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Research Article

Emission Characteristics of PM (PM_{total}, PM_{10}, $PM_{2.5}$), NOx, CO and VOCs Emitted from LNG-fired Gas Turbine and Small Domestic Boiler

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ABSTRACT In recent years, natural gas is increasingly being used in the heating and power generation sectors as a clean fuel with an aim to reduce air pollution. In this study, a standard test method was used to measure air pollutants and identify emission characteristics for gas turbines and small domestic boilers, which use LNG as fuel. For gas turbines, the air pollutants were measured at 14 sites, whereas for small domestic boilers, six of them were installed in a laboratory to run tests due to limitations in on-site measuring and testing. However, the small domestic boilers were all new machines and were operated for long consecutive hours for testing, meaning that the results could vary from that of on-site boilers. The results show that gas turbines and small domestic boilers not only emit $PM_{2.5}$, but also particulate matters larger than $PM_{2.5}$. According to the measurements, the average concentration level of PM_{total}, PM_{10}, and $PM_{2.5}$ generated from gas turbines are 51.8, 38.5, and 28.1 μg/m^3 (@O_2 15%), respectively. Those generated from small domestic boilers were 31.3, 26.2, and 20.0 μg/m^3 (@O_2 4%), respectively. The NOx concentration levels complied with the emission limits. Especially where a NOx control device was in place, both the NOx and CO concentration levels were relatively low. However, the NOx and CO concentration levels were generated from small domestic boilers were relatively high, since the emission limits were not applied. VOCs were measured at 10 facilities where 28 samples were collected. The compounds that were identified were Aromatics, Oxygenated VOCs, Alkanes, in that order, which were consistent across the samples. Aromatics consisted mostly of toluene, *o*,*m*,*p*-xylenes, benzene, and ethylbenzene. Among oxygenated VOCs, ethyl acetate, vinyl acetate, and isopropyl alcohol, etc. were identified. In other words, gas turbines generated a wider range and higher concentration levels of VOCs compared to small domestic boilers. The emission factors of gas turbines and small domestic boilers were derived from the measurements, and then compared with the standard emission factors of other countries (NAER, U.S. EPA AP-42, EMEP/EEA). PM emission factors calculated in this study were lower than that of existing emission factors and the calculated NOx emission factors (uncontrolled) for the small boilers were also lower. The CO emission factor for gas turbines was lower than that of existing emission factors, but higher for the small domestic boilers. Emission factors of benzene, toluene, and xylenes, which are hazardous air pollutants, were lower than those of U.S. EPA AP-42.

KEY WORDS Gas turbine, Small domestic boiler, Emission factor, Particle size distribution, VOCs

1. INTRODUCTION

Fuel transtion policies have been in place for a long time as basic policies to manage air pollution. These policies encourage the change to fuels that emit less air pollutants such as particulate matter (PM), sulfur oxides (SOx), and carbon monoxide (CO) (Vallero, 2008; Molina and Molina, 2002). Against this backdrop, Liquefied Natural Gas (LNG), a clean fuel has seen an increase in its supply globally, since it is a clean fuel with very low emissions of SOx, PM, and CO compared to coal and petroleum,

A case in point is South Korea, which saw an increase of LNG supply from 46.3 million toe (ton of oil equivalent) in 2010 to 53.2 million toe in 2018 (KEEI, 2020). As of 2018 54.7% of natural gas consumption is for industrial use and 24.8% is for domestic use and such domestic use is mainly for heating.

Power generation facilities that use LNG as fuel have systems of combined cycle power plants that uses gas turbines and combined heat and power plant. A combined heat and power plant refers to a system that improves energy efficiency (by approximately 87%) by retrieving heat released as a byproduct of electricity generation and using it as an energy source for heating and cooling (IPPC, 2017). According to the Ninth Basic Plan for Power Supply and Demand, the share of LNG fuel will be increased from 37.4% (2020) to 47.3% (2034) based on the capacity factor (MOTIE, 2020). As such, LNG will be increasingly used down the road, and as a result, air pollutant emissions are also expected to increase (KEA, 2020).

Small domestic boilers that use LNG as fuel are classified into conventional and condensing types. The exhaust gas temperature of conventional boilers is higher than the dew point, and all water vapor in the exhaust gas is released into the atmosphere. In the case of condensing boilers, a heat exchanger is installed at the back end of the boiler to condense the water vapor in the exhaust gas through the heat exchange between the water vapor and the heat-circulation water. The temperature of the exhaust gas is approximately 70°C, and the heat efficiency is 92% or higher (Men *et al.*, 2021). In addition, condensing boilers were designated as eco-friendly boilers by installing low-NOx burners, in turn, resulting in lower emission levels of NOx and CO. Thus, a support program to encourage the installation of these boilers was first introduced in 2017 in the Seoul metropolitan area and is currently being implemented nationwide (KMOE, 2018).

In this study, we measured the concentration levels of particulate matter (PM_{total}, PM_{10}, and $PM_{2.5}$), nitrogen oxides (NOx), Carbon monoxide (CO), and volatile organic compounds (VOCs) generated from LNG-fired gas turbines that are used in combined cycle power plants as well as combined heat and power plants, and LNG-fired small domestic boilers. Then, we calculated the emission factors to compare with that of existing emission factors.

2. FIELD EXPERIMENTS

2.1 Measurement Facilities

Experiments were conducted on gas turbines of combined heat and power plants, combined cycle power plants, and small domestic boilers, which used LNG as fuel. We conducted on-site measurements at 4 combined heat and power plants and 10 combined cycle power plants. For small domestic boilers, we installed conventional and condensing boilers in a laboratory to proceed with the measurements. Because boilers are not operated continuously for a long time in residential houses, we continuously operated the boilers installed in the laboratory to perform the measurements. Hence, there is a limitation that the measurement results may differ from actual field measurement results because the measurements were not conducted under the operating conditions of real houses.

