TECHNICAL PAPER

Assessment of penetration through vacuum cleaners and recommendation of wet cyclone technology

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In many commercial vacuum cleaners, the captured aerosol particles contained in the dust collector may accidentally release from the exhaust filtration owing to leakage or penetration. Vacuum cleaners may cause dust to become airborne by exhausting air that is not completely filtered. This may cause the operator to inhale dust, in turn causing health problems. This study aimed to investigate the dust penetration rates from three commercial vacuum cleaners and suggest the best technique for completely filtering exhaust air using a combination of cyclonic separation and water filtration. The commercial vacuum cleaners were tested inside a custom-built hood, and the exhausted particles were monitored using a sampling probe in conjunction with an aerosol particle sizer. Quartzose mineral dusts were added to each vacuum cleaner through the dust transport line. A 2400 L/min wet cyclone was employed as the proposed vacuum cleaner. It was designed using Stokes scaling, and its collection characteristics were evaluated using polystyrene latex beads. Surprisingly, the conventional vacuum cleaners failed to capture an overall average of ∼14% of the particles in the given size range. However, only ∼3.8% of the collected particles escaped from the vacuum cleaner that used the wet cyclone technology. Thus, the proposed vacuum cleaner should potentially be an effective method for vacuuming household dust.

Implications: The successful investigation of conventional vacuum cleaners is useful for both manufacturers and users. As an effective vacuum cleaning mechanism, household dust is able to migrate along the thin water film that forms on the inner walls of the cyclone vacuum cleaner. It collects dust in a small water inflow (3 mL/min), which allows it to capture a higher percentage of contaminants than most of the currently available vacuum cleaners. The significantly low accidental exposure rates achieved by this new vacuum cleaner enable healthy conditions in various environments, including indoors.

Introduction

Vacuum cleaners are used to remove dust and dirt, usually from the floors of homes and commercial buildings. Dirt particles are collected by using either a conventional dust bag or other methods such as canister, cyclonic, or wet collection systems. The importance of indoor air quality is recognized by all; in keeping with this fact, Americans annually spend approximately USD 500 million on whole house and portable air cleaners (Consumer Reports, 2010). Three million Americans are employed in the cleaning industry, and American adults daily spend 20–30 min on cleaning (Nazaroff and Weschler, 2004). In this light, a vacuum cleaner is essential for any household. In addition, nowadays, indoor air quality has attracted considerable interest because of the potential or latent drawbacks of currently available vacuum cleaners, such as resuspension of inhalable particles during vacuuming, escape of already captured particles through the dust bag or exhaust filter, and leaks in the connection parts of the vacuum cleaner (de Blay et al., 1998; Abt et al., 2000; Montoya and Hildemann, 2001, 2005; Ferro et al., 2004; Afshari et al., 2005; Corsi et al., 2008; Knibbs et al., 2012). Owing to such factors, vacuuming may actually worsen the air quality in a home.

Commercially available vacuum cleaners differ in terms of various parameters such as performance, filtration, capacity, storage, and noise level. The well-known bagged-type vacuum cleaner uses a paper- or cloth-type collection method for primary filtration; a so-called high-efficiency particulate air (HEPA) filter could also be used for this purpose. A HEPA has a filtration efficiency of 99.7% and retains particles as small as 0.3 µm. The term "down to 0.3 µm in size" does not refer to the same filtration performance. Instead, it may refer to a mixture of particle sizes for the stated efficiency. HEPAs often capture only 85–90% of the particles, and this efficiency may decrease even further for particles that are 1 µm or less in size because of air leaks or air permeation through the filter. Separately, several studies have noted the importance of periodically replacing the dust bag because of pressure drops, odors, and bacteria from the residual dust inside the bag (Cuneo et al., 1997; Yoa et al., 2001; Oh et al., 2004; Park et al., 2005).

Unlike a bagged-type vacuum cleaner, a cyclone system primarily uses centrifugal force to separate particles from air. It

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collects these particles without the need for a primary filter before finally forcing the air through an exhaust HEPA filter. Numerous studies have focused on enhancing the performance of cyclone systems (Ogawa, 1984; Moore and McFarland, 1996; Lee et al., 2000; Lim et al., 2003; Molhave et al., 2000; Ahn et al., 2006; Ha et al., 2011).

Vacuum cleaners need to be cleaned regularly as an important part of their maintenance. Whenever a disposable filter is replaced or the dust from a washable or reusable filter is removed, dust will inevitably spread again throughout the air. This study focuses on the emission of captured particles from vacuum cleaners during their regular operation or maintenance. We have investigated the release of mineral particles from commercially available vacuum cleaners (e.g., Samsung, LG, and Miele). In addition, a dust-free vacuum cleaner was characterized and recommended by using a system developed to test a water film cyclonic vacuum cleaning system as an alternative. The new cyclonic system was tested, and its performance was analyzed as a function of particle size, slot size, and other parameters such as the geometric dimensions of an inner part. The main objective of this study was to first determine the feasibility of using the proposed vacuuming concept for capturing particles; in this light, polystyrene latex (PSL) particles were utilized in a test. Then, this vacuum cleaner's performance will be compared with those of several previously investigated commercially available vacuum cleaners.

