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Evaluation of the Effect of an Exhaust Reduction System in Fire Stations

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Abstract: Firefighters are known to be exposed to a variety of hazardous materials and combustion products during operational and training activities, as well as in fire stations. However, exposure to diesel exhaust emissions, classified as carcinogenic to humans by the International Agency for Research on Cancer (IARC), is also present in the fire station environment. In this study, concentrations of elemental carbon (EC), which is a surrogate of diesel exhaust and indoor air pollutants, has been measured to compare the effect of an exhaust reduction system (ERS) that was installed in the engine bays of two fire stations to mitigate indoor air pollution levels in the garage, duty offices, and dormitory/shower areas. The levels of most pollutants were reduced after the installation of the ERS. Pollutants may disperse inside of fire stations. Therefore, the ERS is a valuable strategy to mitigate pollutant exposure among firefighters and outdoor air pollution using the filtration ability of an ERS. The results of this study suggest that all truck bays should install an ERS to reduce pollutant exposure and that installation is especially necessary for EURO 3 fire vehicles.

Keywords: exhaust reduction system (ERS); fire station; elemental carbon; indoor air quality; mitigation strategy

1. Introduction

Firefighters are repeatedly exposed to a variety of hazardous materials and situations from both house and industrial fires [1,2]. They have an increased risk of illness and injury compared to those in other occupations [3–5]. Exposure to hazardous pollutants is an important factor underlying why firefighters experience a higher risk of cancer than do the general public and those in other occupational groups in the United States and Scandinavia [5–8]. The most common cancers for firefighters include lung cancer; mesothelioma; melanoma; and esophageal, brain, kidney, prostate, and skin cancer [7–9].

However, most of the previous studies have focused on the exposure during putting out a fire and do not discuss the additional carcinogens that firefighters may be exposed to during prolonged stays at the fire station waiting for calls [10]. Firefighters may be exposed to diesel exhaust, which is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC) and particulate matter (PM) from vehicles and off-gas (volatile organic compounds (VOCs), formaldehyde, etc.) emitted from idling vehicles and firefighting equipment, such as clothes, boots, and gloves, from the fire scene [11–15].

Therefore, due to the pollutants discussed above, it is necessary to control air quality in the fire station environment. According to the hazardous material control hierarchy, the best methods arranged by descending order are: elimination, substitution of source, and engineering controls [16]. Local exhaust ventilation, which is the proper way to control the exhaust, is an example of an engineering control. In Korea, there is no regulation requiring the installation of an exhaust reduction system (ERS) in fire stations. The ERS consists of a hood (direct contact with vehicles exhaust), duct, filtration system, fan, and stack. The Seoul Metropolitan government performed a practice of applying the ERS in 4 fire stations among 117 fire stations to reduce the exhaust from vehicles.

This pilot study had two primary goals: (1) to provide preliminary data on the air quality of fire stations in Seoul, Republic of Korea; and (2) to investigate the effect of the ERS on air pollutants at the fire stations.

2. Materials and Methods

2.1. The Sampling Site Description

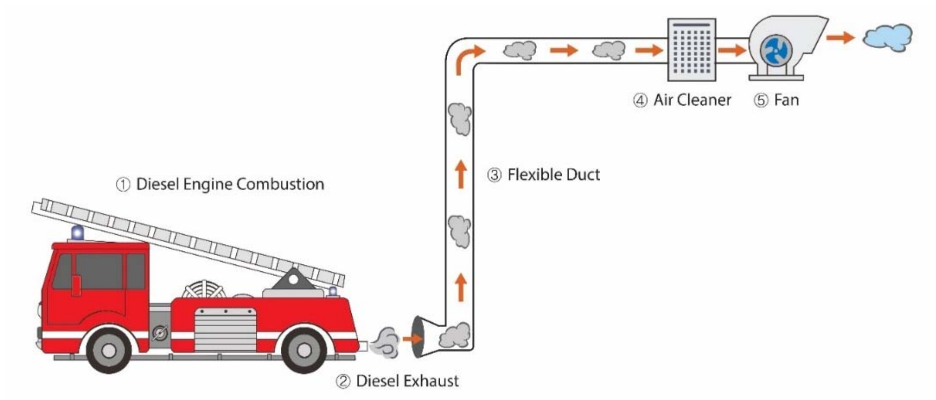
Air samples were obtained from two fire stations in Seoul, Republic of Korea, in March and April 2018. The two fire stations had different characteristics in terms of area, volume, number of vehicles (including motorbikes), diesel engine level (EURO classification), and installation rate of the ERS (Table 1). Fire station A was larger than B for all settings.

Table 1. Basic characteristics of the sampling sites.

Category	Station A	Station B
Construction (year)	1996	2007
Renovation (year)	2004	-
Area (m^3) (W × L)	704 (32 × 22)	189 (18 × 10.5)
Volume (m^3) (H)	4224 (6)	1039.5 (5.5)
Number of Vehicles (Motorbike)	14 (2)	4 (1)
Diesel Engine Level (No. of Vehicles)	EURO3 (1), EURO4 (2) EURO5 (7), EURO6 (4)	EURO3 (1), EURO4 (1) EURO5 (-), EURO6 (2)
Installation rate of Exhaust Reduction System (%) (Installed/Total No. of Vehicles)	71.4% (10/14)	75.0% (3/4)

The ERS consists of a hood, duct, air cleaner, fan, and stack (Figure 1a). When the fire vehicles come into the fire station, the ERS operates. There is a physical distance between the vehicle exhaust outlet and the hood (ERS inlet) shown in Figure 4a. Then, the exhausted pollutants go into the hood and move through the duct of the ERS. The duct exhausts to the outside air through a High Efficiency Particulate Air (HEPA) filter that removes particles and a carbon filter mitigates the gaseous pollutants (Figure 1b). Figure 1c shows the inside of fire station A. The garage door was always closed due to air pollution and complaints from civil sources, except for when vehicles were entering and leaving.

