2008-5435/09/11-1-8
INTERNATIONAL JOURNAL OF OCCUPATIONAL HYGIENE

IJOH 1: 1-8, 2009

ORIGINAL ARTICLE

Design and Set up of an Air Filter Testing Unit to Demonstrate Characteristics and Performance of Particulate Air Filters

FARHANG AKBAR-KHANZADEH[1*], KEN SMIGIELSKI[2]

[1]*Department of Public Health, College of Medicine, University of Toledo Health Science Campus, Toledo, Ohio, USA;* [2]*First Solar Inc., Perrysburg, Ohio, USA.*

Received March 4, 2009; Accepted June 25, 2009

This paper is available on-line at *http://ijoh.tums.ac.ir*

ABSTRACT

An air filter is a significant element of any mechanical ventilation system. However, the importance and performance evaluation of air filters have not been well publicized and related scientific reports are scarce. In this study, a transportable, off-line, air filter-testing unit (the Unit) was designed and utilized to simulate the filter housing of a mechanical ventilation system. The Unit was designed, assembled, and operated in a laboratory. To demonstrate the applications of the Unit, a series of air filter handling and installation scenarios was performed to determine the characteristic curve and capture efficiencies of a selected set of HEPA filters. The research project produced a transportable, closed system air filter testing unit. The Unit incorporated a fan, a damper to adjust air flowrate, a filter-housing (consisting of a mixing chamber, a filter-frame, and a pressure-gauge), and ducting with ports to introduce challenge particles and monitor them after filtration. By using the Unit, the detrimental effects of damaged filter-media, damaged filter-gasket, and improper installation of air filters on their capture efficiencies were clearly demonstrated. An air filter testing unit, similar to the Unit presented here, can readily be designed, fabricated, and assembled to simulate the filter-housing of mechanical ventilation systems. The assembled unit can be used (1) to determine capture efficiency of air filters and their characteristic curve, (2) to demonstrate the negative effects of improper handling and installation of air filters, and (3) as an effective investigative and educational tool.

Keywords: *Air filter testing unit, Filter capture efficiency, HEPA filter test*

INTRODUCTION

Airborne particulate contaminants can be controlled using mechanical ventilation systems. The air filter, installed within a filter-housing on a filter-frame, is one of the major elements of any mechanical ventilation system. Air filters are fragile and can easily be damaged during packaging, handling or upon installation [1, 2]. The integrity of air filters is particularly important in order to prevent contaminated air leakage. According to the U.S. National Institute for Occupational Safety and Health (NIOSH) [3] "the integrity of the ventilation system's filter rack or frame system has a major impact upon the installed filtration efficiency."

***Corresponding Author:** Farhang Akbar-Khanzadeh, Ph.D., E-Mail: Farhang.Akbar@UToledo.edu

Several on-line (in-place) air filter testing recommendations and standards are currently in use worldwide [4-10]. During an on-line (in-place) testing (Fig. 1), the integrity of air filters and the ventilation system is checked during an active production process. However, on-line filter testing is not suitable for on-going research projects, testing the integrity of newly purchased air filters prior to permanent installation, or group training situations because the filter-housings are usually contaminated with harmful particles prior to changing a filter, and the filter-frames are often located in hard-to-reach, odd locations. Therefore, the design and manufacturer of a transportable air filter testing apparatus for off-line testing could meet a recognized need. During an extensive literature review, the authors were unable to find any published reports regarding the existence of an air filter testing apparatus designed

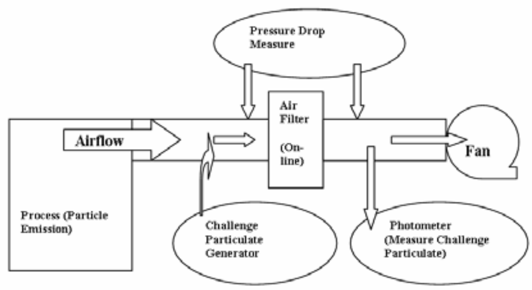

Fig. 1. A simplified general view of the setup for on-line (in-place) filter efficiency testing in mechanical ventilation systems.

specifically to evaluate air filter performance for educational or research purposes. Additionally, except a pilot survey by Morrow [11], no published reports were found describing the pitfalls associated with air filter handling or installation.