Materials and Methods

Measuring dust penetration

This experiment aims to identify the real collection performance (or penetration rates) of vacuum cleaners. The experimental apparatus consisted of a chamber, dust supplier, and particle analyzer.

Test particles

The test dust consisted of slate powder used in automobile air filtration tests and vacuum cleaner tests (Deutsche Montan Technologie, Essen, Germany; density: 2800 kg/m^3, overall size range: 0.3–100 μm). Its size distribution was measured using a particle size analyzer (LS 13 320; Beckman Coulter, Brea, CA).

Selected commercial vacuum cleaners

Three brand new commercially available household vacuum cleaners were chosen for this study. These vacuums were powered by 240 V AC (alternating current), and the power ratings of their motors ranged from 500 to 2200 W. Although it may not be possible to use the product price as a direct variable to estimate the vacuum performance in advance, common products with low motor power ratings were relatively inexpensive. In contrast, the Miele vacuum is known as one of the best-performing vacuum cleaners, and its price was relatively high. All three vacuums had a filtration system consisting of a washable prefilter without a dust bag in a canister and an H13-class (i.e., 3 out of 10,000 particles of 0.3-μm size can penetrate the filter) HEPA filter at the exhaust.

Experimental setup

Test chamber

Figure 1 shows a schematic of the chamber used for investigating dust penetration. The chamber volume was approximately 0.27 m^3. A hole at the bottom of the chamber of the vacuum cleaner was used to inject dust, and a vent pipe for exhausting dust and air was constructed at the top of the chamber. A probe was installed to monitor the dust concentration at this exhaust pipe, and an aerosol particle sizer (model 3321; TSI Inc., Shoreview, MN) was used to verify the concentration. The operating flow rate in the chamber was dependent on the flow rate of the vacuum cleaner, which means that no additional blower or motor was used to generate flow through the chamber. The chamber had to be sealed perfectly, except for the inlet and outlet for the dust, to ensure accurate calculation of the dust penetration efficiency. Then, the chamber was subjected to a sealing test using a tracer gas (sulfur hexafluoride, SF_6). The inlet and exhaust holes were completely blocked, and 100 ppm SF_6 was supplied to the chamber with an inflow rate of 1 L/min for 3 min. Sampling around the chamber was conducted at 10 different locations, and the gas concentration remained at zero for all the sampling locations for 10 min. The background concentration of SF_6 outside the chamber was too low to measure using a photoacoustic gas analyzer (model 1312; CAI Inc., Orange, CA), which had a low measurement limit of 100 parts per trillion (ppt). The Intergovernmental Panel on Climate Change (2001) reported that the background concentration of SF_6 in the ambient atmosphere is approximately 4.2 ppt.

Dust supplier

A schematic of the homemade dust supplier is shown in Figure 2. The test dust was loaded at regular intervals of a groove on the dust supplier. The suction nozzle was

Table 1. Specifications of commercial vacuum cleaners

Manufacturer	Model	Motor Power, Watt	Type	Exhaust HEPA Grade
Samsung	VC-BA730	510	Canister Washable prefilter No dust bag	H13 filter
LG	VC4927FHAY	500		
Miller	S5781	2200		

