



## Characteristics of Emissions from a Portable Two-stroke Gasoline Engine

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### ABSTRACT

This work investigates the engine performance and emission characteristics of a portable two-stroke gasoline engine (P2SGE) fueled by unleaded gasoline #92 blended with different 2-stroke engine oil brands (*CPC Super Low Smoke Two-Stroke Engine Oil* (SLS), *CPC Low Smoke Two-Stroke Engine Oil* (LS), and *MERCURY STAR Two-Stroke Engine Oil* (MS)) and operated at idling (0 kW), medium (1.5 kW) and high load (1.9 kW). Experimental results indicate that the emission factors (EFs) of HC and CO decreased with rising P2SGE load when each of the lubricants was used in the gasoline engine, while that of NO<sub>x</sub> exhibited an opposite trend. Using different brands of two-stroke engine oil did not influence the fuel consumption (FC) or specific fuel consumption (SFC) of P2SGE under the same engine speed. The mass concentrations and EFs of PM when adding the tested three lubricants were in the order MS > SLS > LS at all loads. 85% of the PM mass emitted from the P2SGE was contributed by carbonaceous matters (EC and OC) in all test conditions. The EFs based on the FC and output energy of PM-bound OC were higher than those of EC at idling condition, while an opposite trend (OC < EC) was observed at the medium (1.5 kW) and high (1.9 kW) engine loads. Additionally, the ratio of OC/EC decreased with increasing engine load, regardless of the difference in 2-stroke engine oil composition. Nap and PA dominated in the mass concentration among 16 investigated PAH homologs, while BaP and BaA mainly contributed the BaP<sub>eq</sub> concentrations, except using LS at high-load operation. Compared to the use of MS, the reductions of ΣPAHs and ΣBaP<sub>eq</sub> concentrations were 46.4% and 54.8%, respectively for using SLS, and 59.7% and 49.2%, respectively for using LS.

**Keywords:** Two-stroke gasoline engine, PM, Carbons, Polycyclic aromatic hydrocarbons.

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### INTRODUCTION

Environmental greening (such as park green space and planting) is a critical construction project in metropolitan cities around the world. In the maintenance of green landscapes, small or light engine powered apparatuses are often adopted to save human resources and increase work efficiency. However, these devices (such as mowers and leaf blowers) must be lightweight to reduce the cost in production, so they are often equipped with portable two-stroke gasoline engines (P2SGE), which have almost no exhaust gas treatment equipment. This fact generally results in the emission of large amounts of air pollutants, including carbon dioxide (CO<sub>2</sub>), volatile organic compounds (VOCs), polycyclic aromatic

hydrocarbons (PAHs) and other harmful substances (Volckens *et al.*, 2007; Shipchandler, 2008; Volckens *et al.*, 2008; Chuang *et al.*, 2010; Michaels, 2012; Dhital *et al.*, 2019; Tsai *et al.*, 2019). These compounds emitted from P2SGEs have been of little concern until recently.

Gasoline engines have smaller sizes and weights than diesel engines, and vibrate less during operation, making them suitable for use in different types of high-speed rotation engines, such as motorcycles and lawnmowers. In general, gasoline engines are divided into two types: 2-stroke gasoline engines (2SGE) and 4-stroke gasoline engines (4SGE). Unlike in a 4SGE, the intake of air and the discharge of exhaust occur at the same time in a 2SGE, leading to higher levels of unburned fuel vapor and other incomplete combustion matters in the exhaust. Moreover, the gasoline in a 2SGE, must be blended with an appropriate proportion (approximately 3–5 vol.%) of 2-cycle engine oil (lubricant) which is metal-enriched to lubricate and protect the engine parts. Unfortunately, the added 2-cycle engine oil is frequently hard to be entirely burned in such a short time in the

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combustion chamber; consequently, a 2SGE usually has higher emissions of air pollutants (e.g., PM<sub>2.5</sub>, elemental carbon (EC), organic carbon (OC), water-soluble ions and toxic metals (Jiang *et al.*, 2017; Hao *et al.*, 2019; Yang *et al.*, 2019)) than a 4SGE under the same piston displacement. Therefore, countries are gradually banning on-road 2SGEs. For example, on-road 2SGEs have been banned in Europe and the United States, and their use is prohibited in several China's major cities now. Taiwan is expected to embargo driving 2SGEs on the streets from 2020. However, little attention has been paid to the emissions standards for off-road 2SGE.

Horticultural gasoline-powered equipment (HGPE) is frequently and widely employed for gardening in public spaces such as schools and parks. However, HGPEs yield high levels of air pollutants during operation, which exposes operators and nearby people to such injurious environments and increases their health risks (Banks and McConnell, 2015). Banks and McConnell (2015) also indicated that there were approximately 121 million items of HGPEs in the United States in 2011, of which more than one-third were lawnmowers, followed by trimmers, edgers, brush cutters, leaf blowers and vacuums in order. According to the U.S. Environmental Protection Agency (U.S. EPA, 2017), about 54 million Americans use HGPEs for their garden planting and lawn maintenance every weekend, thus consuming about 800 million gallons of gasoline per year. Carbon monoxide (CO), VOCs and nitrogen oxides (NO<sub>x</sub>) emitted from these engines are thought to contribute around 5% of the nation's air pollution. Additionally, the operation of a new gasoline-powered lawnmower for an hour releases about the same quantities of VOCs and NO<sub>x</sub> as 11 new automobiles running for an hour. The exhausts emitted from gasoline and diesel vehicles have been confirmed as one of the primary emission sources causing poor air quality in the urban areas (Gehrig *et al.*, 2001; Zhu *et al.*, 2002; Lin *et al.*, 2005, 2008; Grivas *et al.*, 2018; Xiang *et al.*, 2018; Wang *et al.*, 2018).

