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Evaluation of Respirator Filter Media under Inhalation-only Conditions

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ABSTRACT

Filter media for respirator applications are typically exposed to cyclic flow condition instead of constant flow adopted in the standard filter media tests. The objective of this study is thus to investigate the effects of breathing frequency (BF) and peak inhalation flow rate (PIFR) on the peak particle penetration of respirator filter media, especially for particles at the most penetration particle sizes under the constant flow condition having equivalent mean inhalation flowrate (MIFR). Five respirator filter media were evaluated under inhalation-only conditions. Three BFs and three PIFRs were selected for the testing. Our study evidenced that both BF and PIFR would increase the peak particle penetration under the cyclic inhalation-only conditions. It is further found that, for each filter media, the peak particle penetration at various PIFRs could be merged into one curve via the newly-defined peak penetration ratio (i.e., the ratio of peak particle penetration at cyclic flow condition to the penetration at the constant flow condition having the equivalent MIFR) and the curve is only a function of BF. The above observation indicates that the increase of peak particle penetration resulted from the increase of PIFR is simply because of the increase of MIFR. The effect of BF on the peak particle penetration is clearly observed using the defined penetration ratio. Based on our finding a semi-theoretical model was further proposed to estimate the peak particle penetration of respirator filter media under inhalation-only conditions.

Keywords: Breathing frequency (BF); Inhalation-only testing; Peak inhalation flowrate (PIFR); Respirator filter media.

INTRODUCTION

Particulate respirators are primarily designed for the protection of workers and the public in various dusty environments. New filter media for respirators have been continuously developed to meet various challenges in the personal particulate matter (PM) protection. It is thus important to evaluate the performance of respirator filter media to assure design engineers and end users that respirators will deliver promised performance for specific applications. The National Institute for Occupational Safety and Health (NIOSH), in cooperation with the Mine Safety and Health Administration (MSHA) issued new regulations for certificating particulate respirator filters in 1996. The detailed information of this regulation has been listed in Title 42 *Code of Federal Regulations (CFR)* Part 84 (1995), where particulate respirator filters with the area of 135 cm^2 are tested against a salt or oil aerosol at a constant flowrate of 85 L min^{-1} (i.e., face velocity of 10.5 cm s^{-1}). Testing aerosol has a mass median diameter (MMD) of 300 nm, assumed to be the most penetration particle size (MPPS). In practice, air flow through respirator filters is cyclic due to the nature of human breathing. It is necessary to evaluate respirator filter under simulated human breathing conditions, i.e., at cyclic flow conditions.

Previous studies have already investigated the performance of particulate respirator filters under cyclic flow conditions and compared it to that under non-cyclic flow conditions (Stafford *et al.*, 1973; Brosseau *et al.*, 1990; Haruta *et al.*, 2008; Eshbaugh *et al.*, 2009; Grinshpun *et al.*, 2009). It was observed that the peak particle penetration through a respirator filter media were higher under cyclic flow conditions than the mean particle penetration under equivalent constant flow conditions. A recent work on testing filter media under cyclic flow conditions was reported by Wang *et al.* (2012). Four waveforms (i.e., two sinusoidal, one trapezoidal, and one exponential cyclic flow patterns) having an equivalent minute ventilation (minute volume of a cyclic flow) were investigated. The Wang's study indicated that, among four tested flow patterns, the highest and lowest particle penetrations through filter media were observed under the cyclic flows of exponential pattern (having the highest peak inhalation flowrate, PIFR) and the cyclic flow with the trapezoidal pattern (having the lowest PIFR), respectively. However, all the filter penetration during cyclic flow conditions was higher than that at the constant flow condition (with equivalent minute ventilation flow). The contribution

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of PIFR on the penetration of respirator was thus identified. However, the effect of breathing frequency on the performance of respirator filter media was largely unknown.

Limited effort had been devoted to study individual effect of breathing frequency (BF) and PIFR on the particle penetration of respirator filter media. Mahdavi *et al.* (2014) studied the individual contribution of BF and PIFR on the performance of N95 filtering facepiece respirators under both inhalation-and-exhalation, and inhalation-only conditions. Scanning mobility particle sizer (SMPS) was applied to measure particle concentration at the up- and down-stream of filter media. The authors observed large increase of particle penetration through filters by increasing the PIFR from 135 to 360 L min^{-1} under the same BF. Slight increase in the particle penetration was observed by increasing the BF from 24 to 42 breaths per minutes (BPM) at the same PIFR.

In view of slow measuring cycle of SMPSs used in the study of Mahdavi *et al.* (2014), we have proposed a new method to test respirator filter media under inhalation-only conditions (Wang *et al*., 2016a). This advanced method consists of the use of a DMA (Differential Mobility Analyzer) to classify testing particles with the most penetration particle size (MPPS) measured at equivalent MIFR (MIFR: the flow rate averaged over the inhalation portion of a breathing cycle), and two condensation particle counters (CPCs) to measure the particle concentrations at the upstream and downstream of filter media. Close-to-instantaneous particle penetration through respirator filter media could be determined by the ratio of readings measured by two CPCs at the sampling frequency of 10 Hz. With the new testing we wish to investigate the effects of BF and PIFR on the performance of respirator filter media. In our study filter media was tested under the inhalation-only condition because of the negligible difference between inhalation-and-exhalation and inhalation-only testing, reported in the work of Mahdavi *et al.* (2014).