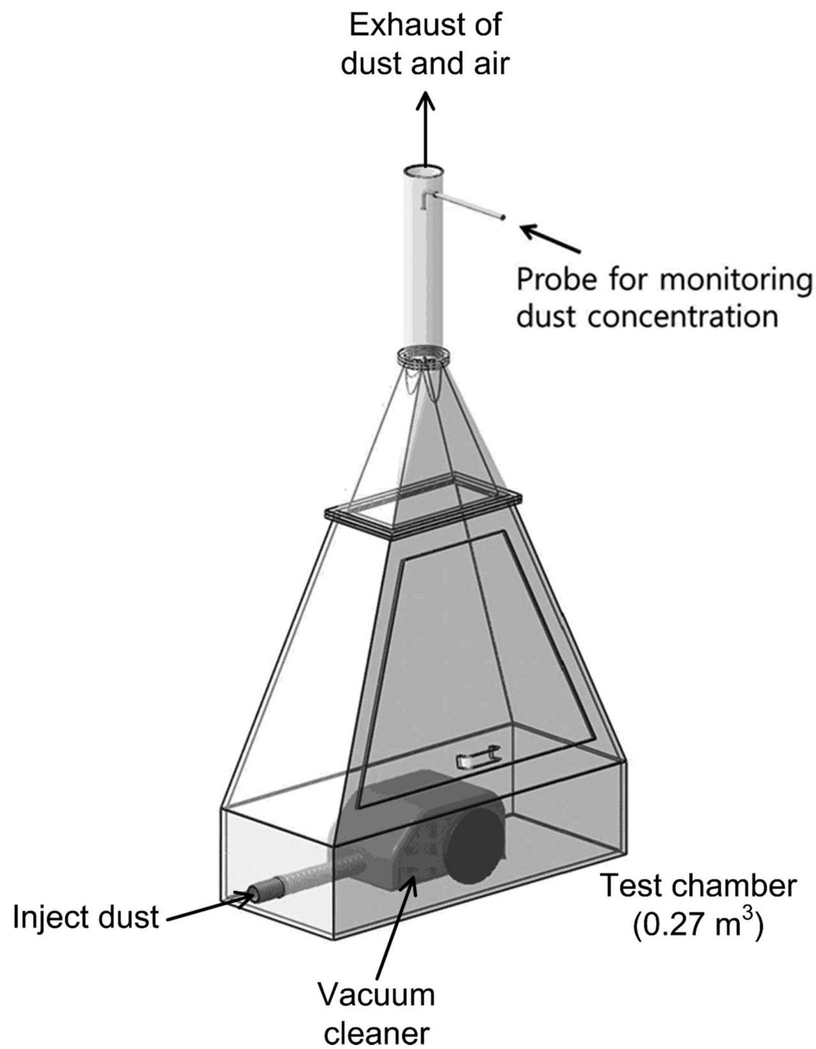

Figure 1. Schematic of dust penetration setup.

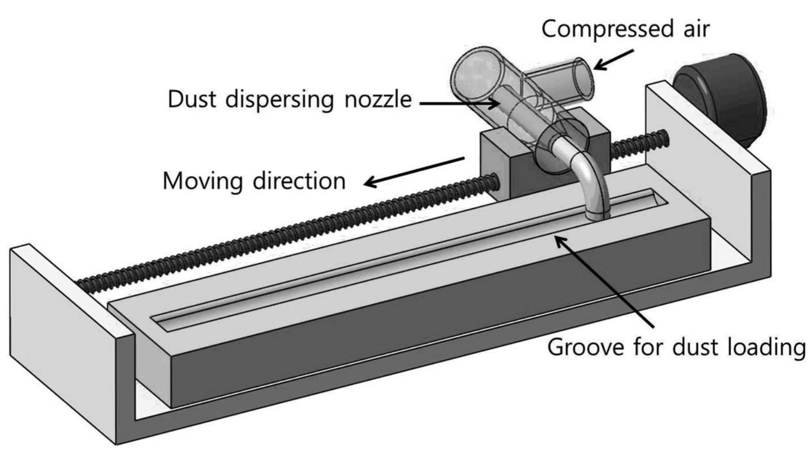

Figure 2. Schematic diagram of dust loading system.

transported at a constant speed. Thus, dust was loaded at a consistent rate (0.550 g/m^3) into the vacuum cleaner. The dispersion period was 2 min. Suction by a vacuum cleaner inlet hose was the main force used to pick up the dust from the groove; this was also beneficial for the effective dispersion of the dust and the prevention of dust agglomeration. The amount of test dust was determined based on the maximum flow rate, and it can be expressed as follows:

$$m = c \times t \times q_{\max} = 66 \times q_{\max} \quad (1)$$

where m (g) is the amount of dust loading; c (g/m^3), the dust concentration; t (sec), the test period; and $q_{\max}$ (m^3/sec), the maximum flow rate.

Determination of dust penetration efficiency

A vacuum cleaner was located at the center of the chamber's base side. The vacuum cleaner was switched on for 10 min, and the background concentration was monitored using an aerosol particle sizer (model 3321; TSI Inc.). Then, the prepared dust in the groove was extracted and dispersed into the vacuum cleaner for 2 min. To collect all the dust exhausted from a vacuum cleaner, the vent pipe was connected with a flexible tube. The dust and air from this tube impinged against the water in a 5-L container. A particle size analyzer (model LS 13 320; Beckman Coulter) was used to analyze the dust distribution and its volume fraction in the water. Dust samples taken before and after the experiments were analyzed to determine their size characteristics and the dust penetration efficiencies. The above test was repeated five times. The average value and standard deviation were reported.

$$\text{Dust penetration efficiency} = \frac{\text{Amount of exhausted dust}}{\text{Amount of injected dust}} \quad (2)$$

Retrofit and characterization of water film cyclone

A wetted wall cyclone collects particles, concentrates them, and coverts the aerosol to a hydrosol. Liquid is input so as to form a film onto which the aerosol particles are impacted. The shear of the airflow carries the liquid to a skimmer, where the hydrosol and airflows are separated, and the hydrosol is aspirated from the system. A cyclone that operated at an air flow rate of 1250 L/min was designed, developed, and finalized for sampling a bioaerosol by Seo (2007). The standard aerosol sampling flow rate was 1250 L/min, and the pressure drop across the cyclone was 5.5 kPa (22 inches H_2O). The liquid effluent flow rate of the cyclone was set at 1.6 mL/min. The cutpoint of this sampler was an aerodynamic diameter (AD) of 1.2 µm, and the average collection efficiency was 90% over the size range of 2–10 µm AD. The slot size of the cyclone inlet was 6.35 mm (0.25 inch).

