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ORIGINAL ARTICLE

Capability of the Airstream Helmet for Protecting Mine Workers from Diesel Particulate Matter

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Abstract

Diesel particulate matter (DPM) is considered carcinogenic to humans by the International Agency for Research on Cancer (IARC), and mine workers have some of the highest exposures to DPM in the USA. Therefore, mines have been developing control strategies for reducing DPM exposures of mine workers. Many of these strategies include engineering and administrative controls. In addition to these types of controls, a respirator program is used at some mines to provide further protection to mine workers where elevated concentrations of DPM exist. However, sometimes mine workers may feel restricted by the use of a half-mask respirator or inconvenienced by the requirement to remove facial hair. Another option which may be more appealing to some mine workers than a half-mask respirator is an airstream helmet, which provides filtered air in the breathing zone of the worker. The airstream helmet does not restrict breathing, provides some cooling, and does not require the worker to be clean shaven to work properly. These helmets are being used to help reduce respirable dust exposures in some coal mines, and this study investigated how effective this helmet may be for reducing DPM exposures. The airstream helmet with a HEPA filter was found to reduce DPM exposures by over 99% in static conditions by both mass and particle counting data. The airstream helmet can be an important part of a mine's DPM control plan because it can provide clean air into a mine worker's breathing zone in areas of elevated concentrations.

Keywords Diesel · Control technology · Personal protective equipment

1 Introduction

Exposure to diesel exhaust is associated with an increased risk for lung cancer and other adverse health effects [1–4]. Pronk et al. [5] reported that the highest exposed groups to elemental carbon (EC) from diesel exhaust worked in underground sites in mining and construction and that they were exposed to concentrations from 27 to 658 μg/m^3. At concentrations from 1 to 25 μg/m^3 EC, well below those observed in mining, diesel particulate matter (DPM) exposures were estimated to increase the risk of cancer by levels exceeding those typically acceptable for occupational risk in the USA and Europe [6]. This suggests that underground mine workers are especially at risk because of their more substantial exposures in confined working spaces. As a protective measure, in 2001, the Mine Safety and Health Administration (MSHA) promulgated a rule to limit exposures of metal/nonmetal underground mine workers to DPM to an 8-h time-weighted average (TWA) of 160 μg/m^3 total carbon (TC) [7–9].

Mines are currently using a variety of control technologies to reduce DPM exposures to mine workers [10, 11]. Some of these technologies include diesel particulate filters, enclosed cabs, ventilation, low emitting engines, and administrative controls. Some mines are even implementing battery-powered vehicles to eliminate some of the emissions [12]. In many cases, these technologies lower the DPM exposures of mine workers to concentrations below compliance levels. However, the safe level of DPM is not known. Therefore, many mines are being conscientious and have a voluntary program for mine workers to further protect themselves with respirators even though they cannot be used to comply with the diesel rule. Respirators are also used to temporarily protect mine workers from elevated concentrations of DPM as control technologies are being implemented in areas where DPM concentrations may exceed the permissible exposure limit (PEL).

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In most cases, a half-mask filtered respirator is used in mines for protection from DPM. The main limitations of this type of respirator are that it can feel uncomfortable, restrict breathing, restrict communication, and require shaving of facial hair. These limitations sometimes hinder their use in underground mines. Alternatively, powered air purifying respirators (PAPRs) can be used to provide a comparable level of respiratory protection with a design that is advantageous to some mine workers. PAPR can be described as respirators that protect the user by filtering out contaminants in the air and use a battery-operated blower to provide the user with clean air through a tight-fitting respirator, a loose-fitting hood, or a helmet. The airstream helmet is a loose-fitting helmet style PAPR and has become more popular in some coal mines (especially in longwall mining) for reducing respirable dust exposures. It allows some verbal communication, does not restrict breathing, and feels cooler to wear. Also, it can be used with facial hair and does not require fit testing. While providing clean air in the mine worker's breathing zone, the airstream helmet also provides hardhat protection and a face shield for eye protection.

Studies have shown that the airstream helmet dramatically reduces respirable dust exposures [13–15]. In static conditions, Treaftis et al. [13] reported reductions close to 100%. In field studies with ventilation less than 400 ft/min (fpm) and taking into account work practices such as visor lifting, Cecala et al. [14] reported over 84% reductions in respirable dust exposures. The increase of mine air ventilation reduced the protection factor of the airstream helmet since it interfered with the airflow from the helmet. Still, due to the success of the airstream helmet for reducing respirable dust, Potts and Divers [15] evaluated it for reducing submicron particles. This helped to determine if the airstream helmet could reduce DPM exposures since the DPM particle size distribution is in the submicron range. They reported reductions of around 94% for submicron particles present in coal mines.

Since conducting these tests, not much more information has been reported concerning the airstream helmet for reducing DPM exposures. A knowledge gap remains concerning the evaluation of the airstream helmet directly in a DPM atmosphere and the evaluation of the modified version developed after the Potts and Divers study. Specifically, in 2000 there were improvements in the airstream helmet that included better airflow and improved filtration, which could lead to better reductions in DPM. The current study evaluated the updated airstream helmet in a DPM atmosphere to determine its efficiency for reducing DPM.