The scope of the problem, created by this void in training and maintenance practices, is evident in the results of the survey by Morrow [11]. His pilot survey was conducted at three relatively large manufacturing sites, each with established maintenance and health and safety departments. The main goal of the pilot survey was to observe compliance with elements of acceptable air filter management. During the pilot survey, no attempts were made by the researcher to quantify the efficiency of the air filters. All three of the facilities demonstrated poor to fair conformance to prudent maintenance practices and appropriate guidelines. Morrow concluded that, non-conformance issues were generally instances of deficiencies in the elements of air filter management including those activities related to their ordering, handling and installation. Often air filters were not ordered based on expert opinion, air filters were not inspected, the shelf life of filters was not documented, and occasionally there was no seal between air filters and filter-frames. Surprisingly, there were also instances of no filter being present on the filter-frame within the ventilation system, clearly defective filters, and poor or no airflow directional alignment. Furthermore, air filters were installed that did not exactly match the filters they replaced, filters were installed with no filter-brackets secured on the filter-frame, the brackets were not tightened as recommended, and the filter-housings were not completely sealed.

The authors' personal experiences confirm that, maintenance technicians, including filter installers and their supervisors, often lack an understanding of the air filters' structure, capabilities, limitations and performance requirements. These individuals rarely have appropriate training, time or the equipment needed to perform an air filter efficiency performance evaluation. Even in the health and safety community the importance of air filters and the procedures necessary to determine their effectiveness are not well publicized. In addition, scientific papers reporting educational information regarding the need for performance evaluation of air filters, or providing effective procedures to accomplish off-line evaluation of air filters, are scarce.

Therefore, this study was initiated with the following main objectives: (a) to design and set up an operator-friendly, transportable air filter testing unit (the Unit) that simulates the filter-housing of mechanical ventilation systems; (b) to utilize the Unit as an effective investigative and educational apparatus; (c) to demonstrate some major applications of the Unit such as determining the characteristics of air filters; and, (d) to set up a variety of pertinent scenarios of air filter handling and installation and to demonstrate their effects on the capture efficiencies of the air filters.

MATERIALS AND METHODS

Air filter testing unit (the Unit)

Some parts of the designed air filter testing unit were fabricated by an outside production company and transported to a thoroughly washed and disinfected laboratory on the university campus. Other parts such as the fan and pressure gauge were ordered. The Unit was assembled and operated in the laboratory. The specifications of the Unit's design are described in the Results section of this report.

Air flowrate measurement

A velometer (Alnor Velometer, Series 6000; Alnor Co., Huntington Beach, CA, USA) was used to determine the flowrate of the air stream at a cross-section of one of the ducts within the Unit by the "10-Point Log-Linear Traverse Points" method of air velocity measurement as recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) [12].

Particulate measurement

In this study, two methods of filter efficiency testing were utilized. Method 1 is a standard method commonly used by the Institute of Environmental Science and Technology recommended practice (IEST-RP-CC034) [13]. This method requires an expert consultant and sophisticated instrumentation, which limits its application. Method 2, also an acceptable technique [5] is often chosen for its ease of use in most places.

Method 1. Following the guidelines for this method [13], a challenge particulate matter (Polyalpha Olefin, POA), with a known concentration (100 μg/L), was generated (Air Operated Aerosol Generator TDA-4B; Air Techniques International, Owings Mills, MD, USA), and injected into the first duct far enough upstream from the installed filter to create a uniform particulate dispersion. After passing through the filter, the concentration of particles in the filtered air was measured downstream, inside the second duct, by using a particle photometer (AT2G Photometer; Air Techniques International, Owings Mills, MD, USA). The two concentration values obtained from the input port and the output port were used to determine the capture efficiency or penetration rate of the particles passing through the air filter.

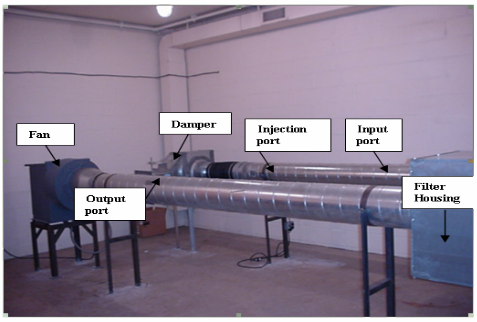

Fig. 2. The Unit - An off-line air filter testing unit with major elements displayed.

