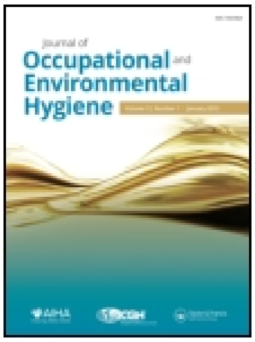

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Determination of pressure drop across activated carbon fiber respirator cartridges

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ABSTRACT

Activated carbon fiber (ACF) is considered as an alternative adsorbent to granular activated carbon (GAC) for the development of thinner, lighter, and efficient respirators because of their larger surface area and adsorption capacities, thinner critical bed depth, lighter weight, and fabric form. This study aims to measure the pressure drop across different types of commercially available ACFs in respirator cartridges to determine the ACF composition and density that will result in acceptably breathable respirators. Seven ACF types in cloth (ACFC) and felt (ACFF) forms were tested. ACFs in cartridges were challenged with pre-conditioned constant air flow (43 LPM, 23°C, 50% RH) at different compositions (single- or combination-ACF type) in a test chamber. Pressure drop across ACF cartridges were obtained using a micromanometer, and compared among different cartridge configurations, to those of the GAC cartridge, and to the NIOSH breathing resistance requirements for respirator cartridges. Single-ACF type cartridges filled with any ACFF had pressure drop measurements (23.71–39.93 mmH_2O) within the NIOSH inhalation resistance requirement of 40 mmH_2O, while those of the ACFC cartridges (85.47±3.67 mmH_2O) exceeded twice the limit due possibly to the denser weaving of ACFC fibers. All single ACFF-type cartridges had higher pressure drop compared to the GAC cartridge (23.13±1.14 mmH_2O). Certain ACF combinations (2 ACFF or ACFC/ACFF types) resulted to pressure drop (26.39–32.81 mmH_2O) below the NIOSH limit. All single-ACFF type and all combination-ACF type cartridges with acceptable pressure drop had much lower adsorbent weights than GAC (≤15.2% of GAC weight), showing potential for light-weight respirator cartridges. 100% ACFC in cartridges may result to respirators with high breathing resistance and, thus, is not recommended. The more dense ACFF and ACFC types may still be possibly used in respirators by combining them with less dense ACFF materials and/or by reducing cartridge bed depth to reduce pressure drop to acceptable levels. ACFF by itself may be more appropriate as adsorbent materials in ACF respirator cartridges in terms of acceptable breathing resistance.

KEYWORDS
Activated carbon fiber; breathing resistance; cartridges; pressure drop; respirator

Introduction

Granular activated carbon (GAC) has been the most common adsorbent used in respirators for protection against gas phase contaminants. Some disadvantages of GAC, however, include the need for containment (i.e., in a cartridge or canister) due to its granular nature. In addition to the weight of the GAC itself, such containment may contribute to the weight and bulkiness of respirators, increasing user discomfort and decreasing user compliance.[1]

Activated carbon fiber (ACF) is considered as an alternative adsorbent to GAC since it has been shown to be effective in capturing volatile organic compounds (VOCs) from gas streams at wide range of concentrations.[2–6] ACFs are obtained from the carbonization and activation of polymeric fibers from various precursors, such as viscose rayon, phenolic resin, polyacrylonitrile, and pitch.[7] The small fiber diameter of ACF (ranging from 10–20 um) allows homogeneous activation of the fibers, resulting to a unimodal, narrow pore size distribution in the micropore range.[8,9] ACFs have been assessed for air pollution control of VOCs.[10–14] Other ACF applications include energy saving and storage,[15–17] CO_2 capture,[18] and SO_2 removal.[19]

Advantages of ACFs over traditional activated carbon adsorbents, such as GAC, include larger surface areas, higher adsorption capacities, thinner critical bed depth, higher number of micropores, and faster heat and mass transfer properties.[20–23] ACF can be manufactured in

