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Environmental Enclosure as a Control Technology for Reducing Exposure of Mobile Underground Mining Equipment Operators to Diesel Aerosols and Gases

Aleksandar D. Bugarski[1] · Dylan A. Ritter[1] · Jeffrey L. Moredock[2]

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Abstract
This study was conducted to evaluate the potential role of the environmental enclosure with an air cleaning system as a technology for controlling operators' exposures to aerosols and criteria gases emitted by diesel-powered mobile equipment in underground environments. This laboratory evaluation was conducted using a testing facility custom designed to allow for evaluation of the environmental enclosures and associated Heating, ventilation, and air conditioning systems while being immersed in the diluted diesel exhaust. Four different configurations of the Heating, ventilation, and air conditioning system for the commercially available environmental enclosure of the underground mining load-haul-dump vehicle were evaluated at the custom-built test facility. The configurations were evaluated while immersed in the diluted diesel exhaust with a concentration of aerosols and criteria gases comparable to those in underground mines. The configurations fitted with high efficiency filter elements were found to provide more than 95 percent reductions in the number concentrations of diesel aerosols. The configurations with elements containing adsorbent reduced the NO_2 concentrations present outside of the enclosure in excess of the current personal exposure standards by more than 85 percent and increased NO concentrations by as much as 37 percent. None of the evaluated configurations had a substantial effect on the CO_2 concentrations present outside of the environmental enclosure system at concentrations equivalent to the current personal exposure standards for underground miners. The results suggest that air quality control systems could be optimized to allow for better control of the flow rates, pressurization of the enclosure, and influx of contaminants at the low-pressure zone of the systems. The control of CO_2 and NO exposures would continue to rest on supplying an adequate quantity and quality of fresh air to dilute those gases below targeted exposure standards.

Keywords Environmental enclosure · Underground mining · Occupational exposure · Diesel aerosols · Diesel gases · Filtration · Adsorption · Control technology

1 Introduction

Diesel engines are the primary source of power to mobile underground mining equipment [1–4]. Since the introduction of diesel-powered equipment in the confined spaces of underground mines, operators have grappled with the daunting task of simultaneously reducing exposure to hundreds of different compounds found in diesel exhaust [1, 5, 6]. The chronic and sub-chronic effects of occupational exposure to individual components and the mixture of diesel exhaust compounds found in gaseous and particulate matter phases were extensively studied [7, 8]. The classification of diesel engine exhaust as a carcinogen to humans (group 1) by the International Agency for Research on Cancer [9] put the underground mining industry on alert. The risk associated with exposure to aerosols and gases emitted by diesel-powered equipment in the underground environment is currently considered as one of the driving factors toward developing new technologies and transforming the mining and metals industry [10].

✉ Aleksandar D. Bugarski
abugarski@cdc.gov

[1] Pittsburgh Mining Research Division, National Institute for Occupational Safety and Health, 626 Cochrans Mill Rd, Pittsburgh, PA 15236, U.S.A.

[2] Sy-Klone International, 4390 Imeson Rd, Jacksonville, FL 32219, U.S.A.

The metal and nonmetal underground mining industry deploys a multifaceted approach and combination of control strategies and technologies to reduce exposure of underground miners to diesel aerosols and gases [11, 12]. Historically, the focus was on improvements in ventilation, controlling diesel emissions at the source [4, 12], and lately substitution of diesel with battery electric power trains [13, 14]. Over the past couple decades, the enclosures, that have been traditionally used on mobile and stationary equipment in surface and metal and nonmetal underground mines to protect the operator(s) of mobile and stationary equipment from elements, noise, falling objects, and roll over, were adopted, with some modifications, as a control technology for various airborne pollutants. The use of effective air cleaning, pressurization, and conditioning systems allowed for the use of environmental enclosures as a dust control technology [15–19]. Noll et al. [20] showed that, when equipped with the air cleaning systems effective in the removal of submicron aerosols (HEPA and MERV16 filter elements), the environmental enclosures can be used to control exposures to diesel particulate matter. In some applications, the environmental enclosures fitted with the carbonaceous and non-carbonaceous adsorbent elements [21–28], could potentially be used to reduce exposures of operators to NO_2, CO_2, hydrocarbons, and other pollutants.

The airtightness of ventilation and enclosure systems and the pressurization of the enclosure and systems are identified as critical design factors for the effectiveness of environmental enclosure air-cleaning systems in the removal of aerosols and selected gases [15, 16, 29, 30]. The filtration elements with a wide variety of the fractional efficiencies, established during certification tests under various superseded [31, 32] or current [33–36] standards, are currently deployed in the environmental enclosure cleaning systems used in underground mining operations. Depending on the standards, the efficiencies of filtration elements are established for: (1) most penetrating particle size (MPPS) aerosols [34, 37] or (2) aerosols with fixed particle size [32, 35]. The efficiencies are typically assessed using various artificially generated polydisperse liquid or solid test aerosols in super-micron and/or submicron size ranges. The data on the removal efficiency of the filter element for the actual aerosols found in workplaces, such as freshly generated diesel aerosols, is rather limited [20]. The ISO 23875:2021 standard [30] does not specify the type of the filter that should be used on mining environmental enclosures, but rather establishes performance criteria for the maximum respirable particulate matter concentration of ≤ 25 µg/m^3 inside the enclosure at the end of a 120-s decay period. Cost, flow restriction, and potential for increase in the systems leakage are some of the other factors that need to be considered during the selection of filter elements [38].

According to ISO 11155–2:2009 [39], the removal efficiency of air filters for gaseous components used in passenger vehicles is determined by establishing breakthrough curves for challenge gases mixed with 23 °C and 50% relative humidity air. The challenge gases such as n-butane (C_4H_{10}) and toluene ($C_6H_5CH_3$) are used in a concentration of 80 ppm, while sulfur dioxide (SO_2) is used in a concentration of 30 ppm. The established breakthrough curves are used to calculate the capacity of the media to remove the specific gas. The adsorption capacity of the media is a function of pore structure and the properties of the surface chemistry. In the case of NO_2 and CO_2, both physisorption and chemisorption play important roles in removal of those gases [23, 40]. In the case of NO_2, the partial removal happens through the catalytic reduction to NO [21, 23].

The recirculating air cleaning is often used to enhance the effectiveness of the filtration systems [15, 18, 41–43]. The factor that limits the use of fractional recirculation in the environmental enclosure is the potential for compromising operator(s) safety due to accumulation of the occupants' generated metabolic and exhaled CO_2 [29, 44–46]. The evidence on the effects of exposure to CO_2 at the levels observed in occupational settings on cognitive performance and decision making is not consistent [47]. Chen et al. [48] showed no clear link between CO_2 levels up to 2,100 ppm in higher educational environments and cognitive performance, perceived indoor environmental quality, and health symptoms. Satish et al. [49] showed that exposure to CO_2 concentrations above 2,500 ppm adversely affect decision making. However, Rodeheffer et al. [50] demonstrated no significant differences in decision making between the submariners exposed to CO_2 concentrations of 600, 2,500, or 15,000 ppm. The current occupational personal exposure level (PEL) standards by OSHA [51] and MSHA [52], and the recommended exposure level (REL) by NIOSH [53] are 5,000 ppm as an 8-h time-weighted average (TWA). The ISO 23875:2021 standard [29] uses the criteria of 400 ppm above ambient level for performance testing of the design and requires keeping the maximum sustained CO_2 concentrations inside the enclosure for mining mobile equipment below 2,500 ppm, the action level based upon the 5,000 ppm PEL.

Beside fractional efficiency of the installed filtration and adsorption element(s), the system efficiency of the environmental enclosures system depends on: (1) the integrity of the clean air supply system and enclosure, and (2) the level of pressurization of the system components to prevent inward penetration of the pollutants through cracks, holes, and joints. The proper design and construction of the environmental enclosures system are critical to minimize the inward leakage. The leakage is controlled by improving the integrity of the systems and minimizing the low-pressure areas in the intake and air cleaning systems. Pressurization of the system components via single or multiple blowers is used to eliminate the inward leakage. The ISO 23875:2021 standard [29] requires the minimum sustained pressurization ≥ 20 Pa when the machine starting device is in the "on" position (activating the electrical system) and with a maximum sustained pressurization of 200 Pa. The overall performance and long-term functionality of environmental enclosure systems is typically secured via maintenance and periodic field evaluations [15, 16, 29].

The objective of this study was to investigate if enclosing operators in the environmental cabs with adequate pressurization and filtration systems could be an effective control strategy for reducing exposures to aerosols and various criteria gases emitted into the underground environment by diesel-powered mobile equipment. The goal was to assess the performance of the integrated systems rather than individual components of those systems. Since previous studies showed that the particle type and composition, gas composition, and environmental conditions [21, 25, 42] can significantly influence the performance of the air-cleaning and enclosure systems, the goal was to evaluate those systems while immersed in a diluted mixture of aerosols and gases emitted by a modern diesel engine at concentrations comparable to those in underground mines.

2 Methodology

2.1 Test Chamber

The evaluation was conducted using a testing facility custom designed to allow for evaluation of the environmental enclosures and associated heating, ventilation, and air conditioning (HVAC) systems while being immersed in the diluted diesel exhaust (Fig. 1).