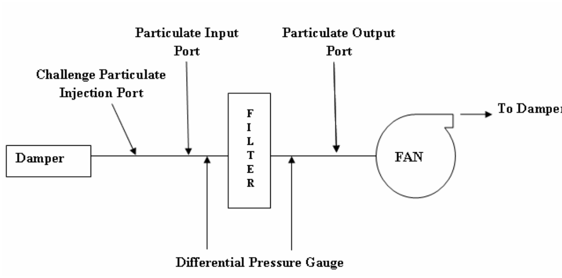

Fig. 3. The Unit - A simplified diagram of the design of the off-line air filter testing unit.

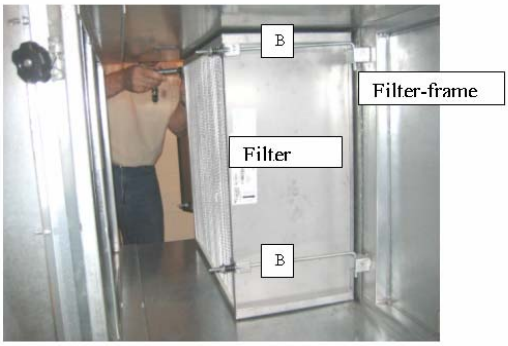

Fig. 4. Filter and filter-frame within the filter-housing of the Unit; two of the four filter-brackets are visible (B); the filter installer is securing a bolt on an upper filter-bracket on the far side of the picture.

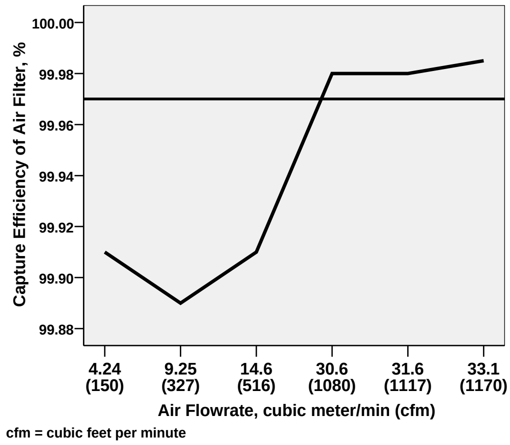

Fig. 5. Capture efficiency of a properly installed HEPA filter (brand A) by air flowrate; the HEPA filter 99.97% capture efficiency criterion line is also shown.

*Method 2***.** In this method, air filter efficiency was determined by measuring the challenge particle counts before and after filtration. A nebulizer (Respironics Inspiration 626 Compressor Nebulizer System; Philips Respironics, Inc., Murrysville, PA, USA) was used as a particle generator. The nebulizer, a medical unit for application of medication for patients with asthma, was a plastic device attached to a compressed air pump converting fogjuice (theater smoke) into airborne particles (poly-dispersed particles). The nebulizer's operation pressure and flowrate were 80 kPa (11.6 psi) and 6.2 L/min (0.013 cfm), respectively. The particles contained a wide diameter range with 87% between 0.5 and 5 µm. The number of particles at 0.3 µm in diameter was measured through both the input and output ports of the Unit. The two measured values were used to calculate the capture efficiency of the air filters. The particle counter (Hach/Ultra, ARTI HHPC-6; RAECO, Bensenville, IL, USA) had the capability of counting particle sizes of 0.3, 0.7, 1.0, 2.0, 5.0, and 10.0 µm in diameter but only particles with diameter of 0.3 µm were recorded in this study. The particle counter and measuring instruments were factory calibrated prior to their application.