Stokes scaling process

An experimental evaluation of a preliminary version of the 2400 L/min cyclone was performed. The critical dimensions (i.e., slot width) of the cyclone were intuitively determined by upscaling the geometrical details of the 1250 L/min wetted wall cyclone (Seo, 2007) according to the Stokes number (Table 2). The Stokes scaling methodology was adopted to design the subsequent version, in which the slot width was reduced by 24% to obtain the desired cutpoint value of 0.5 µm. In the Stokes scaling process, D_j and U were the only parameters that needed to be considered, as shown in eqs 3, 4, and 5.

$$Stk_{50,1} = \frac{d_{p_{50,1}}^2 C_C \rho_P U_1}{9\mu D_{j,1}} = Stk_{50,2} = \frac{d_{p_{50,2}}^2 C_C \rho_P U_2}{9\mu D_{j,2}} \quad (3)$$

$$\frac{d_{p_{50,1}}^2 U_1}{D_{j,1}} = \frac{d_{p_{50,2}}^2 U_2}{D_{j,2}} \rightarrow \frac{d_{p_{50,1}}^2 Q_1}{W_{j,1}^2} = \frac{d_{p_{50,2}}^2 Q_1}{W_{j,2}^2} \quad (4)$$

$$\frac{d_{p_{50,1}}}{W_{j,1}} = \frac{d_{p_{50,2}}}{W_{j,2}} \quad (5)$$

Here, d_{P50} = cutpoint aerodynamic particle diameter; C_C = Cunningham's correction (Hinds, 1999); ρ_P = density of particle; U_i = speed of air in the inlet slot; μ = air viscosity; and $D_j = W_j$ = slot width. Two cyclones with different sizes should collect particles equally well if they are designed and operated with equal values of the Stokes number, *Stk*, and the Reynolds number, *Re*.

Test particles and experiment setup

Figure 3 shows a schematic of the bench-scale test setup used to evaluate the particle collection characteristics of the wetted wall cyclones. Polystyrene latex (PSL) beads (Duke Scientific, Palo Alto, CA; Bangs Lab, Fishers, IN) of four sizes—0.2, 0.5, 1, and 1.9 µm—were used to characterize the aerosol performance. Tests were conducted by alternately exposing the cyclones and a reference filter.

A collision nebulizer (CN60; BGI, Inc., Waltham, MA) was used to generate PSL particles. Prior to the exposure of the cyclone or reference filter, the generated aerosol was passed through a 2-mCi Po-210 neutralizer, following which it traveled through a mixing box to enhance the mixing of the aerosol

Table 2. Design parameters of 2400 L/min cyclone (unit: mm)

Component	Parameter	Abbreviation	Measurement (mm)		
Inlet	Diameter	D_I	78.9		
Slot width		W	7.1	4.8	
Body	Length	L	166.6		
	Diameter	D_e	47.3		
Vortex finder	Diameter	D_v	25.4	19.1	12.7
	Length	L_1	90.9	82.8	80.5
	Type	D_v/D_e	0.54	0.40	0.27
		D_v/D_I	0.32	0.24	0.16
		L_1/D_e	1.92	1.75	1.70

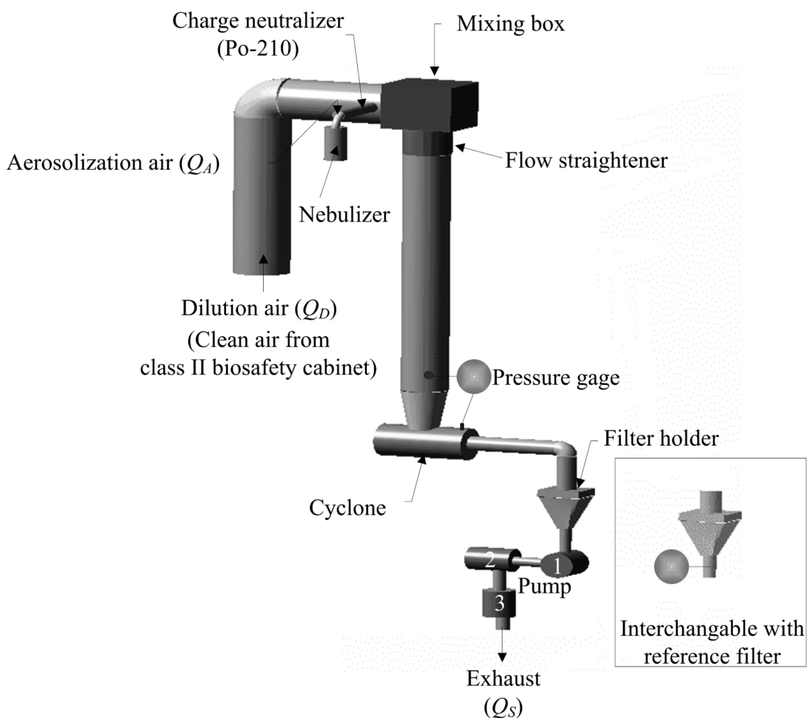

Figure 3. Schematic of experimental setup. The reference filter was used to determine the aerosol reference concentration.

stream. The electrically neutralized aerosol passed through a flow straightener and entered the testing chamber, where it was collected by the cyclone or a reference filter at a flow rate of 2400 L/min. Liquid, at a predetermined inflow rate, was provided to the cyclone by a syringe pump (Genie Plus; Kent Scientific Corp., Torrington, CT). Distilled water was used as the collection fluid. The hydrosol sample was recovered from the 2400 L/min cyclone by using a peristaltic pump (Fisher Variable-Flow Peristaltic Pumps; Fisher Scientific, Inc., Austin, TX). Three blowers (models 119104, 119153, and 119153; Ametek, Inc., Paoli, PA) provided airflow through the system.