During this study, approximately 210 m^3/h (124 ft^3/min, 3,500 lpm) of diluted exhaust flowed through the 37 m^3 (1,315 ft^3)-chamber (5.89m × 2.35m × 2.69 m) using custom-designed distribution and extraction systems (Fig. 1). Prior to introduction in the chamber, approximately 10 m^3/h (5.9 ft^3/min, 166 lpm) of raw exhaust was diluted using the two-stage ejector diluter system. The primary dilution was provided by the filtered and dried compressed air supplied to the ejector dilutor by the rotary screw compressor (Ingersoll Rand UP6-10). The secondary dilution was provided by filtered and dried air supplied by the regenerative blower (Gast R7100A-3). The diluted exhaust was introduced in the test chamber through eight

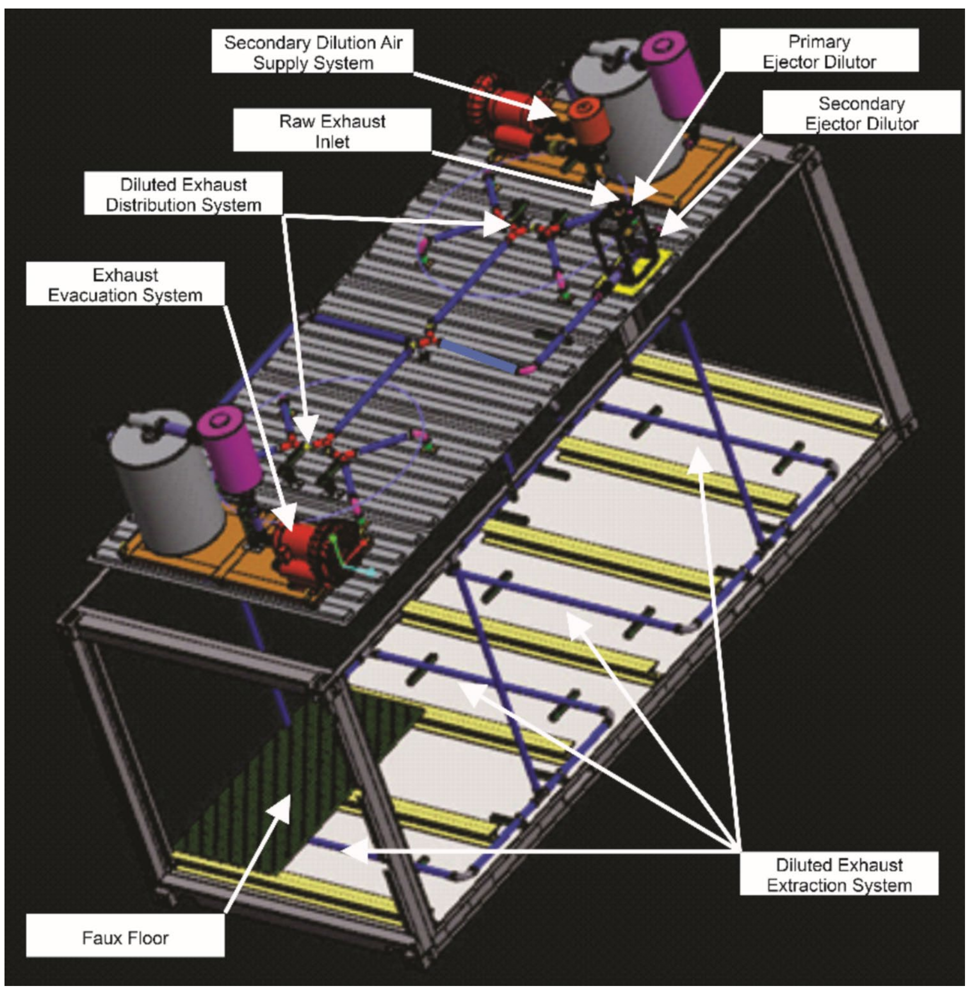


Fig. 1 Environmental enclosure testing facility

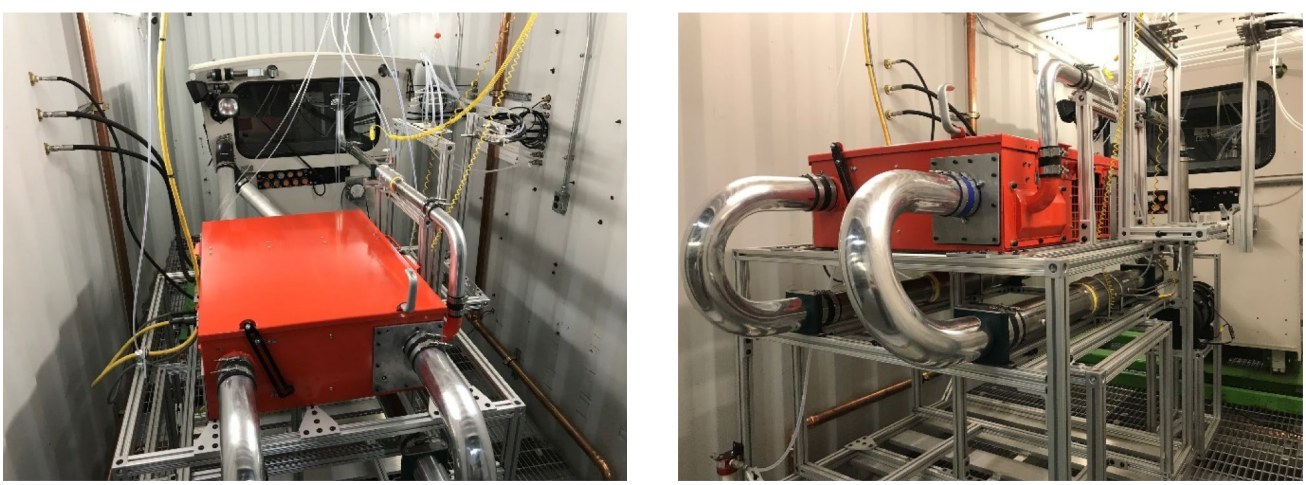
nozzles located on the ceiling of the test chamber and evacuated from the chamber via a system of perforated tubes located under the faux floor and an extraction system. The diluted exhaust was removed from the chamber by a regenerative blower identical to the one in the distribution system (Gast R7100A-3). The speeds of the motors on the regenerative blowers were controlled by variable frequency controllers. The background concentrations, defined as the concentrations of sub-500 nm aerosols inside the chamber with the distribution and extraction systems operated at the targeted capacity but with raw exhaust feed replaced with feed of the HePA filtered air, were measured daily. The average for the study, was 6800$\pm$2900 #/cm^3. The variations in the background concentrations were result of variability in the concentrations of aerosols in the laboratory air supplied to the test chamber. Environmental enclosure and configurations of filtration and pressurization system.

The experimental work was conducted using the environmental enclosure for the 17-ton underground mining load-haul-dump vehicle (Fig. 2). This well-constructed and sealed enclosure was ventilated by the modular HVAC system. With the operator's seat removed, the volume of the enclosure was estimated to be approximately 2.0 m^3. Some minor modifications were made on the enclosure prior to the evaluation: removal of the seat, replacement of a small acrylic side window with an aluminum plate with sealed measurement ports, and installation of the seal in the accelerator pedal access port in the floor. The hydraulically driven air-conditioning compressor and heating components of the HVAC system were not operated during these tests. The door and window were kept closed during the evaluation.

Four configurations of the pressurization and filtration system of the HVAC system were evaluated in this study (Table 1). The first two configurations, CONFIG 1 and CONFIG 2, were provided by the load-haul-dump (LHD) machine manufacturer. In both of those configurations (Fig. 2a and Fig. 3), the systems were fitted with an identical intake air pre-cleaner (Donaldson Top Spin HD, Model H002850), primary blower (pressurizer), evaporator (not functional), secondary blower (pressurizer), and associated transfer lines.

The differences between CONFIG 1 and CONFIG 2 are associated with the type of the panel air filter elements used for intake and main filtration and adsorption (Table 1). In the CONFIG 1, the intake filter element was made of electrically charged polypropylene (PP) melt-blown nonwovens filter, and the main filter was the F5 filter (EN 2004) [31] with nominal efficiency in the removal of 400-nm particles between 40 and 60% (Fig. 4a). In the CONFIG 2, the intake air to the unit was filtrated using F6 class cellulose and PP-melt-blown panel filter (EN 2004) [31] with nominal efficiency in removal of 400-nm particles between 60 and 80% (Fig. 4b). In the CONFIG 2, the mixture of intake and recirculated air was additionally filtered using the filter element impregnated with bonded carbon-based adsorbent designed to adsorb organic and inorganic gases and vapors (Fig. 4b). The CONFIG 2 with the adsorbent impregnated filter element was selected to allow for assessment of the effectiveness of such elements in limiting penetration of NO_2 in the enclosure.

In the cases of other two evaluated configurations, CONFIG 3 and CONFIG 4 (Fig. 2b and Fig. 5), the system was modified using the components from Sy-Klone International (Fig. 6) in attempt to improve efficiency of the system in aerosol removal. In these two configurations, the 24 V axial fan, integrated into the Sy-Klone International RESPA-CF2 unit, was used to pressurize the environmental enclosure (Fig. 5 and Fig. 6a). The cylindrical HEPA filter element (Sy-Klone International FEFF219) or organic/



(a) (b)

Fig. 2 The system unit integrated with environmental enclosure in: (**a**) CONFIG 1 and CONFIG 2 and (**b**) CONFIG 3 and CONFIG 4 configurations

Table 1 Evaluated configurations of the pressurization and filtration system

System configurations	Intake pre-cleaner	Intake filter	Main (recirculation) filter
CONFIG 1	Donaldson Top Spin HD air pre-cleaner (Model H002850)	Original equipment manufacturer (OEM), polypropylene (PP) melt-blown nonwovens filter	OEM, F5 class filter
CONFIG 2	Donaldson Top Spin HD air pre-cleaner (Model H002850)	OEM, F6 class cellulose and PP-melt-blown panel filter	OEM, filter element impregnated with bonded carbon-based adsorbent
CONFIG 3	Sy-Klone International RESPA-CF2 (Powered Precleaner/Filter/Pressurizer unit)	Sy-Klone International FEFF004 HEPA (99.978% at MPPS of 143 nm)	Sy-Klone International FEFF219 HEPA (99.956% at MPPS of 63 nm)
CONFIG 4	Sy-Klone International RESPA-CF2 (Powered Precleaner/Filter/Pressurizer unit)	Sy-Klone International FEFF204 (99.978% at MPPS of 143 nm)	Sy-Klone International FEFF230 (ABEK1 P3/HEPA, 99.956% at MPPS of 63 nm)