ERS was not used at all vehicle bays at both fire stations due to the budget. Station A had 10/14 bays (71%) and station B had 3/4 bays (75%) that had installed the ERS. The engine type for vehicles were classified by EURO in terms of emission standards of the European Union [17]. Each fire station had one EURO 3 vehicle that possibly exhausted more pollutants compared to the new vehicles. Other vehicle engines were in EURO 4, 5, and 6 classifications.



(**a**)

(**b**) (**c**)

Figure 1. Experimental setup: (**a**) schematic diagram of the ERS, (**b**) air cleaner and fan of the ERS in fire station A, and (**c**) installed ERS in fire station A.

2.2. Sampling Strategy

To achieve the objective of this study, sampling was divided into two procedures. First, area sampling was performed for the following indoor air pollutants according to the Korean Ministry of Environment (MOE) standard for indoor air quality control in public use facilities: PM, carbon monoxide (CO), carbon dioxide (CO_2), total VOC (TVOC), and formaldehyde (HCHO) [18]. Sampling campaigns were taken on 14 March 2018 for fire station A and 15 March 2018 for fire station B. Investigation of the effect by measuring before and after operation was performed on same day, except for elemental carbon (EC).

Second, EC, which is a surrogate of diesel exhaust particulates (DEPs), was sampled on 20 April 2018 for fire station A and 13 April 2018 for fire station B, and was analyzed in terms of NIOSH 5040 for investigating the direct effect of the diesel exhaust [19]. NIOSH 5040 is designed for personal sampling. However, area sampling was conducted because it was difficult to conduct personal sampling to achieve the goal of this study, which was the investigation of the effect of the ERS. Sampling inlets were placed 1.2–1.5 m above the floor level. The abovementioned pollutants were sampled at the vehicle bay (the center of the fire station), office, waiting room, shower room, and outdoors.

2.3. Sampling and Analysis

Data were collected continuously for one hour in the center of the vehicle bay (indoor) and stack on the roof top (outdoor) for online and offline measurement. In the case of elemental carbon, the sampling time was varied, and indoor sampling locations were the center of the truck bay, office, shower room, and waiting room to investigate the effect on indoor air quality. Outdoor measurement was performed in both fire stations. A detailed indication of the sampling locations is in the Supplementary Materials.

To describe the diesel exhaust emission (elemental carbon) in fire stations and compare the effect of the installation of the ERS, we simulated three scenarios to mimic the situation:

1. Before the installation of the ERS to determine the effect of EURO 3 vehicles: which entailed idling all vehicles with the EURO 3 (the ERS was not installed at the bay for the EURO 3 vehicle).
2. Before the installation of the ERS (without EURO 3 vehicle operating): this included idling all the vehicles (without the EURO 3 vehicle operating) without operation of the ERS to simulate the before installation status.
3. After the installation of ERS: this involved idling all vehicles (except for EURO 3 vehicles) with the operation of the ERS to mimic the installation effect.

Additionally, to evaluate the effect of the background, the outdoor background was sampled at the outside of the fire stations.

2.4. Online Measurement

PM was measured to compare the reduction rate using direct reading instruments (Aerosol Mass Monitor 831, Met One Instruments, Inc., Grants Pass, OR, USA) approved by the Korean Ministry of Environment for particulate matter measurements regarding indoor air quality. The sampling interval was 1 min and measurements took place over one hour. According to the MOE standard for a parking indoor space, the sampling time should be over 6 h. However, we measured one hour because the main purpose of this study was to evaluate the effectiveness of the ERS system. The concentration range was from 0 to 1000 $\mu g/m^3$ with an accuracy within 0.1 $\mu g/m^3$. The aerosol flow rate was 2.83 L/min. The zero calibration was operated using a high-efficiency particulate air (HEPA) filter before sampling.

CO_2 and CO were measured using a IQ-610 (Graywolf Sensing Solutions, Shelton, CT, USA) for an hour. The sampling interval was 5 min. The measurement range was from 0 to 10,000 ppm for CO_2 and from 0 to 500 ppm for CO. The factory calibration was performed annually, and the two-point span gas calibration was performed before sampling.

The capture velocity, which is the air velocity in front of the hood for the ERS, was measured to confirm the quantification of flow by an anemometer (TSI 8455, TSI Inc., Shoreview, MN, USA).

2.5. Offline Measurement

TVOCs were collected in Tenax tubes (New PKI Tenax TA 60/80, N9309130, Perkin Elmer, Waltham, MA, USA) using low-volume pumps (MP-SIGMA-30KN, Sibata, Saitama, Japan) with a calibrated flow rate of about 0.1 L/min with two samples for 30 min each [20]. Results of the two samples were calculated using an arithmetic mean according to the Korean MOE standard procedure [21]. All samples, including field blank samples, were stored in a freezer at −20 °C before analysis. The analysis was conducted using gas chromatography (GC, GC-2010, Shimazu, Kyoto, Japan). A custom VOC standard was used (217031349, AccuStandard Inc., New Haven, CT, USA). The concentrations of TVOCs was obtained as a toluene equivalent concentration; that is, the area of total chromatogram was converted into the concentration of toluene using a toluene calibration curve [22].