2 Methods

2.1 Determining Airflow of the Airstream Helmet

The airstream helmet was sent to the National Institute for Occupational Safety and Health (NIOSH) National Personal Protective Technology Laboratory (NPPTL) to determine the airflow in the helmet and to ensure that it meets the minimum required airflow for a loose fitting PAPR, which is further described in the results and discussion section. NPPTL certifies PAPRs and other respirators and follows standard procedures for determining the airflow of the PAPR systems. The airflow test was performed in a chamber as shown in Fig. 1 according to STP-0012 Determination of Air Flow For Powered Air-Purifying Respirators [16]. Minimum certification standards for these standards are set in 42 CFR, part 84, subpart G, section 84.63(a)(c)(d), and subpart KK, section 84.1157(a)(c) [17].

2.2 DPM Laboratory in Experimental Mine

At the Pittsburgh site of NIOSH, a coal mine, which was a working mine over 100 years ago, is used for performing tests to simulate mining conditions. In this experimental mine, a section as shown in Fig. 2 was partitioned to form a chamber where a constant and uniform concentration of DPM can be maintained. This section is about 3.97 m (13 ft) across, 2.14 m (7 ft) high, and 12.2 m (40 ft) long. Tubing is extended from the end of the section to the first crosscut where a 4000-cfm fan draws air from the entry. Fresh air enters through a 0.61-m (2-ft) by 1.22-m (4-ft) window opening of a stopping. DPM is inserted by an Onan diesel generator (Model number 12.5HDKCB-11506E) (Cummins, Gibsonia, PA). Fresh air and diesel are introduced at the beginning of the section, and a fan is used for mixing. DPM continuously fills the section and is drawn at about 9.15 m/min (30 fpm) to the end of the entry and the mine's ventilation system removes the DPM out of the mine.