P2SGEs are commonly fueled with two-cycle engine oil/gasoline mixtures, without exhaust-control devices, and even lack routine maintenance, and therefore emit more pollutants than regular gasoline vehicle engines. Nevertheless, the characteristics of emissions from P2SGE have not been extensively studied so far. Research has demonstrated that

exposure to PM<sub>2.5</sub> will cause anxiety symptoms, which may get worse when exposed to a higher PM<sub>2.5</sub> concentration or closer emission source (Power *et al.*, 2015; Zhang *et al.*, 2018). In order to investigate the emission characteristics of P2SGE, this investigation utilized a small commonly used sprayer (KAWAGOE, C12E) as a testing engine. To prepare fuels for testing, unleaded gasoline #92 was used as the base oil to blend (4 vol.% engine oil + 96 vol.% gasoline) with one of three two-cycle engine oil brands: *CPC Super Low Smoke Two-Stroke Engine Oil* (SLS), *CPC Low Smoke Two-Stroke Engine Oil* (LS), and *MERCURY STAR Two-Stroke Engine Oil* (MS). The emissions of particulate matter (PM), particle-bound carbonaceous species, PAHs (gas-phase + particle-phase) and gaseous pollutants, and even fuel consumption (FC) and engine power were measured at various engine loads (speeds).

## MATERIALS AND METHODS

### *Two-stroke Gasoline Engine, Test Fuels and Sampling Procedures*

This study selected as the test object a small portable gasoline-powered sprayer (KAWAGOE, Model: C12E), equipped with a single-cylinder, naturally aspirated, and air-cooled two-stroke gasoline engine (Model: G45H; manufactured by Chaang Cherng Co., Ltd., TAIWAN); the cylinder displacement is 41.5 c.c., and the maximum horsepower is 2.2 ps. The base oil—unleaded gasoline #92 used in this investigation was purchased from CPC (Chinese Petroleum Corporation) in Taiwan. Three 2-stroke engine oils were used: *CPC Super Low Smoke Two-Stroke Engine Oil* (SLS), *CPC Low Smoke Two-Stroke Engine Oil* (LS), and *MERCURY STAR Two-Stroke Engine Oil* (MS). Table 1 shows the properties of these 2-stroke engine oils.

The flue sampling equipment adopted in this work referred to U.S. EPA Method 5. Before starting the sampling, the exhaust gas flow velocity of the engine was measured using an S-type Pitot tube. After converting the flow rate, a constant flow sampling system equipped with a 47 mm dia. quartz fiber filter (Pallflex Tissuquartz 2500QAT-UP) was installed downstream of the P2SGE's exhaust to gather the particle-phase samples. Gas-phase PAH samples were collected by two connected cartridges, each of which was packed with around

**Table 1.** The characteristics of 2-stroke engine oils.

Test Item	Unit	2-stroke engine oils			Method
		SLS	LS	MS	
Kinematic Viscosity @40°C	cSt	52.73	48.46	62.47	ASTM D445-17a
Kinematic Viscosity @100°C	cSt	8.20	7.83	8.90	ASTM D445-17a
Viscosity Index	–	127	129	118	ASTM D2270-10(2016)
Specific Gravity @15.6°C	–	0.8645	0.8680	0.8682	ASTM D4052-18a
Sulfate Ash	wt%	0.13	0.15	0.01	ASTM D874-13a(2018)
Total Acid Number	mg KOH g <sup>-1</sup>	0.43	0.46	0.22	ASTM D664A-18
Total Base Number	mg KOH g <sup>-1</sup>	2.7	2.8	0.46	ASTM D2896B-15
Carobn Residue, Rams	wt%	0.28	0.27	0.05	ASTM D524-15
Flash Point	°C	94	98	136	ASTM D92-18
Pour Point	°C	-27	-15	-24	ASTM D97-17b

–: Unavailable.

30–35 g of XAD-2 resin, supported by two polyurethane foam (PUF) plugs. Tests of particle and PAH emissions were performed at rotating speeds of 3,800 rpm (idling), 5,000 rpm, and 7,000 rpm of the P2SGE fed with three fuel types. For each combination of parameters, the experiments were performed three times (each sampling time = 15 min). Sampling data were accumulated after the engine had been run for at least 10 min.

The quartz filters were pretreated before sampling by heating them in a muffle furnace in air for 2.5 h at 900°C. The filters were dried for 24 h in a desiccator at  $25 \pm 1^\circ\text{C}$  temperature and  $40 \pm 5\%$  relative humidity before and after each sampling. They were then weighed on an electronic seven-digit balance (UMX2, Mettler Toledo) with a resolution of 0.1  $\mu\text{g}$ .

### HC, CO, and NO<sub>x</sub> Emissions Analysis

A portable gaseous pollutant analyzer (E8500 Plus; E Instruments, USA) was applied to monitor online hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NO<sub>x</sub>) emissions in the exhaust tailpipe. The E8500 Plus measured NO<sub>x</sub> concentrations using an electrochemical detector with a concentration range of 0–5,000 ppm (1 ppm resolution and 4% relative accuracy), while HC and CO were measured by a non-dispersive infrared (NDIR) analyzer with concentration ranges 0–3 vol.% (0.01% resolution and 3% relative accuracy) and 0–15 vol.% (0.01% resolution and 3% relative accuracy), respectively.

### Carbonaceous Component Analysis

The contents of particle-bound carbonaceous matters collected by the quartz filters were analyzed by a CHN-O-Rapid elemental analyzer (Model: 2400, Perkin Elmer Company, USA). Acetanilide (N = 10.36%, C = 71.09%, H = 6.71%, O = 11.80%) was adopted as the standard to prepare the calibration curve. Analysis conditions consisted of heating for 1.5 min with an oxidation tube temperature of 950°C and a reduction tube temperature of 600°C. An NDIR detector was utilized to detect the CO<sub>2</sub> content carried by helium after heat treatment. Finally, data were processed and the carbon content of a sample was obtained. However, organic carbon (OC) was not directly obtained by the EA. Therefore, one quarter of each filter was heated in an oven at 350°C for 100 min to eliminate the OC content, and was then placed in the elemental analyzer to determine the elemental carbon (EC) content; another quarter of each filter was then fed directly into the elemental analyzer without pre-treatment to measure the total carbon (TC) content. Accordingly, OC was then determined by subtracting EC from TC:  $\text{OC} = \text{TC} - \text{EC}$ .