Penetration Rate (Percentage Leak) and Filter Capture Efficiency - Penetration Rate (Percentage Leak) was defined as $L = 100\ (C_d / C_u)$; where L is percentage leakage, C_d is downstream concentration of particles (measured at output port) and C_u is upstream concentration of particles (measured at input port). Percentage capture efficiency (Eff) was defined as: $Eff = (100 – L) = 100\ (C_u - C_d)/ C_u$**.**

Particulate air filters

Filter specifications - Six high-efficiency particulate air (HEPA) filters, two each from three manufacturers (brands) A, B, and C, were purchased and evaluated based on design principles, particulate capture efficiency (or penetration rate), and consistency of effective installation. Each of the HEPA filters was 61 x 61 x 29 cm (24 x 24 x 11.5 inch).

Brand A HEPA filter (Camfil Farr, Northern Illinois, USA) was manufacturer rated at 99.97% efficient with 2.1 cm (0.82 inch) water gauge pressure drop at a flowrate of 30.02 m^3/min (1060 ft^3/min). Its maximum recommended flowrate was 30.59 m^3/min (1080 ft^3/min). The filter was equipped with a one-piece, seamless, urethane gasket. Brand B HEPA filter (TRI DIM, Phoenix, AZ, USA) was manufacturer rated at 99.97% efficient with 2.34 cm (0.92 inch) water gauge pressure drop at a flowrate of 30.02 m^3/min (1060 ft^3/min). The filter was equipped with dovetailed gaskets. Brand C HEPA filter (BLC Industries, Louisville, KY, USA) was manufacturer rated at 99.97% efficient with 2.25 cm (0.90 inch) water gauge pressure drop at a flowrate of 30.02 m^3/min (1060 ft^3/min). The filter was equipped with two-piece flush gaskets.

Filter inspection - When received, each filter package was visually inspected for dents, foot prints, a broken outer box, a punctured outer box, holes, information regarding proper storage, and directions or arrows for installation. During unpacking, each filter was inspected to observe technical issues related to removing the filter from its shipment container and to note filter structure and texture, labels (e.g., recommended air flow, pressure drop across the filter), signs or arrows indicating air flow direction and gasket types.

Proper installation conditions - The filters and filter-gaskets were dry and undamaged; they were installed in the recommended vertical position, in the proper direction for airflow; and all four filter-brackets on the filter frame were finger-tightened, with 5 additional turns with a nut-driver to ensure equal and adequate tightening. The number of additional complete turns (e.g., 5) was chosen based on researchers' experience.

Characteristic curve – A HEPA filter was randomly selected and installed properly. Counts of particle diameter of 0.3 μm were obtained by using Method 2, and its capture efficiencies were determined at a set of air flowrates through the filter. A graph was drawn to depict the changes in capture efficiency versus changes in flowrate. The graph served as the characteristic curve of that air filter under the laboratory conditions.

Filter installation scenarios - The capture efficiencies of different filter brands were measured under a total of 20 different test scenarios, including proper handling and installation. These scenarios were created by combinations of different conditions within three potentially problematic categories: Filter Balance/Imbalance due to changes in bracket tightening; Filter Damage; Gasket Damage; and slightly Wetted Filter/Gasket (condition of very high relative humidity).

Filter bracket tightening - To simulate the actual field practices in which the filter-brackets are finger-tightened by the filter installer, the same approach was employed in this study and the specific tension (torque) on the brackets was not quantified by using torque wrenches. Additional turns of nuts by using a nut-driver were to determine changes of the capture efficiency when the installer used this common approach.

Air flowrate used in test scenarios - HEPA filter charatistic curves, provided by the manufacturers, collectively showed that the capture efficiencies corresponding to the air flowrates of more than 29.71 m^3/min (1050 ft^3/min) through the filter met the criterion of 99.97% capture efficiency. In relation, for the test scenarios in this study, a flowrate of 30.02 m^3/min (1060 ft^3/min) was chosen and used throughout.

Statistical data analysis

During each test scenario, three readings were taken consecutively and the reading with minimum value (worst-case from a health and safety perspective) was reported as the test value.

The statistical package SPSS (SPSS Inc., Chicago, IL, USA) was used to organize, analyze and graph data collected. T-test was used to determine differences between two means. ANOVA was used to test the differences among more than two means.