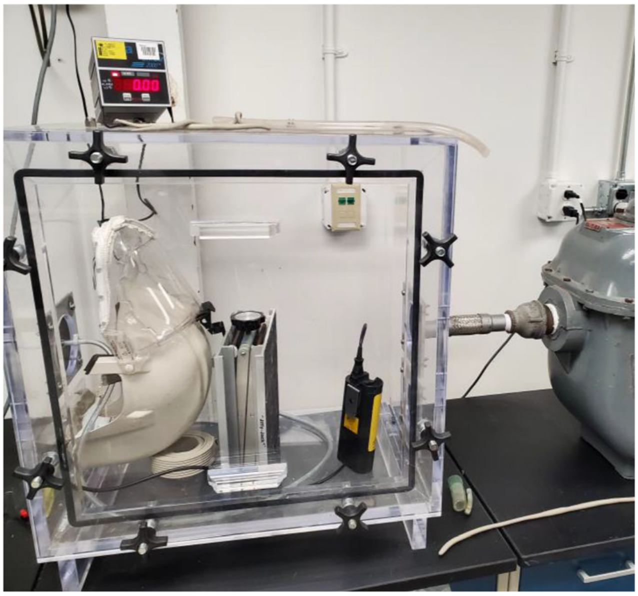

Fig. 1 Chamber used to test flow from airstream helmet

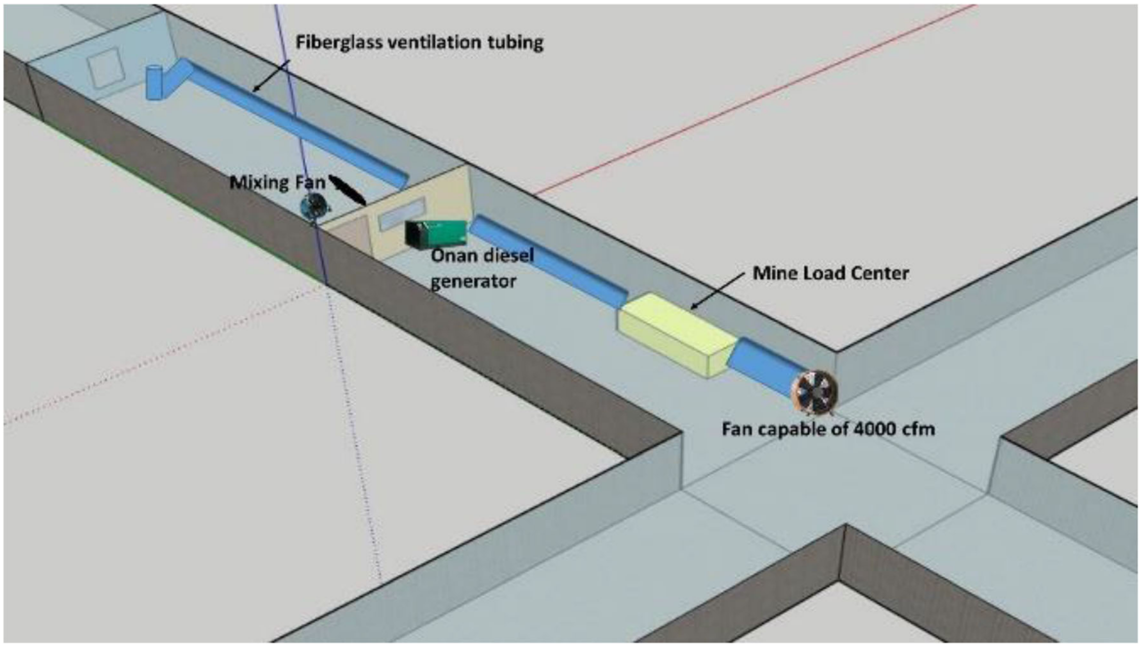

Fig. 2 Schematic of diesel laboratory in the Experimental Mine at NIOSH Pittsburgh

2.3 Evaluating Airstream Helmet in DPM Atmosphere

Inside of the DPM laboratory in the experimental mine, the an Airstream™ Mining Headgear-mounted PAPR (AS-600LBC, 3 M, St. Paul, MN) was attached to a manikin as shown in Fig. 3 to simulate a miner wearing the airstream helmet. Elemental carbon (EC) concentrations were measured under and outside of the helmet to determine the reduction in DPM concentration when wearing the helmet. Elemental carbon via NIOSH method 5040 was used as surrogate since it is a major component of DPM and the analysis is not affected by the presence of interferences [18]. In addition, it is one of the surrogates used for MSHA compliance sampling and NIOSH occupational DPM exposure assessments [18–20].

To determine the concentration of EC under the helmet, conductive tubing was taped to the nose or location of the breathing zone and extended outside of the airstream helmet. The tubing was connected to a high sensitivity (HS) cassette with a quartz fiber filter (QFF) (see Fig. 4) to collect NIOSH method 5040 samples. Lower concentrations of DPM than the standard sampling methods, such as the SureSeal three-piece cassette and SKC DPM cassette, can be detected [21]. It has been shown to provide similar accuracy for measuring EC as the SureSeal three-piece cassette [21]. The HS cassette (see Fig. 4) concentrates the DPM onto a smaller spot size so that all of the DPM collected on the filter is included in the section analyzed by the instrument. The HS cassette uses the top two sections of a SureSeal three-piece cassette (SKC, Inc., Eighty Four, PA) with a modified bottom section. The modified bottom section is designed to fit a 37-mm filter but directs the DPM onto just a 0.5-cm^2 section of the filter. This concentrates the DPM and allows the measurement of lower concentrations with the standard flow rate. The HS cassette is the same size as the standard three-piece cassette and can be plumbed with the standard size selectors of a Dorr-Oliver cyclone (SKC, Inc.) and SKC impactor (SKC, Inc.). The HS cassette was able to detect about five times less DPM concentrations compared with the SKC DPM cassette at the same flow rate. For the compliance method, in which the SKC DPM cassette [22] is used, the DPM is collected on an 8.04-cm^2 area of a QFF (a metal ring is part of the SKC cassette which causes the DPM to only collect on 8.04 cm^2 section of the 37 mm filter), but only a 1.5-cm^2 section is inserted into the instrument for the carbon analysis. Since the limit of detection (LOD) for EC via NIOSH method 5040 analysis is 0.3 μg per filter section [20], 1.6 μg needs to be collected on the filter to be at the LOD. The HS cassette concentrates the DPM onto a smaller spot size so that all of the DPM collected on the filter is included in the section analyzed by the instrument, meaning that only 0.3 μg of DPM instead of 1.6 μg to be collected on the filter to be at the LOD. The HS cassette is especially beneficial for a situation like this where the control technology could substantially reduce the DPM concentrations. An Elf pump (Zeflon International, Ocala, FL) was used to pass flow through the HS cassette. The flow rate was set at 1.7 l/min (lpm) and was checked with an electronic soap film flow meter calibration device (Gilibrator, Gilian Instrument Group, West Caldwell, NJ) for each sampler as described by Bugarski et al. [11].

In order to determine the concentration of EC on the outside of the airstream helmet, a standard SureSeal three-piece cassette, which was fitted with a QFF and connected to an Elf