### PAH Analysis

The gas-/particle-phase PAH samples accumulated from the P2SGE exhausts were extracted using 1:1 (volume ratio) *n*-hexane/dichloromethane for 24 hr. The extracts were then concentrated, cleaned by a silica column of ~27 cm silica gel particles (size range = 0.04–0.063 mm) under a layer of anhydrous Na<sub>2</sub>SO<sub>4</sub> (~1 cm high) and above a support of glass fibers, and re-concentrated by purging with ultra-pure

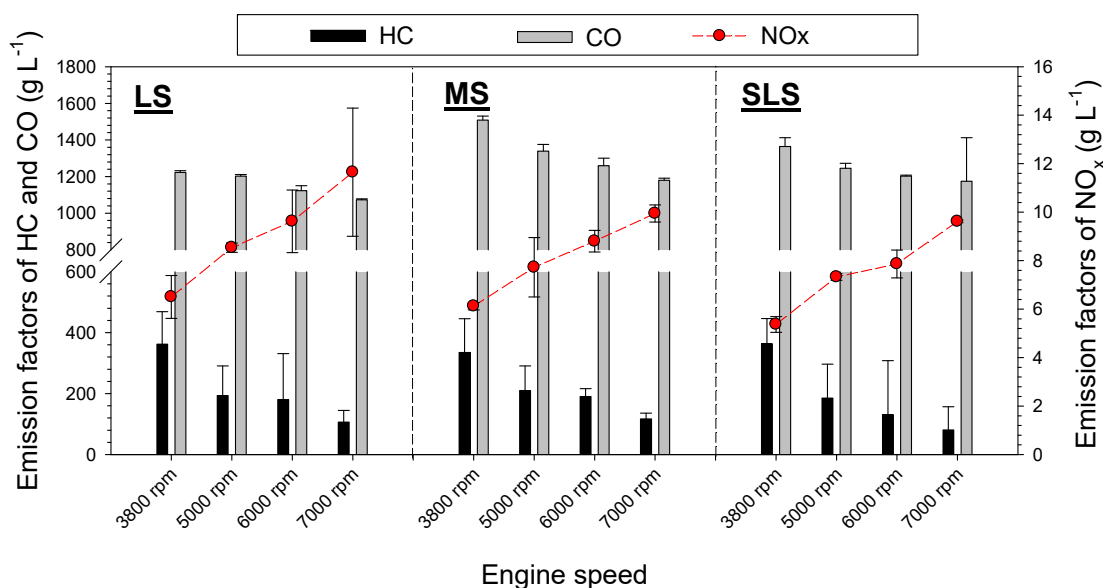
nitrogen to exactly 1.0 mL for the subsequent identification of 16 PAHs by a gas chromatograph/mass selective detector (GC/MSD; model: GC 6890N/HP 5973). The GC/MSD, equipped with a capillary column (HP Ultra 2; 50 m × 0.32 mm × 0.17  $\mu\text{m}$ ) and an automatic sampler (HP-7683), was run under the following conditions; injection volume, 1  $\mu\text{L}$ ; splitless injection temperature, 310°C and ion source temperature, 310°C. The oven temperature increased from 50°C to 100°C at 20°C per min, and then from 100°C to 290°C at 3°C per min; the final temperature, 290°C, was maintained for 40 min. The limits of detection (LODs) for the 16 PAH compounds were 0.023–0.106 ng, and the recovery efficiencies were 83.9–92.6% (average = 86.4%). Additional analysis parameters and procedures of GC/MSD can be found elsewhere (Lin et al., 2017).

The 16 PAHs compounds were divided into three categories based on their molecular weights as low molecular weight (LMW), medium molecular weight (MMW), and high molecular weight (HMW). The LMW-PAHs were naphthalene (Nap), acenaphthylene (AcPy), acenaphthene (Acp), fluorine (Flu), phenanthrene (PA), and anthracene (Ant), while the MMW-PAHs were fluoranthene (FL), pyrene (Pyr), benzo[a]anthracene (BaA), and chrysene (CHR). The HMW-PAHs were benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo(a)pyrene (BaP), dibenzo[a,h]anthracene (DBA), indeno[1,2,3-cd]pyrene (IND), and benzo[ghi]perylene (Bghip). The carcinogenic factors of the identified PAHs were determined in terms of BaP<sub>eq</sub>, from the toxic equivalence factors (TEFs) of these compounds (PAH concentration × TEF). This study utilized the TEFs were specified by Nisbet and LaGoy (1992). The carcinogenic potency of Total-PAHs (Total-BaP<sub>eq</sub>) was evaluated by summing the BaP<sub>eq</sub> concentrations of individual PAH compounds.

## RESULTS AND DISCUSSION

### Emission Factors of HC, CO, and NO<sub>x</sub>

The tested fuels were first prepared by adding 4% of three 2-stroke engine oils (LS, MS, and SLS) to each respective sample of 92-gasoline. A P2SGE was operated at 3,800 rpm (idling), 5,000 rpm, 6,000 rpm, and 7,000 rpm to investigate the emission factors (EFs) based on the fuel consumption ( $\text{g L}^{-1}$ ) of HC, CO, and NO<sub>x</sub> by using various fuels (as displayed in Fig. 1). Experimental results show that the HC and CO EFs decreased with increasing engine speed, while NO<sub>x</sub> EFs exhibited the opposite trend. Generally, HC and CO are the products of incomplete combustion from hydrocarbon. HC was formed from the quenching zone near the cool inner wall of the cylinder during combustion. The lower temperature condition reinforced this phenomenon, but inhibited the NO<sub>x</sub> emission. The P2SGE exhaust temperatures were  $40.9 \pm 0.67$ ,  $52.3 \pm 0.95$ ,  $72.6 \pm 2.89$ , and  $92.4 \pm 3.04^\circ\text{C}$ , when operated at 3,800 rpm, 5,000 rpm, 6,000 rpm, and 7,000 rpm, respectively. Thus, the idling condition had the lowest temperature, indicating the most incomplete combustion among the tests, and leading to higher EFs of HC and CO and lower EFs of NO<sub>x</sub>. The data in Fig. 1 indicate that, at various speeds except for idling condition, the additions of 4% LS



**Fig. 1.** Emission factors of HC, CO, and NO<sub>x</sub> from a P2SGE by using SLS, LS, and MS operated at various loads.

and SLS could reduce HC emissions by 16% (on average) compared with adding MS, while the average reduction rate of CO emissions was 8.8%. Additionally, using SLS additive lowered NO<sub>x</sub> emissions by 7.9% (on average). The above phenomenon could result from the different physical and chemical properties of the 2-stroke engine oils used in gasoline.