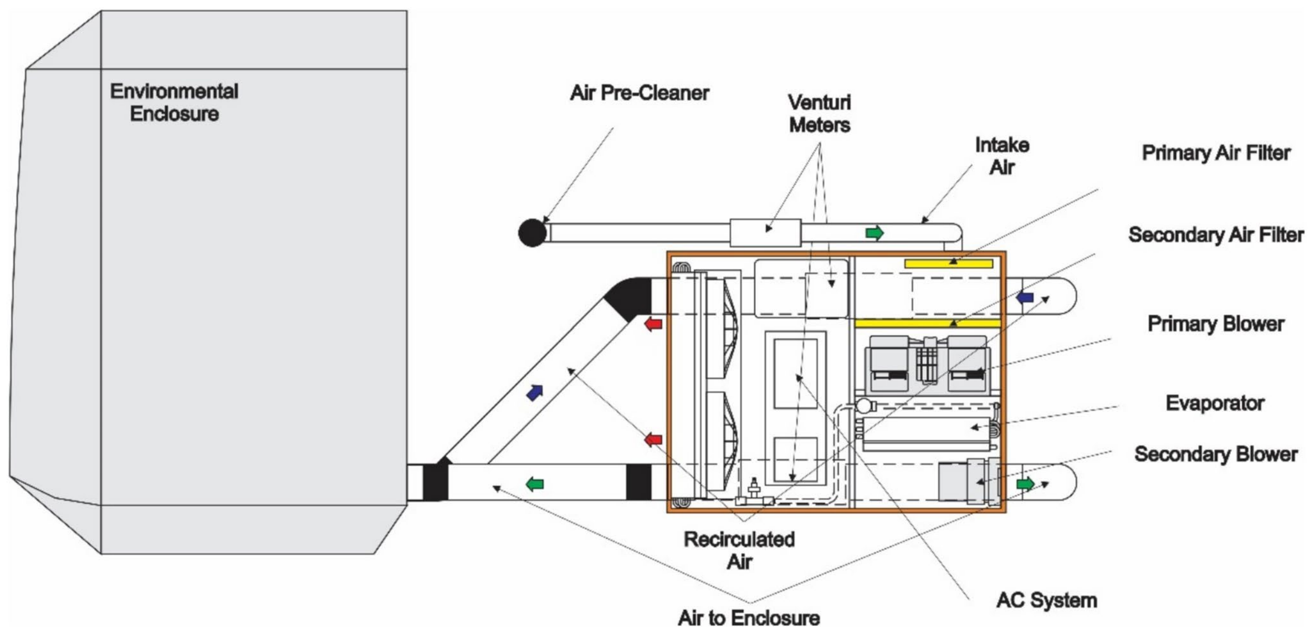


Fig. 3 The components of the system for CONFIG1 and CONFIG 2

inorganic/acidic/ammonia vapors and gases (ABEK) plus HEPA filter element (Sy-Klone International FEFF230), housed inside the RESPA-CF2 filtration and pressurization unit (Fig. 5), replaced the panel intake filters used in CONFIG 1 and CONFIG 2 (Fig. 3). The intake and main panel filter elements and associated holders used in CONFIG 1 and CONFIG 2 (Fig. 4) were removed from the casing to accommodate the replacement cylindrical HEPA filter elements (Fig. 6b) from Sy-Klone International, Model FEFF004 in CONFIG 3 and Model FEFF204 in CONFIG 4. Similarly to the filter element in the CONFIG 2, the adsorbent treated filter element in the CONFIG 4 was selected in the attempt to reduce penetration of NO_2 in the enclosure.

In all four configurations, two concurrently operated blowers housed in the system were used to move air through the filtration and pressurization section of the system and pressurized the environmental enclosure (Fig. 3 and Fig. 5) using the primary and secondary blowers. In the case of the CONFIG 3 and CONFIG 4, the 24-V axial fan situated inside the RESPA-CF2 (Fig. 6a), was used to provide additional air movement and pressurization. The operating points for the blowers for all four configurations were selected based on the voltage output from the blower potentiometers. When the CONFIG 3 and CONFIG 4 were evaluated, the fan in the RESPA CF2 was operated at a single setting.

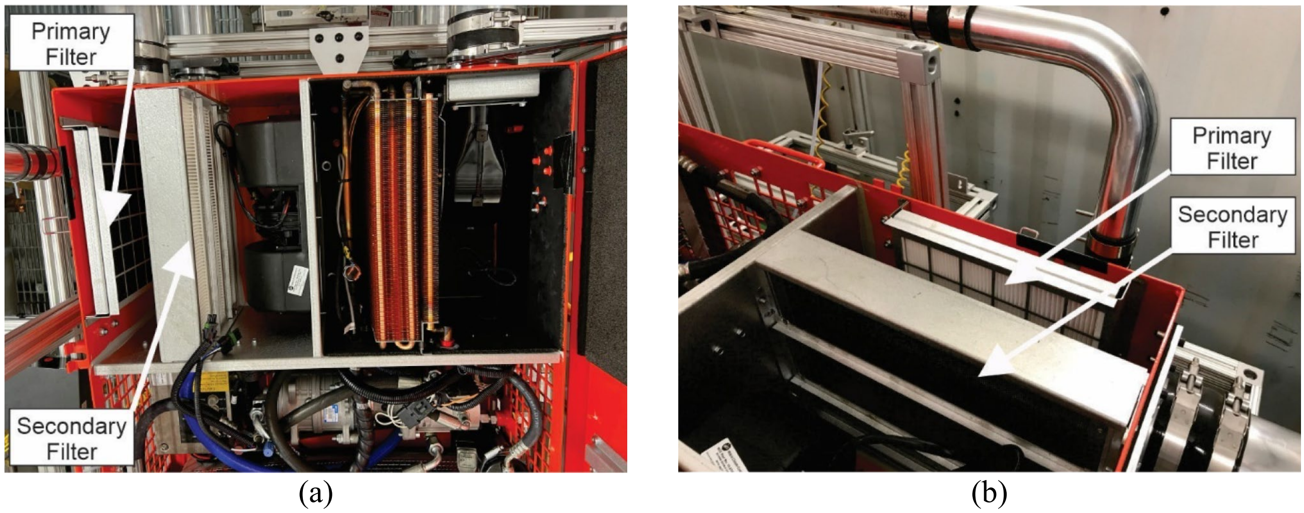


Fig. 4 The filter element for: (**a**) CONFIG 1 and (**b**) CONFIG 2

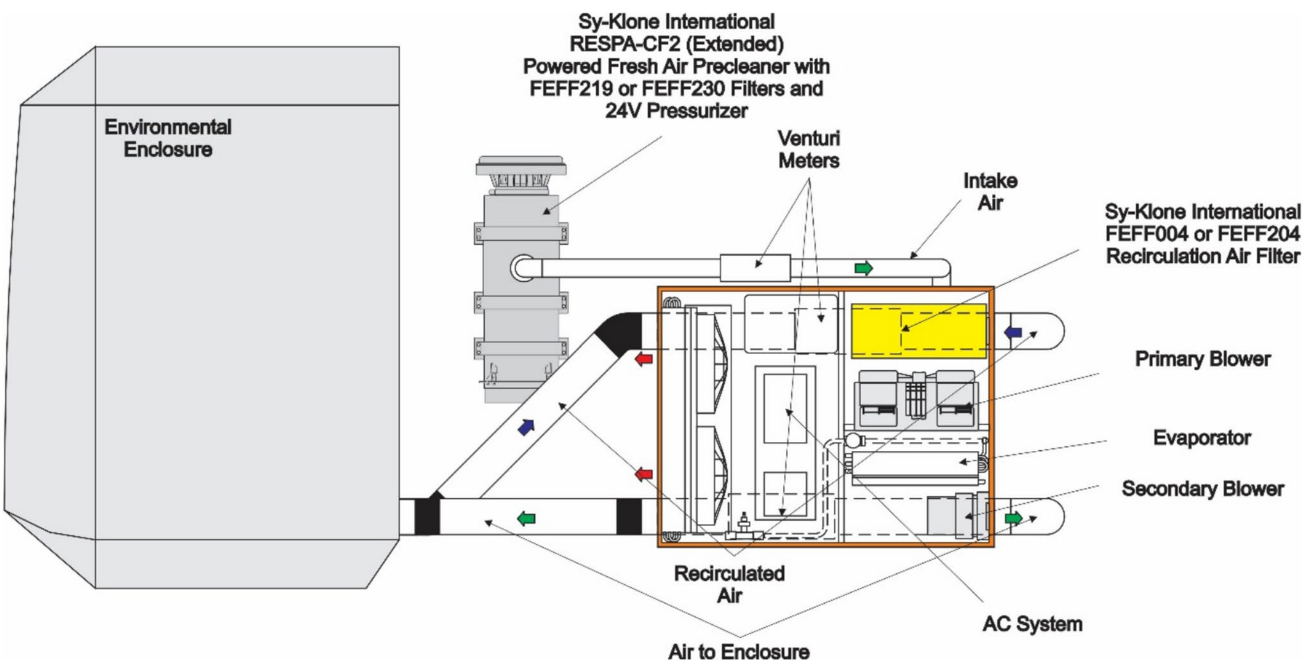


Fig. 5 The components of the system for CONFIG 3 and CONFIG 4

2.2 Flow and Pressure Measurements

The volumetric flow rates through the intake (Q_i), recirculation (Q_r), and main (Q_m) lines of the system were continuously monitored using Venturi meters incorporated in the intake (Fig. 7a), main (Fig. 7b), and recirculation lines (Fig. 7b). The nominal intake flow rates were calculated using a 2″ Venturi meter with a Magnehelic pressure gauge (Dwyer Model 200-10VF3). The nominal flow rates in the main and recirculation lines were calculated using 4″ Venturi meters with Magnehelic pressure gauges (Dwyer Model 200-10VF5). It is important to note that those flow rates and enclosure pressurization were affected by the additional restrictions introduced by the Venturi meters.