HCHO was sampled using a 2,4-dinitrophenylhydrazine (2,4-DNPH) cartridge (TS-300 DNPH cartridge, Top Trading Eng. Co. Ltd., Seoul, Korea) using a low-volume pump (MP-SIGMA-100HN, Sibata, Saitama, Japan), with a flow rate of 0.5 L/min with two samples for 30 min each. Results of the two samples were calculated using an arithmetic mean according to the Korean MOE standard procedure [21]. After sampling, samples were sealed using aluminum foil to protect samples from exposure of light and were kept under 4 °C until desorption. Aldehydes were eluted with 5 mL of acetonitrile (HPLC grade, J.T. Baker, Phillipsburg, NJ, USA). All experimental equipment used for analysis was washed and cleaned using acetonitrile and baked at 60−80 °C. Extracted aldehydes were analyzed using HPLC (LC-20AT, Simazu, Kyoto, Japan). Acetonitrile (60%, HPLC grade, J.T. Baker, Phillipsburg, NJ, USA) and water were used as a carrier liquid with flow rate of 1.0 mL/min. The carrier liquid was filtered before analysis. The column temperature was 25 °C, and the injection volume was 20 μL. The field blank and spiked samples were analyzed simultaneously for quality control.

For EC, prior to sample collection, quartz filters (225-1825, SKC Inc., Eighty Four, PA, USA) were heated at 600 °C for 2 h. Each filter was placed in a conductive polypropylene cassette (225-3-23, SKC Inc., Eighty Four, PA, USA) for reducing sample loss due to electrostatic effects. The cassettes were connected to separate sampling pumps (TUFF 3, Casella, Bedford, U.K.) calibrated at a flow rate of 2 L/min. A cassette and Tygon tubing were used to connect for sampling. The filters were analyzed using NIOSH 5040 with an OC/EC analyzer (Sunset Laboratory, Tigard, OR, USA) [23]. Field blank samples were analyzed simultaneously for quality control. To figure out the profile of the EC concentration, triple samples were collected for three scenarios, the office, and outdoors. One sample was collected in the shower room for fire station A and waiting room for fire station B. The limit of detection for EC was 0.3 μg/sample. External sucrose solution (47289, Sucrose analytical standard, Merck, Darmstadt, Germany) and methane gas carbon standards were used for calibration.

Integrated sampling using a filter media was performed for electron microscope analysis. A polycarbonate filter (37 mm, 0.8 μm, SKC Inc., Eighty Four, PA, USA) and a high-volume sampler (2 lpm, ELF Escort, Zefon, Ocala, Florida, USA) with an open-faced two-piece cassette was used to capture airborne particles. Six samples were taken in fire station A (figures are not shown) and four samples were taken in fire station B (Figure 3). Sampling was performed over 5 min during idling time near the exhaust pipe of a vehicle. Filters were pre- and post-equilibrated in an environmentally controlled weighing room maintained at a temperature of 20 °C ± 1 °C and a RH (relative humidity) of 50% ± 5%. The cassettes were tightly sealed using silicon tape after the sampling and carried in a clean and desiccation box until analysis. The morphologies, elemental compositions, and size of the particles were analyzed with a field emission scanning electron microscope (FE-SEM, SU-70, Hitachi, Ibaraki, Japan) and an energy dispersive spectrometer (EDS, MONOCL4, Gatan Inc., Pleasanton, CA, USA). The filters were coated with platinum for electron microscope analysis. We explored the whole surface of samples and decided the representative image with the aid of a microscopy specialist and an industrial hygienist.

2.6. Statistical Analysis

Descriptive statistics were calculated. Distributions of ERS variables and indoor air pollutant variables were summarized using mean values and standard deviations (SD). Time-series plots were used to illustrate changes in PM_{10}, $PM_{2.5}$, CO, and CO_2 concentrations over time. Data analysis was implemented using R (version 3.0.2; R Development Core Team, Vienna, Austria) and Sigmaplot 14.0 (Sysstat Inc., San Jose, CA, USA).

3. Results

3.1. About ERS

The average face velocity was 5.25 (0.51) m/s as the mean (SD) for 10 ERS hoods in fire station A and 4.34 (0.47) m/s with the mean (SD) for 3 ERS hoods in fire station B.