#### **Performance of Engine Power and Fuel Consumption**

Table 2 presents the fuel consumption (FC) and specific fuel consumption (SFC) of P2SGE using 4 vol.% of LS, MS, and SLS lubricants in 92-gasoline. In these tests, the LS additive showed the best power output, followed by SLS at 5,000 rpm, while the SLS additive provided the highest P2SGE output power at 7,000 rpm. Use of SLS and LS increased the engine power from using MS by 3.3% and 3.5%, respectively. The three lubricants applied in the current study did not have significant effect on FC or SFC of P2SGE at the same speed, while the consumption of fuels (FC and SFC) all increased with an increase in engine speed. Additionally, the power output was 0 kWh, 1.46–1.52 kWh, and 1.85–1.91 kWh, while the P2SGE was operated at 3,800 rpm, 5,000 rpm, and 7,000 rpm, respectively. Therefore, the following discussion focuses on the variation of pollutant emissions at idling (0 kW), medium load (~1.5 kW), and high load (~1.9 kW).

#### **PM Concentrations and Emission Factors in the Exhaust**

The PM concentrations and emission factors (EFs) of PM in terms of unit fuel consumption (EF<sub>FC</sub>) and output energy (EF<sub>energy</sub>) from the exhaust of P2SGE operated at idling (0 kW), medium load (~1.5 kW), and high load (~1.9 kW) when using 4 vol.% of SLS, LS, or MS as the additive in 92-gasoline are shown in Figs. 2 and 3. According to Fig. 2, the PM emission decreased with increasing engine load when using all lubricants, while the addition of 4 vol.% LS led to the lowest PM emission concentration. Thus, the idling operation

had the highest PM emission level, followed by medium-load (5,000 rpm) and high-load conditions (7,000 rpm). This result might be caused by the higher combustion temperature at high load ( $92.4 \pm 3.04^\circ\text{C}$ ) than at medium load ( $52.3 \pm 0.95^\circ\text{C}$ ) and idling ( $40.9 \pm 0.67^\circ\text{C}$ ) operation, which provided more complete combustion of fuels, thus reducing the formation of PM. Compared with 4% MS additive, the LS addition could reduce the mass concentrations, EF<sub>FC</sub>, and EF<sub>energy</sub> of PM by 25.4–42.2% (average 35.1%), 21.7–42.3% (32.6% in average), and 25.0–37.2% (31.1% in average), respectively, under all tested loads (as shown in Fig. 3). This could result from MS having a significantly lower flash point ( $136^\circ\text{C}$ ) than the others (Table 1), since a higher flash point leads to lower vaporization ability at the early stage of combustion. The lower vaporization speed from using MS could lead to less complete combustion, and caused higher PM emissions than using other lubricants.

Ålander *et al.* (2005) focused on the effects of particle emissions from a small two-stroke gasoline engine using various fuels, lubricants and catalytic converters. The untreated emission from the test engine fueled with alkylate fuel-biodegradable oil had a higher PM emission factor ( $3.42 \pm 0.15 \text{ g kWh}^{-1}$ ) and 19–50% lower PM ( $1.72 \pm 0.11 \text{ g kWh}^{-1}$ ) when adopting a catalytic converter. The average overall PM emission factor was  $2.59 \text{ g kWh}^{-1}$ , which was only about 1% of those found in the current study ( $35.9\text{--}57.2 \text{ g kWh}^{-1}$ , avg.  $43.3 \text{ g kWh}^{-1}$ ).

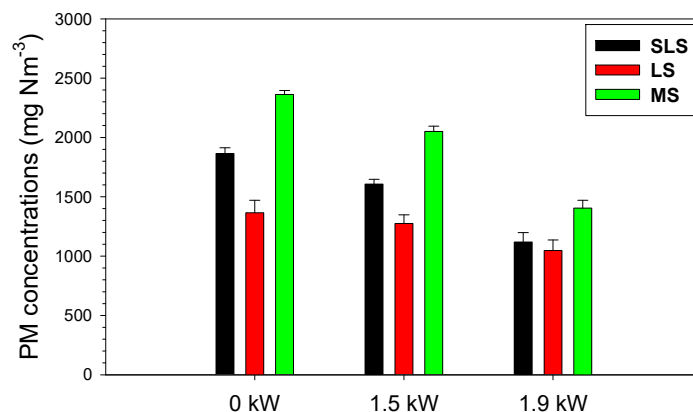
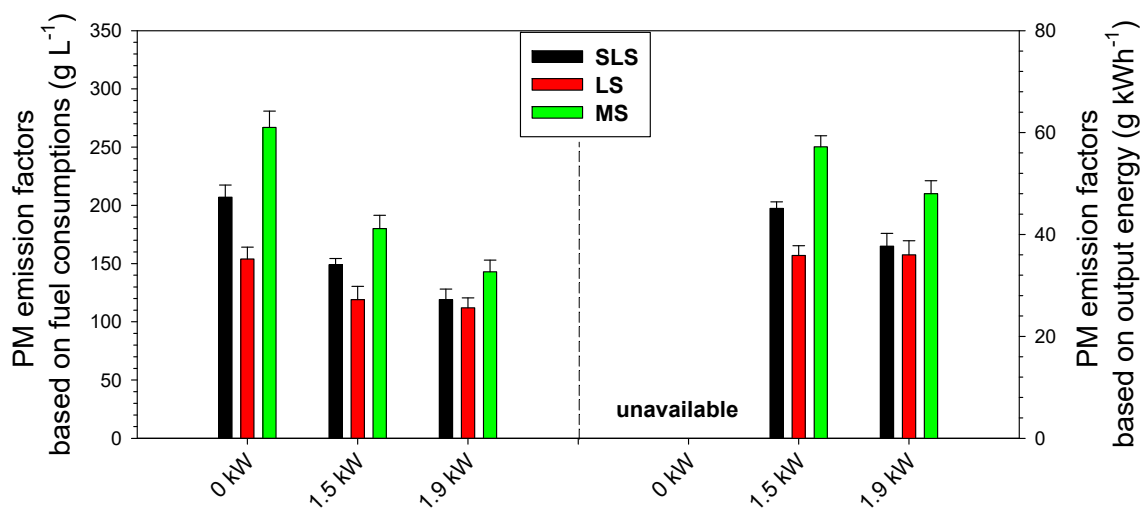
#### **Concentrations and Emission Factors of PM-bound Carbonaceous Species**

Table 3 lists the mass concentrations and emission factors of PM-bound carbonaceous species (TC, EC and OC) from the exhaust of P2SGE using 4 vol.% of LS, MS, and SLS lubricants in 92-gasoline. Increasing P2SGE load reduced the TC and OC emission concentrations regardless of the lubricant used. The maximum EC concentration occurred at medium load, followed by the idling and high-load operations.