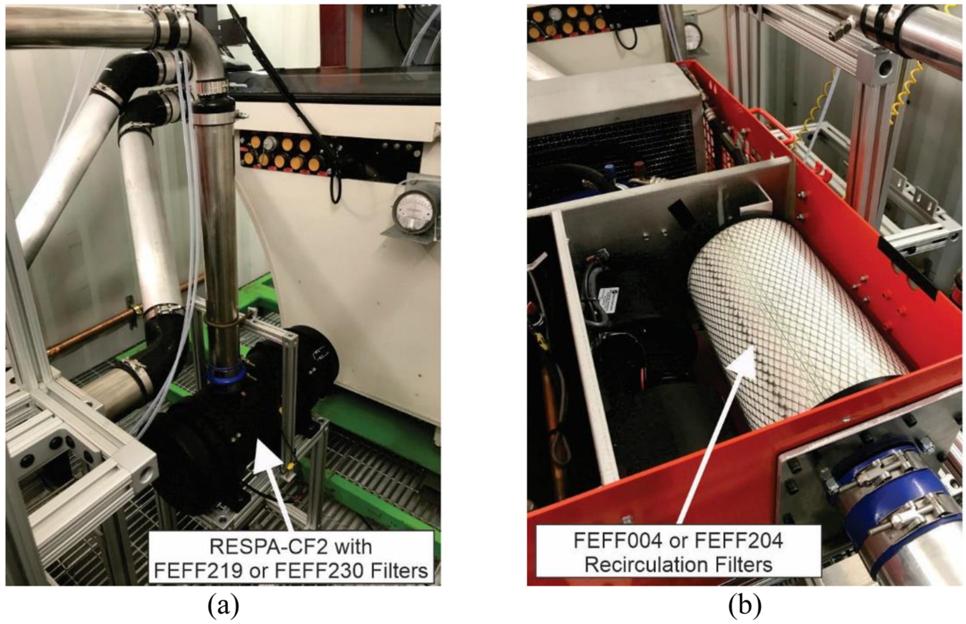


Fig. 6 The modifications for the CONFIG 3 and CONFIG 4: (**a**) RESPA-CF2 system and (**b**) recirculation filter

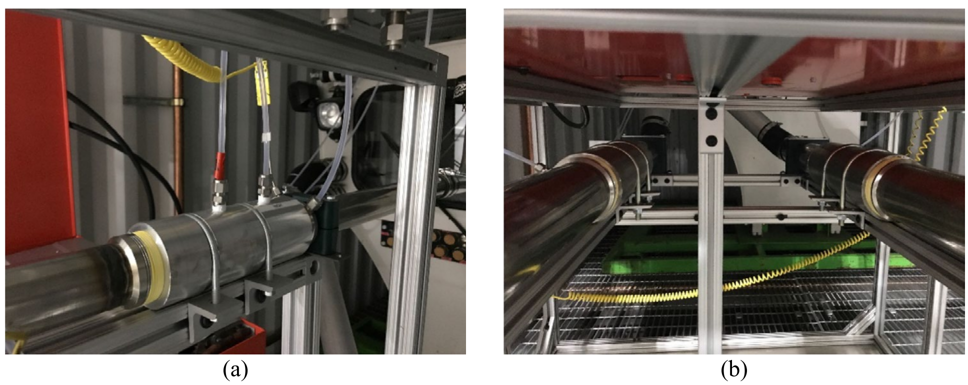


Fig. 7 Volumetric flow rate measurements using Venturi meters installed in the: (**a**) intake, and (**b**) main (left) and recirculation (right) lines

The barometric pressure outside of the environmental enclosure was measured with a high-accuracy transducer (Serta Model 270). The differential pressure between the environmental enclosure and chamber was measured with a high-accuracy low differential pressure transducer (Serta Model 239). The relative humidity and temperatures inside and outside of the environmental enclosure were measured with the humidity and temperature probes (Vaisala Model HMT330).

All four configurations were tested at six fan operating settings (S1-S6). The flow rates (Q_m, Q_i, and Q_r) and corresponding differential pressures between enclosure interior and exterior (Δp) for those settings are provided in Table 2. The average chamber temperature for all tests conducted was 31.83 ± 2.46 °C. The heat introduced by diluted diesel engine exhaust and the intake blower contributed to already relatively high ambient temperatures and resulted in relatively high temperatures inside the chamber. The "fresh" air exchange rates for the system at the test operating points were estimated to be between 8 h^{-1} and 35 h^{-1}.

2.3 Test Aerosols and Gases

The configurations were evaluated using aerosols and gases from diluted exhaust of the Deutz TD2.9 L4 engine operated in the engine test cell, situated next to the environmental enclosure test chamber. The specifications for the test engine are provided in Table 3. This engine is representative of the category of engines that meets Epa Tier 4 final emissions standards [54] for engines below 55 kW using only a diesel oxidation catalytic converter [55]. The engine was coupled to an SAJ AE 400 eddy-current dynamometer and was operated at two steady-state conditions: (1) intermediate speed and 50% load (I50, 117Nm @ 1,800 rpm), and (2) rated speed and 50% load (R50, 92 Nm @ 2,600 rpm). The engine was fueled with ultralow sulfur diesel with the properties listed in Table 4.

Table 2 Flow rates and differential pressure between the interior and exterior of the enclosure for various primary and secondary fan operating points

Configuration	Operating point	Flow rates (Q)			Differential pressure (Δp)
		Main (Q_m)	Intake (Q_i)	Recirculation (Q_r)	-
		[m^3/h]	[m^3/h]	[m^3/h]	[Pa]
CONFIG 1	S1	93.4	17.0	76.5	2.6
	S2	118.9	20.4	98.5	6.2
	S3	161.4	25.5	135.9	9.5
	S4	195.4	32.3	163.1	14.6
	S5	229.4	34.0	195.4	19.4
	S6	248.1	39.1	209.0	24.0
CONFIG 2	S1	93.4	17.0	76.5	3.1
	S2	110.4	20.4	90.0	6.4
	S3	161.4	25.5	135.9	10.1
	S4	186.9	30.6	156.3	14.5
	S5	212.4	34.0	178.4	18.7
	S6	229.4	35.7	193.7	21.0
CONFIG 3	S1	85.0	34.0	51.0	140.3
	S2	96.8	37.4	59.5	198.7
	S3	118.9	42.5	76.5	278.2
	S4	134.2	49.3	85.0	366.0
	S5	152.9	54.4	101.9	459.6
	S6	169.9	57.8	110.4	514.0
CONFIG 4	S1	101.9	25.5	76.5	84.3
	S2	135.9	32.3	103.6	106.4
	S3	152.9	34.0	118.9	135.7
	S4	203.9	35.7	168.2	169.1
	S5	224.3	37.4	186.9	201.0
	S6	243.0	39.1	203.9	220.1

Table 3 Specifications for Deutz TD2.9 L4

Manufacturer and model	Deutz TD2.9 L4
Configuration	I-4
Displacement [l]	2.9
Rated power [kW] @ engine speed [rpm]	55/2600
Rated torque [Nm] @ engine speed [rpm]	260/1600–100
Turbocharged	Yes
Exhaust after treatment	Diesel oxidation catalytic converter (DOC)
Exhaust gas recirculation	Yes
EPA emission standard	Tier 4 final
EPA PM standard [g/kW-hr]	0.03
MSHA approval	No

Table 4 Fuel properties

Property	Unit	Value
API gravity	[°API]	35.0
Specific gravity	-	0.850
Aromatics	[% volume]	27.0
Olefins	[% volume]	0.7
Paraffins	[% volume]	72.3
Cetane number	-	44.4
Flash point	[°C]	58
Heat of combustion	[MJ/kg]	45.4
Heat of combustion	[BTU/lb]	19,522
Sulfur content	[% weight]	6.5

2.4 Aerosol and Gaseous Instrumentation

The number concentrations and size distributions of aerosols and concentrations of selected gases were measured (1) inside the environmental enclosure in the hypothetic operators breathing zone, and (2) outside of the environmental enclosure, in the vicinity of the intake to the filtration and pressurization system. The number concentrations and size distributions of aerosols were measured with the fast mobility particle sizer spectrometer (FMPSs, TSI Model 3091) (Fig. 8). The FMPS measures the number concentrations and size distributions of aerosols with an electrical mobility diameter (D_{em}) between 5.6 nm to 560 nm at a frequency of 1 Hz. The second FMPS and scanning mobility particle sizer (SMPS, TSI Model 3936) were used for continuous quality checks (Fig. 8). The SMPS measures the number concentrations and size distributions of aerosols with electrical mobility diameters between 10 and 400 nm every 120 s. To enhance the clarity of the figures, the aerosol size distributions were fitted with log-normal curves using DistFit software from Chimera Technologies (Forest Lake, MN). Concurrently, the concentrations of criteria gases (CO, CO_2, NO, and NO_2) were measured from both locations using the Fourier transform infrared spectroscopy analyzer (FTIR, Gasmet Technologies; Vantaa, Finland, Model DX4000). This instrument collected data every 20 s.

Fig. 8 The aerosol instrumentation (two FMPSs and the SMPS) outside of the test chamber

2.5 Test Matrix

The results of the seven hundred twenty (720) 10-min core tests (Table 5) performed for three fan settings (S1-S3) were used to evaluate the configurations. In addition, background concentrations and concentrations inside the chamber During the 20-min conditioning period after introduction of diesel aerosols were measured at the commencement of each of the twenty-four sessions of testing. The results of the additional one hundred forty-three measurements (Table 5) performed for six operating points (Table 2) were used to assess the effects of the fan settings on the effectiveness of the configurations.

The results of the core tests were used to assess the effects of the configurations on aerosol concentrations and NO_2 concentrations. The system efficiencies (η_{PN} and η_{NO_2}) were calculated as the ratios of aerosol or gas concentrations inside the enclosure (C_e) and inside the chamber, outside of the enclosure (C_c) for two consecutive measurements performed outside and inside of the enclosure:

Table 5 Test matrix

Configuration	Engine operating condition	Measurement location	Core			Additional					
			S1	S2	S3	S1	S2	S3	S4	S5	S6
CONFIG 1	R50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	2	3	3
	I50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	3	3	3
CONFIG 2	R50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	3	3	3
	I50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	3	3	3
CONFIG 3	R50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	3	3	3
	I50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	3	3	3
CONFIG 4	R50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	3	3	3
	I50	Chamber	12	12	12	-	-	-	-	-	-
		Enclosure	12	12	12	3	3	3	3	3	3

$$\eta = 1 - \frac{C_e}{C_c}$$

3 Results

3.1 The Aerosols and Gases in the Test Chamber

The concentrations (Fig. 9) and size distributions (Fig. 10) of ultrafine aerosol inside the chamber were found to be consistent throughout the study. Error bars display the standard deviation for the test. Relatively consistent concentrations outside of the enclosure allow for direct comparisons of the evaluated configurations. The selected engine operating conditions provided a relatively wide spread of aerosol concentrations (Fig. 9) in the range of those observed in underground mines. Maintaining relatively high and consistent concentrations outside of the enclosure proved to be critical to the accuracy of the assessment of the system efficiencies [56].