A low-NOx burner (LNB) and a Selected Catalytic Reduction System (SCR) were included as air pollution prevention devices in each gas turbine in the combined heat and power plants and combined cycle power plants. In the case of small domestic boilers, only the condensing boiler was equipped with an LNB. Table 1 shows a summary of the measurement facilities and measured species. NOx and CO were measured in all facilities, and particulate matter (PM_{total}, PM_{10}, and $PM_{2.5}$) were measured at gas turbines of 8 facilities and small domestic boilers of 6 facilities. VOCs were measured at gas turbines of 8 facilities and small domestic boilers of 2 facilities.

2.2 Measurement Methods

For the particulate matter, we measured the concentration of total particulate matter (PM_{total}) and the concentration by size ($PM_{2.5}$, $PM_{2.5\text{-}10}$, and $>PM_{10}$). The PM_{total} concentration was measured by the ES 01301.1 method, and the concentration by particulate matter size was

Table 1. Description of measurement facilities.

Measurement facility		Capacity	Operation year	APCDs	Measurement pollutants	Remark
Gas turbine	GT-1, 2	< 100 MWe	2006, 2008	LNB, SCR	NOx, CO, VOCs	Combined heat & power plant
	GT-3	100 MWe	2012	LNB, SCR	PM, NOx, CO, VOCs	
	GT-4	300 MWe	2016	LNB, SCR	PM, NOx, CO, VOCs	
	GT-5–8	100 MWe	2003, 2014	LNB, SCR	NOx, CO, VOCs	Combined cycle power plant
	GT-9–11	300 MWe	2014	LNB, SCR,	PM, NOx, CO	
	GT-12	500 MWe	2013	LNB, SCR	PM, NOx, CO	
	GT-13, 14	200 MWe	2010	LNB, SCR, Filter**	PM, NOx, CO	
Gas boiler	GB-1–3	Small boiler*	New product	–	PM, NOx, CO, VOCs	Domestic boiler
	CB-1–3			LNB		

GT; Gas Turbine, GB;Gas Boiler, CB; Condesing Boiler, * Small boiler; Household boiler (70 kW or less), ** Filter; Unknown filter

measured by the ISO 23210 method. On-site measurements were performed using a PM sampler and a cascade impactor at the same measurement point simultaneously. The PM_{total} concentration was calculated using the value measured by the PM sampler; the ratios of $PM_{2.5}/PM_{total}$ and PM_{10}/PM_{total} were calculated using the concentration values measured by the cascade impactor, and they were applied to the value of PM_{total} concentration to calculate the PM_{10} and $PM_{2.5}$ concentrations. NOx and CO concentrations were measured while collecting samples of particulate matter or VOCs.

The samples of VOCs were collected on-site in Tedlar bags, according to the "ES01113.1" method, and adsorbed in an adsorption tube (adsorbent: TX TA 100 mg, CT 200 mg) by letting them pass through the tube at a rate of 100–200 cc/min using a micro-flow control pump (MP-Σ30, Sibata, Japan). Based on the flow rate, the VOC concentrations were measured on-site using a portable PID (Tiger, Ionscience, UK), and the sampling time was determined considering the adsorption capacity of the adsorbent. The measurement data of the portable PID were used only for determining the sampling flow rate. The adsorption tube was analyzed in a laboratory using a method equivalent to "ES01606.1."

Because it was difficult to measure low-molecular-weight, highly volatile VOCs using the adsorption tube method, due to the characteristics of the adsorption method, we chose to analyze aromatic and organochlorine VOCs that exhibit high environmental toxicity. The gaseous standard mixed materials used in the qualitative and quantitative analyses of VOCs were SUPELCO standard VOC mixture for TO-15 (1 ppm, nominal) and standard VOC mixture for TO-14 (1 ppm, nominal); 66 materials were isolated and identified. Baek *et al.* (2020) have explained the VOC analysis, quality control, and analysis conditions of the equipment in detail. NOx and CO were measured on-site using a portable gas analyzer. In the case of SO_2, the detection limit of the measuring device was 1 ppm and the SO_2 concentration level measured on site was lower than the detection limit, hence the exclusion from this study.

In the case of LNG-fired gas turbines, the measurement points were places where the telemetering monitoring system (TMS) of the stack was in place. In the case of small boilers, the boilers were installed in a laboratory, two measuring instruments were installed between 0.5 and 0.7 m where the exhaust gas passes through at the back end of the boiler, and the PM sampler, cascade impactor, and gas-phase material measurements were performed simultaneously.

Table 2 shows the measuring equipment for each species. The particulate matter samples were collected at each facility by considering the isokinetic sampling and low weight concentration. The sampling flow rate was approximately 10–12 Sm^3 or higher, and we conducted the experiment for about 10 hr to collect one sample and performed the measurement three times or more at each measurement point. We also collected three or more samples of VOCs at each point.

3. RESULTS AND DISCUSSION

3.1 Concentration

The measurement results of PM (PM_{total}, PM_{10}, and $PM_{2.5}$) for 8 facilities of gas turbines and 6 small domes-

Table 2. Measuring equipment.