**Table 2.** The performance of engine power, fuel consumption, and specific fuel consumption.

Engine speed (rpm)	Engine Power (kWh) (N = 15)			FC (L hr <sup>-1</sup> ) (N = 6)			SFC (L kWh <sup>-1</sup> ) (N = 6)		
	SLS	LS	MS	SLS	LS	MS	SLS	LS	MS
3800 rpm (idling)	0.00	0.00	0.00	0.288 (± 0.008)	0.290 (± 0.011)	0.293 (± 0.010)	–	–	–
5000 rpm	1.50 (± 0.03)	1.52 (± 0.03)	1.46 (± 0.03)	0.455 (± 0.012)	0.460 (± 0.040)	0.463 (± 0.015)	0.303 (± 0.008)	0.303 (± 0.026)	0.318 (± 0.010)
7000 rpm	1.91 (± 0.05)	1.90 (0.04)	1.85 (± 0.03)	0.608 (± 0.010)	0.613 (± 0.016)	0.618 (± 0.020)	0.318 (± 0.005)	0.323 (± 0.009)	0.335 (± 0.011)

–: Unavailable.

**Fig. 2.** Mass concentrations of PM emitted from a P2SGE by using SLS, LS, and MS operated at various loads.**Fig. 3.** Emission factors of PM from a P2SGE by using SLS, LS, and MS operated at various loads.

Among the tested lubricants, the LS had the lowest PM-carbonaceous species emissions, while the MS had the maximum emissions at all engine loads. The application of LS provided 13.1%, 14.7%, and 17.1% lower emissions of TC, EC, and OC, respectively, than those of using SLS, except that of EC at high load. Conversely, the MS addition increased 32.8% TC, 39.0% EC, and 24.7% OC emissions in comparison to the SLS addition. Additionally, OC was found to be higher concentrations than EC at idling condition of P2SGE, but an opposite trend was observed at the middle or high load. This finding was associated with the incompletely combusted hydrocarbons at idling operation of the two-

stroke engine (with the lowest exhaust temperature). Moreover, the temperature of emission rose to 50–90°C at 1.5 kW and 1.9 kW loads, indicating more complete combustion in engine cylinder. Irrespective of the use of different 2-stroke oils, the EFs of OC in terms of unit fuel consumption ( $EF_{FC}$ ) and output energy ( $EF_{energy}$ ) were lower than those of EC at medium and high loads, while the opposite trend ( $OC > EC$ ) was observed at idling operation. Additionally, emissions of carbonaceous  $EF_{FC}$  and  $EF_{energy}$  were lowest when utilizing the LS additive, followed by the SLS and MS, at all three engine loads. Compared to SLS additive, the  $EF_{FC}$  reductions of TC, EC, and OC for using 4 vol.% LS additive under the three

**Table 3.** Mass concentrations and emission factors of particle-bound TC, EC, and OC.

	SLS			LS			MS		
	TC	EC	OC	TC	EC	OC	TC	EC	OC
<b>Mass concentrations (<math>mg\ Nm^{-3}</math>) (<math>N = 3</math>)</b>									
0 kW (idling)	1566	655	912	1235	547	689	2090	867	1223
	( $\pm 46.3$ )	( $\pm 42.5$ )	( $\pm 57.0$ )	( $\pm 66.7$ )	( $\pm 92.1$ )	( $\pm 25.8$ )	( $\pm 33.5$ )	( $\pm 31.0$ )	( $\pm 23.4$ )
1.5 kW	1333	726	608	1110	633	477	1753	1031	723
(medium load)	( $\pm 60.4$ )	( $\pm 32.1$ )	( $\pm 36.3$ )	( $\pm 61.3$ )	( $\pm 16.5$ )	( $\pm 55.8$ )	( $\pm 38.1$ )	( $\pm 57.9$ )	( $\pm 91.7$ )
1.9 kW	913	526	386	901	535	366	1217	750	467
(high load)	( $\pm 74.0$ )	( $\pm 23.0$ )	( $\pm 49.6$ )	( $\pm 62.7$ )	( $\pm 44.8$ )	( $\pm 23.1$ )	( $\pm 52.4$ )	( $\pm 25.2$ )	( $\pm 55.6$ )
<b>Emission factors</b>									
<b>Based on fuel consumptions (<math>g\ L^{-1}</math>) (<math>N = 3</math>)</b>									
0 kW (idling)	0.171	0.071	0.100	0.138	0.061	0.077	0.242	0.101	0.142
	( $\pm 0.011$ )	( $\pm 0.002$ )	( $\pm 0.011$ )	( $\pm 0.005$ )	( $\pm 0.009$ )	( $\pm 0.005$ )	( $\pm 0.006$ )	( $\pm 0.002$ )	( $\pm 0.006$ )
1.5 kW	0.125	0.068	0.057	0.106	0.060	0.045	0.146	0.086	0.060
(medium load)	( $\pm 0.008$ )	( $\pm 0.004$ )	( $\pm 0.004$ )	( $\pm 0.004$ )	( $\pm 0.003$ )	( $\pm 0.004$ )	( $\pm 0.004$ )	( $\pm 0.004$ )	( $\pm 0.008$ )
1.9 kW	0.097	0.056	0.041	0.094	0.056	0.038	0.121	0.074	0.046
(high load)	( $\pm 0.008$ )	( $\pm 0.003$ )	( $\pm 0.005$ )	( $\pm 0.009$ )	( $\pm 0.006$ )	( $\pm 0.003$ )	( $\pm 0.006$ )	( $\pm 0.002$ )	( $\pm 0.006$ )
<b>Based on output energy (<math>g\ kWh^{-1}</math>) (<math>N=3</math>)</b>									
0 kW (idling)	–	–	–	–	–	–	–	–	–
1.5 kW	37.2	20.3	17.0	31.2	17.8	13.4	47.4	27.9	19.5
(medium load)	( $\pm 1.37$ )	( $\pm 0.90$ )	( $\pm 0.76$ )	( $\pm 1.60$ )	( $\pm 0.44$ )	( $\pm 1.52$ )	( $\pm 0.92$ )	( $\pm 2.06$ )	( $\pm 2.22$ )
1.9 kW	30.7	17.7	13.0	30.7	18.2	12.5	40.8	25.1	15.6
(high load)	( $\pm 2.88$ )	( $\pm 1.19$ )	( $\pm 1.79$ )	( $\pm 2.04$ )	( $\pm 1.49$ )	( $\pm 0.74$ )	( $\pm 1.59$ )	( $\pm 0.94$ )	( $\pm 1.77$ )