The aerosols for both engine operating conditions were characterized by the dominant accumulation mode with count median diameters (CMDs) around 50 nm (Fig. 10 and Table 6). During R50 tests, aerosols in the chamber exhibited single modal distribution. For a small fraction of the I50 tests, less than 10 percent of the total number of aerosols were found in the nucleation mode with CMDs around 15 nm.

The average concentrations of NO_2 and CO_2 inside the chamber during the core tests are given in Fig. 11. The NO_2 and CO_2 concentrations for both I50 and R50 were slightly below corresponding MSHA-adopted threshold limit values (TLVs) for NO_2 (5 ppm) and CO_2 (5,000 ppm) [53, 57]. The NO_2 concentrations for I50 were above corresponding MSHA-adopted TLV. Those elevated concentrations were favorable to improving the accuracy of the assessment of the effects of the evaluated configurations, but not high enough to assess the adsorption capacity of the evaluated media.

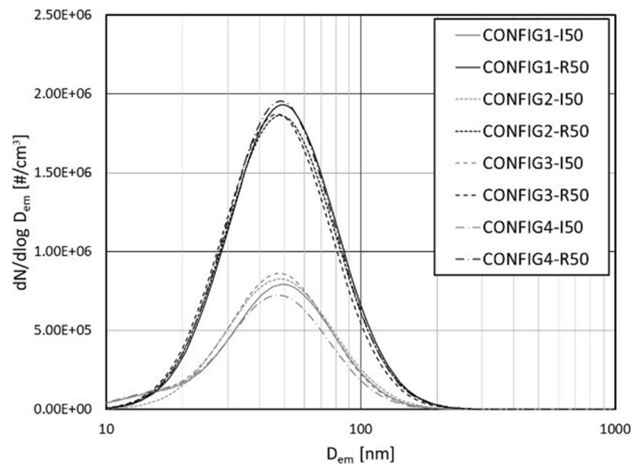


Fig. 10 Average size distributions of aerosols inside the test chamber for different configurations and test conditions

3.2 Effectiveness in Removal of Aerosols and Gases

The system effectiveness of the configurations for aerosols were assessed for the enclosure with the door and window closed. The averaged system effectiveness in removal of aerosols for core and additional tests (Table 5) are shown in Fig. 12 and Fig. 13, respectively. The CONFIG 3 and CONFIG 4 were found to be substantially more effective in removal of diesel aerosols than the CONFIG 1 and CONFIG 2. The efficiencies

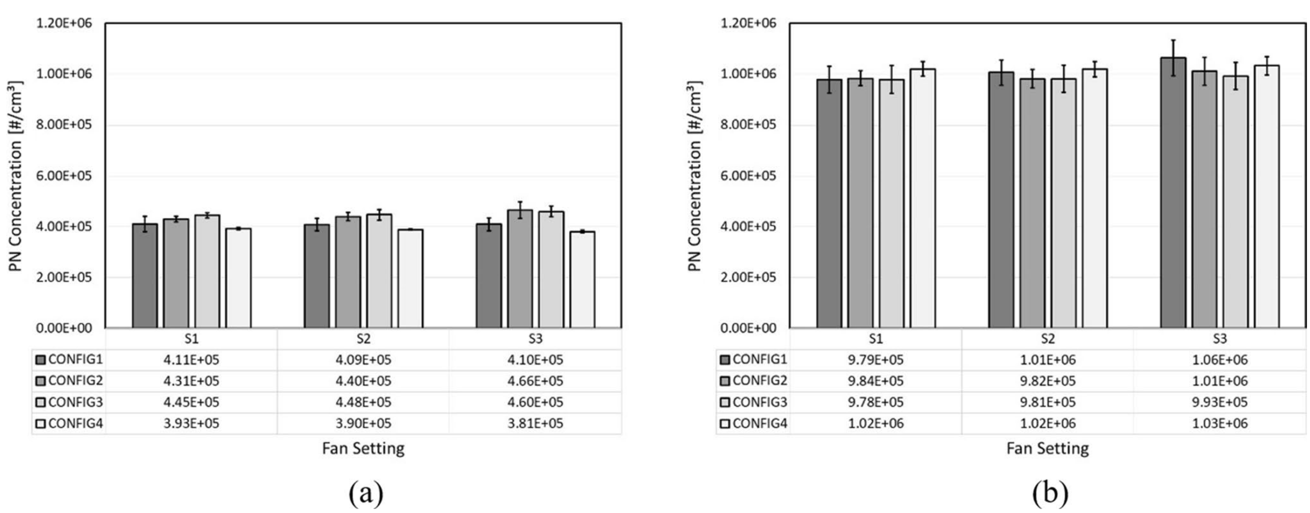


Fig. 9 Average aerosol concentrations inside the chamber measured during the core tests (S1, S2, and S3) for: (**a**) I50, and (**b**) R50 engine operating conditions

Table 6 Statistical parameters including CMDs, spreads (σ), and total concentrations, for the average aerosol size distributions in the tests chamber

Configuration	Engine operating conditions	MODE 1			MODE 2		
		CMD	σ	Total conc	CMD	σ	Total conc
		Nm	-	#/cm^3	nm	-	#/cm^3
CONFIG 1	I50	15.2	1.412	3.11E+04	49.6	1.570	3.90E+05
	R50				49.5	1.621	1.02E+06
CONFIG 2	I50				48.2	1.616	4.33E+05
	R50				48.4	1.631	9.93E+05
CONFIG 3	I50	14.6	1.385	2.77E+04	47.9	1.570	4.23E+05
	R50				47.0	1.621	9.86E+05
CONFIG 4	I50	15.0	1.394	3.21E+04	47.6	1.569	3.56E+05
	R50				48.5	1.618	1.02E+06

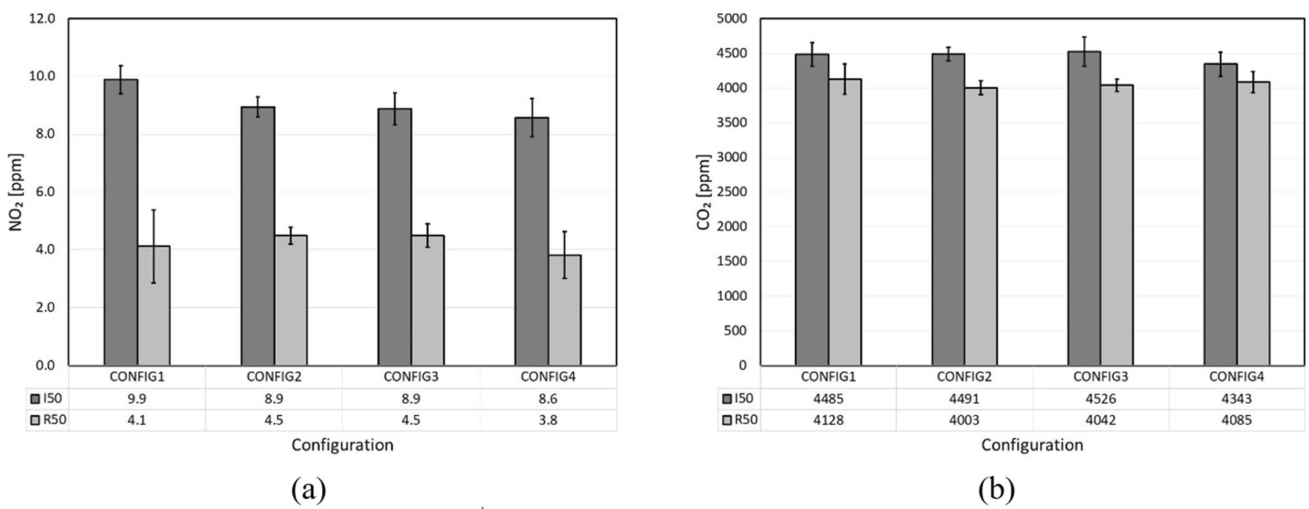


Fig. 11 Average concentrations inside the chamber of: (**a**) NO_2 and (**b**) CO_2