3.2. Indoor Air Quality

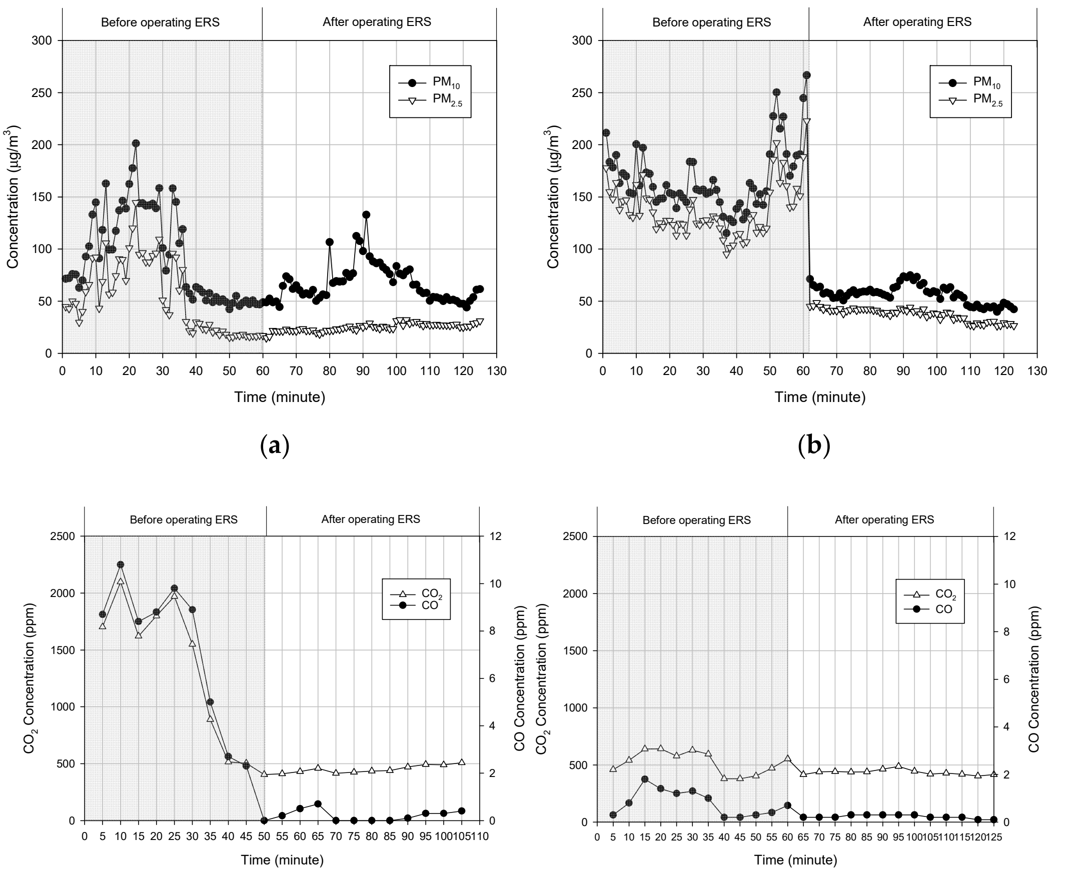
The concentration of all indoor air pollutants was reduced after installation of the ERS in the fire stations. For fire station A, PM_{10}, $PM_{2.5}$, TVOC, CO_2, and HCHO exceeded the MOE standard before installation of the ERS. In fire station B, PM_{10}, $PM_{2.5}$, and TVOC exceeded the MOE standard before the installation. After installation of the ERS, all pollutants were reduced to a level under the standard, except for TVOC in fire station B (Table 2).

Table 2. Results of the measured indoor air pollutants in the two fire stations (given as mean (SD)).

Pollutant	Location	Fire Station A				Fire Station B				Unit	Indoor Air Quality Standard (MOE [2])
		N	**Before**	**N**	**After**	**N**	**Before**	**N**	**After**		
PM_{10}	Inside of fire station, center of vehicle bay	62 [1]	92.2 (43.2)	63	67.2 (17.9)	61	168.0 (30.9)	62	56.6 (8.8)	μg/m^3	100 μg/m^3 (6-h average)
$PM_{2.5}$		62 [1]	52.1 (34.1)	63	25.2 (3.2)	61	137.4 (25.4)	62	37.2 (6.0)	μg/m^3	50 μg/m^3 (6-h average)
CO_2		9 [4]	1405.7 (575.9) [5]	13	448.6 (33.2)	12	522.5 (95.8)	13	435.1 (21.6)	ppm	1000 ppm
CO		9 [4]	7.3 (2.9)	13	0.2 (0.2)	12	0.8 (0.5)	13	0.2 (0.1)	ppm	10 ppm
TVOC		2	1443.5 [5]	2	297.2	2	928.8 [5]	2	894.6 [5]	μg/m^3	500 μg/m^3
HCHO		2	197.5	2	8.6	2	34.0	2	6.5	μg/m^3	100 μg/m^3 150 μg/m^3 (MOEL [3])

[1] Real-time measurement sampling interval of $PM_{10/2.5}$. According to the MOE standard, a PM measurement should be performed for at least 6 h. Measurements were performed for about one hour in this study to evaluate the effectiveness of the ERS; [2] MOE: Ministry of Environment; [3] MOEL: Ministry of Employment and Labor; [4] CO/CO_2 sampling time intervals were 1 min and 5 min, respectively; [5] Exceeded the MOEL standards.

The PM_{10}, $PM_{2.5}$, CO, and CO_2 concentrations depicted in Figure 2 show a high concentration before operating the ERS at both fire stations.