The objectives of this study are thus: (1) to investigate the individual effect of BF and PIFR on the penetration of respirator filter media via our newly proposed testing method; (2) to evaluate the performance of various respirator filter media under inhalation-only conditions; (3) to develop a semi-theoretical numerical model to predict the peak particle penetration through filter media under inhalation-only conditions.

EXPERIMENTAL SETUP AND DESIGN

Experimental Setup

The experimental setup that was recently introduced by our group was used in this study. The detail of the experimental setup has been described in the work of Wang *et al.* (2016a). A brief description of the setup is given herein. A custom-made Collison Atomizer was used to generate polydisperse aerosol by atomizing sodium chloride (NaCl) solutions. Polydisperse solid aerosol was obtained by passing polydisperse droplets through a diffusional dryer with silica gel as the desiccant. Polydisperse solid aerosol was then introduced into a differential mobility analyzer (DMA TSI model 3081) to classify particles based on their electrical mobility. DMA-classified particles were electrically neutralized by passing them through a 10 mCi Kr-85 neutralizer (TSI Model 3012) (Romay *et al.*, 1998; Wang *et al.*, 2016b).

Test filter media was placed in a filter holder (Pall Model 2220) with 47 mm OD and challenged by DMA-classified particles. Two identical sampling ports were located in the up- and down- streams of the filter holder for particle sampling and measuring. Condensation particle counter (CPC; TSI Model 3775) and water-based CPC (TSI Model 3787) were utilized to measure the up- and down- stream concentrations of test aerosol, respectively. Both CPCs have a sharp response time of 0.1 sec. (i.e., 10 Hz) for measuring particle concentration. Particle penetration of filter media was calculated by taking the ratio of downstream concentration to the upstream. The cyclic flow was generated by a human breathing simulator (Model ASL5000, IngMar Medical, PA, US). Two one-way valves (Model BE 130-22B, Instrumentation Industries, Inc., US) were placed at the inlet of the breathing simulator for inhalation-only testing. The parameters of cyclic sinusoidal flow patterns used in this study are given in Table 1. For each run, the data were collected for 4 minutes after the cyclic flow reached reproducible periodical status. Prior to each run, test flow condition was also verified by a mass flow meter (TSI Model 4143).

Table 1. Summary of tested sinusoidal cyclic flow conditions.

Cyclic Flow Types	Breathing Frequency (breath min^{-1})	Peak Inhalation Flow at test area of 15.3 cm^2 (L min^{-1})	Peak Inhalation Flow at test area of 135 cm^2 (L min^{-1})	Tidal Volume (L breath^{-1})	Peak Face Velocity (cm s^{-1})	Mean Inhalation Flowrate (L min^{-1})
1	6	9.42	82.94	0.5	10.24	6
2	12			0.25		
3	25			0.12		
4	6	13.5	119.43	0.72	14.74	8.64
5	12			0.36		
6	25			0.17		
7	6	18.14	159.97	0.96	19.70	11.55
8	12			0.48		
9	25			0.23		

* The face velocity for testing a typical N95 respirator having the surface area of 135 cm2 (at the defined 85 L min^{-1} flowrate) is ~10.5 cm s^{-1}.

Due to the particle loss in the filter holder and two different CPCs used in the experiment, a calibration experiment was further performed to correlate the readings of two CPCs. No filter media was in the holder during the calibration experiment. Negligible particle loss (less than 10% difference in two CPC readings) was observed in this calibration experiment. Additionally, the background CPC readings were also checked to ensure their zero reading prior to each run.

Experimental Design

Under the consideration of the worse scenario, particles at the maximal penetration size (i.e., MPPS at the constant flow condition of equivalent MIFR) were measured and selected to challenge respirator filter media. The measured MPPS was approximately 100 nm under the face velocity of 10 cm s^{-1} for all tested filter media except the filter #3. The MPPS was 150 nm for the filter media #3.

Five respirator filter media were collected and tested in this study. Table 2 gives the basic properties of test filter media. Filter media #1 and #3 are fiberglass respirator filter media. Filter #2 is a charged media. Filter media #4 and #5 are composite filter media. Test filter media samples were randomly cut from large filter sheets for testing.

Cyclic flows with the sinusoidal and inhalation-only patterns were selected for the testing. Three breathing frequencies (BFs) of 6, 12 and 25 breaths min^{-1} (BPM) and three peak inhalation flow rates (PIFRs) of 9.42, 13.5 and 18.14 L min^{-1} were chosen as the testing flow conditions. A total of nine flow conditions were applied. For a specific filter media three runs were performed for each test flow condition. The selection of 9.42 L min^{-1} is to match the face velocity given at the NIOSH standard. The selection of BFs was based on the earliest data available on spontaneous BF of human beings on 300 subjects (Quetlet, 1842) and on 1714 adult subjects (Hutchinson, 1850) mentioned by Benchetrit (2000) in his study.

RESULTS AND DISCUSSION

Effect of Breathing Frequency (BF) and Peak Inhalation Flowrate (PIFR)

Fig. 1 shows the comparison of measured peak particle penetrations (at the particle size of 100 nm) for filter media #1 and #3 under selected cyclic flow conditions and constant flow condition of equivalent MIFR. The peak penetration data given in Fig. 1 are the average of measured peak penetrations in one run. It is found that, for filter media #1 (Fig. 1(a)), the particle penetration at constant flow rates was the lowest compared with those peak penetration measured under cyclic flow conditions. When PIFR is 9.42 L min^{-1}, the smallest peak penetration is 8.68% at constant MIFR flow, and the peak penetration values are 13.04%, 17.22% and 20.42% for BFs of 6, 12 and 25 BPM (beats per minute), respectively. The peak particle penetration under the cyclic flow conditions were increased as the BF increased. The similar trends could be found in the cases with PIFRs of 13.5 and 18.1 L min^{-1}. The similar testing result was obtained for the filter media #3 (Fig. 1(b)).