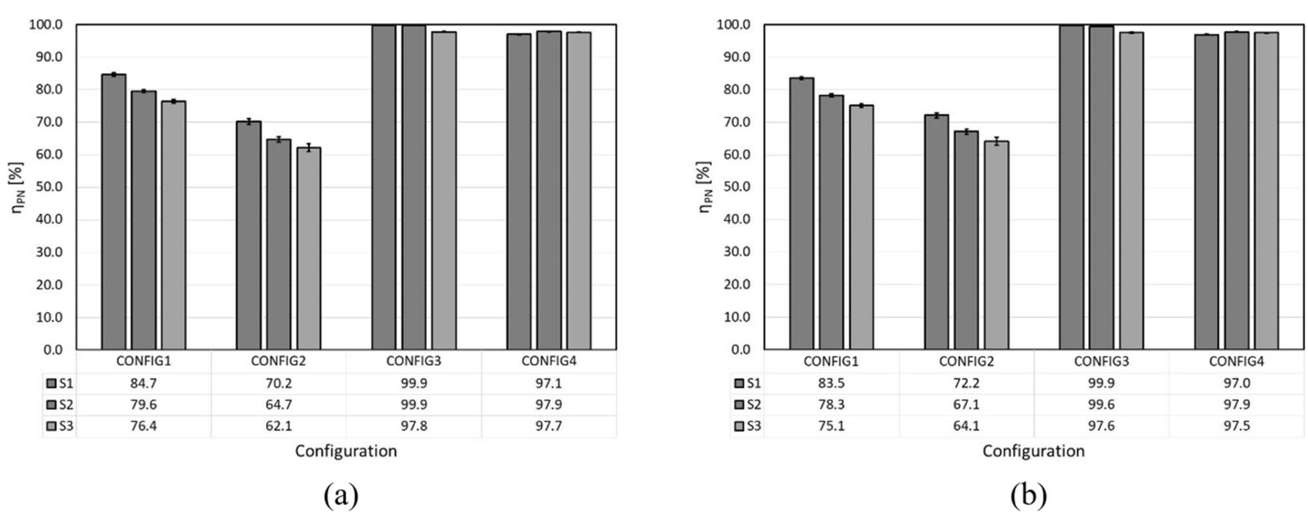
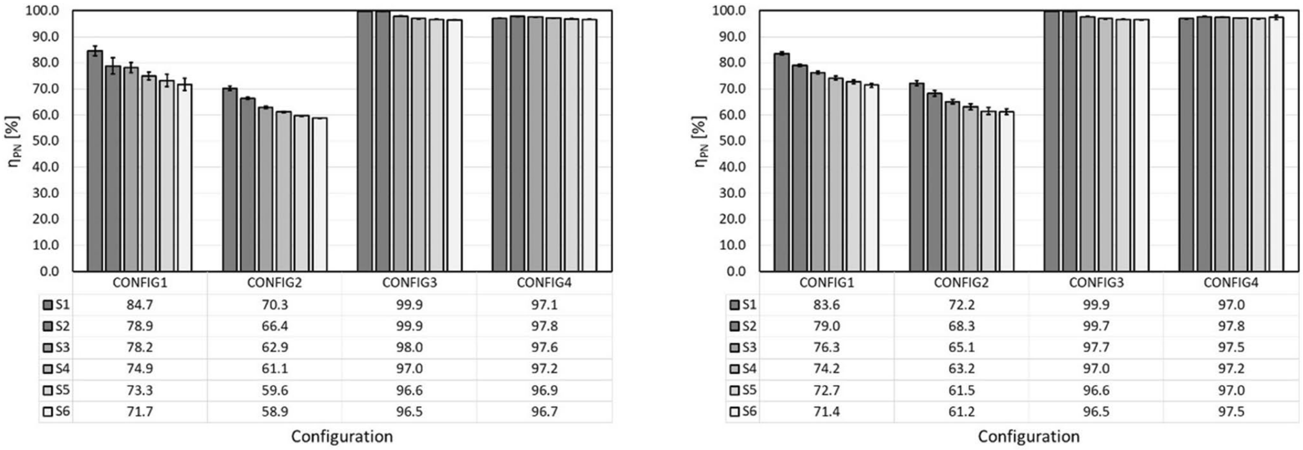


Fig. 12 The average system efficiencies for aerosols determined for S1, S2, and S3 using the results of core testing for: (**a**) I50 and (**b**) I75



(a) (b)

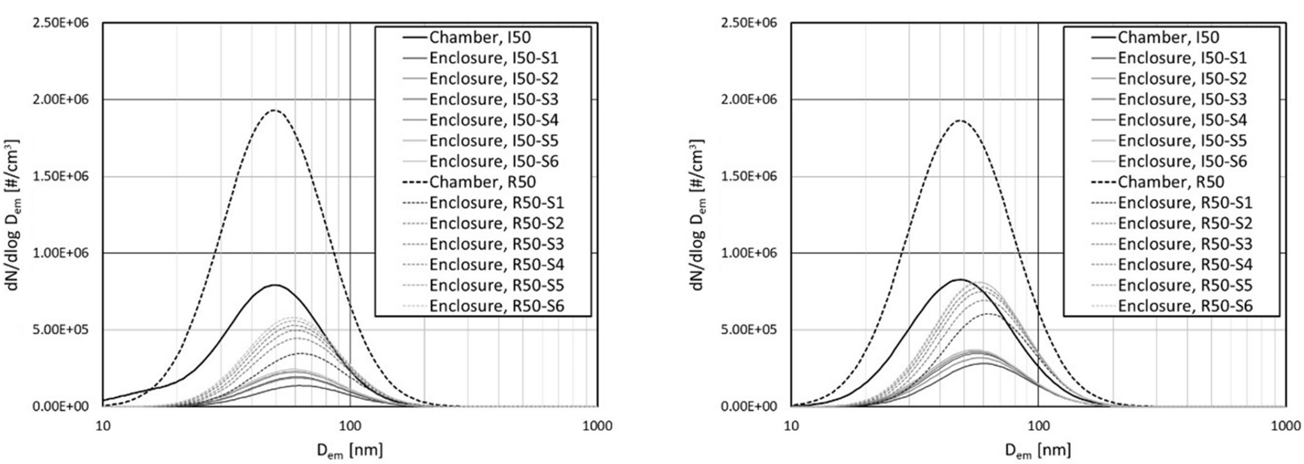
Fig. 13 The average system efficiencies for aerosols determined for S1, S2, S3, S4, S5, and S6 using the results of additional tests for: (**a**) I50 and (**b**) I75

measured during the core and additional tests (Fig. 12 and Fig. 13) do not appear to be significantly affected by the substantial difference in the concentrations of aerosols in the chamber during I50 (Fig. 9a) and R50 (Fig. 9b) tests.

The results of core testing showed that the system efficiencies of CONFIG 1, CONFIG 2, and CONFIG3 were affected by the fan speed settings (Fig. 12). The results of additional testing confirmed adverse effects of main, recirculation, and intake flow rates on the system efficiencies for CONFIG 1, CONFIG 2, and CONFIG 3 configurations (Fig. 13). The effects of the fan speed settings on the system efficiency of CONFIG4 were not evident from the generated data.

The average size distributions of the aerosols outside and inside of the environmental enclosure are shown for CONFIG 1 and CONFIG 2 in Fig. 14. The corresponding statistical parameters for those distributions are provided in Table 7. In the case of CONFIG 3 and CONFIG 4, the randomly distributed aerosols, present in very low concentrations, could not be successfully fitted with single or multimodal log-normal curves.

When tested at I50 and R50, the aerosols inside the enclosure for both CONFIG 1 and CONFIG 2 were distributed in single accumulation mode with count median diameters (CMDs) between 55 and 64 nm (Table 7). The CMDs of the aerosol inside the enclosure decreased



(a) (b)

Fig. 14 Average size distributions of aerosols outside (chamber) and inside the environmental enclosure for different test conditions for: (**a**) CONFIG 1 and (**b**) CONFIG 2

Table 7 Statistical parameters for the average aerosol size distributions in the environmental enclosure for CONFIG 1 and CONFIG 2

Configuration	Engine operating conditions	Operating point	CMD Nm	[σ] -	Total conc #/cm^3
CONFIG 1	I50	S1	63.3	1.5	6.32E+04
		S2	61.0	1.5	8.74E+04
		S3	61.0	1.5	9.08E+04
		S4	60.0	1.5	1.07E+05
		S5	59.4	1.5	1.10E+05
		S6	59.0	1.6	1.17E+05
	R50	S1	63.6	1.5	1.59E+05
		S2	61.7	1.5	2.06E+05
		S3	60.7	1.5	2.30E+05
		S4	59.9	1.5	2.49E+05
		S5	59.2	1.5	2.63E+05
		S6	58.7	1.5	2.75E+05
CONFIG 2	I50	S1	59.9	1.5	1.30E+05
		S2	57.9	1.5	1.50E+05
		S3	56.7	1.5	1.63E+05
		S4	56.0	1.5	1.70E+05
		S5	55.4	1.6	1.77E+05
		S6	55.1	1.6	1.79E+05
	R50	S1	62.6	1.5	2.73E+05
		S2	60.4	1.5	3.18E+05
		S3	59.0	1.5	3.46E+05
		S4	58.2	1.5	3.65E+05
		S5	57.5	1.5	3.79E+05
		S6	57.2	1.5	3.84E+05

measurably with an increase in filtration and pressurization system flow rates, and consequently an increase in environmental enclosure pressurization (Table 7).

The averaged system efficiencies for the criteria gases for core and additional tests (Table 5) are shown in Fig. 15 through Fig. 19. The system efficiencies for NO_2 averaged over core tests for the evaluated configurations are shown in Fig. 15. Although all four configurations exhibited favorable effects on NO_2, only CONFIG 2 and CONFIG 4 demonstrated the capacity for removal of NO_2 in excess of 85 percent from the levels found in air delivered to the enclosure (Fig. 15). Over less than fifteen hours accumulated during the tests on any individual activated carbon elements, and the NO_2 breakthrough was not evident for the adsorbents in CONFIG 2 and CONFIG 4.

The additional testing conducted for all six fan operating conditions (Table 2) showed that for CONFIG 1, CONFIG 2, and CONFIG 4 configurations, the filtration and pressurization system flow rates had adversely affected the adsorption of NO_2 (Fig. 16). Due to the overall small magnitude of changes and relatively large uncertainty of generated data, the same effects were not evident for CONFIG 3.

The effects of the system on average NO for the evaluated configurations operated at six settings are shown in Fig. 17. The adverse effects on NO observed for CONFIG 3 and CONFIG 4 can be attributed to a reduction of NO_2 to NO on the surface of the activated carbon that acted as a catalyst [22, 23].

The system efficiencies for NO_x ($NO_x = NO + NO_2$) (Fig. 18) were substantially lower than those for NO_2 (Fig. 16).

The effects of all configurations on concentrations of CO_2 were found to be negligible, within the boundaries of the experimental error (Fig. 19). The adverse effects observed for some cases could be attributed to generation of oxo-functionalized groups on the inner surface of the activated carbon which could result in the formation of CO_2 [22].