RESULTS AND DISCUSSION

Design outcome of air filter testing unit

The Unit was assembled as a closed system (Fig. 2 & 3) with the components connected in the order that follows; (1) An electric fan with its related motor and electrical wiring; (2) A manually operated industrial damper, used to adjust the air flowrate; (3) The first round duct, having 3.36 m (11 feet) length and 25.4 cm (10 inch) inside-diameter. Two ports were drilled into the first duct. The first port (injection port) was used to inject challenge particles into the system. The second port (input port) was located downstream from the injection port and was used to monitor the injected challenge particles upstream before they entered the mixing-chamber of the filter-housing; (4) The filter-housing (Fig. 4), with operator-access doors on two sides, consisted of a mixing-chamber and a filter-frame. The filter frame was equipped with 4 brackets to hold the filter in place and two ports, on two sides, connected to a magnehelic differential pressure gauge (0 to 5 w.g., Series 2000; Dwyer Instruments, Michigan City, IN, USA) that was used to monitor the pressure drop across the air filter when one was installed within the filter-frame; and, (5) A second round duct having 3.36 m (11 feet) length and 25.4 cm (10 inch) inside-diameter. One port (output port) was drilled into the second duct to monitor the downstream concentration of the challenge particles in the filtered air after the particles passing through the air filter and before entering the fan for recirculation. The unit was assembled in a very clean laboratory and was leak checked by a professional contractor to assure its integrity.

During each test: an air filter was installed on the filter-frame; the fan was engaged; the air flowrate was adjusted; the challenge particles were introduced through the injection port and measured at the input port; the particles passed through the air filter medium were measured again at the output port. The two measured values used to calculate capture efficiency of the filter.

Air filter characteristic curve

To demonstrate the application of the air filter testing unit in determining a characteristic curve of filters, one randomly selected HEPA filter (brand A) was properly installed and tested. The capture effeciencies of the filter were determined at six different air flowrates as shown in Fig. 5. The filter's characteristic curve obtained in this experiment was comparable to that provided by the manufacturer of the filter.

Capture efficiency of installed filters

The Unit can be used to easily determine particle capture efficiency of filters that have been installed under a variety of conditions. To demonstrate this important application of the Unit, 20 experimental test scenarios, organized in three sets (Tables 1-3), were conducted in the laboratory using the Unit. From each set of scenarios, one or two scenarios were selected

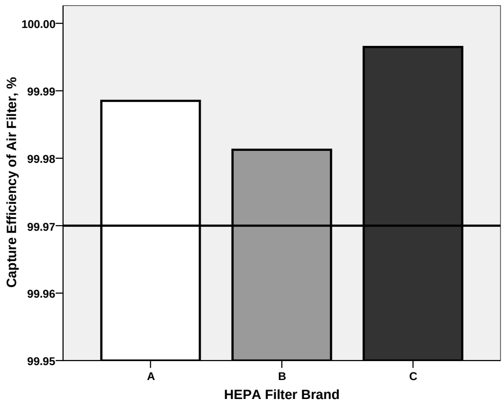

Fig. 6. Capture efficiencies of properly installed HEPA filters; the HEPA filter 99.97% capture efficiency criterion line is also shown.

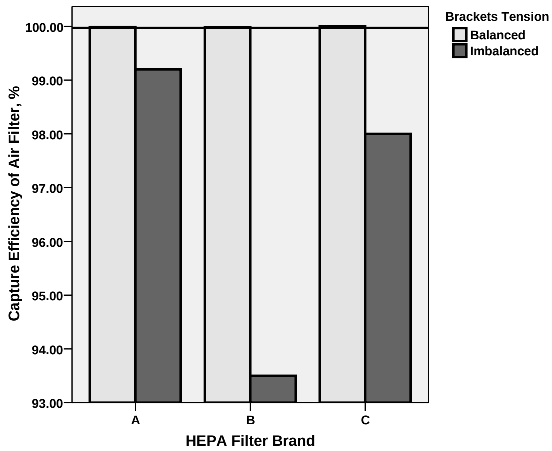

Fig. 7. Capture efficiency reduction due to imbalance; the 2 brackets closest to installer finger-tightened + 5 additional turns on bracket bolts, and the 2 brackets farthest from installer only finger-tightened; the HEPA filter 99.97% capture efficiency criterion line is also shown.