Item	Methods	Instruments
> PM_{10}, $PM_{2.5\text{-}10}$, $PM_{2.5}$	KS I ISO 23210	2-stage cascade impactor (Stage-X MS, X Ear Pro, Italy)
PM_{total}	ES 01301.1	PM sampler (KNJ-5, KNJ, Korea)
VOCs	ES 01501.1a	Thermal desorber (Ultra/Unity, Makers, UK) GC/MS (HP6890, Hewlett Packard, USA)
NOx, CO	ES 01204	Gas analyzer (Testo 350k, Testo, Germany)

Table 3. Concentrations of PM_{total}, PM_{10}, and $PM_{2.5}$ for LNG-fired gas turbines and small domestic boilers.

Pollutants		Gas turbine (n=29) @O_2 15%	Conventional boiler (n=9) @O_2 4%	Condensing boiler (n=9) @O_2 4%
Particulate matters (μg/Sm^3)	PM_{total}	51.8 (15.8–90.0)	28.4 (13.7–43.1)	34.2 (17.6–55.0)
	PM_{10}	38.5 (14.6–87.0)	24.5 (12.9–42.0)	27.9 (16.9–38.8)
	$PM_{2.5}$	28.1 (10.0–85.1)	18.3 (8.6–35.8)	21.8 (11.0–35.8)

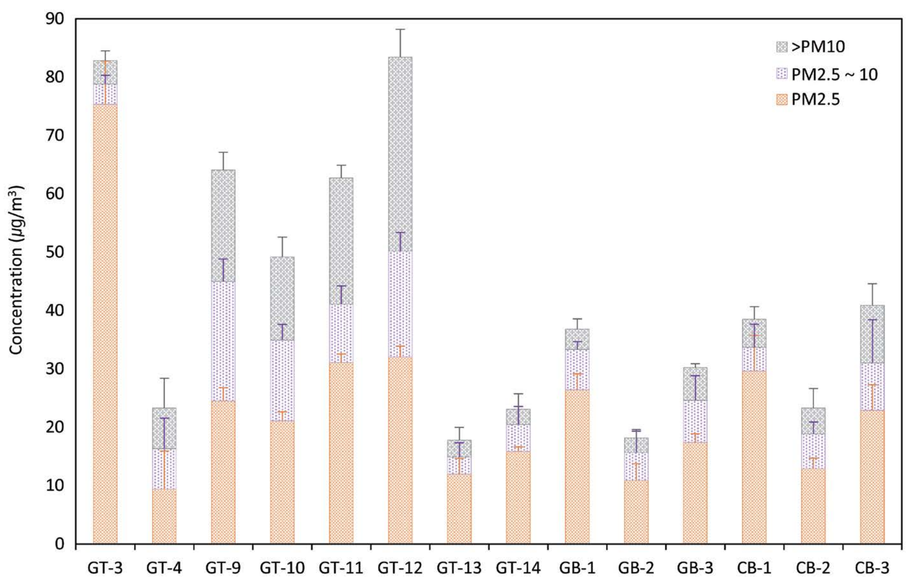

Fig. 1. PM_{total}, PM_{10}, and $PM_{2.5}$ concentration results for LNG-fired gas turbines and small domestic boilers.

tic boilers are presented in Table 3 and Fig. 1. The particle size distribution and concentration emit from combustion may vary depending on combustion condition (air fuel ratio, capacity, load etc.) (Puri, 1993). As shown in Fig. 1, this measurement result also differed between facilities. The averaged concentrations of PM_{10} and $PM_{2.5}$ generated from the LNG-fired gas turbines were 38.5 and 28.1 μg/m^3 (@O_2 15%), respectively, and those generated from the small domestic boilers were 26.2 and 20.0 μg/m^3 (@O_2 4%), respectively, which were low; they were slightly higher than the PM_{10} and $PM_{2.5}$ levels in the atmosphere. In the case of combustion facilities using coal, oil, etc. as fuels, the concentrations of PM emitted are higher than those emitted from LNG-fired facilities although they equipped with high-efficiency treatment using electrostatic precipitators and fabric filter (Yu *et al.*, 2021; Kim and Hwang, 2016; Yang *et al.*, 2014).

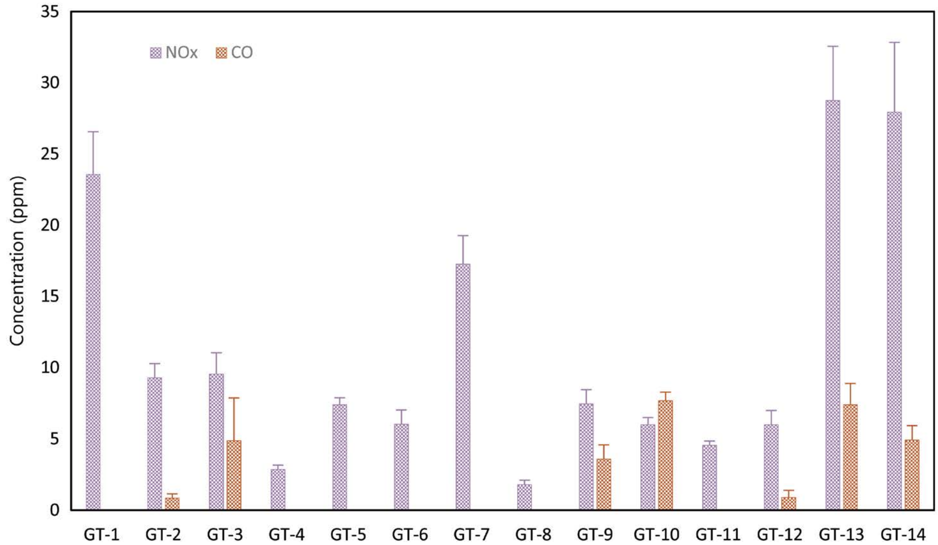

Fig. 2. NOx and CO concentrations at LNG-fired gas turbines.