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various forms (i.e., cloth and felt) and, thus, is easier to handle than GAC.[7,24] Cloth forms of ACF, compared to the felt forms with similar surface area, were found to have higher adsorption capacities and lower critical bed depths.[25] Its advantages make ACF a promising alternative adsorbent for the development of thinner, lighter, and efficient respirators for short-term protection during accidental or intentional release of toxic gases and vapors in a catastrophic event.[22] Recent studies have demonstrated the possible application of various ACF types for respiratory protection against VOCs based on breakthrough, critical bed depth and adsorption capacity.[1,22,25]

Pressure drop is defined as the difference in static pressure between two pressure points located before and after an air-cleaning media, which is a function of flow rate and face velocity. Pressure drop is equivalent to breathing resistance when applied to respiratory protection. The static pressure point downstream of the media is lower than the static pressure point upstream, resulting in a drop in pressure. Pressure drop may be translated into the breathability of a respirator. Thus, it is important for respirators to have pressure drop as low as possible, since it has been shown that increasing inhalation and exhalation resistances across respirators decrease workers' performance.[26] Pressure drop across ACFs assembled as a filter in air treatment devices has been previous studied,[27,28] but not as an adsorbent for respirators. Moreover, one of the NIOSH requirements for respirator certification is on breathing resistance. NIOSH has standard testing procedures (STPs) for determining both inhalation and exhalation breathing resistances for air-purifying respirators. For chemical cartridge respirators other than single-use vinyl chloride respirators, the maximum allowable resistance requirement is 20 mmH_2O for exhalation resistance,[29] and 40 mmH_2O for inhalation.[30]

Activated carbon fibers (ACFs) have great potential for the development of lighter and more efficient respirators for airborne contaminants due to their high adsorption capacities. The service life of ACF respirator cartridges may be further extended by increasing the thickness or density of the adsorbent in the cartridge. However, this may lead to an increased resistance to air flow and a greater physiological burden on the respirator user. To optimize the ACF cartridge configuration, it is crucial to determine how the composition and density of the ACF materials in cartridges affect breathing resistance. The purpose of this pilot study was to determine and compare the pressure drop across different types of ACFs in realistic respirator cartridges. The main goal was to develop ACF cartridge configurations that have acceptable breathing resistance according to NIOSH certification requirements.

Table 1. Activated carbon fiber (ACF) structural properties by ACF type.

ACF Type	Weave Type	Thickness (cm)[a]	Density (g/cm^3)
ACFC	Woven	0.11	0.101
ACFF1	Non woven	0.23	0.043
ACFF2	Non woven	0.29	0.069
ACFF3	Non woven	0.29	0.057
ACFF4	Non woven	0.24	0.043
ACFF5	Non woven	0.30	0.041
ACFF6	Non woven	0.50	0.070

[a]average of 2 samples (n = 2)

Methods

Materials

Two forms of commercially available ACF were used as adsorbent materials: woven cloth (ACFC, 1 type) and non woven felt (ACFF, 6 types), with a total of 7 types of ACFs tested. The ACFs were obtained from American Technical Trading, Inc. (Pleasantville, NY) and were manufactured from novoloid, a phenol aldehyde-based fiber. Table 1 shows the designation for each ACF type and their corresponding structural properties, including thickness and density. The thickness of the ACFC is 0.11 cm and that of the ACFF types range from 0.23–0.50 cm, which is more than 2 times greater than that of the ACFC. However, the ACFF types are less dense (0.041–0.070 g/cm^3) than the ACFC (0.101 g/cm^3), giving the ACFF a spongier characteristic. The ACFs were cut into 3-in diameter discs, with a diameter similar to that of a typical respirator cartridge container. The ACF discs were thermally treated in a Precision Compact Model 665 oven (Thermo Scientific, Marietta, OH) at 200°C overnight prior to testing to desorb any volatile impurities and remove excess moisture on the adsorbent materials. After oven treatment, the ACF discs were weighed (in grams) using a Voyager Pro analytical balance (Ohaus Corp., Parsippany, NJ), and the thickness (in cm) was measured using a Vernier caliper. The ACF discs were then placed in a respirator cartridge (3-in internal diameter, 1-in depth) for pressure drop testing. Granular activated carbon (GAC) in an organic vapor cartridge (Willson, Reading, PA) was also tested in this study for comparison. The GAC was thermally treated, weighed and placed in a cartridge similarly as the ACF materials prior to pressure drop testing.