Also shown in Fig. 1(a), the peak penetration values measured for respirator filter media #1 are 8.68%, 12.16% and 15.3% for PIFR of 9.42, 13.5 and 18.14 L/min under the constant flow of MIFRs, respectively. At each breathing frequency, the measured peak penetration was increased with the increase of PIFRs (from 9.42 to 18.14 L min^{-1}). It is evidenced that higher PIFRs results in higher particle penetration.

To understand the effect of breathing frequency on the peak particle penetration of respirator filter media we defined the peak penetration ratio as the measured peak penetration at cyclic test flow conditions to the penetration at the constant flow condition of equivalent MIFR. Fig. 2 shows the relationship of defined peak penetration ratio as the function of BF under various tested PIFR conditions for filter media #1 and #3. It is interesting to observe that, for each test filter media, the peak penetration ratios under three test PIFR conditions were merged into one curve and the curve is now the function of BF only. For PIFR of 9.42 L min^{-1}, the value of ratio is 1.4 at BF of 6 BPM for media #1 (Fig. 2(a)) and it increased to 1.9 as BF increased to12 BPM and to 2.2 at BF of 25 BPM. Approximate 60% increase in the penetration ratio was obtained for media #1 as the BF increased from 6 to 25 BPM. The similar observations were found in the cases with PIFRs of 13.5 and 18.14 L min^{-1}. For media #3, the defined peak penetration ratio was increased to 2.7 at BF of 25 BPM from 1.5 at BF of 6 BPM (Fig. 2(b)).

Effect of Filter Media

In addition to filter media #1 and #3, three other types of respirator filter media (i.e., filter media #2, #4 and #5) were also tested in this study. Media #2 is an electrically charged filter media. The observation of peak penetration at the test cyclic flow and constant flow conditions for media #2 is consistent with those for media #1 and #3. The values of particle penetration under the equivalent MIFR are the lowest in each of the PIFR groups of 9.42, 13.5 and

Table 2. Basic properties of respirator filter media used in this study. Filter media #1, #2, and #3 belong to single-layer fibrous media. Filter media #4 and #5 are composite media.

Filter Media	Media Type	Basic Weight [g m^{-2}]	Pressure Drop at face velocity 1.1 cm s^{-1} (1.0 L min^{-1}) [inH_2O]	Thickness [mm]	Permeability [m^2]
1	Fibrous	80.27	0.090	0.63	5.02E-12
2	Fibrous (charged)	56.44	0.015	0.94	5.51E-11
3	Fibrous	79.61	0.115	0.84	5.51E-12
4	Fibrous (Composite)	86.46	0.035	0.93	1.80E-11
5	Fibrous (Composite)	78.39	0.030	0.94	2.32E-11

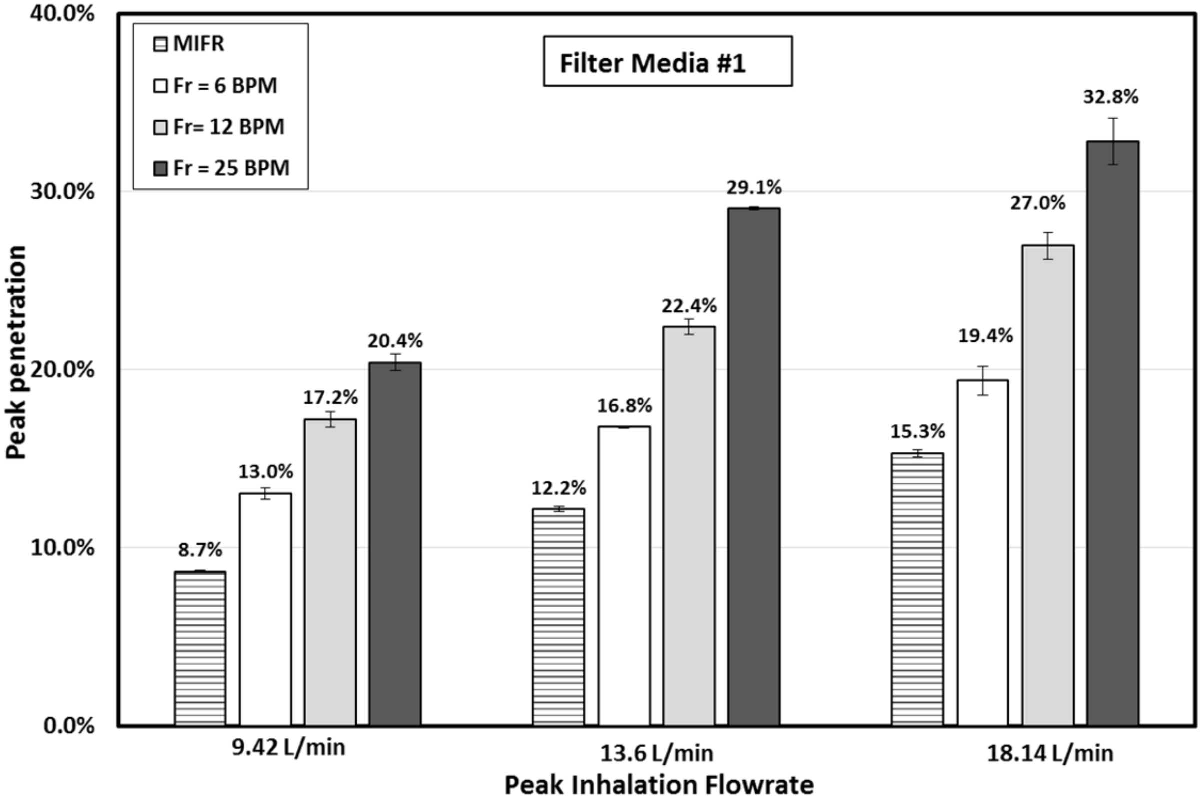


Fig. 1(a). Comparison of the peak penetration of filter media #1 with different breathing frequencies under three different peak inhalation flowrates (PIFRs).