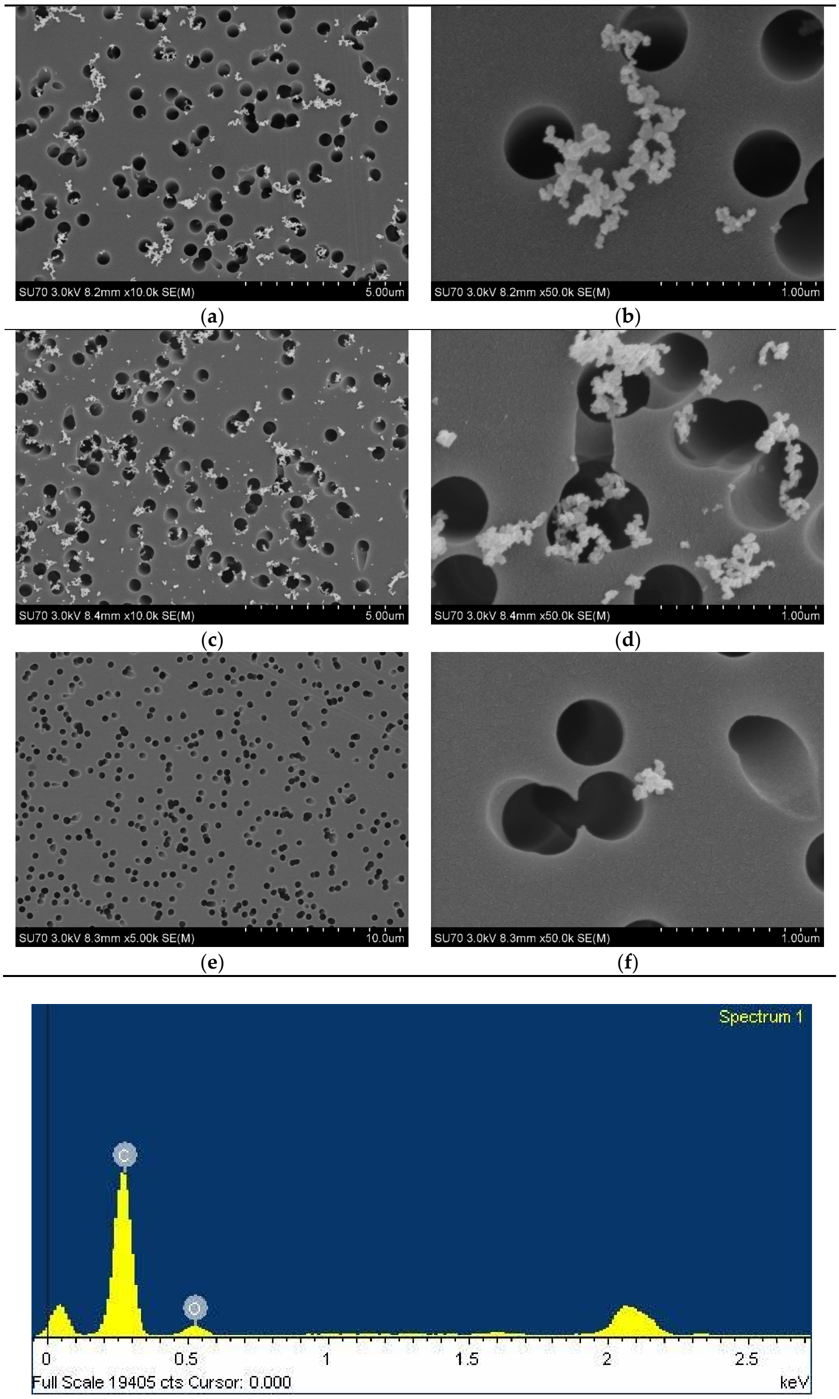
(**a**) (**b**)

(**c**) (**d**)

Figure 2. Time-series graphs comparing before and after the operation of ERS for $PM_{10/2.5}$ and CO/CO_2 at fire stations A (**a**,**c**), at fire stations B (**b**,**d**), respectively.

3.3. Electron Microscopy Image

The results of the SEM-EDS analysis for identifying the shape of the particles and the chemical composition at the fire stations is shown in Figure 3 (fire station B). There were particles of various sizes, amounts, and shapes on the filter. Figure 3a,b shows the particles collected from EURO 3. Figure 3c,d shows the particles collected from EURO 6 of an older vehicle. Figure 3e,f shows the particles collected from EURO 6 of a newer vehicle.



(g)

Figure 3. Electron microscope image from fire station B: (**a**) EURO 3 (×10k), (**b**) EURO 3 (×50k), (**c**) EURO 6-Old (×10k), (**d**) EURO 6-Old (×50k), (**e**) EURO 6-New (×5k), (**f**) EURO 6-New (×50k), and (**g**) EDS graph from particle of (**f**).

3.4. Mitigation Effect Confirmed for EC

Table 3 shows the concentrations of elemental carbon (EC) measured in the fire stations. Scenario 1, which entailed idling all vehicles including the EURO 3 (the ERS was not installed for the EURO 3 vehicle because it will be disused due to the life cycle stated by governmental property policy; however, it was still in operation due to the budget problem of fire station) shows the highest concentration at fire station A (31.85 (0.80) μg/m^3) and B (41.69 (2.05) μg/m^3) in terms of the mean value and SD. Scenario 2, which included idling all the vehicles (without the EURO 3 vehicle operating) without operation of the ERS to simulate the before installation status showed a lower EC concentration than Scenario 1. Scenario 3 was involved the idling of all vehicles (except for the EURO 3 vehicles) with operation of the ERS to mimic the installation effect. In fire station A, 13 vehicles were idling, 10 of which were connected to the ERS, and in fire station B, 3 vehicles were idling, all of which were connected to the ERS. The result showed the lowest concentration among scenarios.

Table 3. Concentrations of elemental carbon (EC) measured in the fire stations (unit: μg/m^3).

Category	Fire Station A				Fire Station B			
Location (unit: μg/m^3)	**N**	**Sampling Time (min.)**	**Conc. and Mean (SD)**	**I/O Ratio**	**N**	**Sampling Time (min.)**	**Conc. and Mean (SD)**	**I/O Ratio [3]**
Scenario 1: Vehicle bay (before) incl. EURO 3	3	119	32.73 32.04 30.79	10.11	3	211	44.56 39.92 40.60	39.7
			31.85 (0.80)				41.69 (2.05)	
Scenario 2: Vehicle bay (before) without the EURO 3 vehicle operating	3	120	8.87 9.12 8.88	2.84	3	133	6.64 7.35 9.61	7.49
			8.96 (0.12)				7.87 (1.26)	
Scenario 3: Vehicle bay (after)	3	123	2.91 2.90 2.95	0.92	3	85	0.0004 0.0010 <LOD [1]	<1.00
			2.92 (0.02)				0.0006 [2]	
Office 1F	3	403	2.06 2.22 2.25	0.69	3	424	3.09 2.76 2.79	2.74
			2.18 (0.08)				2.88 (0.15)	
(Fire station A) Shower room 2F	1	416	3.13	0.99	- [4]	-	-	-
(Fire station B) Waiting room 1F	- [4]	-	-	-	1	430	2.58	2.45
Outdoor	3	419	3.10 3.17 3.17		3	430	1.10 1.07 0.98	
			3.15 (0.03)				1.05 (0.05)	

[1] Limit of Detection; [2] Arithmetic mean of two samples were presented because one sample was below than limit of detection; [3] I/O ratio: indoor/outdoor ratio; [4] Sampling location was different between fire stations.