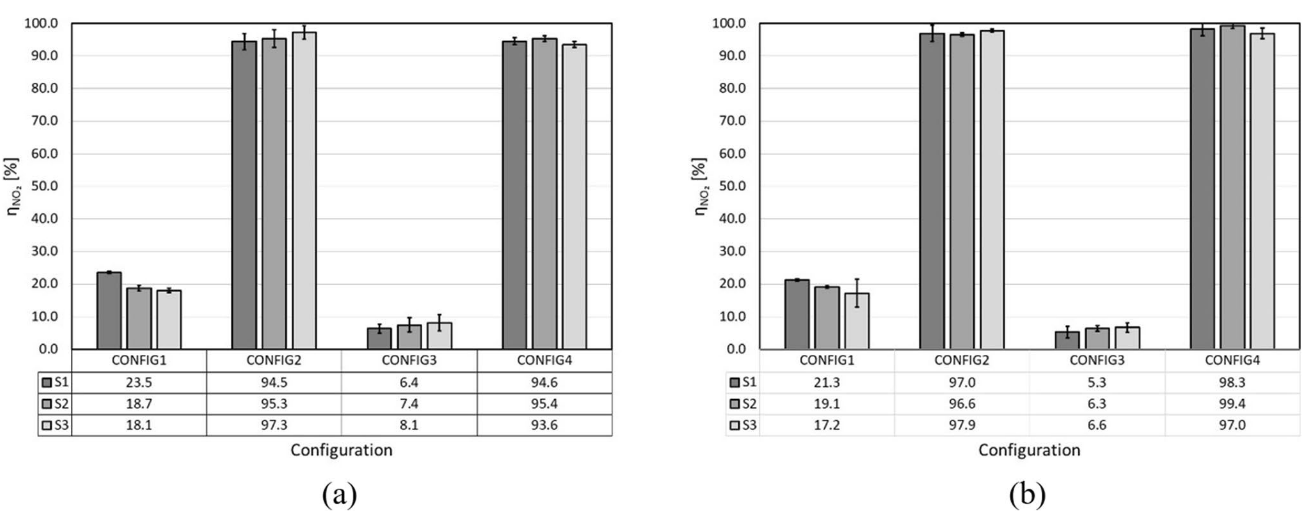
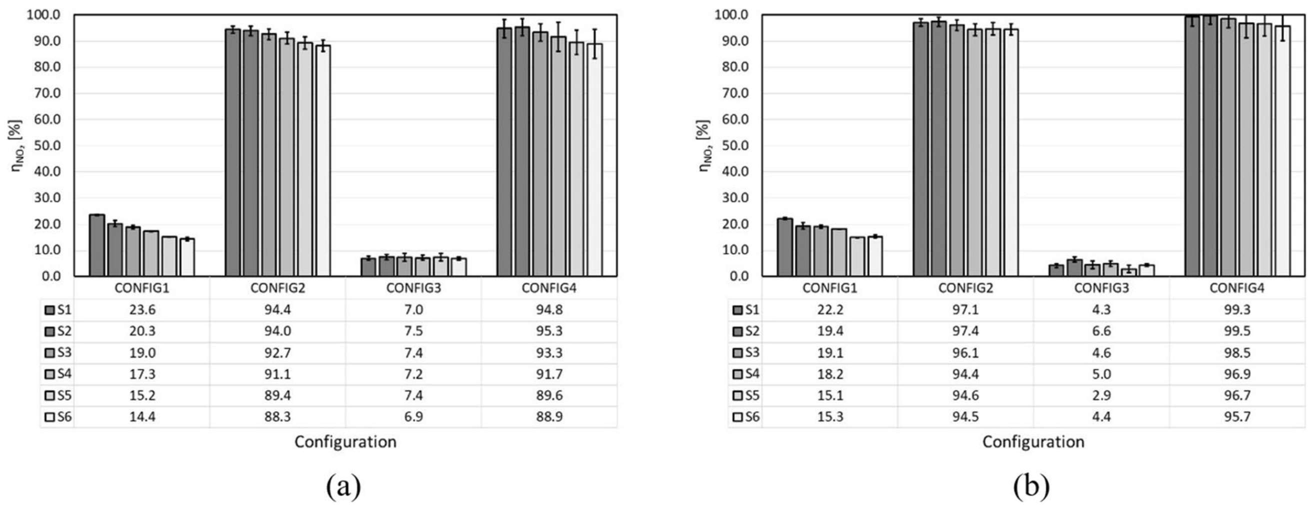


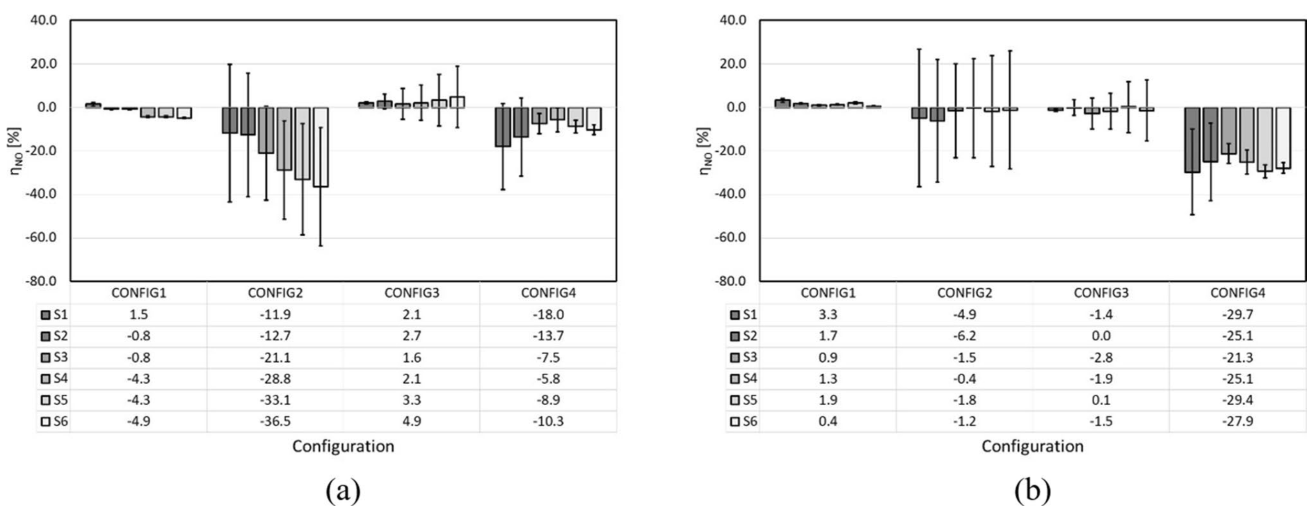
Fig. 15 The average system efficiencies for NO_2 determined for S1, S2, and S3 using results of core testing for: (**a**) I50 and (**b**) I75



(a)	CONFIG1	CONFIG2	CONFIG3	CONFIG4
S1	23.6	94.4	7.0	94.8
S2	20.3	94.0	7.5	95.3
S3	19.0	92.7	7.4	93.3
S4	17.3	91.1	7.2	91.7
S5	15.2	89.4	7.4	89.6
S6	14.4	88.3	6.9	88.9

(b)	CONFIG1	CONFIG2	CONFIG3	CONFIG4
S1	22.2	97.1	4.3	99.3
S2	19.4	97.4	6.6	99.5
S3	19.1	96.1	4.6	98.5
S4	18.2	94.4	5.0	96.9
S5	15.1	94.6	2.9	96.7
S6	15.3	94.5	4.4	95.7

Fig. 16 The average system efficiencies for NO_2 determined for S1, S2, S3, S4, S5, and S6 for: (**a**) I50 and (**b**) I75



(a)	CONFIG1	CONFIG2	CONFIG3	CONFIG4
S1	1.5	-11.9	2.1	-18.0
S2	-0.8	-12.7	2.7	-13.7
S3	-0.8	-21.1	1.6	-7.5
S4	-4.3	-28.8	2.1	-5.8
S5	-4.3	-33.1	3.3	-8.9
S6	-4.9	-36.5	4.9	-10.3

(b)	CONFIG1	CONFIG2	CONFIG3	CONFIG4
S1	3.3	-4.9	-1.4	-29.7
S2	1.7	-6.2	0.0	-25.1
S3	0.9	-1.5	-2.8	-21.3
S4	1.3	-0.4	-1.9	-25.1
S5	1.9	-1.8	0.1	-29.4
S6	0.4	-1.2	-1.5	-27.9

Fig. 17 The average system efficiencies for NO determined for S1, S2, S3, S4, S5, and S6 for: (**a**) I50 and (**b**) I75

3.3 Integrity of the Enclosure and Ventilation Systems

The differences in the architecture between the tested configurations had a profound impact on the volumetric flow rates (Q_m, Q_r, and Q_i) and pressures. The primary factors affecting those were: (1) the blower settings, (2) pressure drops across the combinations of the filter elements used in the specific configurations, and (3) in the case of CONFIG 3 and CONFIG 4, pressure provided by an axial-vane fan (Fig. 5). The main flow rates were comparable for the CONFIG 1, CONFIG 2, and CONFIG 3, and slightly lower for CONFIG 4. The major differences were in the distribution between intake and recirculated air flow rates. Depending on the blower setting, the intake flow rates made the following percentages of the main flow rates: (1) between fourteen and nineteen percent for CONFIG 1 and CONFIG 2, (2) between thirty-four and forty percent for CONFIG , and (3) between sixteen and twenty-five percent for CONFIG 4.