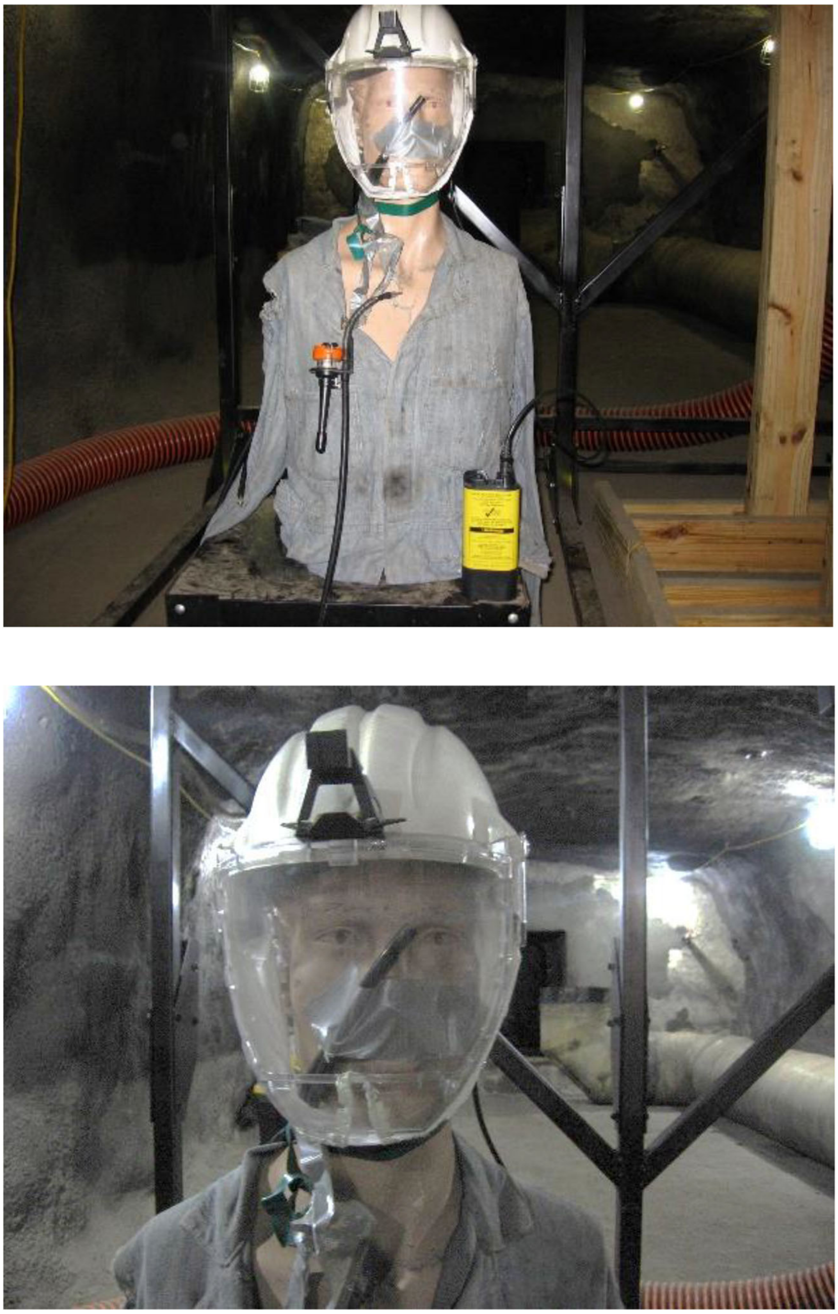

Fig. 3 Pictures of the 3 M airstream helmet attached to the manikin in the diesel laboratory of the Experimental Mine at NIOSH Pittsburgh

Fig. 4 The picture on the left shows a side view and the one on the right shows the top view of the high-sensitivity cassette

pump, was attached to the lapel of the manikin. In addition, an Airtec diesel particulate monitor (FLIR Systems Inc., Wilsonville, OR) [23, 24] was attached to the lapel to provide near real-time EC analysis of the air outside of the helmet. The flow rate of instruments was set at 1.7 lpm and checked as described above.

At the beginning of a test, the samplers, airstream helmet, mixing fan, and exhaust fan were turned on. Next, DPM was introduced into the section of the experimental mine described earlier using the Onan diesel generator (Cummins, Gibsonia, PA). Sixty-four percent load was applied to the engine by a Simplex Swift-E plus 15 kW portable load bank (Simplex, Springfield, IL). At this loading, the EC-to-total carbon (TC) ratio simulates the composition observed in underground mines [19]. After 2–3 h, the DPM was turned off. After the DPM laboratory was purged of exhaust, the samplers were turned off. QFF samples were analyzed the same day or stored in a freezer. QFF samples from the HS and three-piece cassettes (samplers outside and under the helmet, respectively) were analyzed at NIOSH Pittsburgh for EC content by NIOSH method 5040 [19, 20]. The Airtec data was downloaded, and real-time EC graphs were constructed to demonstrate the EC concentration outside of the helmet.

The EC concentration outside of the helmet (three-piece cassette on lapel of manikin) and inside the helmet (HS cassette) was compared with the % reduction in DPM exposures. This also demonstrated the % efficiency of the helmet for removing DPM. Below is the equation used to determine % reductions in DPM:

$$\%reduction = \left(1 - \frac{conc\ \ inside}{conc\ outside}\right) x\ 100$$

EC could not be detected on the QFF when the HEPA grade filter was utilized in the airstream helmet. Therefore, the tests for % reduction were performed three times with the airstream helmet containing the P2 rated filter (060–23–16) which is rated to collect at least 94% of particles smaller than 0.5 μm and designed for mechanically generated particles such as dust and not necessarily thermal generated such as DPM. The test was repeated again three times with the airstream helmet containing the AS-140-25 highly efficient filter (HEPA grade) which is designed for both mechanically and thermally generated particles. The triplicate results for the % reductions were averaged, and a 95% confidence limit was calculated as described in Skoog and West [25].