According to the measurement results, the concentrations of PM generated from the gas turbines were higher than those generated from the small domestic boilers, and if the applied standard oxygen concentration is converted to 4%, the concentrations of PM_{10} and $PM_{2.5}$ emitted from the gas turbines were 109.0 and 79.6 μg/m^3 (@O_2 4%), respectively, indicating a greater difference. In the case of the small domestic boilers, the PM concentrations were slightly higher in the condensing type than in the conventional type. In the condensing boilers, the temperature of the exhaust gas decreased in the process of recovering heat contained in the exhaust, and thus gave rise to PM (Feng *et al.*, 2018; Yu *et al.*, 2018; Corio and Sherwell, 2000).

In addition, particulate matters generated from LNG-fired gas turbines and small boilers included not only smaller $PM_{2.5}$ but also larger ones, as opposed to our expectations. Out of the overall particulate matters generated from gas turbines, conventional small domestic boilers, and condensing small domestic boilers, $PM_{2.5}$ accounted for, on average, 52.6%, 64.3%, 63.8%, respectively. This was similar to the results Brewer *et al.* (2016) reported, where $PM_{2.5}$ concentration was 48.06 μg/m^3 those larger than $PM_{2.5}$ concentration was 52.63 μg/m^3. Further study on the mechanism in which particulate matters are generated in the process of LNG, LPG, etc. combustion is necessary.

Fig. 2 shows the measurement results of NOx and CO concentrations for the gas turbines, and Fig. 3 shows the results for the small domestic boilers. Table 4 provides a summary for these two figures. The NOx emission limits of each facility vary depending on the year of installation of the facility; the limits are lower in more recently installed facilities than in those installed relatively long ago, such as GT-1, GT-7, GT-13, and GT-14. As of 2021, the most strict NOx emission limits applied for gas turbines is 20 ppm (@O_2 15%) (KMOE, 2021). The NOx concentrations emitted from the gas turbines met the applied emission limits at each facility. The CO concentration detected was below the detection limit or very low.

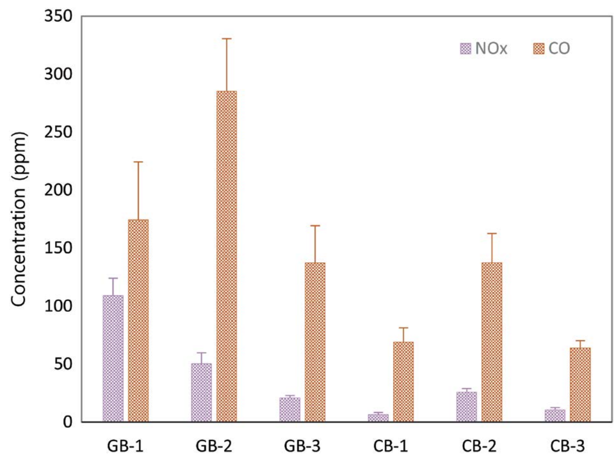

Fig. 3. NOx and CO concentrations at LNG-fired small domestic boilers.

Table 4. Concentrations of NOx and CO for LNG-fired gas turbines and small domestic boilers.

Pollutants		Gas turbine* (n = 60) @O_2 15%	Conventional boiler (n = 9) @O_2 4%	Condensing boiler** (n = 9) @O_2 4%
Gaseous pollutants (ppm)	NOx	11.3 (1.8–28.8)	60.1 (20.9–109.0)	14.3 (6.4–25.9)
	CO	2.2 (~7.7)	198.9 (137.2–285.2)	90.1 (63.9–137.4)

*Gas turbine; LNB and SCR installation, **Condensing boiler; LNB installation

Fig. 3 shows the measurement results for the NOx and CO concentrations of the small domestic boilers. The small domestic boilers used in the experiments were new products purchased for the experiments, and in the case of the condensing type, we purchased eco-friendly boilers. The eco-friendly boilers were equipped with LNB to satisfy the eco-label certification criteria (gas boilers: EL 261:2015, ≤30 ppm for NOx, ≤200 ppm for CO). Hence, the concentrations of NOx and CO emitted from the condensing boilers were about 23% and 45% lower, respectively, compared to those emitted from the conventional boilers.

When we converted the concentrations of NOx emitted from LNB-installed gas turbines and small boilers at the same standard oxygen concentration of 4%, we found that the concentration emitted from the gas turbines was about twice higher. On the other hand, the CO concentration emitted from the condensing boilers was about 14.7% higher than that emitted from the gas turbines.

Table 5 summarizes the concentration measurement results of VOCs with detection frequencies and average concentrations for tested gas turbines and small domestic boilers. More types of VOCs were detected at the gas turbines than at the small domestic boilers, and the concentrations were also higher. Toluene, *o,m,p*-xylenes, benzene, and ethylbenzene comprised most of the aromatics. Among the oxygenated VOCs, we detected ethyl acetate, vinyl acetate, and isopropyl alcohol, which showed that their concentrations were low. Heptane and cyclohexane were detected in the case of alkanes. In the case of halocarbons, most materials showed low detection frequencies and concentrations. In the case of the gas turbines, 26 samples of 8 facilities were analyzed, but in the case of the small boilers, 3 samples were analyzed for each conventional and condensing boiler. Among the 66 materials that could be isolated and detected, up to 44 and 16 materials were detected at the gas turbines and small boilers, respectively.