The CONFIG 1 and CONFIG 2 met the ISO 23875:2021 requirement for minimum sustained pressurization of 20 Pa (Table 2) only for the highest blower setting. The axial-vane fan in the intake of CONFIG 3 and CONFIG 4 contributed to substantially higher pressures inside the enclosure for CONFIG 3 and CONFIG 4 than for CONFIG 1 and CONFIG 2 (Table 2). For CONFIG 3, the pressurization exceeded substantially the ISO 23875:2021 requirement for the maximum 200 Pa for all but the two

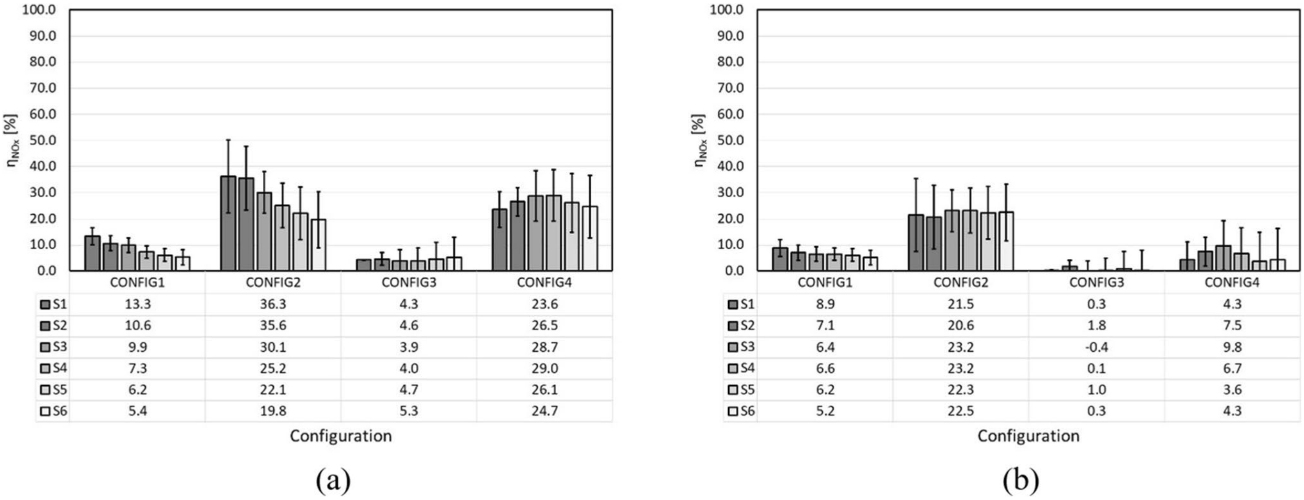


Fig. 18 The average system efficiencies for NO_x determined for S1, S2, S3, S4, S5, and S6 for: (**a**) I50 and (**b**) I75

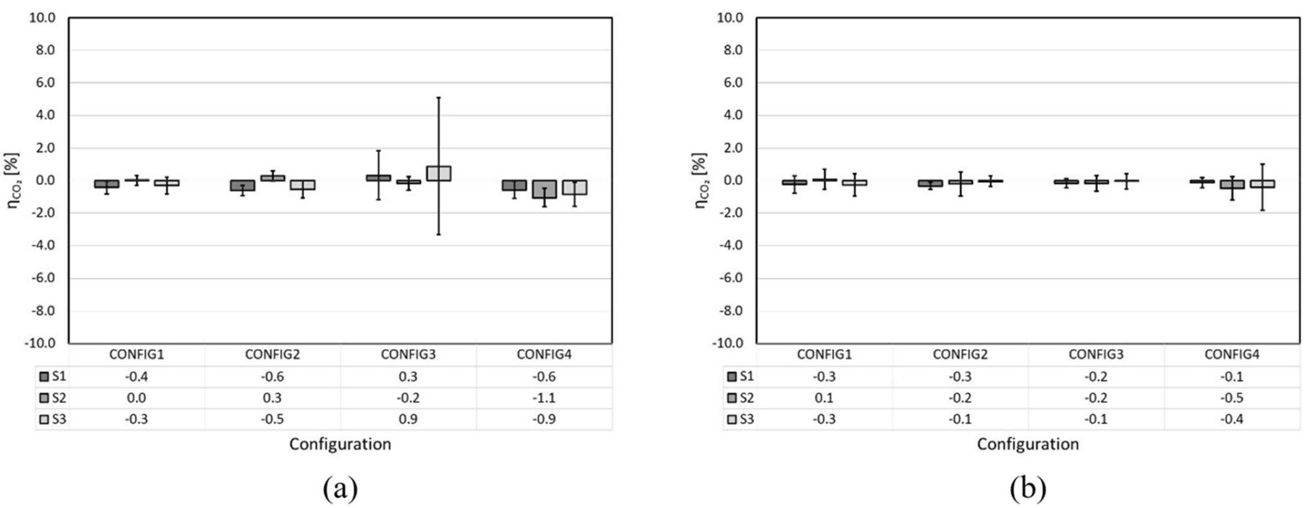


Fig. 19 The average system efficiencies for CO_2 determined for S1, S2, and S3 using results of core testing for: (**a**) I50 and (**b**) I75

lowest blower settings. In the case of CONFIG 4, the pressurization exceeded the same requirement only for the highest blower setting.

For the CONFIG 1 and CONFIG 2, the negative pressure zone extended from the pre-cleaner to the intake to the secondary blower for all six flow settings. In the case of the first three blower settings, the pressurization of the intake section of CONFIG 3 and CONFIG 4 by the axial-vane fan eliminated the negative pressure zone in the intake parts of those configurations. In the case of the three highest blower settings, the negative pressure zone extended into the inlet section of the CONFIG 3 and CONFIG 4. The negative pressure in those zones created potential for penetration of aerosols in the systems through the various cable and hose penetration holes and joints within those zones. The observed losses in the efficiency of tested configurations were found to be directly proportional to increases in the main flow rate.

4 Discussion

Compliance with various occupational personal exposure standards [53, 58–61] defines the operation of diesel-powered mobile equipment in confined spaces of underground mines [62, 63]. The requirements for limiting exposures to gaseous components of diesel exhaust, specifically carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), and nitrogen dioxide (NO_2), are fundamental to establishing ventilation rate requirements needed to ensure the health and safety of underground workers [57, 64, 65]. For the environments where adequate fresh-air ventilation is supplied to dilute criteria gaseous emissions, the control strategies for reducing exposures of underground miners to diesel particulate matter emissions are primarily based on controlling particulate matter emissions at the source [58, 59]. The aforementioned strategies could be successfully complemented with strategy based on enclosing the operator inside the environmental enclosures with adequate filtration/adsorption, pressurization, and air conditioning systems.

The configurations with filter elements efficient in removal of ultrafine (CMD < 100 nm) aerosols evaluated in this study provided more than 95 percent reductions in concentrations of aerosols emitted by contemporary Epa Tier 4 [66] diesel engines (Fig. 12 and Fig. 13). The filtration efficiencies reported in this study for high efficiency filter elements (CONFIG 3 and CONFIG 4) are comparable to those previously reported in literature [20] for a properly sealed cab equipped with HePA or MERV 16 filter elements. The concentrations of aerosols inside the enclosure for the CONFIG 3 and CONFIG 4 were at least one order of magnitude lower than those configurations that used lower grade filter elements (CONFIG 1 and CONFIG 2). The configurations with lower rated filter elements (CONFIG 1 and CONFIG 2) were able to provide only relatively moderate fractional reductions in concentrations of diesel aerosols. With practically only a single F5 filter, partially effective in removal of submicron aerosols, the CONFIG1 was still measurably more efficient in removal of diesel aerosols than CONFIG 2 which used the combination of the F6 intake filter and the main filter element designed for NO_2 adsorption (Fig. 12 and Fig. 13). The lowest observed reductions provided by configurations with lower grade filter elements were comparable in the magnitude to the differences in concentrations of aerosols outside the enclosure produced by two test conditions, R50 and I50 (Fig. 9).

The air cleaning systems did not only reduce concentrations, but also changed the size distributions of aerosols. The CMDs of the aerosol inside the enclosure (57–64 nm) were found to be larger than CMDs of aerosols ingested by filtration and pressurization systems (~ 50 nm). This indicates that filter elements preferentially remove smaller aerosols, most probably through diffusion.

The configurations with active carbon adsorbent in the main filtration/adsorption element (CONFIG 2), and in the intake element (CONFIG 4) proved to be effective in preventing infiltration of NO_2 into the enclosure (Fig. 15 and Fig. 16). It appears that substantial improvements in NO_2 reductions were associated with an increase in aerosol (Fig. 15 and Fig. 16) and NO (Fig. 17) concentrations inside the enclosure. The quantity of activated carbon in CONFIG 2 and CONFIG 4 elements were found to be adequate to adsorb and reduce NO_2 present in the test chamber at concentrations as high as 9.3 ppm (Fig. 16) but were not adequate to adsorb CO_2 present in the test chamber at concentrations as high as 4,500 ppm (Fig. 19).

Since current exhaust aftertreatment control technologies are not effective in controlling CO_2 emissions and CO_2 adsorption elements with relatively larger quantities of the activated carbon or alternative an adsorbent would be required to achieve the desired reductions, the control of CO_2 exposures would continue to rest on supplying an adequate quantity and quality of ventilation air to work zones or operators' breathing zone [67] to dilute CO_2 below targeted standards. Similarly, due to the effects of the adsorbents on the NO, the control of NO exposure would also continue to rest on an adequate dilution by fresh air.

Therefore, the viability of enclosing operators in the well-designed environmental enclosures as a control strategy for the reduction of exposures of underground miners to diesel pollutants would depend on the successful integration with other elimination, substitution, engineering, administrative, and personal protective equipment control strategies. Concurrent control of exposures of all occupations in underground mines to multiple pollutants emitted by various diesel-powered equipment would require a multifaceted, integrated holistic approach [11].

5 Conclusion

The results of this study demonstrated that enclosing miners in an environmental enclosure equipped with adequate filtration, pressurization, and air conditioning systems like the one evaluated in this study could play an important role in the overall strategy for addressing exposures of selected occupations to diesel pollutants. The selected configurations evaluated in this study provided more than 95 percent reductions in the number concentrations of aerosols and an 85 percent reduction in NO_2 concentrations. All evaluated configurations were found to have no substantial effect on CO_2 concentrations and those with active carbon adsorbent to have an adverse effect on NO concentrations.

The results also showed that the performance of the configurations of filtration and the pressurization system varied dramatically with several design and operating factors. The performance and the efficiencies could be potentially improved by changing the characteristics of the fans to optimize balance between intake, main and return flow rates, prevent over pressurization of the enclosure, and reduce leaks in the low-pressure zones.

Due to time constraints, the scope of this study was limited to the short-term performance of filtration and pressurization systems in the laboratory conditions. The design of this study did not allow for assessing various other aspects of viability of this strategy for underground mining applications. Assessing breakthrough behavior of filtration and adsorption elements as a function of the concentrations, aging, and loading was beyond the scope of this study. Assessing the effects of environmental factors such as the presence of super-micron aerosols, humidity, and temperature [21, 25, 42] and air-conditioning functions on the overall performance and economic viability of the environmental enclosure warrant additional studies.

6 Disclaimer

The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of company names or products does not constitute endorsement by NIOSH or CDC.

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Data Availability The data underlying this article will be shared on reasonable request to the corresponding author.

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