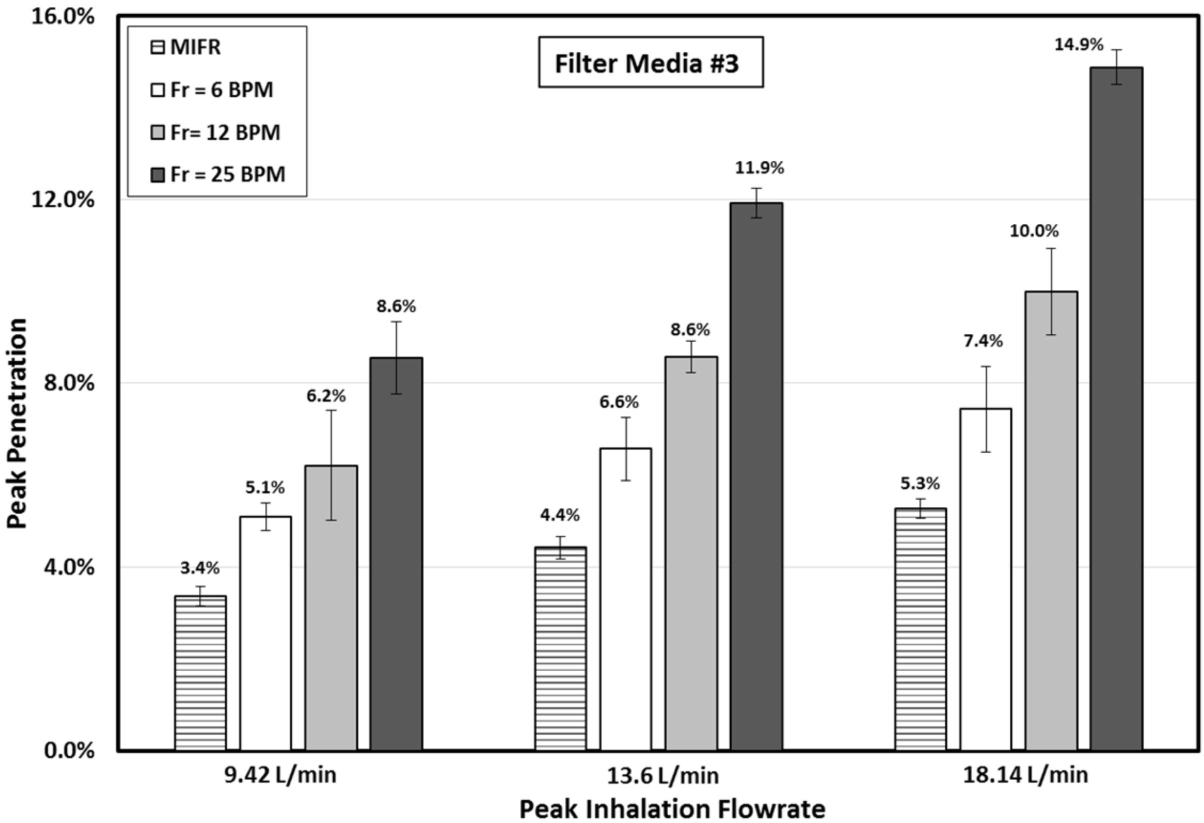


Fig. 1(b). Comparison of the peak penetration of filter media #3 with different breathing frequencies under three different peak inhalation flowrate conditions.

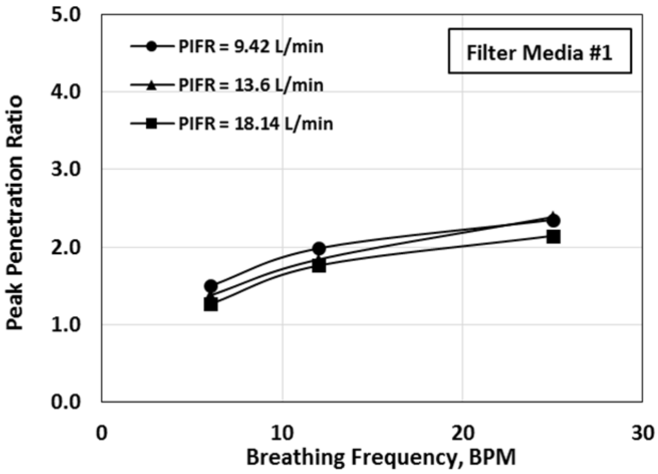


Fig. 2(a). The ratio of peak penetration with each cyclic flow condition to constant flow at MIFR vs breathing frequency for filter media #1.