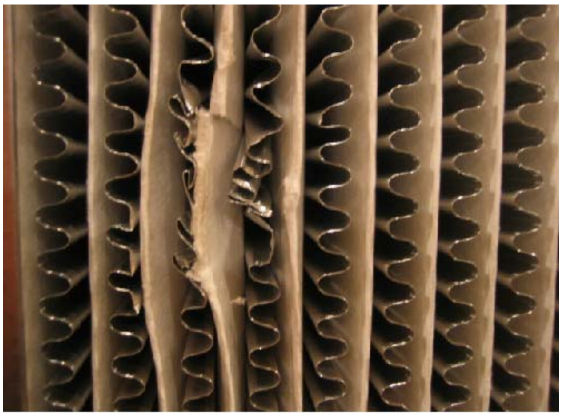

Fig. 8. Damage to brand B HEPA filter; 1x5 cm (0.04x0.20 inch) tear; the capture efficiency of this filter is shown in Fig. 9**.**

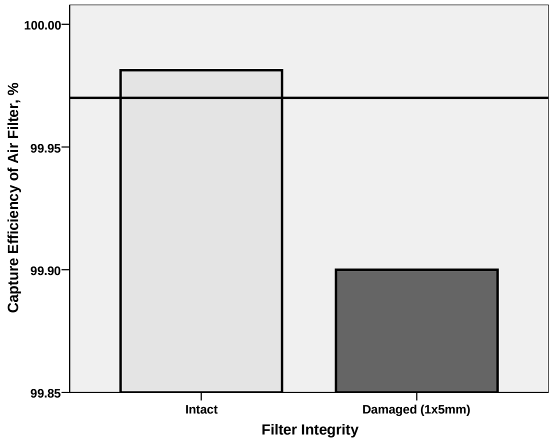

Fig. 9. Capture efficiency reduction for brand B HEPA filter due to an accidental damage to filter media [torn 1x5 mm (0.04-0.20 inch) as shown in Fig. 8]; all 4 filter-brackets finger tight + 5 additional turns with nut drive; the HEPA filter 99.97 % capture efficiency criterion line is also shown.

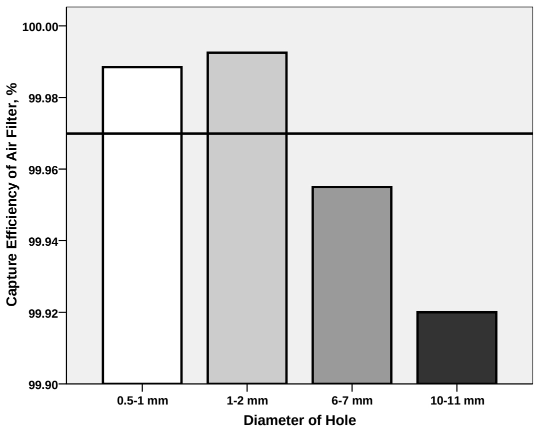

Fig. 10. Capture efficiency for a properly installed brand A HEPA filter, by diameter of hole in air filter media; the HEPA filter 99.97 % capture efficiency criterion line is also shown.

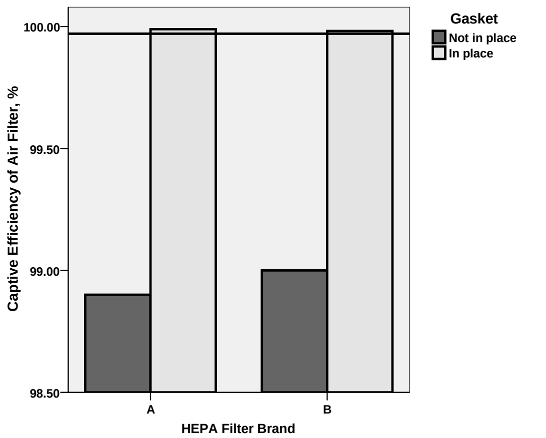

Fig. 11. Change in capture efficiencies due to installing the air filter backwards (filter-gasket not in place); the HEPA filter 99.97 % capture efficiency criterion line is also shown**.**

based on their educational importance and presented as graphs (Figs. 6, 7, 9-11).