In addition to EC measurements, particle number concentration data was also used to determine reductions in DPM for the airstream helmet with the HEPA filter. The particle number concentration data included mostly DPM, potentially some dust, and ambient particles. The number of particles from DPM contains mostly ultrafine particles (< 100 nm), while these particles can represent a much smaller portion of the mass [26–28]. Therefore, a control technology could reduce the mass but still allow ultrafine particles, which can penetrate deeper into the lungs, to penetrate. By investigating the particle number as well as the mass, one can determine the effects of the airstream helmet on particles represented in the mass measurements and ones represented by particle counting. For the number concentration measurements, first the fans were turned on but DPM was not released into the section in order to measure the background particle concentrations or non-DPM particles. Particle number concentration was measured for 5 min with a condensation particle counter (CPC) (Model 3776, TSI Inc. Shoreview, MN). The CPC measures 2.5 nm to > 3 μm particles and determines the total number concentration for values up to 3×10^5 #/cc. After the background measurements, DPM was introduced into the experimental mine laboratory as before, but the outside particle number concentrations were measured for 5 min. Then the number concentration inside the helmet was measured for 5 min with the CPC. Outside- and inside-helmet CPC measurements were repeated three times. The concentrations outside of the helmet were above the maximum readable levels. Therefore, the maximum readable level was used for this value in the equation for % reduction. To determine the concentration inside the helmet, the three values were averaged, and a 95% confidence limit was calculated as described by Skoog and West [25]. The Airtec was also used to measure EC in near real time outside of the helmet.

3 Results and Discussion

The airflow from the airstream helmet used in this study was found to be 211 lpm (7.45 cfm). This is important because the airflow from the helmet must be higher than the rate of breathing or respiratory flow rate, or some contaminates may leak into the breathing space of the miner. This condition is called over breathing. The airstream helmet is a loose-fitting helmet style and requires at least 170 lpm (6 cfm) flow rate to prevent over breathing [17]. This is based on studies from industrial settings such as mining [17, 29, 30]. For example, a study by Bloomfield and Greenburg [30] determined that at least 170 lpm flowrate from the blower in the helmet is needed to reduce worker exposures to acceptable levels of silica dust concentrations outside and inside abrasive blasting helmets. In most cases, 211 lpm should be sufficient to provide enough airflow, such that over breathing will not occur. However, studies have shown that some peak respiratory airflows when performing strenuous exercise (80–85% oxygen consumption) can exceed 300 lpm and potentially reduce the efficiency of the PAPR [31, 32].

With the use of the P2 060–23-16 filter, which is designed to collect mechanically generated particles, EC reductions were 91 ± 8% as shown in Table 1. EC was used as a surrogate for DPM to determine the reductions because it is not influenced by interferences, such as dust and cigarette smoke, and can be measured at lower concentrations than particle mass, TC, or organic carbon (OC) [33, 34]. In addition, reductions in EC have been shown to represent reductions in total DPM [18, 35]. Therefore, with the P2 filter and in static ambient airflow conditions, 91% of the DPM was removed by the airstream helmet. The P2 filters are rated for at least 94% efficiency in capturing particles greater than 0.5 μm (500 nm). The P2 was expected to reduce submicron particles in the 90% range, and since most DPM particles have particles sizes between 10 and

Table 1 % Reduction of EC values for the Airstream Helmet with P2 Filter

Test	EC concentration outside (μg/m^3)	EC inside (μg/m^3)	% reduction
1	157	16	90
2	212	24	89
3	174	9	95
		Average with 95% confidence limit	91 ± 8

1000 nm [28], the 91% reduction achieved was expected as long as there was minimal leakage. Our results are also similar what Potts and Divers [15] achieved when determining reductions in submicron particles with the airstream helmet on a manikin in a coal mine (94 ± 3%).

With the HEPA grade filter, the airstream helmet was able to reduce DPM exposures to even lower levels as expected. HEPA filters are rated for 99.97% reduction for particles down to 0.3 μm and for both mechanically and thermally produced particles. Studies have also found HEPA filters to be over 99% efficient for nanometer size particles. Golanski et al. [36] reported HEPA filters to be at least 99.8% efficient in capturing particles of platinum and titanium dioxide between 10 and 20 nm and over 99.9% for particles of graphite in the same size range. Kim et al. [35] showed HEPA filters to be 99.99% efficient for silver particles ranging between 3 and 20 nm, and Held et al. [37] showed HEPA filters to be over 99.97% efficient in capturing DNA particles around 200 nm. Since most diesel exhaust particles are within 10–1000 nm [28], the HEPA filter should be efficient in capturing DPM. The concern is about leakage around the filter and through the mask as well as how well the PAPR seals around the face.