–: Unavailable.

engine loads were 12.6%, 12.8%, and 16.7%, respectively, while the  $EF_{energy}$  reduction values were 8.2%, 12.3%, and 12.7%, respectively. In contrast, the use of MS raised the EFs ( $EF_{FC}$  and  $EF_{energy}$ ) of TC, EC, and OC by 16.7–42.0%, 25.6–41.8%, and 5.6–42.6%, respectively, in comparison with using the SLS additive.

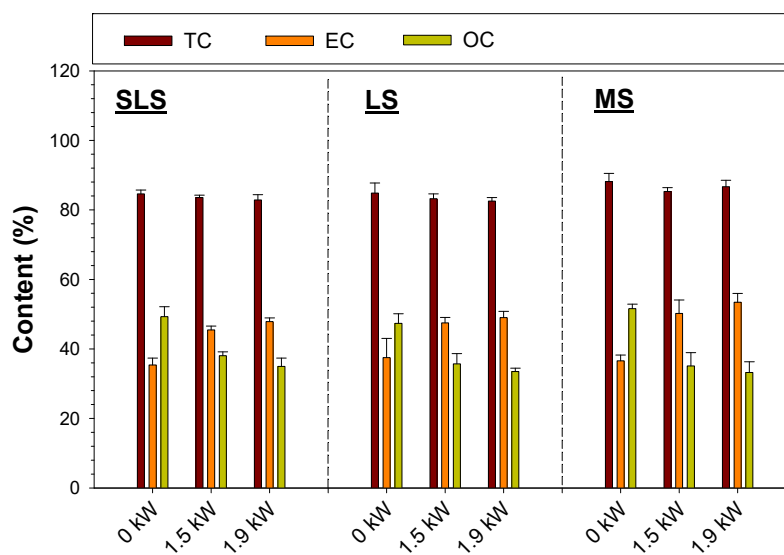
The order of average carbonaceous species contents on PM emitted from the P2SGE using different lubricating oils (as demonstrated in Fig. 4) were: MS (86.7%) > SLS (83.7%) > LS (83.5%) for PM-bound TC; MS (46.7%) > LS (44.7%) > SLS (42.9%) for PM-bound EC; and SLS (40.8%) > MS (40.0%) > LS (38.9%) for PM-bound OC. The PM mass contribution from EC and OC (or  $TC = EC + OC$ ) was 85%, which declined with rising engine operation loads; this finding could strongly affect the combustion temperature and efficiency as stated in previous discussion. Similarly, some researchers have reported that particulate carbonaceous matters account for roughly one or two of third of PM mass in gasoline vehicle exhausts (Hao et al., 2019; Yang et al., 2019).

Zielinska et al. (2004) concluded that about 60% of PM-bound TC were provided from OC mass ( $EC/TC = 0.4$ ). Ålander et al. (2005) found that PM-bound TC contributed about 80% of mass of PM in the exhaust of a two-stroke gasoline engine (chainsaw), while PM-bound TC comprised almost entirely OC ( $EC/TC$  comprised only 1–6%). Our finding that EC and OC contributed about 85% of PM weight is very similar to the aforementioned results. However, our finding that the PM-bound EC emissions increased with rising engine loads was different from those found in the references. The EC was emitted from the pyrolysis of oil droplets, while the OC content was mainly formed by the

unburned fuel oil and lubricants (Abdul-Khalek et al., 1998). Additionally, EC and OC emission could be also affected by factors such as engine type, fuel property, and combustion control.

#### **PAH Mass and $BaP_{eq}$ Concentrations and Emission Factors in the Exhaust**

The  $\Sigma PAHs$  (total concentrations of 16 PAHs) or  $\Sigma BaP_{eq}$  concentrations showed a minimum value by using LS, followed by using SLS and MS at medium and high loads (Fig. 5). The use of SLS and LS reduced PAH concentrations by 46.4 and 59.7%, respectively, in comparison to using MS. The  $BaP_{eq}$  concentration was reduced by 54.8 and 49.2%, respectively. The LMW-PAHs, MMW-PAHs, HMW-PAHs,  $\Sigma PAHs$ , and  $\Sigma BaP_{eq}$  concentrations fell with increasing engine load, possibly owing to the higher combustion efficiency and destruction of aromatic structures at higher temperatures. Moreover, LMW-PAHs contributed 51.3–80.7% (71.2% on average) of  $\Sigma PAHs$  concentrations, when MMW-PAHs was secondarily dominated (11.5–29.2%, avg. 17.1%) and followed by HMW-PAHs (6.41–19.5%, avg. 11.7%) by using all kind of lubricants (as shown in Fig. 6). In contrast, the  $\Sigma BaP_{eq}$  concentration was predominated by HMW-PAHs (83.9–91.9%, avg. 86.7%), followed by MMW-PAHs (6.18–13.1%, avg. 10.5%) and LMW-PAHs (1.46–4.36%, avg. 2.78%). Additionally, Nap and PA dominated the PAH mass concentration (40.0% and 14.0%) among 16 investigated homologs, while BaP and BaA mainly contributed the  $BaP_{eq}$  concentrations (69.4% and 10.9%, respectively), except using LS at high-load operation. Yang et al. (2005) reported that the BaP, IND, and DBA were the major components which accounted for 68.9%, 10.9%, and 6.10% of PM-bound



**Fig. 4.** Contents of TC, EC, and OC on PM emitted from a P2SGE by using SLS, LS, and MS operated at various loads.

total-BaP<sub>eq</sub> concentrations, respectively, in the exhaust of a two-stroke motorcycle.