A PSL suspension (master suspension) was prepared by diluting commercially available concentrated fluorescently tagged PSL. First, 10 mL of concentrated PSL was added to 100 mL of distilled water to prepare the master suspension for each size. To ensure consistent concentrations of PSL output from the nebulizer, it was refilled with the PSL master suspension before each test. Each run required 10 min, which was an appropriate period for collecting sufficient PSL such that the fluorescence of the reference sample was significantly greater (by at least 20 times) than that of the background fluorescence. At the end of a test, the leftover suspension was placed in a "recycled PSL suspension" container, and it could then be used as the master suspension for other sets of tests.

Aerosol penetration test

A glass fiber filter (type A/E; Pall, East Hills, NY) was used as the reference filter to collect the fluorescent PSL particles. The blowers were switched on, and then the collision nebulizer was switched on to generate the PSL particles. After running for 10 min, the nebulizer was switched off. However, the blowers were run for another 10 sec to collect all the PSL particles at the upstream filter. Then, the filter was transferred into a container. To dissolve the PSL from the filter, a predetermined amount of ethyl acetate was added to the container, and a threaded lid was placed on the container during soaking. Then, the container was left to stand for approximately 1 hr to ensure proper mixing.

All the system components, including the blowers and all the pumps, were actuated simultaneously to determine the aerosol penetration efficiency. When the liquid effluent flow rate reached a steady state, the collision nebulizer was switched on. The system was operated for 10 min, after which it was switched off. At the end of each set of tests (replicate samples for the same test conditions), the cyclone was rinsed with ethyl acetate and then with distilled water. As shown in Figure 3, the after-filter at the cyclone exhaust was analyzed using the same method as that used for the reference filter.

Determination of penetration efficiency

The aerosol penetration efficiency, $\eta_{Penetration}$, was based on the fluorometric readings of the cyclone after-filter and the reference filter. In particular,

$$\eta_{\text{Penetration}} = \frac{C_{\text{exhaust}}}{C_{\text{reference}}} \tag{6}$$

where C_{exhaust} is the aerosol concentration based on the fluorometric reading from the cyclone after-filter and $C_{\text{reference}}$, the aerosol concentration based on the fluorometric reading from the reference sample.

The relative aerosol concentration, C, of the fluorescent dye in the sampled air, as calculated from an analysis of the fluorescence of a solution, was

$$C = \frac{FV}{tQ} \tag{7}$$

Here, C is the concentration of fluorescein eluded in ethyl acetate (fluorometer reading); F, the numerical reading of the fluorometer (model FM109515; Quantech, Barnstead International, Dubuque, IA); V, the solution volume; t, the sampling time; and Q, the air flow rate.

Results and Discussion

The total mass of the tested mineral particles was converted to a fractional amount in each size range. Figure 4 shows the cumulative mass of the particles plotted against the particle size. Apparently, all the particles were smaller than 170 μm. The cumulative mass between 1.7 and 17 μm AD was 36%. Finally, only 3% were smaller than 1.7 μm.

The dust penetration efficiencies for all the vacuum cleaners tested are shown in Figure 5. Unlike the general information provided by commercial manufacturers, we observed very large penetrations in the range of 1–17 μm through different loss modes such as leakage, permeation, and resuspension. The following particle size ranges were considered: 0.5–1.0, 1.0–1.7, 1.7–3.3, 3.3–5.0, 5.0–8.4, 8.4–15.1, and 15.1–16.7 μm AD. The averaged overall dust penetration efficiency was approximately 14 ± 8% (mean ± standard deviation). For all the vacuum cleaners, the penetration efficiency ranged from 2% to 26%, except in three cases where it was more than 30%: A-model at 5.0–8.4 μm, B-model at 0.5–1.0 μm, and D-model at 15.1–16.7 μm, which were 33%, 31%, and 39%, respectively. These three exceptions were likely due to leaks in the connection parts for the HEPA holder at the exhaust. However, overall, significant losses (over ~14%) represent another source of indoor exposure to airborne particles and bacteria. Most users are less aware and seemingly unwilling to consider that there could be a potential risk because of this counterproductive situation. A significant difference ($P < 0.05$) was found between the A-model and the E-model at particle sizes of 1.7–3.3 μm, between the A-model and some of the others (D, E, and F) at particle sizes of 3.3–5.0 μm, between the A-model and the E-model at particle sizes of 5.0–8.4 μm, and between the D-model and the others (A, B, C, E, and F) at particles sizes of 15.1–16.7 μm.