Filter balanced/imbalanced (bracket tightening) Installation Scenarios – The data for this set of experiments were collected by using both Method 1 and Method 2. Paired t-test showed that the capture efficiencies determined by Method 1 were not statistically different from those by Method 2. This indicated that Method 2 can be applied when the use of Method 1 (which is more technical) is not feasible. For this set of experiments, the values determined by the Methods 1 have been reported.

Table 1 summarizes the results of test scenarios 1-6. Scenarios 1-3, demonstrating filter-balance with all 4

Table 1. Capture efficiencies (%) for HEPA filters tested during filter-bracket balance (scenarios 1-3) and filter-bracket Imbalance (scenarios 4-6)

(Scenario#) Filter-bracket balance/imbalance scenarios description	Filter brands		
	A	B	C
(1) 4 filter-brackets finger tight + 5 additional turns on the filter-brackets with nut-driver + additional turns with nut-driver until maximum tension achieved*	99.99	99.98	>99.99
(2) 4 filter-brackets finger tight + 5 additional turns on the brackets with nut-driver	99.99	99.98	>99.99
Same as above	99.99	>99.99	>99.99
(3) 4 filter-brackets finger tight	99.97	99.00	99.70
(4) 4 filter-brackets loose (no tension on air filter)	98.70	97.80	99.40
(5) 2 filter-brackets closest to installer finger tight +5 additional turns with nut-driver; 2 filter-brackets farthest from the installer finger tight**	99.20	93.50	98.00
(6) 2 filter-brackets closest to installer finger tight +5 additional turns with nut-driver; 2 filter-brackets farthest from the installer with no tension	0.00	80.00	35.00

*Test scenario 1 is illustrated in Fig. 6.
** Illustrated in Fig. 7; when comparing the capture efficiency values between the columns or rows, the measurement errors (approximately ± 0.02%) should be taken into consideration.

Table 2. Capture efficiencies (%) for HEPA filters tested during filter-damage scenarios

(Scenario#) Filter-damage scenarios description	Filter brand	Capture efficiency
(7) 0.5-1 mm diameter hole (created with a needle), 4 filter-brackets finger tight + 5 additional turns with nut driver	A	99.99
(8) 1-2 mm diameter hole (created with the tip of a sealant dispenser), 4 filter-brackets finger tight + 5 additional turns with nut driver	A	> 99.99
(9) 6-7 mm diameter hole (created with a drill bit), 4 filter-brackets finger tight + 5 additional turns with nut driver	A	99.96
(10) 10-11 mm diameter hole (created with an ink pen), 4 filter-brackets finger tight + 5 additional turns with nut driver*	A	99.92
(11) Damaged-filter (shown in Fig. 8), 4 filter-brackets loose, no tension on filter	B	98.95
(12) Damaged-filter, 4 filter-brackets finger tight	B	99.87
(13) Damaged-filter, 4 filter-brackets finger tight + 5 additional turns with nut driver**	B	99.90
(14) Damaged-filter, installed with media in horizontal position, 4 filter-brackets finger tight + 5 additional turns with nut driver	B	92.92
(15) Damaged-filter, 4 filter-bracket loose, no tension on air filter	B	98.95

*Capture efficiencies in test scenarios 7-10 are compared in Fig. 10.
** Illustrated in Fig. 9.

filter-brackets equally tightened, and scenarios 4-6, demonstrating filter-imbalance with the 4 filter-brackets unequally tightened, were performed to determine capture efficiencies of HEPA filters. Fig. 6 demonstrates results of scenario 1, in which the capture efficiency of all three filter brands exceeded the HEPA criterion limit of 99.97% when properly installed. Fig. 7 demonstrates the results of test scenario 6, in which filters' capture efficiencies were reduced due to the imbalance of filter-bracket tension.

The filters' capture efficiencies met the HEPA filter requirements when all four brackets holding the filter had enough and equal tension. Imbalance of tension in any of the brackets reduced the filter capture efficiency significantly. During the actual field filter installation, an installer is not able to easily reach the two farthest filter brackets and may leave them loose, which will result in reduced, unacceptable filter capture efficiencies. The capture efficiencies determined for the three filter brands of A, B, and C during each scenario were not exactly the same, but the ANOVA test showed that overall the differences were not statistically significant.