Figs. 7 and 8 illustrate the PAH mass and toxicity emission factors based on the fuel consumption ( $EF_{\text{mass/FC}}$  and  $EF_{\text{toxicity/FC}}$ ) and output energy ( $EF_{\text{mass/energy}}$  and  $EF_{\text{toxicity/energy}}$ ) from the P2SGE in this study. The  $EF_{\text{mass/FC}}$ ,  $EF_{\text{toxicity/FC}}$ ,  $EF_{\text{mass/energy}}$ , and  $EF_{\text{toxicity/energy}}$  (except  $\Sigma$ PAHs  $EF_{\text{mass/energy}}$  using LS) of HMW-PAHs and  $\Sigma$ PAHs decreased when the engine load rose with all the 2-stroke engine oil additives. The  $EF_{\text{mass/FC}}$ ,  $EF_{\text{toxicity/FC}}$ ,  $EF_{\text{mass/energy}}$ , and  $EF_{\text{toxicity/energy}}$  of  $\Sigma$ PAHs for using the lubricants were in the order MS > SLS > LS (except  $EF_{\text{toxicity/FC}}$  at idling operation). Compared to MS, the reductions of  $EF_{\text{mass/FC}}$ ,  $EF_{\text{toxicity/FC}}$ ,  $EF_{\text{mass/energy}}$ , and  $EF_{\text{toxicity/energy}}$  of  $\Sigma$ PAHs by using SLS were 9.5%, 57.1%, 87.6%, and 90.0%, respectively, while the corresponding data were 61.6%, 51.3%, 92.1%, and 91.8%, respectively, for using LS. As we know, the formation mechanisms of PAH during the engine operation comprise: (1) the PAH contents in fuels and lubricating oil; (2) the pyrosynthesis of from unburn hydrocarbon radicals; (3) the cyclization reaction from low-ring to high-ring PAHs or the thermal breakdown from high-ring to low-ring PAHs (Buñuel *et al.*, 2006), and (4) the residual PAHs in the sampling system (Hall *et al.*, 1998). In this work, the LS had the lowest PAH emissions among the three 2-stroke engine oils, which is possibly associated with their different aromatic content.

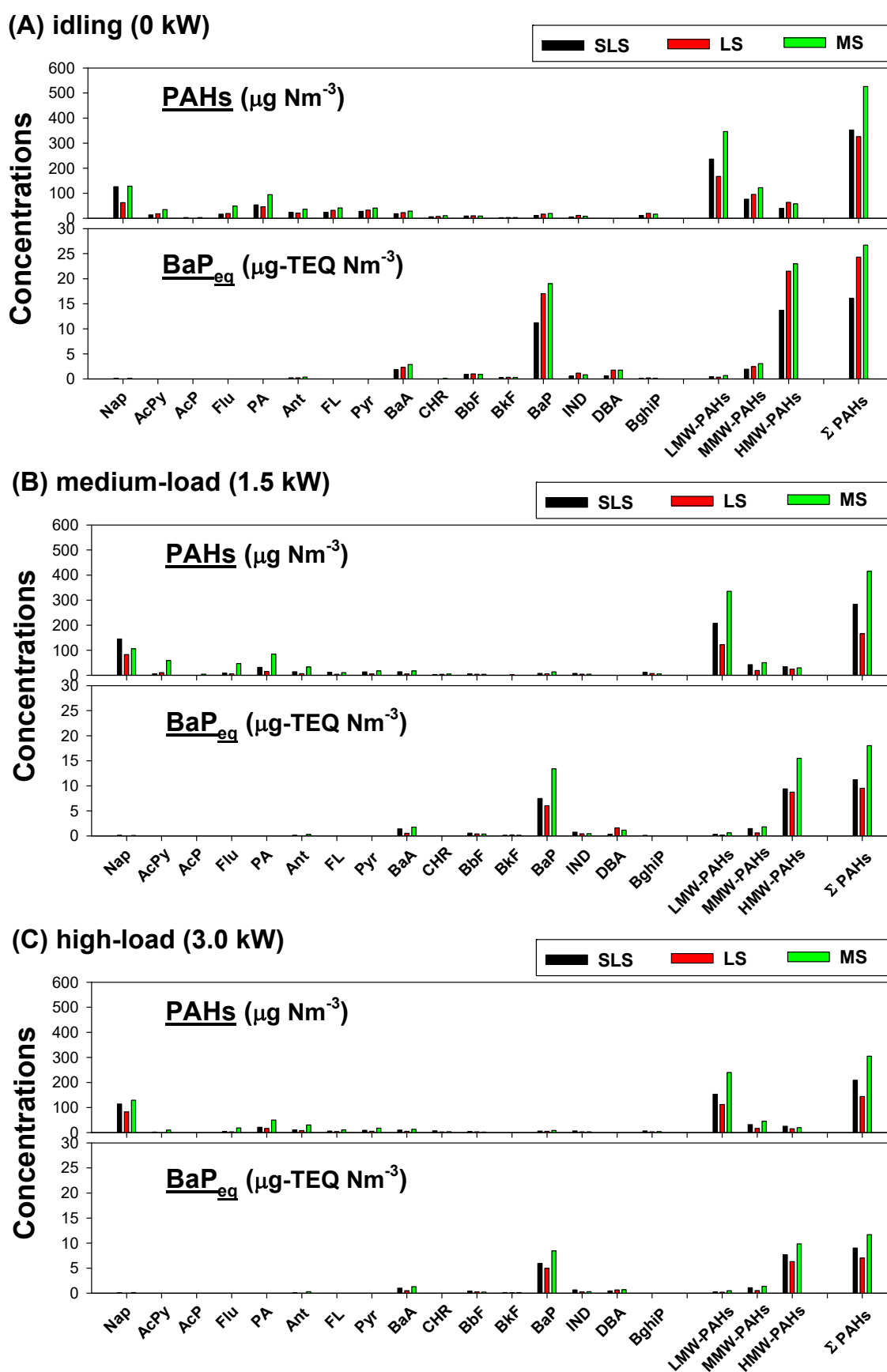
## CONCLUSIONS

This study focuses on the use of different 2-stroke engine oil additives in a P2SGE with operation loads of idling (0 kW), medium-load (1.5 kW), and high-load (3.0 kW). The energy performance, traditional gaseous pollutants, PM, particle-bound carbons, and PAHs in the exhausts were explored. From this framework, the following conclusions can be derived.