As a recommendation to prevent accidental penetration from existing commercial vacuum cleaners based on the abovementioned results, an impact-type cyclone vacuum cleaner that utilizes a water film on the inner surface was tested. For two different sizes of prototypes (with slot sizes of 7.1 mm [0.28 inch] and 4.8 mm [0.19 inch]), the penetration efficiencies were experimentally measured with different particle sizes: 0.51, 1.02, and 1.95 μm PSL for the 7.1-mm slot size cyclone and 0.20, 0.51, 1.02, and 1.95 μm PSL for the 4.8-mm slot size cyclone. The results of the efficiency measurements are shown in Figure 6. The penetration efficiency is plotted as a function of the aerodynamic particle size for each slot size. In these cases, the curves are similar in shape, but the slope of each curve is dependent on the slot size. The penetration efficiency decreases with an increase in the Stokes number, which is a function of the particle diameter, face velocity, and characteristic length. Because of the different slot sizes involved in the impaction regime, the penetration results as a function of the particle diameters of the 7.1-mm slot unit, for 2400 L/min, are 87.7 ± 3.4% (0.51 μm), 35.9 ± 2.4% (1.02 μm), and 1.5 ± 0.1% (1.95 μm) (Figure 6). For the 4.8-mm slot unit, these decreased to 69.1 ± 3.5% (0.20 μm), 50.9 ± 3.7% (0.51 μm), 6.4 ± 1.9% (1.02 μm), and 1.4 ± 0.1% (1.95 μm). By improving the 1250 L/min wetted wall cyclone (Seo, 2007), based on the Stokes scaling method, the desired cutpoint for 2400 L/min, 0.5 μm, was achieved here through an optimizing process. The cutpoint (particle size corresponding to 50% collection efficiency) of the 7.1-mm unit was 0.89 μm for 2400 L/min, whereas that for the 4.8-mm unit was 0.52 μm. The pressure drops across the 7.1- and the 4.8-mm slot units were approximately 6.0 kPa (24 inches H_2O)

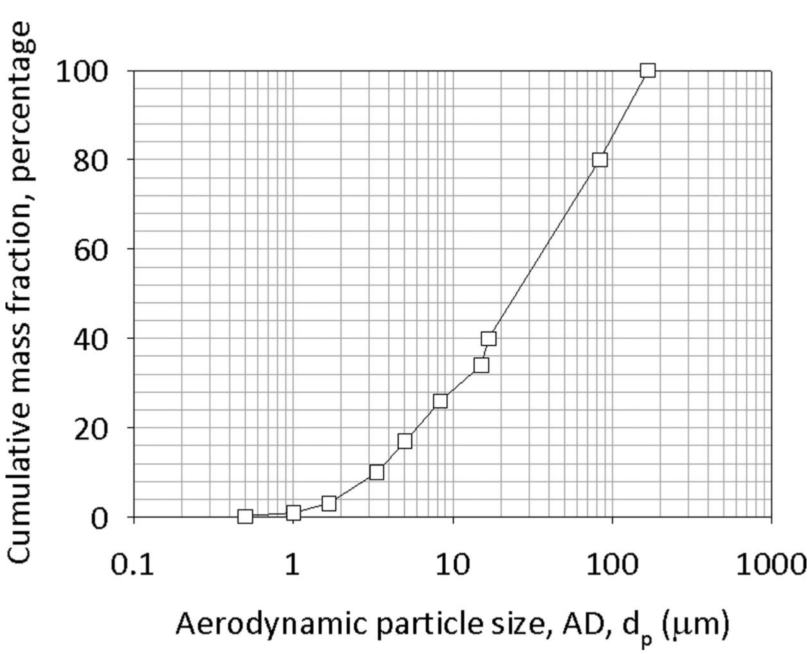

Figure 4. Cumulative mass distribution curves as function of aerodynamic diameter for tested mineral particles.

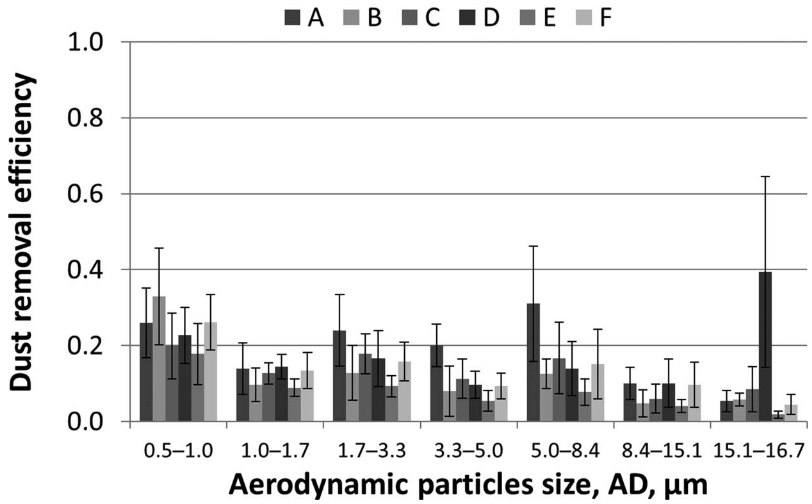

Figure 5. Dust penetration efficiencies of three vacuum cleaners under two different operation conditions: Samsung (A: 2000 L/min and B: 1560 L/min), LG (C: 1866 L/min and D: 1260 L/min), and Miller (E: 2430 L/min and F: 1020 L/min).

and ~10.2 kPa (41 inches H_2O), respectively. Unfortunately, although almost twice the amount of air, 2400 L/min, could be brought into the collector, the unavoidable pressure drop was approximately doubled compared with 1250 L/min.