Filter-damage scenarios - Table 2 shows the capture efficiencies determined by using Method 1 for HEPA filters while performing a total of 9 filter-damage scenarios: scenarios 7-10 for man-made destructive holes in the filter media and scenarios 11-15 for an accidentally damaged filter as shown in Fig. 8. Holes less than 2 mm in diameter had no immediate and significant effects on the capture efficiency of the filters. Since the size of hole may change over time during the filtration, the long-term effects of this type of damage need to be investigated. Fig. 9 demonstrates a significant reduction in the capture efficiency due to an accidental damage to the air filter media (scenario 13). Even with a damaged filter in line, proper installation considerably improved the filter's capture efficiency.

Fig. 10 shows HEPA filter capture efficiency change due to the variation in diameter of the holes created in

Table 3. Capture efficiency (%) of HEPA filters tested during gasket-damage and wetted filter/filter-gasket scenarios

(Scenario#) Gasket-damage & wetted filter/gasket scenarios description	Filter brand	Capture efficiency
(16) Filter installed backward, no filter-gasket seal*	A	98.90
Same as above*	B	99.00
(17) Filter-gasket was damaged (length of one half inch was cut off); 4 brackets finger tight + 5 additional turns with nut driver	C	98.65
(18) Filter-gasket was damaged as above; 4 brackets finger tight + 5 additional turns with nut driver + additional turns with nut driver until maximum tension was achieved	C	98.60
(19) Damaged filter-gasket was repaired using silicone sealant; 4 brackets on + 5 additional turns with nut driver	C	>99.99
(20) Filter and filter-gasket were wetted with water; 4 filter-brackets on + 5 additional turns with nut driver	C	>99.99

*Fig. 11 compares capture efficiency of the two air filters in this scenario to capture efficiency of the same filters when installed properly.

the air filter media (scenarios 7-10). In this figure, it appears that the air filter with a hole diameter of 1-2 mm might have performed slightly better than the filter with a hole diameter of 0.5–1 mm; however, the difference between the values in two cases is in the range of measurement errors. In general, when comparing the capture efficiency values between any two or more tests, the measurement errors (approximately ± 0.02%) should be taken into consideration.

Gasket-damage and wetted filter/gasket scenarios - The capture efficiencies of HEPA filters determined during scenarios 16-19 for gasket-damage and scenario 20 for wetted filter/gasket are shown in Table 3. During this set of experiments, all filters were tested using Method 1. The filters did not reach required capture efficiency when installed backward (filter gasket not in place) or when the gasket was damaged by removing a 1.3 cm (0.5 inch) of the gasket material. When the gasket was repaired using silicon sealant, the capture efficiency of the filter was restored to an acceptable level for HEPA filter rating. Making the filter and gasket slightly wet did not reduce the filter's efficiency.

Fig. 11 demonstrates the effect of the filter-gasket on the capture efficiency of filter brands A and B (scenario 16). When the filter-gasket was intact and the filter was installed properly, the efficiency of each filter brand exceeded the criterion capture efficiency of 99.97%. The filters with no filter-gasket in place showed capture efficiency below the criterion.

CONCLUSIONS

It is possible and relatively easy to design and assemble an air filter-testing unit, which successfully simulates the filter-housing of mechanical ventilation systems. The Unit can be used:

1. To determine the capture efficiency of air filters.
2. To determine the characteristic curve of air filters (e.g., to validate the curve provided by the vendor).
3. To demonstrate the negative effects of improper handling and installation of air filters on the capture efficiency.
4. As an effective investigative and educational tool.

ACKNOWLEDGEMENTS

We would like to thank Ted Eastway for his technical assistance with filter testing and Mike Rokicki for his technical contribution in setting up the filter-testing unit. We would also like to acknowledge Cynthia Wagner and Mahboubeh Akbar-Khanzadeh for their assistance in preparing this manuscript.

Disclaimer

Although the data in this report are adapted from a research study partially supported by the U.S. National Institute for Occupational Health and Safety/Center for Disease Prevention and Control (NIOSH/CDC) and the Health Pilot Research Project Training Program of the University of Cincinnati Education and Research Center Grant #T42/OH008432-01, it does not necessarily reflect the views of these Agencies, and no official endorsement should be inferred.

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