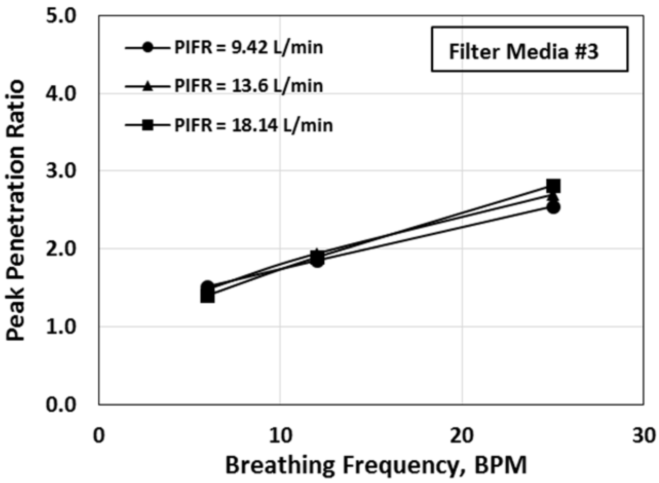


Fig. 2(b). The ratio of peak penetration with each cyclic flow condition to constant flow at MIFR vs breathing frequency for filter media #3.

18.14 L min^{-1}. The breathing frequency (BF) enhanced the peak penetration under each PIFR condition. The detailed data for the above comparison for media #2 is given in the appendix. Fig. 2(c).i shows the penetration ratio as the function of breathing frequency for filter media #2. It is again found that the ratios under three test PIFRs were merged into one and is the function of BF only. The penetration ratio for media #2 increased to 2.5 at the BF of 25 BPM from 1.5 at the BF of 6 BPM.

In addition to electrically charged media, we further tested respirator composite filter media #4 and 5. The comparison of particle penetration under equivalent MIFRs and three PIFR conditions (at three BFs) are also included in the appendix. The similar trend for the increase of peak penetration due to the increase of BF and PIFR was observed for two test composite filter media. Figs. 2(c).ii and 2(c).iii show the penetration ratios as a function of BF at three PIFRs for filter media # 4 and 5. Again the penetration ratios at three test PIFRs were collapsed into one and only a function of BF. However, it shall be noted that the values of penetration ratios are different from those obtained in filter media #1, #2 and #3 (single layered media). In Fig. 2(c).ii, the penetration ratio is ~2.0 at the BF of 6 BPM for media #4, and it is 4.2 at the BF of 25 BPM, much higher than those obtained in the cases with media #1, #2 and #3. Slight variation on the penetration ratio at each BF for media #4 was further found. For filter media #5 (shown in Fig. 2(c).iii), the penetration ratio was 3.0 at the BF of 25 BPM. The increase in the peak penetration ratio with breathing frequency is more pronounced with the use of cyclic flow patterns with composite filter media. It is concluded that the effect of breathing frequency is more obvious in the cases with composite filter media (as compared to single-layer filter media). More study is required to understand the causes for the above experimental observation.

Modeling of Peak Particle Penetration under Cyclic Flow

Based on the experimental observation on the defined penetration ratio as a function of BF for each filter media, we proposed a semi-theoretical model to calculate the peak