In every case, the penetration efficiency against particle size led to a curve whose slope and *y*-intercept both depended on the slot size, as shown in Figure 6. The relationship between the efficiency and particle size can be obtained in the following form (sigmoid, 4-parameter) using commercial graphing software (SigmaPlot, 2004).

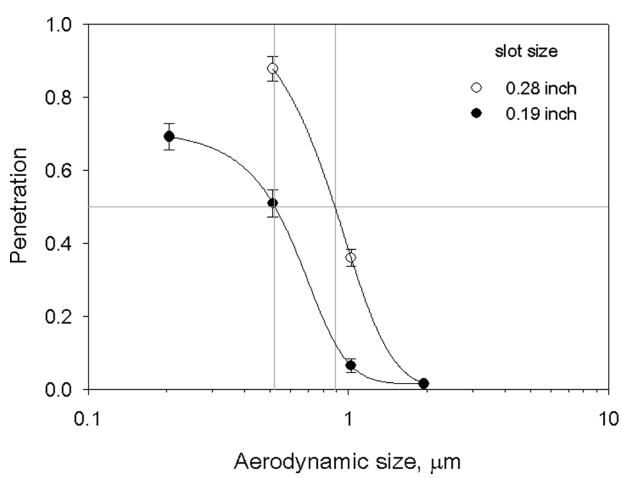

Figure 6. Aerosol penetration as function of particle size according to two different slot sizes (7.1 mm versus 4.8 mm).

$$\eta = \frac{a}{1 + e^{-\left(\frac{D_p - x_0}{b}\right)}} + y_0 \qquad (8)$$

The constants a, b, x_0, and y_0 for all the screens are listed in Table 3 to express the final correlation between the standardized screen efficiency and the Stokes number.

Figure 7 shows the collector performance according to (a) the ratio of the diameter of the vortex finder to the diameter of the exit and (b) the ratio of the length of the vortex finder to the diameter of the exit for different particle sizes. The dimensions of the two cyclones and all the other dimensions are summarized in Table 2. The diameter of the vortex finder is directly related to the width of the annular section between the vortex finder and the sidewall of the cyclone. Thus, a vortex finder with a small diameter produces a large annular space, which may lead to an increase in the swirling component of the fluid velocity, making the cyclone more efficient. However, the efficiencies are almost the same at all three ratios and three particle sizes as a result of employing impaction as a major collecting mechanism, unlike the conventional cyclone, which uses a centrifugal separator. This difference was not statistically significant ($P > 0.05$).

For the dust penetration test, a prototype was fabricated with the tested cyclone. Figure 8 shows the full setup of the applied cyclone, a bottle for water injection, and a bottle for water extraction. Finally, the dust penetration efficiency of the cyclonic vacuum cleaner was tested, as shown in Figure 9. Unlike the commercial vacuum cleaners investigated in this study, we

Table 3. Values of a, b, x_0, and y_0 in eq 8 obtained by regression analysis

Slot size	a	b	x_0	y_0	R^2	d_{50}
7.1 mm (0.28 inch)	1.1449	−0.2604	0.8210	0	1.0	0.89
4.8 mm (0.19 inch)	0.7172	−0.1508	0.6332	0.0138	1.0	0.52

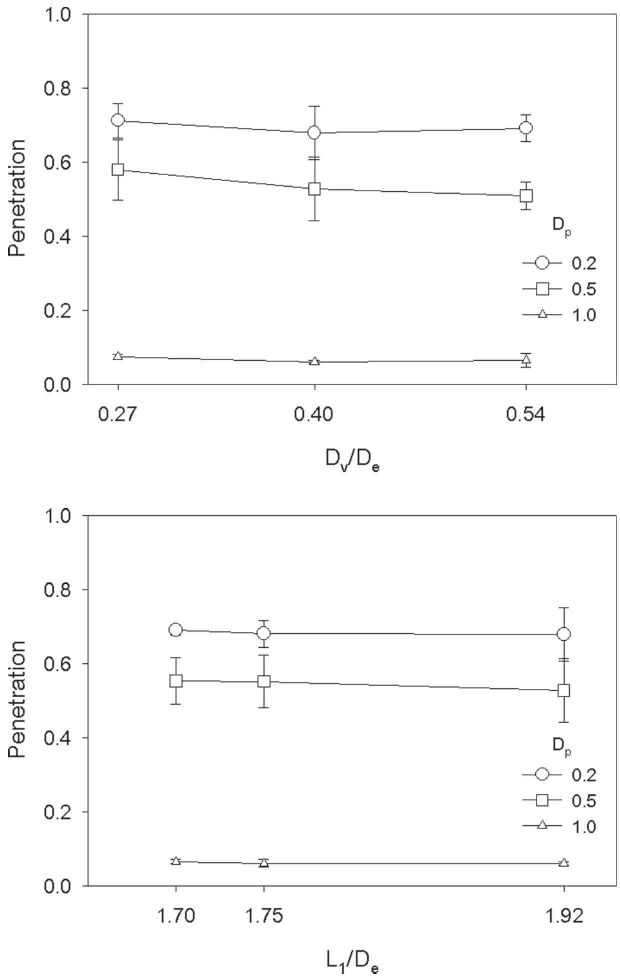

Figure 7. Comparison of penetration as function of ratio of (a) vortex finder diameter to exit diameter and (b) vortex finder length to exit diameter according to different particle sizes.