After 3 h of sampling, no EC could be detected inside the airstream helmet even when the outside concentrations were around 200 μg/m^3 EC. Therefore, the LOD was used as the concentration inside the helmet to calculate the % reduction since the levels of EC were below the LOD and could not be measured. The actual reduction efficiency is greater than the one calculated with the LOD since the actual values of EC are lower than the LOD and their input would result in higher reduction efficiencies. As shown in Table 2, the airstream helmet provided over 99% in reductions of DPM.

Another metric used to determine the reductions in DPM is the number of particles. As mentioned earlier, this metric can provide us with an indication of the airstream helmet capability of capturing ultrafine particles (less than 100 nm). This is because most of the number of particles comes from ultrafine particles which may not be a major contributor to the mass [26–28]. Therefore, major reductions in the particle number would have to be associated with major reductions in particles less than 100 nm. In the DPM experimental mine laboratory, the main source of particles was DPM since the background particle number was about 110,000 #/cm^3, while with DPM, the number of particles was greater than 300,000 #/cm^3. The number of airborne particles measured with the DPM was greater than the maximum readable levels (300,000 #/cm^3) for the instrument; hence the number of particles outside of the helmet is some number greater than 300,000 #/cm^3. Although the exact number was not determined, the test levels were relevant as indicated by EC concentrations, which were within ranges observed in underground mines. As seen in Fig. 5, the outside-the-helmet EC concentrations were between 120 and 160 μg/m^3 while performing the particle counting measurements, and this EC concentration range has been observed in several mines [24, 35].

The CPC showed reductions greater than 99.91%. The exact value for percent reduction could not be determined with the CPC because the outside concentration was higher than the maximum readable levels (300,000 #/cm^3). The number of particles inside the airstream helmet could be measured accurately. Therefore, the maximum readable level was used as the concentration outside the helmet to determine the % reductions, and since any value greater would again mean higher reduction efficiencies, the actual reduction efficiency would be greater than the calculated value. The average concentration under the helmet was 280 ± 122 #/cm^3. As seen in Fig. 6, the number of particles drastically dropped when measuring inside the helmet compared with outside the helmet. This figure provides a good visual perspective of the effect of the airstream helmet on the concentrations of DPM and how the

Table 2 % Reduction of EC values for the Airstream Helmet with HEPA grade filter

Test	EC concentration outside (μg/m^3)	EC inside (μg/m^3)	% reduction
1	111	< 1.52	> 98
2	169	< 1	> 99
3	218	< 1	> 99