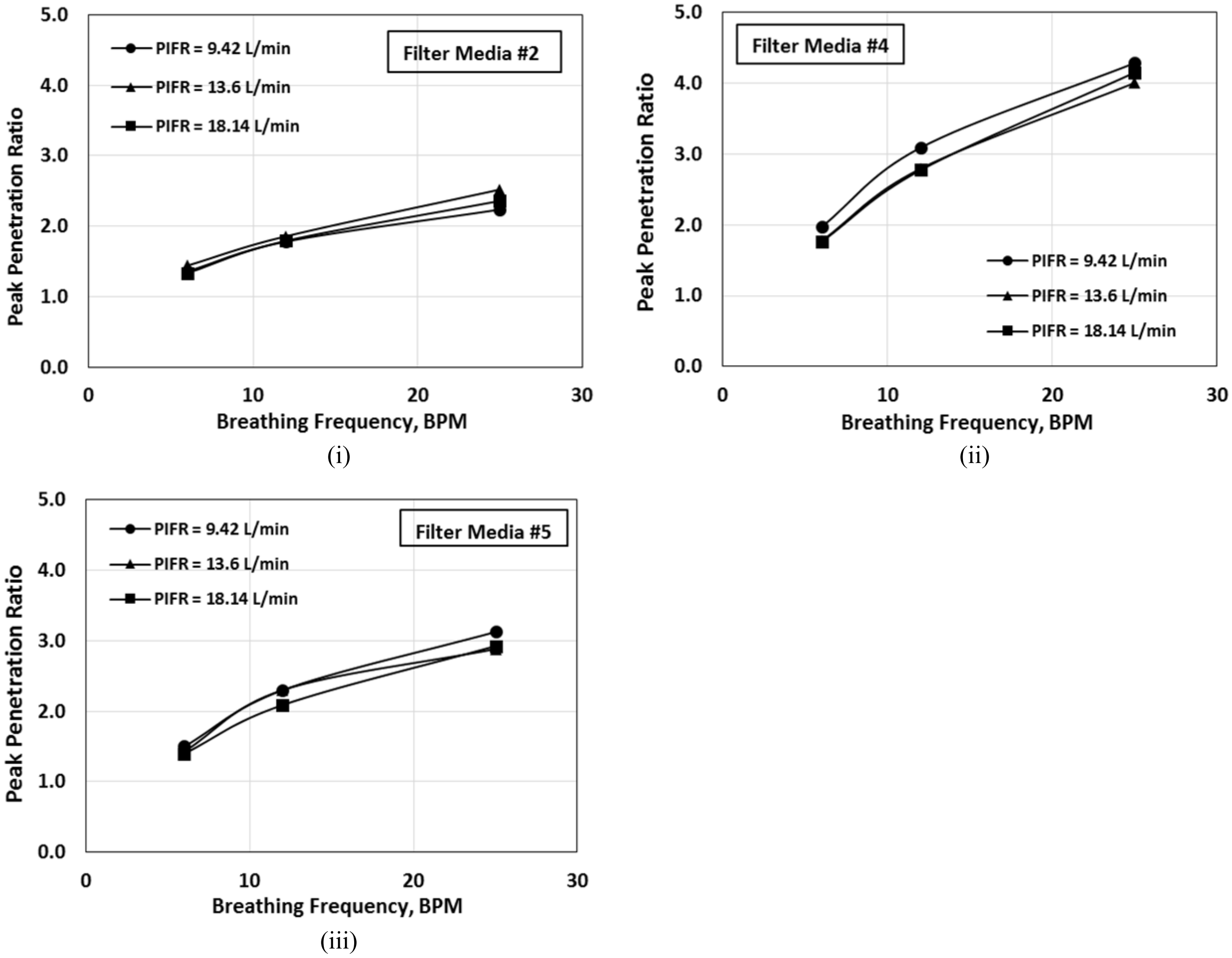


Fig. 2(c). Peak penetration ratio to breathing frequency for filter media i) #2 ii) #4 iii) #5.

penetration at various cyclic flow conditions. For each filter media under a given PIFR and BF, the proposed model first estimates the penetration of max.-penetration-particle-sized (MPPSed) particles at the equivalent MIFR (using the single fiber theory) and the peak particle penetration at the given BF was then obtained by multiplying it with the penetration ratio calculated from the penetration ratio equations curve-fitted from the experimental data.

Modeling of Particle Penetration at MIFR

Single-fiber theories have been widely applied to describe the overall collection efficiency of particles for a filter media under constant flow rates. Under the theory, Eq. (1) gives the overall particle penetration, P (defined as 1-E, where E is the overall particle collection efficiency), of a filter media, relating it to the microscopic properties of a filter media and single-fiber efficiency, E_Σ, where α, t, and d_f are solidity, thickness and fiber diameter of filter media, respectively (Brown, 1993).

$$P = 1 - \mathrm{E} = e^{-rt} = \exp\left(\frac{-4\alpha E_\Sigma t}{\pi d_f}\right) \tag{1}$$

The overall particle collection efficiency, E_Σ of a single fiber is the sum of the collection efficiencies due to both interception and diffusion mechanisms. Note that the impaction mechanism is neglected herein because of small MMPSs tested in the study. Eq. (2) is the overall collection efficiency of a single fiber, where E_R, E_D, and E_{DR} are the collection efficiencies for both interception and diffusion, as well as the high order term taking the consideration of interaction between interception and diffusion, respectively.

$$E_\Sigma = E_R + E_D + E_{DR} \tag{2}$$

The single-fiber efficiency due to the interception E_R is given as (Lee and Ramamurthi, 1993)

$$E_R = \frac{(1-\alpha)R^2}{K_u(1+R)} \tag{3}$$

where $R = d_p/d_f$ (ratio of particle diameter to filter diameter) is a dimensionless parameter, *Ku* is the Kuwabara hydrodynamics factor, a dimensionless factor compensating for the effect of flow distortion due to its proximity to other fibers. Note that the Ku depends only on the media solidity, α, (i.e., 1-porosity)

$$K_u = -\frac{1}{2} ln\alpha - \frac{3}{4} + \alpha - \frac{1}{4}\alpha^2 \quad (4)$$

The single-fiber efficiency due to particle diffusion, E_D, is a function of the dimensionless Peclet number, Pe (Stechkina and Fuchs, 1966),

$$E_D = \left(\frac{1-\alpha}{Ku}\right)^{\frac{1}{3}} Pe^{-\frac{2}{3}}, \quad Pe = \frac{d_f U_0}{D} \quad (5)$$

The high-order term to account for the interaction of particle inception and diffusion in a single-fiber theory is shown in Eq. (6) (Hinds, 2012):

$$E_{DR} = \frac{1.24R^{2/3}}{\left(KuPe\right)^{1/2}} \quad (6)$$

Fig. 3 shows the comparison of calculated and measured penetrations of particles at two MIFRs and various particle sizes. For the reference all the parameters used in the single-fiber calculation are given in the supplementary document. The good agreement was obtained between experimental and calculated data sets. Note that the above comparison was only given for media #1 and #3 because the charge effect was not considered in the above single-fiber theory.