successfully observed very limited penetration with our cyclonic vacuum cleaner, with an overall average of less than 3.8% in the full range of 0.5–17 μm. When the impaction-type cyclonic duct collector was used with 3 mL/min of liquid inflow for dust collection, the overall penetration rate could be much lower than that of the other vacuum cleaners, which may have been due to the difference in the design of the collection/removal mechanism. The unique tangential slot arrangement in the collector created strong impaction on the inside water film and helped to minimize reentrainment of already collected particles from the liquid, which resulted in better collector performance. The recommendations to decrease the overall penetration rates of existing commercial vacuum cleaners based on this study are (1) better sealing, (2) designing and retrofitting a removal mechanism, or (3) using a new device.

Conclusion

In this study, the penetration rates of three brands of commercially available vacuum cleaners were investigated and compared with that of a unique cyclonic collector that employed a small amount (~2 mL/min) of water as a collection tool. A tangential-type cyclone with an inlet, a very narrow slot, a vortex finder, a small hole for dust removal, and an air outlet was evaluated using different particle sizes, and different inner geometric sizes for the vortex finder were compared (e.g., diameter and length). The summarized conclusions are as follows: (1) All three commercial vacuum cleaners investigated in this study had an average penetration rate of 14% in the full range (0.5–17.0 μm), by accident or by design. (2) The penetration efficiency of the tested 4.8-mm slot cyclone by itself was less than 6% with 1.0-μm PSL particles. (3) The penetration rate of the new vacuum cleaner with the cyclonic mechanism was slightly less than 3.8% in the full range (0.5–17.0 μm). The new prototype vacuum cleaner with a narrow slot size (4.8 mm) had high removal efficiency, and the optimal dimensions for the impaction-type vacuum cleaner were derived.

Acknowledgment

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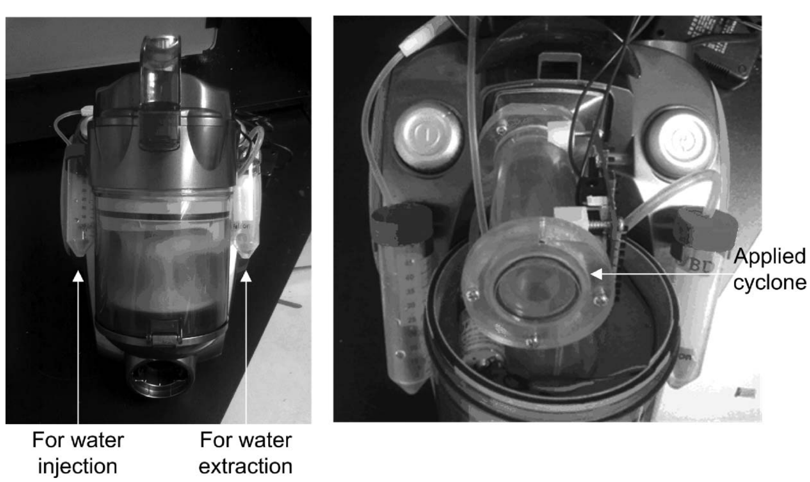

Figure 8. Photographs of prototype employing test cyclone for dust penetration test.

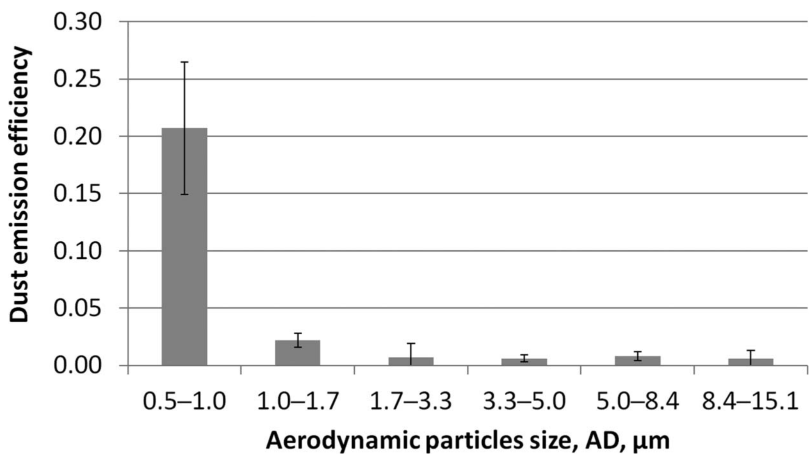

Figure 9. Dust penetration rate from cyclonic vacuum cleaner at different particle size ranges.

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