Fig. 4 shows the concentration results by classifying the VOCs into aromatics, alkanes, oxygenated VOCs, and halocarbons for each facility. The oxygenated VOC generated primarily from gas turbines is known to be formaldehyde (AP-42, 2000); however, we could not measure it in this study. The oxygenated VOCs in this study excluded not only formaldehyde but also other carbonyl compounds. Aromatics, alkanes, and oxygenated VOCs were always detected in every sample measured, and among them, the concentration of aromatics was the highest, followed by that of oxygenated VOCs, alkanes, and halocarbons.

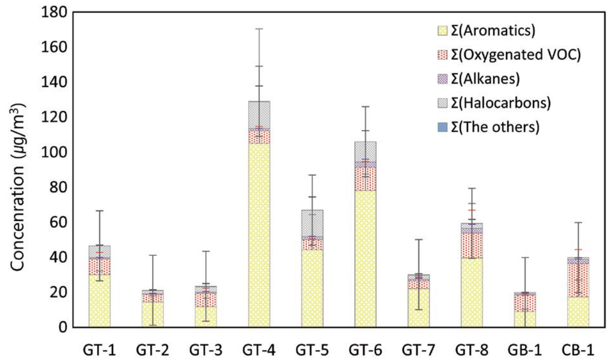

Fig. 4. VOC concentration results for LNG-fired gas turbines and small domestic boilers.

3.2 Emission Factors

Based on the air pollutant concentrations and the fuel usage measured at each facility, the emission factors were calculated using Eq. (1) (Yu *et al.*, 2021; Wu *et al.*, 2020; Jang *et al.*, 2011). Therefore, the emission factor of the combustion device may serve as a measure of combustion state or level of combustion technology. Table 6 shows the amount of fuel used during the sampling periods at each facility.

$$\text{Emission factor}\ (kg/10^3\ m^3) = \text{Concentration}\ (\mu g/Sm^3) \times \text{amount of flue gas}\ (Sm^3/hr) \times 10^{-9} / \text{amount of fuel feeding}\ (10^3\ m^3/hr) \quad (1)$$

Table 5. Concentrations of detected VOCs for LNG-fired gas turbines and small domestic boilers.

Compounds ($\mu g/Sm^3$)	Gas turbine (n = 26) @O_2 15%		Conventional boiler (n = 3) @O_2 4%		Condensing boiler (n = 3) @O_2 4%	
	Frequency (%)	Mean	Frequency (%)	Mean	Frequency (%)	Mean
Ethylbenzene	100.0	8.17	100.0	0.63	100.0	1.22
m,p-Xylenes	100.0	7.63	100.0	0.68	100.0	1.93
Hexane	100.0	4.10	100.0	0.64	100.0	1.00
1,2,4-Trimethylbenzene	100.0	4.02	100.0	0.18	100.0	0.74
Benzene	100.0	3.80	100.0	4.61	100.0	2.67
o-Xylene	100.0	2.51	100.0	0.20	100.0	0.59
1,3,5-Trimethylbenzene	100.0	1.04	–	N.D	–	N.D
4-Ethyltoluene	100.0	0.94	–	N.D	–	N.D
Styrene	100.0	0.51	100.0	0.19	100.0	5.67
Naphthalene	100.0	0.38	100.0	0.42	100.0	0.45
Heptane	96.2	2.31	–	N.D		N.D
Ethyl acetate	92.3	3.89	100.0	1.87	100.0	3.63
N,N-Dimethylformamide	88.5	1.50	–	N.D	–	N.D
Methyl isobutyl ketone	88.5	0.43	–	N.D	–	N.D
Cyclohexane	80.8	1.40	–	N.D	–	N.D
Isoproyl alcohol	76.9	1.29	100.0	2.95	100.0	2.87
1,4-Dichlorobenzene	76.9	0.57	–	N.D	–	N.D
Toluene	73.1	20.05	100.0	1.85	100.0	3.67
Vinyl acetate	69.2	1.71	100.0	4.63	100.0	12.64
Trichloroethylene	46.2	1.02	–	N.D	–	N.D
1,3-Dichlorobenzene	46.2	0.42	–	N.D	–	N.D
1,3-Butadiene	42.3	0.24	–	N.D	–	N.D
Chloroform	38.5	0.17	–	N.D	–	N.D
Chlorobenzene	34.6	0.26	66.7	0.24	100.0	0.20
Tetrahydrofuran	30.8	0.59	100.0	0.86	66.7	1.41
Methyl tert-butyl ether	30.8	0.16	–	N.D	–	N.D
Carbon tetrachloride	30.8	0.12	–	N.D	–	N.D
2-Methoxyethanol	26.9	1.91	–	N.D	–	N.D
Methylene chloride	26.9	0.35	–	N.D	–	N.D
1,4-Dioxane	19.2	0.61	–	N.D	–	N.D
Bromodichloromethane	19.2	0.15	–	N.D	–	N.D
1,2-Dichlorobenzene	19.2	0.06	33.3	0.26	100.0	0.27
1,2-Dichloroethane	15.4	0.11	–	N.D	–	N.D
1,2-Dichloropropane	15.4	0.09	–	N.D	–	N.D
Bromoform	11.5	0.79	–	N.D	–	N.D
trans-1,2-Dichloroethylene	11.5	0.31	–	N.D	–	N.D
Freon11	11.5	0.07	–	N.D	–	N.D
Tetrachloroethylene	7.7	0.10	–	N.D	–	N.D
Carbon disulfide	7.7	0.09	–	N.D	–	N.D
cis-1,2-dichloroethylene	3.8	1.63	–	N.D	33.3	0.91
2-Hexanone	3.8	0.84	–	N.D	–	N.D
Chloroethane	3.8	0.63	–	N.D	–	N.D
Freon114	3.8	0.16	–	N.D	–	N.D
Freon 113	3.8	0.06	–	N.D	–	N.D

*N.D; Not detected

As shown in Table 7, We calculated the emission factors for the air pollutants of the LNG-fired gas turbines measured in this study and compared them to the emission factors used officially in other countries (NAER,

Table 6. Fuel usage during sampling periods at facilities.