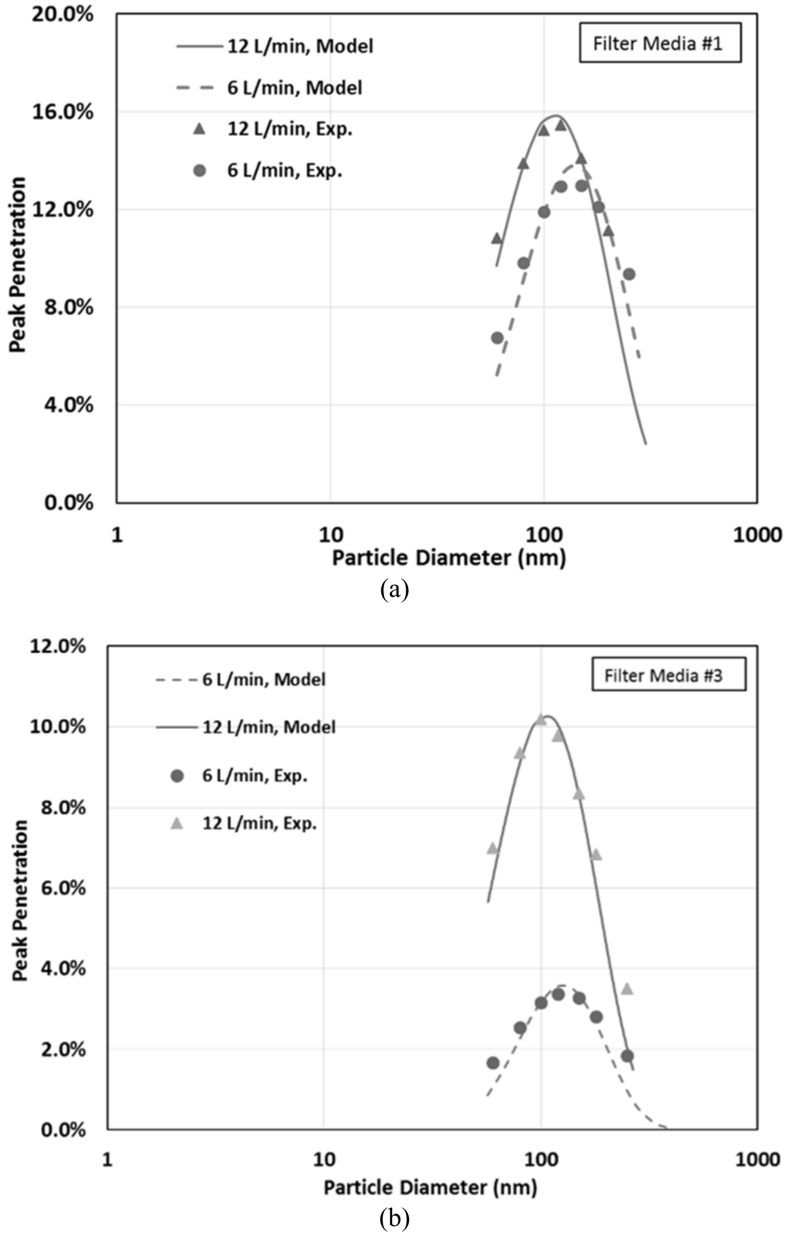


Fig. 3. Comparison of penetration calculated with single-fiber theory with experimental measurements for (a) Filter media #1 (b) Filter media #3.

Semi-Theoretical Modeling for Peak Particle Penetration at Various PIFRs and BFs

Based on our experimental observation it is hypothesized that the peak particle penetration under cyclic test flow conditions could be calculated as the product of particle penetration at MPPS calculated by single-fiber theory under equivalent MIFR and the penetration ratio calculated from the equations obtained by curved-fitting our experimental data (shown in Eq. (7)):

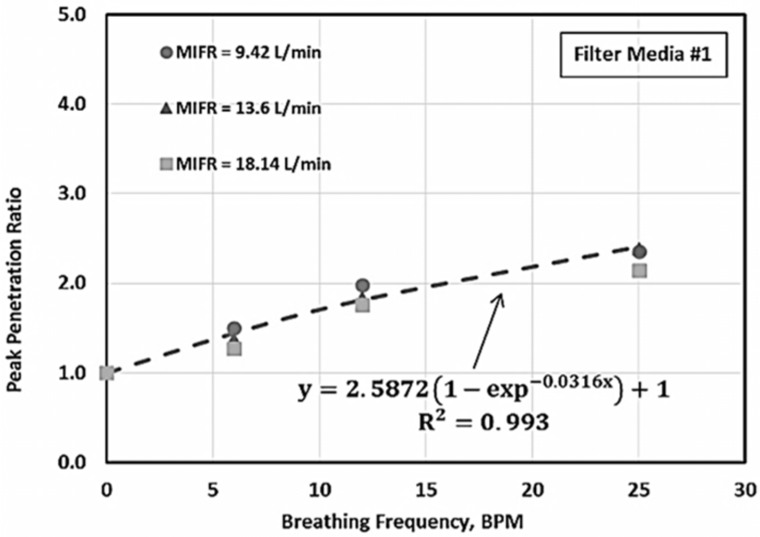
$$P = f\left(BF\right)\times \exp\left(\frac{-4\alpha E_{\Sigma} t}{\pi d_f}\right) \tag{7}$$

The cut-fitted equations for filter media #1 and # 3, *f*(*BF*), are given in Fig. 4.