Scanning electron microscopy

The organization and morphology of the ACF's individual fibers, particularly the weaving tightness, was examined using a scanning electron microscope (SEM). SEM images of the ACFs were obtained at three magnifications (50x,

Table 2. Activated carbon fiber (ACF) composition and average pressure drop and weight (n = 3) of single-ACF type cartridges.

Cartridge Designation	ACF Composition	Pressure Drop, mmH_2O (mean ± SD)	Weight, g (mean ± SD)
CS1	100% ACFF1 (density 1)	23.71 ± 0.64	4.24 ± 0.11
CS2	100% ACFF1 (density 2)	26.83 ± 0.67	4.67 ± 0.09
CS3	100% ACFF1 (density 3)	29.95 ± 0.26	5.09 ± 0.03
CS4	100% ACFF2	31.73 ± 0.91	7.49 ± 0.27
CS5	100% ACFF3	35.94 ± 0.22	5.89 ± 0.30
CS6	100% ACFF4	36.70 ± 0.39	4.57 ± 0.08
CS7	100% ACFF5	37.40 ± 1.29	4.78 ± 0.09
CS8	100% ACFF6	39.93 ± 0.67	9.17 ± 0.23
CS9	100% ACFC	85.47 ± 3.67	14.00 ± 0.22
GAC	100% GAC[a]	23.13 ± 1.14	60.34 ± 0.10

[a]Composed of granular activated carbon for comparison with ACF

200x, and 800x) to visualize the fiber arrangement in ACF samples.

Pressure drop determination

Respirator cartridges were filled with ACF materials of varying composition and were designated based on the ACF composition and densities (Tables 2 and 3). Table 2 shows single-ACF type cartridges that are composed of 100% of a specific ACF type. CS1, CS2, and CS3 cartridges contain the same ACF type (ACFF1) but its density was increased by increasing the number of layers (9, 10, and 11 layers, respectively) compressed in the cartridge. Table 3 shows the combination-ACF type cartridges that are composed of 2 ACF types, with percentage by weight for each ACF type indicated. Polypropylene sheets (Pall Life Sciences, Port Washington, NY) cut into 3-in diameter discs were placed on both outer sides such that the ACF discs were sandwiched between the polypropylene sheets, which are intended to prevent the inhalation of carbon particulates from the ACF cartridge when used in a respirator.

The ACF cartridge was placed in a customized cylindrical Teflon chamber (internal diameter of 6 in, length of 12 in) and challenged with pre-conditioned air at a constant airflow (43 LPM), temperature (23°C) and relative humidity (50%). The cartridge tested in this study is usually used in pairs in a dual cartridge respirator, with each cartridge receiving half of the total airflow. Since a single cartridge was tested at a time, the flow rate used in this study was approximately half of the constant airflow (85 LPM) used by NIOSH in testing the breathing resistance of respirator chemical cartridges for certification.[29,30] Clean, dry air was supplied by an air compressor equipped with air filtering units (Parker Hannifin Corp., Haverhill, MA), and controlled at constant temperature, relative

Table 3. Activated carbon fiber (ACF) composition and average pressure drop and weight (n = 3) of combination-ACF type cartridges.