Facilities	Fuel usage (m^3/hr)	Facilities	Fuel usage (m^3/hr)	Facilities	Fuel usage (m^3/hr)
GT-1	29,449	GT-8	66,166	GB-1	2.50
GT-2	20,248	GT-9	211,030	GB-2	3.94
GT-3	35,374	GT-10	265,217	GB-3	4.08
GT-4	67,089	GT-11	265,759	CB-1	2.37
GT-5	41,502	GT-12	102,604	CB-2	3.56
GT-6	37,563	GT-13	273,341	CB-3	4.08
GT-7	41,295	GT-14	293,618		

Table 7. Air pollutant emission factor (uncontrolled) for LNG-fired gas turbines.

Emission factors ($kg/10^3 m^3$)	This study	NAER (2020)	U.S. EPA AP-42 (2000)	EMEP/EEA (2019)
PM_{total}	2.48E-03 7.43E-04*	3.60E-02	3.10E-02 (1.9E-03 lb/10^6 Btu)	8.79E-03 (2.0E-01 g/GJ)
PM_{10}	1.76E-03 6.53E-04*	3.60E-02	3.10E-02 (1.9E-03 lb/10^6 Btu)	8.79E-03 (2.0E-01 g/GJ)
$PM_{2.5}$	1.24E-03 5.11E-04*	3.60E-02	3.10E-02 (1.9E-03 lb/10^6 Btu)	8.79E-03 (2.0E-01 g/GJ)
NOx	4.63E-01**	6.04E+00	5.22E+00 (3.2E-01 lb/10^6 Btu)	2.11E+00 (4.8E+01 g/GJ)
CO	2.01E-01	1.55E+00	1.34E+00 (8.2E-02 lb/10^6 Btu)	2.11E-01 (4.8E+00 g/GJ)
Benzene	8.25E-05	–	1.96E-04 (1.2E-05 lb/10^6 Btu)	–
Toluene	4.09E-04	–	2.12E-03 (1.3E-04 lb/10^6 Btu)	–
Ethylbenzene	1.40E-04	–	5.22E-04 (3.2E-05 lb/10^6 Btu)	–
Xylene	2.07E-04	–	1.04E-03 (6.4E-05 lb/10^6 Btu)	–

*Controlled (Filter), **Controlled (LNB + SCR)

2020; U.S. EPA, 2000; EMEP/EEA, 2019). The NAER, U.S. EPA AP-42, and EMEP/EEA data provide the same values, regardless of the PM size, for the emission factors of PM_{total}, PM_{10}, and $PM_{2.5}$. The emission factor values are similar between the data of NAER and U.S. EPA AP-42, and the emission factors in the EMEP/EEA data are lower than those of the two datasets mentioned above. On the other hand, the results of our study are relatively similar to the emission factor values of EEA. England *et al.* (2002) calculated the emission factors of gas turbines using natural gas by classifying them by PM size; the emission factors of PM_{total}, PM_{10}, and $PM_{2.5}$ were 6.1×10^{-4}, 2.9×10^{-4}, and 9.6×10^{-4} (lb/10^6 Btu), respectively. If these values are converted, the results are 9.96×10^{-3}, 4.73×10^{-3}, and 1.57×10^{-3} ($kg/10^3 m^3$), which are similar to the results obtained in this study.

Because the gas turbines measured in this study were equipped with LNB and SCR for NOx treatment, "controlled" emission factors were calculated. When they were compared to the emission factors of NAER ("uncontrolled"), the removal performance was approximately 92%, and when compared to the emission factors of

Table 8. Air pollutant emission factor (uncontrolled) for LNG-fired small domestic boilers.

Emission Factors ($kg/10^3 m^3$)		This study	NAER (2020)	U.S. EPA AP-42 (1998)	EMEP/EEA (2019)
PM_{total}	Conventional	2.46.E-04	3.00E-02	3.04E-02 ($1.9E+00 lb/10^6 ft^3$)	8.79E-03 (2.0E-01 g/GJ)
	Condensing	4.31.E-04			
PM_{10}	Conventional	2.14.E-04	3.00E-02	3.04E-02 ($1.9E+00 lb/10^6 ft^3$)	8.79E-03 (2.0E-01 g/GJ)
	Condensing	3.51.E-04			
$PM_{2.5}$	Conventional	1.59.E-04	3.00E-02	3.04E-02 ($1.9E+00 lb/10^6 ft^3$)	8.79E-03 (2.0E-01 g/GJ)
	Condensing	2.74.E-04			
NOx	Conventional	8.10E-01	3.70E+00	1.60E+00 ($1.0E+02 lb/10^6 ft^3$)	3.21E+00 (7.3E+01 g/GJ)
	Condensing	2.43E-01*			
CO	Conventional	2.26E+00	6.40E-01	1.34E+00 ($8.4E+01 lb/10^6 ft^3$)	1.06E+00 (2.4E+01 g/GJ)
	Condensing	1.21E+00			

*Controlled (LNB)

EEA (“uncontrolled”), the removal performance was at a level of approximately 78%. This was because the emission factors of NAER were higher than those of EEA. The CO emission factors calculated in this study were very similar to the EMEP/EEA data, and the emission factor values were similar for NAER and U.S. EPA AP-42.