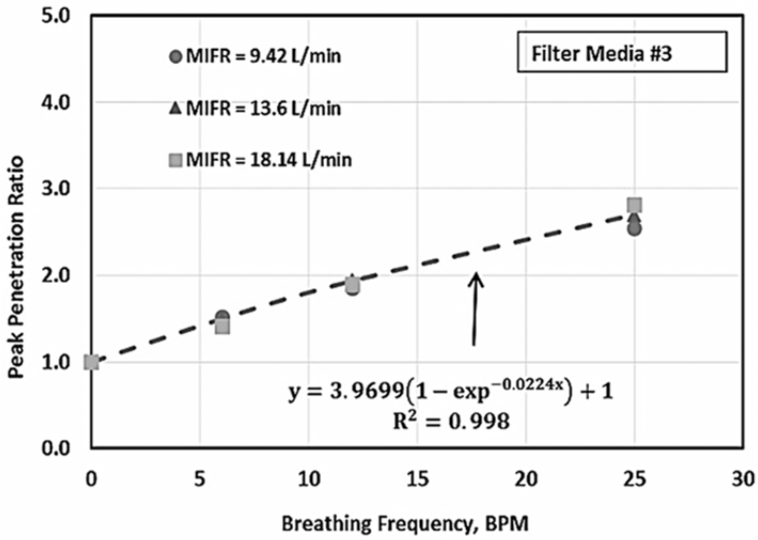
Fig. 5 shows the comparison between the calculated and measured peak particle penetration under various cyclic test flow conditions. Reasonable agreement between the two sets of data is obtained.

CONCLUSIONS

We investigated the individual effects of BF and PIFR on the peak penetration of respirator filter media for particles with the maximal particle sizes at the constant flow condition of equivalent MIFRs. The performance of five respirator filter media under the worse scenario cases was evaluated via the newly developed inhalation-only testing method (Wang *et al.*, 2016a). Three breathing frequencies, i.e., 6, 12 and 25 BPM and three different peak inhalation flow rates i.e., 9.42, 13.5 and 18.14 L min^{-1} were selected in the experiments. Our experimental data evidenced that the increase of either BF or PIFR would increase the peak

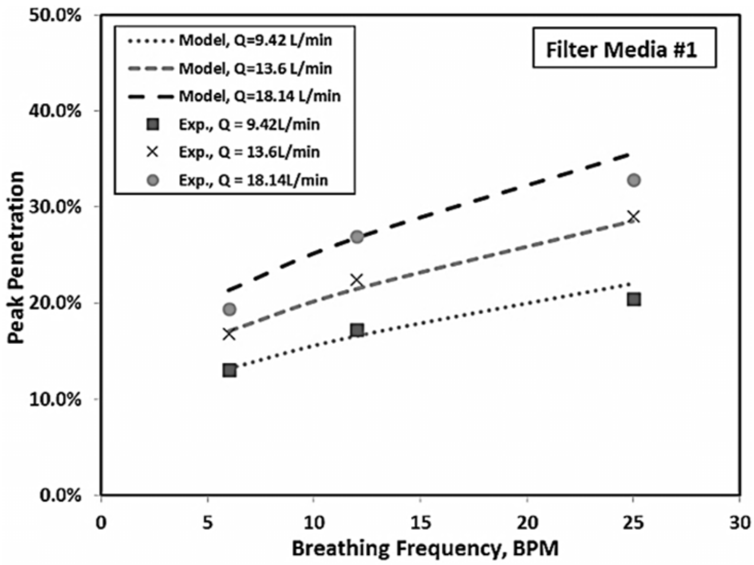


(a)

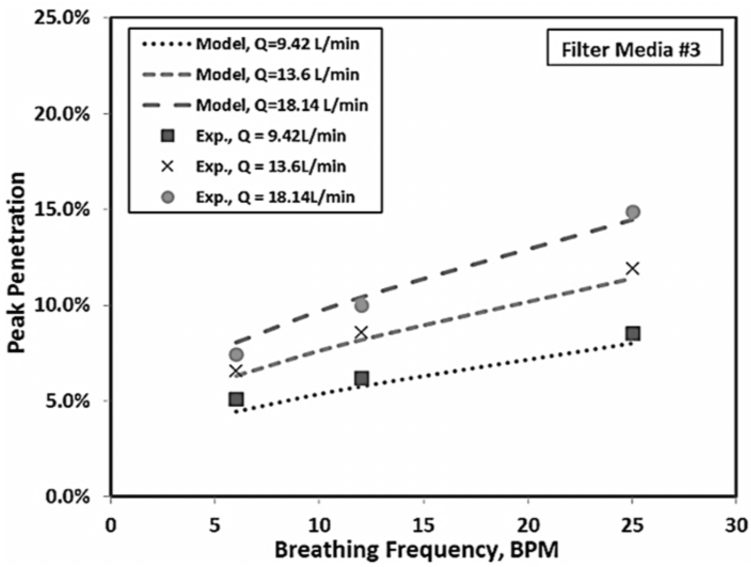


(b)

Fig. 4. Comparison of peak penetration ratio between semi-theoretical model and experimental for (a) Filter media #1 (b) Filter media #3.



(a)



(b)

Fig. 5. Comparison between semi-theoretical modeling and experimental results for (a) media #1 (b) media #3.

penetration of filter media under the cyclic flow conditions. The penetration ratio, defined as the ratio of peak penetration at cyclic flow conditions to the penetration at equivalent MIFR condition was further defined to study the effect of PIFR. It is interesting to find that, by using the above-defined penetration ratio, the peak penetrations at various PIFRs were merged into one curve and the ratio curve is only a function of BF. It is thus concluded that the increase of peak particle penetration of filter media is simply because the increase of MIFRs under the testing conditions considered in this study. Based on our finding a simple semi-theoretical model was proposed to estimate the peak penetration of respirator filter media of particles with the MMPS under cyclic inhalation-only conditions. The proposed model applied the single-fiber theory to find out the penetration of particles with the MPPS under the constant flow condition with MIFRs and estimate the peak particle penetration under the inhalation-only conditions by multiplying the above penetration value with the peak penetration ratio calculated from the equations obtained by curve-fitting the collected experimental data.

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Yancheng Environmental Protection; and NIOSH.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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