Cartridge Designation	ACF Composition by % Weight	Pressure Drop, mmH_2O (mean ± SD)	Weight, g (mean ± SD)
CC1	70% ACFF1/ 30% ACFC	28.91 ± 0.14	5.50 ± 0.17
CC2	80% ACFF1/ 20% ACFC	31.06 ± 0.43	6.47 ± 0.12
CC3	67% ACFF1/ 33% ACFF6	32.81 ± 1.53	5.51 ± 0.20
CC4	43% ACFF1/ 57% ACFF6	27.56 ± 2.42	5.68 ± 0.31
CC5	40% ACFF1/ 60% ACFF2	27.47 ± 0.70	5.84 ± 0.07
CC6	30% ACFF1/ 70% ACFF2	27.39 ± 0.42	6.29 ± 0.34
CC7	20% ACFF1/ 80% ACFF2	28.55 ± 1.13	6.78 ± 0.36
CC8	44% ACFF1/ 56% ACFF3	30.76 ± 0.26	5.01 ± 0.17
CC9	54% ACFF1/ 46% ACFF3	30.08 ± 0.73	5.03 ± 0.12
CC10	68% ACFF1/ 32% ACFF3	28.33 ± 0.25	4.79 ± 0.01
CC11	50% ACFF1/ 50% ACFF4	29.52 ± 0.67	4.87 ± 0.08
CC12	60% ACFF1/ 40% ACFF4	30.35 ± 0.80	4.90 ± 0.02
CC13	69% ACFF1/ 31% ACFF4	30.17 ± 0.41	5.03 ± 0.34
CC14	61% ACFF1/ 39% ACFF5	29.75 ± 0.68	4.98 ± 0.49
CC15	50% ACFF1/ 50% ACFF5	29.86 ± 0.70	4.81 ± 0.21
GAC	100% GAC[a]	23.13 ± 1.14	60.34 ± 0.10

[a]Composed of granular activated carbon for comparison with ACF

humidity and flow rate using a Miller-Nelson Model HCS-501-100 instrument (Assay Technology, Livermore, CA). A reagent grade water purification system (Aqua Solutions, Inc., Jasper, GA) was used to supply purified water to the Miller-Nelson unit for relative humidity control. The temperature and relative humidity in the test chamber were monitored using a HOBO Model U14-002 temperature and relative humidity datalogger (Onset Computer Corp., Pocasset, MA). Pressure drop (in mmH_2O) across the ACF cartridges was measured and logged using a DP-Calc Model 5825 micromanometer (TSI Inc., Shoreview, MN). Pressure drop measurements across each ACF cartridge were obtained every 30 seconds for 20 minutes, resulting to a total of 40 pressure drop data points per test. The average pressure drop was calculated per test. Each test was conducted in triplicates. The instruments and materials were set up in such a way that the direction of airflow is towards the outer (i.e., inlet) side of the cartridge, thus representing the inhalation pressure drop across the ACF materials. Figure 1 shows the schematic diagram of the experimental setup for the pressure drop determination.

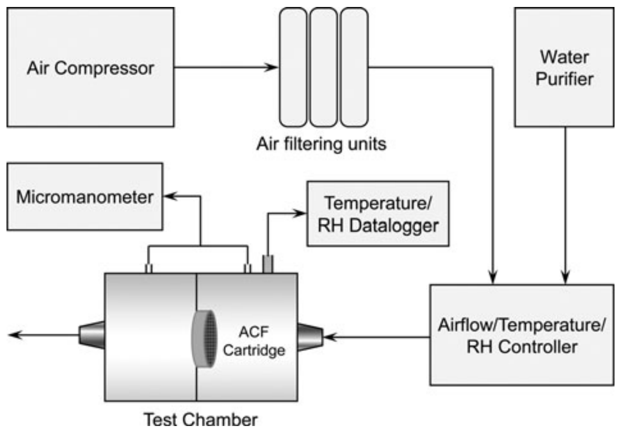

Figure 1. Experimental setup for pressure drop determination using constant airflow.

Data analysis

The Statistical Package for the Social Sciences (SPSS version 20) was used to analyze the data. One-way analysis of variance (ANOVA) test was used for the comparison of means. The pressure drop measurements across cartridges were compared among the different ACF cartridge configurations, between GAC and ACF cartridge configurations, and to the NIOSH requirements in breathing resistance testing for respiratory cartridges. The mean adsorbent (ACF and GAC) weights were also compared by cartridge configuration. $P < 0.05$ was considered statistically significant.