Additionally, the concentration of EC (mean and SD) in the office room at fire stations A and B was 2.18 (0.08) μg/m^3 and 2.88 (0.15) μg/m^3, respectively. In the shower room at fire station A, the concentration of EC was 3.13 μg/m^3, and in the waiting room at fire station B, the concentration was 2.58 μg/m^3. The outdoor concentration of EC was 3.15 (0.03) μg/m^3 for fire station A and 1.05 (0.05) μg/m^3 for fire station B.

The final part of the ERS is the stack for exhausting to outdoors through an air cleaner and the fan of the ERS; this reduced the concentration of PM compared with that found before installation. For fire station A, the decrease was 74%. The mean value and SD were from 143.2 (36.8) μg/m^3 to 37.1 (24.9) μg/m^3 for PM_{10} and 83% from 135.2 (36.9) μg/m^3 to 2.4 (0.37) μg/m^3 for $PM_{2.5}$. For fire station B, the decrease was 86%. The mean concentration and SD were from 323.9 (26.5) μg/m^3 to 46.0 (2.6) μg/m^3 for PM_{10} and 93% from 275.5 (20.7) μg/m^3 to 21.2 (1.4) μg/m^3 for $PM_{2.5}$.

The indoor/outdoor (I/O) ratio of EC was calculated. Before installing the ERS, the I/O ratios of EC were higher than 1. That is the indoor air quality of both fire stations was worse than outdoors. After installation, the I/O ratios of EC was less than 1. For other indoor spaces, fire station A was less than 1 and fire station B was greater than 1 for the I/O ratio.

4. Discussion

We investigated the data on air quality in terms of the concentrations of PM, CO_2, CO, TVOC, and HCHO of fire stations and the effect of the ERS installation on the EC of diesel exhaust emissions in the air at the two fire stations.

This study represents the effect of ERS installation at the fire station and confirms the method of mitigation of air pollutants indoors and outdoors. The result of the study showed that ventilation practices using ERS on emissions from firefighting vehicles at the fire station are associated with the mitigation of air pollutants.

4.1. Status of Indoor Air Quality in the Fire Station

TVOC, CO_2, and HCHO exceeded the MOE standard before the installation of the ERS at fire station A. At fire station B, TVOC exceeded the standard before installation. A limited number of studies have assessed the exposure to pollutants in fire stations. Firefighters may be exposed to PM that increases at the fire scene. It is difficult to compare with the concentration at the fire scene directly, but the exposure levels of total airborne particulates from diesel exhaust were 170 to 480 μg/m^3 as a time-weighted average (TWA) [13].

We performed the measurement of PM_{10} and $PM_{2.5}$ to evaluate the efficiency of ERS. The ERS was effective at reducing the indoor air pollutants from fire stations. Nevertheless, after controlling using ERS, the concentrations of $PM_{2.5}$ still had an average of 25.2 μg/m^3 and 37.2 μg/m^3 in fire stations A and B, respectively. This may be due to the baseline concentration of PM in Seoul, Korea. According to the data provided by Ministry of Environment at that time, the nearest air quality monitoring station within 1.5 km from the fire stations reported the PM_{10} as 59.3 μg/m^3 and the $PM_{2.5}$ as 38.2 μg/m^3 near fire station A and the PM_{10} as 47.5 μg/m^3 and $PM_{2.5}$ as 31.7 μg/m^3 near fire station B in March. Therefore, it is necessary to undertake additional effort, such as an indoor air cleaner, to mitigate the PM in the fire stations. However, as seen in Figure 3, the size of the particles ranged from 20 nm to 50 nm as a primary particle (aggregated to micro size) in the air of fire station A found using the FE-SEM. Nanoparticles less than 100 nm in diameter are emerging, and the occupational health issues associated with these are unknown. The investigation of exposure to nanoparticles is actively performed in many occupational settings, such as engineered nanoparticle manufacturing workplaces, welding, 3D printing, and even the semiconductor industry [24–26]. Figure 3g shows that the particles shown in Figure 3f consisted of carbon and oxygen, as analyzed using EDS. The FE-SEM image was used to support the interpretation of particle size and morphology. However, it was helpful to check the characteristics and visualize the particles for a better understanding.

In fire station A, the concentration of HCHO exceeded the standard. The health effect of HCHO on humans is classified in Group 1 (carcinogenic) by the IARC. Also, HCHO might be the cause of acute poisoning, such as symptoms of irritated eyes, sneezing, chest congestion, tearing, coughing, fever, heartburn, and loss of appetite, as well as pulmonary function damage, such as abnormalities in the airway shrinkage and high resistance to pulmonary ventilation [27]. Automobile exhaust is a source of HCHO [28]. After installation of the ERS, the HCHO concentration was dramatically reduced from 197.5 μg/m^3 to 8.6 μg/m^3 in fire station A. In fire station B, the concentration of HCHO was reduced from 34.0 μg/m^3 to 6.5 μg/m^3. To the best of our knowledge, there is no previous report on HCHO exposure in fire stations but there is personal exposure among Australian firefighters. The concentration levels range from 20 ppb (parts per billion) to 570 ppb (equivalent to 25 μg/m^3 to 701 μg/m^3) during ignition, patrol, and suppression [29].