VOC emission factors vary depending on various conditions, such as the sampling method, standard materials used in the qualitative and quantitative analyses, and detection limits of the analysis devices. In this study, the emission factors for benzene, toluene, ethylbenzene, and xylenes were only estimated with acceptable analytical precisions, and compared them to the emission factors of U.S. EPA AP-42. The comparison showed that the emission factors calculated in this study were lower than those of U.S. EPA AP-42.

Table 8 shows a summary of the emission factors for the LNG-fired small domestic boilers measured in this study. The NAER, U.S. EPA AP-42, and EMEP/EEA data suggest the same emission factor for PM_{total}, PM_{10}, and $PM_{2.5}$, respectively, irrespective of the PM size, as in the case of gas turbines. Furthermore, the emission factor values are similar between the data of NAER and U.S. EPA AP-42, as in the case of gas turbines, and the emission factors in the EMEP/EEA data are lower than these. The results obtained in this study are lowest for all emission factors. In a research report, McDonald (2009) classified the $PM_{2.5}$ emission factors of domestic natural gas boilers into the conventional and condensing types, which were estimated to be 3.8×10^{-5} and 8.3×10^{-5} ($lb/10^3$ Btu), respectively. Our results agreed well with this previous study.

Because the condensing boilers used in this study were equipped with LNB for NOx treatment, a “controlled” emission factor was calculated. The calculated NOx emission factor (“uncontrolled”) of the conventional small boilers was lower than the emission factors of NAER, U.S. EPA AP-42, and EMEP/EEA, respectively. The CO emission factor of the condensing boilers in this study was similar to that of U.S. EPA AP-42 and EEA, whereas the emission factor of the conventional boilers was higher than that of NAER. The occurrences of NOx and CO in the combustion process are inversely proportional in certain areas (Vallero, 2008). The results for the “uncontrolled” emission factors of NOx and CO in this study also show that the NOx emission factors are lower than those of NAER, U.S. EPA AP-42, and EMEP/EEA, and inversely, the CO emission factors are higher. We did not calculate the VOC emission factors because the number of measured facilities and the number of samples were small.

4. CONCLUSION

The use of natural gas, which emits small amounts of air pollutants, is continuously growing in the power generation and heating sectors, not only in South Korea but worldwide. In this study, we measured the air pollutants in the field and laboratory for LNG-fired gas turbines and small boilers, and calculated the emission factors.

We measured PM_{total}, PM_{10}, $PM_{2.5}$, NOx, CO, and VOCs on-site for 14 gas turbines and for the small domestic boilers three times or more at each facility, based on standard test criteria or an equivalent method.

The LNG-fired gas turbines and small domestic boilers produced not only small-sized $PM_{2.5}$ but also particulate matter larger than $PM_{2.5}$. Nevertheless, their concentrations were at a very low level compared to those generated from coal or oil-fired facilities. The average concentrations of PM_{total}, PM_{10}, and $PM_{2.5}$ generated from the gas turbines were 51.8, 38.5, and 28.1 μg/m^3 (@O_2 15%), respectively, and those generated from the small boilers were 31.3, 26.2, and 20.0 μg/m^3 (@O_2 4%), respectively.

The emitted NOx concentrations were at a level complying with the emission limits, and when NOx reduction devices were in place, both the NOx and CO concentrations were relatively low. The concentrations of NOx and CO emitted from the conventional small domestic boilers without emission limits were relatively high. In the case of VOCs, we always detected aromatics, followed by alkanes and oxygenated VOCs, in 28 samples and 10 facilities. The detected aromatics were mostly toluene, *o,m,p*-xylenes, benzene, and ethylbenzene. Among the oxygenated VOCs, we detected ethyl acetate, vinyl acetate, and isopropyl alcohol. There were more types of VOCs with higher concentrations at the gas turbines than at the small domestic boilers.

The PM_{total}, PM_{10}, and $PM_{2.5}$ emission factors of the gas turbines and small domestic boilers, calculated based on the measurement results of this study, were similar to those obtained in some previous studies (McDonald, 2009; England *et al.*, 2002), but lower than the existing emission factors (NAER, U.S. EPA AP-42, and EMEP/EEA). The "uncontrolled" emission factor of NOx calculated for the small domestic boilers was lower than the existing emission factors. Compared to the conventional data, the CO emission factor calculated for the gas turbines was lower, and that calculated for the small domestic boilers was higher. The emission factors of benzene, toluene, ethylbenzene, and xylenes, which are hazardous air pollutants, were calculated for only the gas turbines, and were lower than the U.S. EPA AP-42.

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REFERENCES

Baek, S.-O., Seo, Y.-K., Kim, J.H. (2020) Occurrence and distribution of volatile organic compounds in the ambient air of large petro-chemical industrial complexes: focusing on Daesan area. Journal of Korean Society for Atmospheric Environment, 36(1), 32–47, (in Korean with English abstract). https://doi.org/10.5572/KOSAE.2020.36.1.032

Brewer, E., Li, Y., Finken, B., Quartucy, G., Muzio, L., Baez, A., Garibay, M., Jung, H.S. (2016) $PM_{2.5}$ and ultrafine particulate matter emissions from natural gas-fired turbine for power generation. Atmospheric Environment, 131, 141–149. https://doi.org/10.1016/j.atmosenv.2015.11.048

Corio, L.A., Sherwell, J. (2000) In-stack condensable particulate measurements and issues. Journal of the Air & Waste Management Association, 50, 207–218. https://doi.org/10.1080/10473289.2000.10464002

Derwent, R.G., Jenkin, M.E., Utembe, S.R., Shallcross, D.E., Murrells, T.P., Passant, N.R. (2010) Secondary organic aerosol formation from a large number of reactive man-made organic compounds. Science of the Total Environment, 408, 3374–3381. https://doi.org/10.1016/j.scitotenv.2010.04.013

EMEP/EEA (European Monitoring and Evaluation Programme/European Environmental Agency) (2019) Air Pollutant Emission Inventory Guidebook 2019.