Results and discussion

Fiber organization

The SEM images demonstrate the fiber organization of the ACF materials. At 50x magnification, the ACFC illustrates tightly woven fibers that show a denser appearance, while the ACFF types have more randomly distributed, non woven loose fibers that give a spongier appearance (Figure 2). At higher magnifications (200x and 800x), the ACFC shows fibers that are more tightly bundled together, while the fibers of ACFF1 are separated from each other, showing more spaces between them.

Pressure drop

Single ACF-type cartridges

The 20-min average pressure drop measurements across respirator cartridges were obtained per test. Table 2 shows the average pressure drop and weight measurements across 9 single-ACF type cartridge configurations and a GAC cartridge. The average pressure drop results for cartridges filled with GAC (23.13 ± 1.14 mmH_2O) and all ACFF types (CS1 to CS8, ranging from 23.71–39.93 mmH_2O) were within the NIOSH inhalation resistance requirement of 40 mmH_2O. However, the cartridge filled with ACFC (CS9) had a mean pressure drop (85.47 ± 3.67 mmH_2O), which exceeded twice the NIOSH limit and is significantly higher than the mean pressure drop of the ACFF ($p < 0.01$) and GAC cartridges ($p < 0.01$). This may be attributed to the tighter weaving of the fibers of ACFC as shown in the SEM images (Figures 2 and 3), thus resulting to the restriction of airflow through the material. The high-pressure drop across the ACFC cartridge demonstrates that the use of 100% ACFC in cartridges is not recommended and will likely result in respirators that are difficult to breathe through. Compared to the GAC cartridge, all the ACFF cartridges (CS1–CS8) in general had a significantly higher mean pressure drop (32.77 ± 5.44 mmH_2O, $p = 0.01$) but had significantly much lower mean adsorbent weight (4.74 ± 1.66 g, $p < 0.01$) compared to the GAC (60.34 ± 0.10 g) (Table 2). This demonstrates the ACFF weights in cartridges that are 15.2% of the GAC weight or less, and thus showing potential for lighter respirator cartridges. CS1, CS2, and CS3 cartridges

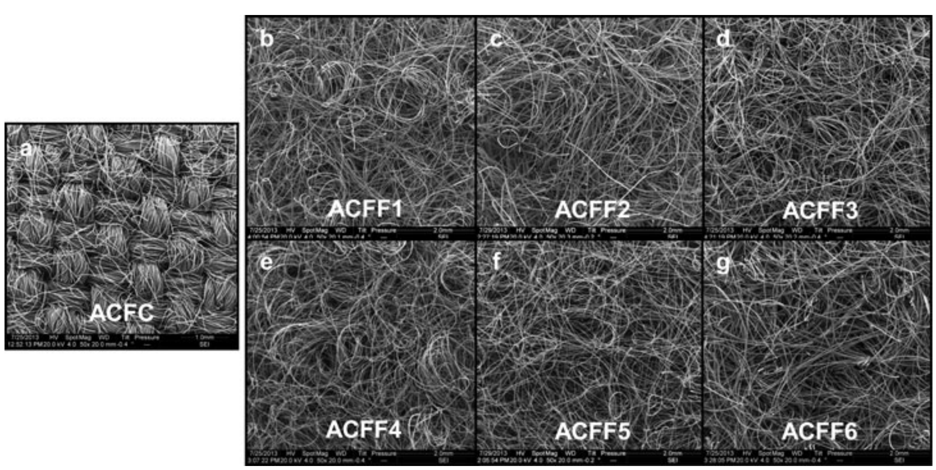

Figure 2. SEM images of activated carbon fibers at 50x magnification: (a) ACF cloth (ACFC) and (b–g) ACF felt (ACFF)/