EC is the surrogate indicator for diesel exhaust. Previous studies report that EC was used as a marker for human exposure to diesel exhaust [30–32]. The health effect of diesel exhaust is well reported, including in terms of cardiovascular function, lung function changes, headache, fatigue, nausea, irritation of the nose, and a small risk of increasing of rectal cancer [33–35]. The threshold limit value (TLV) by the American Conference of Governmental Industrial Hygienist (ACGIH) was 20 μg/m^3 in 2002. However, the TLV of EC was withdrawn by the ACGIH and placed on an understudy list [36]. Measurement of the EC concentration was the highest in the engine bay when a EURO 3 vehicle was idling in this study (fire station A with a mean and SD: 31.85 (0.80) μg/m^3, fire station B: 41.69 (2.05) μg/m^3). Additionally, firefighters can be exposed to EC even with EURO 4, 5, and 6 vehicles. Another study showed a concentration with a geometric mean of 86.7 μg/m^3 for tunnel construction workers, 10.7 μg/m^3 for garage workers, 6.7 μg/m^3 for taxi drivers, and 4.1 μg/m^3 for outdoor workers exposed to diesel and petrol exhaust [37]. In the case of tunnel construction workers, the tunnel is an enclosed site with insufficient ventilation and many diesel-operated machines working inside it. Also, workers might be exposed to EC in a garage with petrol, but more EC is emitted from a diesel exhaust than from a petrol exhaust [38]. Indoor air quality can be interpreted as an I/O ratio. We confirm that this was clearly explained by the I/O ratio under the influence of the ERS at both fire stations (Table 3). For spaces other than vehicle garages, fire station A showed an adequate indoor air quality, in terms of the EC concentration and I/O ratio, while fire station B did not have good indoor air quality compared to fire station A. This might have been caused by the size of the building since fire station A was larger than the fire station B in volume and area. For firefighters, therefore, proper ventilation is necessary to improve in the fire stations. If there is inadequate ventilation, firefighters may be exposed to a very harmful environment. To mitigate this problem, the best practice is to replace the old vehicles, such as EURO 3, with newer vehicles. However, there is often not a budget to buy new vehicles for many reasons. Therefore, the ERS system is an alternative and the most realistic method to minimize the exposure to firefighters.

After installation of the ERS, the concentration of TVOC was dramatically reduced from 1443.5 μg/m^3 to 297.2 μg/m^3 in fire station A. In fire station B, the concentration of TVOC was reduced from 928.8 μg/m^3 to 894.6 μg/m^3. The concentration in fire station B after installation exceeded the indoor air quality standard from the Korean Ministry of Environment. The efficiencies of ERS were 80% for fire station A and 4% for fire station B. This might have been affected by another source of VOC in the fire station because other pollutants, such as PM_{10} and $PM_{2.5}$, showed high efficiencies. Therefore, it is necessary to manage the sources of VOCs, such as fuel and cleaning agents. Indoor air quality management is required because TVOC was reported from 579.3 μg/m^3 to 1750.3 μg/m^3 in the garage of fire stations, from 470.6 μg/m^3 to 4497.3 μg/m^3 in the fire truck, and from 639.6 μg/m^3 to 2384.6 μg/m^3 in the waiting room at the fire station in Korea [39].

For CO_2, it is the surrogate indicator of ventilation. In rooms with insufficient ventilation, CO_2 concentrations range from 700 to 800 ppm [40]. For crowded or poorly ventilated indoor areas, the CO_2 level can rise to 2000–5000 ppm [41]. For fire station A, ventilation was required to reduce the CO_2 in the fire station. After operating the ERS, CO_2 reduced from an average of 1405.7 ppm to 448.6 ppm, which was a 68% reduction. Also, for fire station B, averages of 522.5 ppm and 435.1 ppm were found before and after operating of the ERS, respectively. Therefore, the results of this paper portray strong evidence that the risk of firefighters' exposure to indoor air pollutants was reduced when the ERS was installed (Figure 2).

4.2. Effect of the ERS

We found that the ERS was an effective method to minimize exposure to indoor air pollutants in the fire station. The installation rates were 71.4% and 75.0% in fire stations A and B, respectively. ERS was not installed in the EURO 3 truck bay because EURO 3 vehicles will be phased out when the end of the useful life governmental policy is over but are still operated due to budget issues.

It is more important to install an ERS for the lower levels of EURO, such as EURO 3, than the higher levels of the EURO system, such as EURO 6, because the higher tiers of EURO vehicles have lower emission rates of air pollutants. Since 1992, the European Union has established the emission standards for heavy-duty diesel engines with steady-state testing from EURO 1, EURO 2 (1996/1998), EURO 3 (2000), EURO 4 (2005), EURO 5 (2008), and EURO 6 (2013). Also, there has been transient testing for heavy-duty diesel and gas engines since EURO 3 (2000). In this study, we found that there was no installation of the ERS for EURO 3 vehicles in both fire stations. However, the emission of the EURO 3 vehicles was the most dominant, as shown in Table 2 and Figure 2. Therefore, the order of priority for installation of the ERS should start from the lower levels of the EURO system.

From an industrial hygiene point of view, the elimination of a pollutant emission source is the most effective approach to reducing hazards associated with that source. However, it is impossible to immediately eliminate the diesel engine of firefighting vehicles and replace it with another type. Substitution to a cleaner vehicle may be one alternative and use of engineering control can also be a reasonable alternate. Also, installing the ERS is difficult to implement in an existing fire station because it takes more effort. If the fire station is still at the design or development stage, installation of the ERS to eliminate pollutants may be inexpensive and simple to implement.