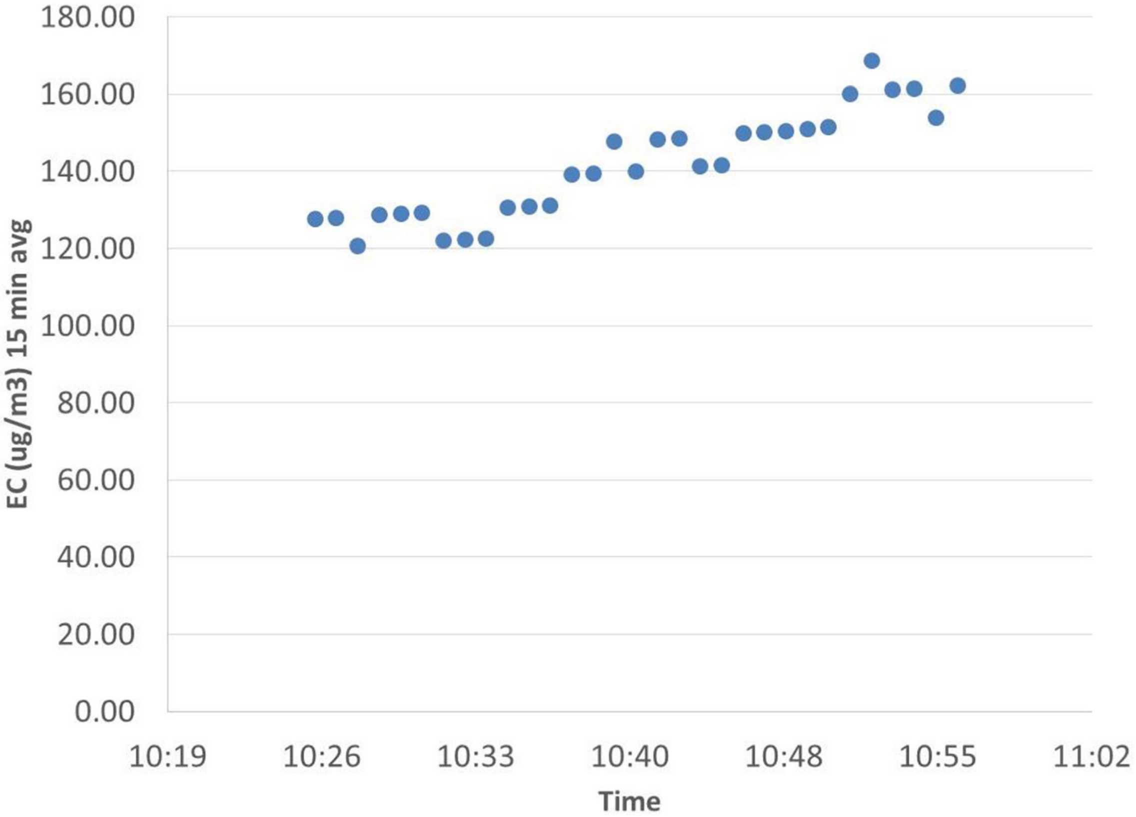

Fig. 5 Elemental carbon (EC) concentrations via Airtec outside of the helmet while making the particle number concentration measurements

DPM concentrations drop significantly from over 300,000 to less than 300 #/cm^3 under the helmet. The airstream helmet under static conditions and with a HEPA filter can capture nanometer particles from DPM as well as the EC mass. In fact, the concentrations of particles inside the helmet are as low as those found in office buildings [38].

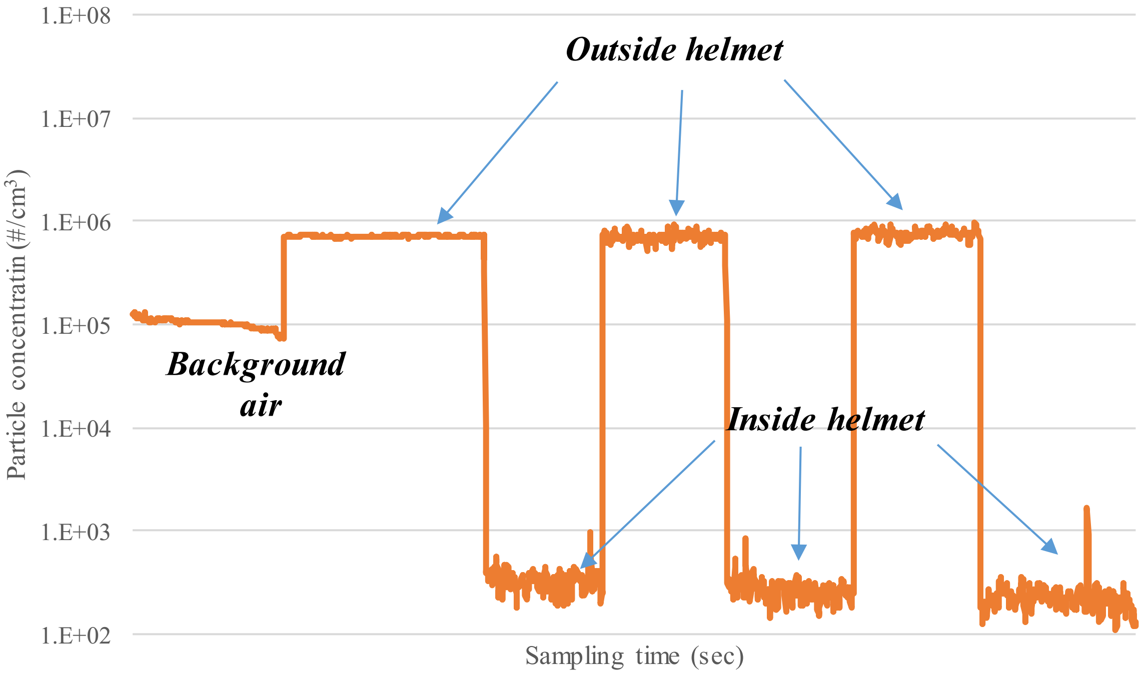

Fig. 6 The number of airborne particles was measured before DPM was introduced (background) and after DPM was introduced outside and inside of the airstream helmet

The airstream helmet with the HEPA grade filter can give high reductions in DPM exposures and provides a clean environment in the mine worker's breathing zone at static conditions. In other words, in optimal conditions, over 99% reductions in DPM were achieved. This was demonstrated for EC mass which is selective to DPM and when measuring particle number which mostly represents particles less than 100 nm.

