transport conditions such as weather-dependent humidity and temperature, using decane gas and GC/electron capture detector (ESD) measurement methods. These methods still required a test period of several hours because of the size of the test facility and the long measurement time of the analytic method. Using a relatively small test chamber (6.3 m$^3$) and measurement time of approximately 30 to 90 minutes for a test, Niu et al. [18] tested 27 air cleaners with toluene gas; they proposed that this test method could quantify the initial cleaning capacity of an air cleaner for gaseous phase pollutants.

To evaluate the time-dependent gas-removal performance of air cleaners for various gases more quickly (<30 min for a single test), we developed a novel method of measuring CADRs that uses the same statistical calculations as applied in ANSI/AHAM AC-1-2006, a relatively small closed chamber (4.0 m$^3$), and a real time multi-gas measurement system with a Fourier-transfer infrared spectrometer (FTIR) that is used by the US EPA and the National Institute for Occupational Safety and Health (NOISH) as a standard analytic method for measuring organic and inorganic gas-phase gases [24–26]. In addition, we evaluated 18 air cleaners that are commercially available in Korea and Japan using the current Korean and Japanese test methods and compared the results to those of the new test method.

## 2. Experimental setup

### 2.1. Test gases and specimens

Table 2 lists the physical and chemical properties of the test gases used in this study. Four gases were selected for the gas-removal performance tests: ammonia ($NH_3$), acetic acid ($CH_3COOH$), acetaldehyde ($CH_3CHO$), and toluene ($C_7H_8$); the first three are also used in the Korea Air Cleaning Association (KACA) and Japan Electrical Manufacturers' Association (JEMA) standards, and toluene is a representative VOC. All four gases are sources of malodorous indoor irritants, and have been used in many previous studies [18,27–29].

Eighteen indoor air cleaners commercially available in Korea and Japan were tested in this study. Descriptions are provided in Table 3, where the cleaners are grouped on the basis of manufacturing company and type of filtration. All products were equipped with HEPA filters for particle removal and carbon filters