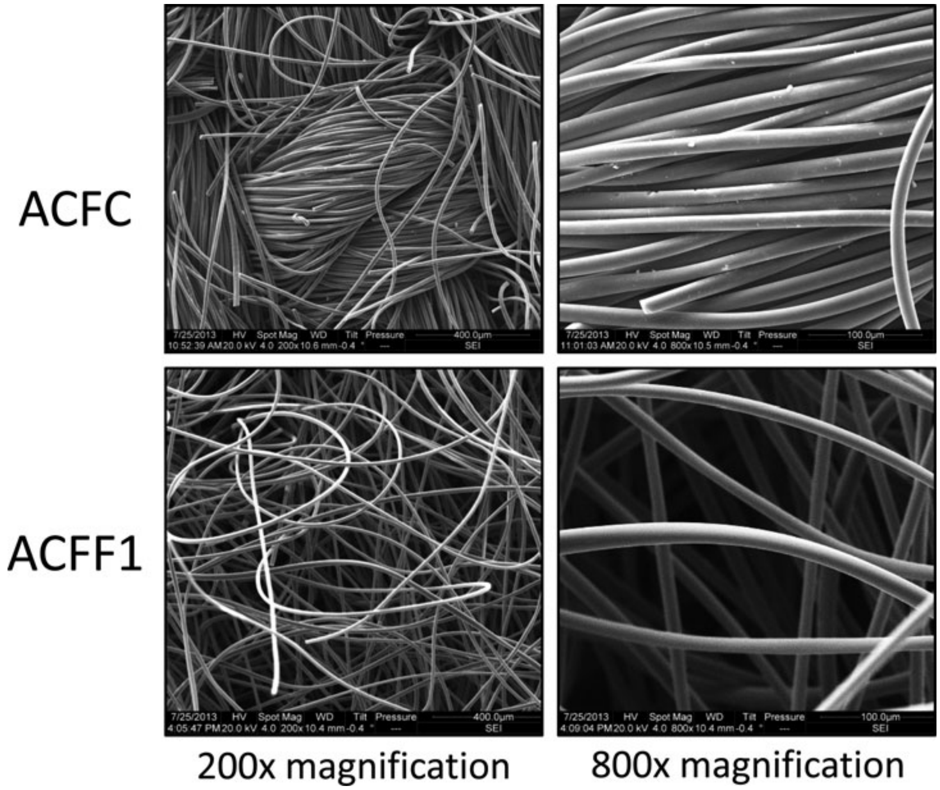

Figure 3. SEM images of activated carbon fibers at 200x and 800x magnifications.

contain the same ACF type but with increasing density, resulting to increasing pressure drop (Table 2). Cartridges filled with different ACFFs showed varied pressure drop measurements depending on the density of the adsorbent materials, wherein less dense ACFF types had lower pressure drop. Among the ACFF types, the CS8 cartridge (filled with ACFF6) has the highest mean pressure drop (39.93 ± 0.67 mmH_2O), which is essentially at the NIOSH limit and is significantly higher than the mean pressure drop of the other ACFF cartridges, CS1–CS7 ($p < 0.01$ to $p = 0.04$). This may be due to the ACFF6 having the most dense material (0.07 g/cm^3) among the ACFF types, although its fibers were non woven.

Combination ACF-type cartridges

The ACF combinations placed in a cartridge were designed to have a pressure drop below 40 mmH_2O. The ACF types and number of layers in the ACF combination were determined based on preliminary pressure drop measurements across each ACF type at different number of layers. Table 3 shows the average pressure drop and weight measurements across the 15 combination ACF-type cartridge configurations (ranging from 27.39–32.81 mmH_2O) and a GAC cartridge (23.13 ± 1.14 mmH_2O). Compared to the GAC cartridge, each of the ACF cartridge configurations (CC1–CC15) has significantly higher mean pressure drop ($p < 0.01$ to $p = 0.05$) but has a significantly much lower mean adsorbent weights (ranging from 4.79 – 6.78 g; $p < 0.01$) compared to the GAC (60.34 ± 0.10 g) (Table 3). This demonstrates that ACF in cartridges are 11.2% of the GAC weight or less, resulting to lighter respirator cartridges.