England, G.C., Chang, O., Wein, S. (2002) Development of fine particulate emission factors and speciation profiles for oil and gas-fired combustion systems. GE Energy and Environmental Research Corporation, pp. 4–7.

Feng, Y., Li, Y., Cui, L. (2018) Critical review of condensable particulate matter. Fuel, 224, 801–813. https://doi.org/10.1016/j.fuel.2018.03.118

Gao, M., Teng, W., Du, Z., Nie, L., An, X., Liu, W., Sun, X., Shen, Z., Shi, A. (2021) Source profiles and emission factor of VOCs from solvent-based architectural coatings and their contributions to ozone and secondary organic aerosol formation in China. Chemosphere, 275, 129815. https://doi.org/10.1016/j. chemosphere.2021.129815

IPPC (Integrated Pollution Prevention and control) (2017) Best Available Techniques (BAT) Reference Document for Large Combustion Plants, pp. 58–63.

Jang, K.W., Kim, H.C., Song, D.J., Jung, N.E., Hong, J.H., Lee, S.J., Han, J.S. (2011) Estimating PM emission factor from coal-fired power plants in Korea. Journal of Korean Society for Atmospheric Environment, 27(5), 485–493, (in Korean with English abstract).

Jenkin, M.E., Derwent, R.G., Wallington, T.J. (2017) Photochemical ozone creation potentials for volatile organic compounds: rationalization and estimation. Atmospheric Environment, 163, 128-137. https://doi.org/10.1016/j.atmosenv.2017.05.024

KEA (Korea Energy Agency) (2020) 2020 Energy Statistics Handbook.

KEEI (Korea Energy Economics Institute) (2020) 2019 Yearbook of Energy statistics.

Kim, J.H., Lee, J.J. (2013) Management changes of hazardous air pollutants sources and its proposed improvement in Korea. Journal of Korean Society for Atmospheric Environment, 29(5), 536-544, (in Korean with English abstract). https://doi.org/10.5572/KOSAE.2013.29.5.536

Kim, J.H., Whang, I.J. (2016) The characterization of PM, PM_{10}, and $PM_{2.5}$ from stationary source. Journal of Korean Society for Atmospheric Environment, 32(6), 603-612, (in Korean with English abstract). https://doi.org/10.5572/KOSAE.2016.32.6.603

Kim, M.J., Seo, Y.K., Kim, J.H., Baek, S.O. (2020) Impact of industrial activities on atmospheric volatile organic compounds in Sihwa-Banwol, the largest industrial area in South Korea. Environmental Science and Pollution Research, 27, 28912-28930. https://doi.org/10.1007/s11356-020-09217-x

KMOE (Ministry of Environment in Korea) (2018) A study on the distribution of eco-friendly domestic boiler.

KMOE (Ministry of Environment in Korea) (2021) Enforcement rule of the clean air conversation act.

McDonald, R. (2009) Evaluation of gas, oil and wood pellet fueled residential heating emissions characteristics. Brookhaven National Laboratory, pp. 28-32.

Men, Y., Liu, X., Zang, T. (2021) A review of boiler waste heat recovery technologies in the medium low temperature range. Energy, 237, 121560. https://doi.org/10.1016/j.energy.2021.121560

Molina, L.T., Molina, M.J. (2002) Air quality in the Mexico megacity: an integrated assessment. Kluwer Academic Publishers, pp. 45-47, 80-89.

MOTIE (Ministry of Trade, Industry and Energy) (2017) The 9th basic electricity supply and demand plan.

NAER (National Air Emission Inventory and Research Center) (2020) Air pollutant emission calculation manual (IV).

Park, J.H., Kang, S., Song, I.H., Lee, D.W., Cho, S.Y. (2018) Characteristics of long-term behavior of VOC species in Korea-PAMS data analysis. Journal of Korean Society for Atmospheric Environment, 34(1), 56-75, (in Korean with English abstract). https://doi.org/10.5572/KOSAE.2018.34.1.056

Puri, I.K. (1993) Combustion Processes, CRC press. pp. 73-93.

U.S. EPA (United States Environmental Protection Agency) (2015) AP-42, Compilation of air pollutants emission factors.

Vallero, D.A. (2008) Fundamentals of Air Pollution 4^{th} Edition, Academic press. pp. 777-778.

Yang, H.H., Gupta, S.K., Dhital, N.B., Wang L.C., Elumalai, S.P. (2020) Comparative investigation of coal- and oil- fired boilers based on emission factor, ozone and secondary organic aerosol formation potentials of VOCs. Journal of Environmental Sciences, 92, 245-255. https://doi.org/10.1016/j.jes2020.02.024

Yang, H.H., Lee, K.T., Hsieh, Y.S., Luo, S.W., Li, M.S. (2014) Filterable and condensable fine particulate emissions from stationary sources. Aerosol and Air Quality Research, 14, 2010-2016. https://doi.org/10.4209/aaqr.2014.08.0175

Yu, J.H., Lim, S.G., Song, J.H., Lee, D.Y., Yu, M.S., Kim, J.H. (2018) A study on the change of condensable particulate matter by the SO_2 concentration among combustion gases. Journal of Korean Society for Atmospheric Environment, 34(5), 651-658, (in Korean with English abstract). https://doi.org/10.5572/KOSAE.2020.34.5.651