However, these results do not include effects of ambient air ventilation, work habits such as lifting the visor, or moving the head of the miner, which could affect the seal around the face. A decrease in efficiency would be expected with increased ambient air velocities. In static conditions, Treaftis et al. [13] reported over 99% efficiency for capturing respirable dust with dust filters. Cecala et al. [14] showed a decrease in efficiency as the ambient air velocity increased. They reported a 94% efficiency when using a tracer gas at air velocities of 2 m/s (400 fpm) and down to 60% at an air velocity of 6.1 m/s (1200 fpm). In the field where a miner will be moving, which could affect the seal, and where at times, the face shield was lifted while performing their work. Cecala et al. [14] measured 84% efficiency in capturing respirable dust at face velocities of 2 m/s (400 fpm). This efficiency decreased to 49% at air velocities of 6.1 m/s (1200 cfm). Potts and Divers [15] performed a field study by measuring submicron particles while the airstream helmet was attached to a manikin and reported a 94 ± 3% efficiency for reducing submicron particles at air velocities less than 2 m/s (400 fpm) which is similar to what we achieved with the P2 filter in static conditions. In general, in situations that have ambient air velocities of less than or equal to 2 m/s (400 fpm), the efficiency may be in the 90% range or even close to 99% if the visor is not lifted. If the visor is lifted periodically, reduction efficiencies in the 80% range may occur such as was observed by Cecala et al. [14]. As ambient air velocities increase over 2 m/s (400 fpm), the efficiency of DPM reduction could decrease.

This helmet is considered as personal protective equipment (PPE) and can be implemented in the plan of mines for reducing DPM exposures. It cannot be used for compliance with mine air regulations but can be a resource for providing additional protection for mine workers even if only worn when performing certain tasks or for part of a shift. For example, the 2016 compliance data indicated that two of the most overexposed miners were blasters (36% of all overexposures) and load haul dump (LHD) operators (20% of all overexposures). In stone mines, blasters can be exposed to concentrations of DPM above the exposure limit while loading a face with ANFO. Ventilation air velocities can be low at the face, and good protection may be achieved when using the airstream helmet while performing this task. LHD drivers may experience higher ambient air velocities and their exposure reductions may be lower than the 99% range. In cases where the LHD is operating in a dead-end entry, the helmet could provide better protection than in higher ventilation velocities or when traveling. In addition, a mine worker may just want additional protection from DPM even if their exposure is at the PEL. Given that in optimal conditions, the airstream helmet provides 99% reductions in DPM and particle concentrations similar to those observed in an office building, wearing an airstream helmet may reduce the risk of health issues from DPM exposures. Half masks can provide some of these same protections and in some cases such as high ventilation can work better. However, mine workers may prefer the airstream helmet due to the advantages previously mentioned.

Another major question to consider is the acceptance and use of the helmet by mine workers. A study of the pre-2000 version of the airstream helmet in four coal mines showed that mine workers would not wear the helmet during highly labor-intensive tasks due to fogging of the visor. In addition, at times, the visor was up and was not being used, thus reducing the helmet's effectiveness [37]. As mentioned earlier, when performing strenuous exercises, the efficiency of the PAPR may also decrease due to over breathing. There were modifications in 2000 to the helmet such as the prevention of fogging. Therefore, it would be beneficial to evaluate fogging but also the potential reduction in efficiency due to over breathing. Furthermore, the comfort, efficiency in real situations, effects of work practices, and overall willingness for miners to use the post-2000 airstream helmet should be studied. It is also important to determine if dust may interfere with vision in areas with high dust concentrations, to ensure that the filter is changed when necessary and that the helmet is properly maintained [39].

Dust can collect on clothes and the helmet and potentially cause some exposure to dust when removing the helmet [38]. A mine worker may want to remove the dust before removing the helmet. Some methods for removing dust from clothes are vacuuming and using a single compressed air hose [35]. Cecala et al. [40] developed a clothes cleaning booth where a miner enters a booth with a respirator on. Then a manifold of sprays supply compress air to the clothes to extract the dust and an exhaust system removes the dust from the chamber. This system was reported to be 41% more effective than vacuuming dust from clothes [40, 41]. Before removing the helmet, this booth could be used to remove the dust from clothes and helmet.

4 Conclusion

In static air flow conditions, the airstream helmet with HEPA filter can provide over 99% reductions in DPM exposures and clean air into a mine worker's breathing zone. This is almost ideal performance, and more research is needed looking at effects of ventilation, fogging, over breathing, comfort, and work practices on the function of the airstream helmet. The airstream helmet can be an important part of a mine's DPM control plan. Even though the airstream helmet cannot be used for compliance, it can be used as PPE to provide additional protection, especially when mine workers are performing certain tasks in elevated concentrations of DPM. The airstream helmet may be preferred over a half-mask respirator by some mine workers since it does not restrict breathing, can provide some cooling, and does not require the mine worker to be clean shaven. Like most types of control technologies, it is important to perform necessary routine maintenance. The airstream helmet is one type of powered air-purifying respirator (PAPR) system. With comparable filtration media, other PAPR helmet systems could provide the same type of protection against DPM but would need tested.

4.1 Limitations

The data collected in this study was for near static conditions. The efficiency of the airstream helmet under different ventilation rates was not tested in this study. The comfort of wearing the airstream helmet and any necessary maintenance tasks were also not evaluated. In addition, the reductions reported in this study are from laboratory data and could be different when measuring in the field.

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Authors' Contributions Not applicable.

Compliance with Ethical Standards

Declarations None to declare.

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Disclaimer The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company name or product does not constitute endorsement by NIOSH.

Code Availability Not applicable.

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