One specific purpose of combining ACF types in a respirator cartridge is to decrease the pressure drop to acceptable values when using the more dense ACF materials (i.e., ACFC, ACFF6) by incorporating less dense materials with them. Considering that adsorption capacity is related to the adsorbent mass, which consequently is related to its bulk density, it is expected that the more dense ACFs have higher adsorption capacities for airborne pollutants, which is essential in respiratory protection application. ACFCs have been found to have higher adsorption capacities for toluene compared to ACFFs, which may be directly attributed to the difference in micropore size distribution and indirectly to the difference in ACF density and fiber surface accessibility to activating gas during the activation process.[25] ACFCs were also demonstrated to provide longer protection against toluene based on breakthrough time compared to ACFF because of the ACFC's denser form.[1] Thus, in CC1 and CC2 cartridge configurations, ACFC was combined with ACFF1, which is the thinnest ACFF (0.23 cm) and among those with the lowest density (0.043 g/cm^3). Compared to the CS9 cartridge (100% ACFC) with an unacceptable pressure drop (85.47 ± 3.67 mmH_2O), such combinations (predominantly composed of ACFF) reduced the pressure drop to acceptable values (32.81 ± 1.53 and 27.56 ± 2.42 mmH_2O for CC1 and CC2, respectively). Moreover, in CC3 and CC4 cartridges, ACFF6, which is the thickest (0.50 cm) and most dense (0.070 g/cm^3) among the ACFF types, was combined with ACFF1. Compared to the CS8 configuration (100% ACFF6) with a pressure drop almost at the NIOSH limit (39.93 ± 0.67 mmH_2O), such ACFF combinations resulted to much lower pressure drop values (28.91 ± 0.14 and 31.06 ± 0.43 mmH_2O for CC3 and CC4, respectively). CC1–CC4 cartridge configurations demonstrate the possibility of achieving acceptable pressure drop by combining dense ACF types with high pressure drop with other less dense ACF types with low pressure drop, with the goal of obtaining a compromise between absorbent bulk density and permeability.

Summary and conclusion

This study investigated the ACF composition that may result to respirator cartridges with acceptable breathing resistance. All cartridges with single ACFF types showed acceptable pressure drop based on NIOSH certification requirements, as well as cartridges with certain combinations of ACFC and ACFF types, and thus demonstrating the ACF's potential application in respiratory protection. All ACF cartridges, either single or combination ACF-type, were shown to have much less weight than GAC cartridges, thus indicating potential for the development of lighter respirators.

ACFC, although shown to have higher adsorption capacity in previous studies, were found to have unacceptably high pressure drop and are, therefore, not recommended for use in respirators if used by itself (i.e., 100% ACF) at the cartridge thickness or bed depth (i.e., 1 in) tested in this study. ACFF by itself may be more appropriate as adsorbent materials in ACF respirator cartridges in terms of acceptable breathing resistance. However, ACFC may still be utilized in respirator cartridges if used in fewer layers in combination with ACFF types with lower pressure drop. Such combination technique may also be used for denser ACFF types to further reduce pressure drop across the cartridge. Another option to reduce pressure drop while using 100% of these dense ACF materials would be reducing the bed depth of the cartridge (i.e., ½ in).

The potential of ACF for use in realistic cartridges for respiratory protection was assessed in this pilot study based on pressure drop alone. However, the adsorption characteristics (i.e., adsorption capacity, breakthrough) of these tested ACF cartridge configurations with acceptable breathing resistance must be further investigated to determine their service lives for protection against airborne contaminants (i.e., VOCs) in various environmental conditions (i.e., temperature, relative humidity) and worker scenarios (i.e., sinusoidal vs constant airflows, breathing rate). Considering that the adsorbent mass in these ACF cartridge configurations is lighter compared to a typical GAC cartridge and that adsorbent mass is related to adsorbate captured, it is important to understand the effects of each configuration to these adsorption characteristics. Other factors that may be studied further is the possibility of encasing the ACF adsorbent in lighter materials (i.e., to produce an air-purifying media similar to a pancake filter for particulates) and of developing lighter and thinner N95-like ACF respirators.

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