Modification of the design is necessary to maximize the efficiency of the ERS. There is a significant physical distance between the ERS inlet and the vehicle exhaust outlet in the current system (Figure 4a). The installation may cause a loss of capture efficiency. Therefore, it is necessary to put the vehicle exhaust outlet into the ERS hood to minimize the loss of efficiency (Figure 4b).

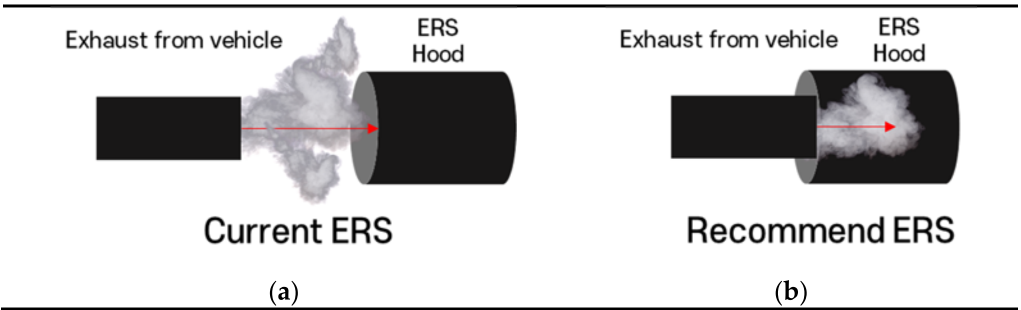


Figure 4. Schematic diagram of ERS: (**a**) current ERS and (**b**) recommend ERS.

4.3. Exhaust to Outdoor Air

We found that firefighting vehicles are a source of pollutant emission and installing the ERS reduced concentrations in the vehicle bay of the fire station. However, air containing pollutants is vacuumed from fire stations by the ERS and vented into the atmosphere through the rooftop exhaust stacks. This may cause air pollution from an environmental health point of view. In the ERS, there is a filtration system from the vehicle exhaust to the outside. For manufacturing industries in Korea, stack emission control regulation is well established, but in some areas, such as fire stations, restaurant kitchens, and university laboratories, it is not [42]. The effect of air cleaners was shown to be effective in Table 2. The reduction rate of PM_{10} was 74–86%, and 83–93% for $PM_{2.5}$. Therefore, it should be mandatory to install the air cleaner before emitting the pollutant from combustion or experiments. Various filters could be used. The HEPA (high-efficiency particle air) filter was installed in the ERS and other filtering systems, such as an electric precipitator, could be applied to reduce the exhaust that is released outdoors [43]. Also, another diesel emission source, such as commuter rail and buses, should be considered as pollution source and mitigation of their emissions should be made [44].

4.4. Strengths and Limitation

To the best of our knowledge, this is the first study to valid the effect of the ERS at a fire station. A few previous studies have assessed the effects of chemical and physical agent exposure on firefighters. As such, occupational and environmental problems become more complex, especially in the 21st century, where the risk must be managed more systemically. Compared with some of the exposures encountered during firefighting, exposures at the fire station may be easily modified through changes in systems, thus potentially representing useful intervention targets. Although the study was at a pilot scale, the results of this study include useful knowledge for firefighters and policymakers.

Many fire stations are in urban areas. The outdoor measurement, such as effect of road traffic, was not considered in the concentration of pollutants (TVOC, HCHO, PM, CO, and CO_2), except for EC, in this study. Indoor and outdoor ratios could help to interpret the degree of indoor air quality. In future studies, outdoor measurements might be measured to compare the indoor and outdoor concentration ratios for various pollutants. Nevertheless, we measured the outdoor air concentration of EC as a background concentration to distinguish between it and the emission source from firefighting vehicles.

Only a small sample size (two fire stations) was investigated among four that had the ERS installed. We used area sampling rather than personal sampling to estimate personal exposure. Further research is required to increase the sample size for improving the reliability of the results. Additionally, further studies are required to establish strategies for reducing firefighter exposure to components of diesel engine exhaust in the fire station environment. Still, there is no guideline for the installation of the ERS for fire stations. Therefore, it is recommended that the Seoul Metropolitan Fire and Disaster Headquarter should try to minimize exposure via engineering and administrative control, such as ventilation, an alternative engine type, an air cleaner, and prohibiting unnecessary idling through policy for mitigating air pollution. For PM measurements, the MOE standard requires 6 h of measurement, but since we measured for 1 h, it is difficult to compare it with the MOE standard. However, it was meaningful data for evaluating the efficiency of the ERS.

For PM measurement, we used a multi-channel particle counting device that measured PM mass in various size fractions based on light scattering. Light scattering efficiencies differ for particles from different sources. The PM measurement device we used has been approved by the Korean Ministry of Environment. However, to obtain a better accuracy, a reference method (e.g., gravimetric sampling) is required to verify that the particle counter might be appropriately calibrated for a diesel exhaust.

5. Conclusions

A broad range of pollutants have been measured in two fire stations and the effect of the ERS in reducing indoor pollutants was investigated. It was found that concentrations of pollutants, such as CO_2, TVOC, HCHO, and EC, in the fire stations exceeded Korean MOE standards. Installation of the ERS in the fire station effectively mitigated these pollutant concentrations in the vehicle bays and would likely reduce the exposure of firefighters to these pollutants. Also, ERS reduced the emissions to the outdoor air using HEPA and carbon filters found in the ERS.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/22/6358/s1, Figure S1: Layout of Fire station A, Figure S2: Layout of Fire station B.

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