- The emission factors of HC and CO decreased with increasing P2SGE load in spite of using different

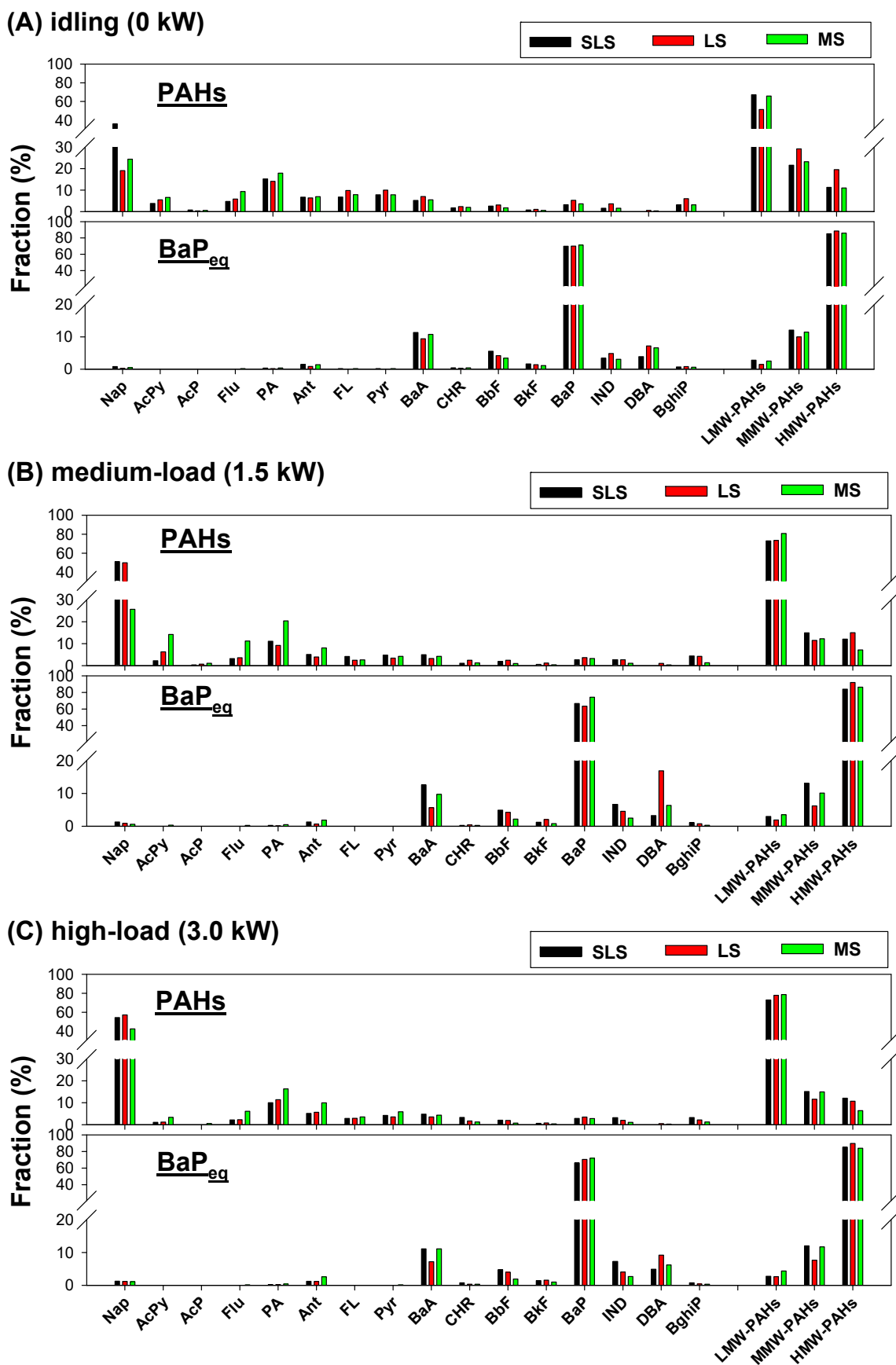
kinds of lubricants added into a two-stroke gasoline engine, but those of NO<sub>x</sub> exhibited the opposite trend. The LS and SLS additives reduced HC CO emissions by 16% and 8.8%, respectively, in comparison to the addition of MS in 92-gasoline at all engine speeds. Using LS increased NO<sub>x</sub> by 10.8% when compared to those of using MS at all engine speeds, while adding SLS into 92-gasoline reduced NO<sub>x</sub> emission by 7.9%.

- Both BSFC and FC increased with an increase in engine speed, but the addition of each tested lubricant did not significantly influence the FC or BSFC of P2SGE at the same speed. The mass concentrations and emission factors of PM followed the order MS > SLS > LS at all loads. The use of MS raised the PM-bound TC, EC, and OC by 32.8%, 39.0%, and 24.7%, respectively, in comparison to using SLS.
- Carbonaceous matters (EC and OC) contributed 85% of the PM mass emitted from the P2SGE in all test conditions. The emission factors based on the FC and output energy were higher for PM-bound OC than for EC at idling condition, while this trend was opposite (OC < EC) at medium (1.5 kW) and high (1.9 kW) engine loads. Additionally, the value of OC and EC decreased with increasing engine operation loads irrespective of the difference in 2-stroke engine oil composition.
- Nap and PA dominated the PAH mass concentration (40.0% and 14.0%, respectively) among 16 investigated homologs, while BaP and BaA mainly contributed the BaP<sub>eq</sub> concentrations (69.4% and 10.9%, respectively), except using LS at high-load operation. Compared to using MS, the reductions of  $\Sigma$ PAHs and  $\Sigma$ BaP<sub>eq</sub> concentrations by using SLS were 46.4% and 54.8%, respectively, while the reductions by using LS were 59.7% and 49.2%, respectively.
- Overall, the LS additive generated the lowest PM, PM-bound carbons,  $\Sigma$ PAHs, and  $\Sigma$ BaP<sub>eq</sub> emissions at almost all test conditions.

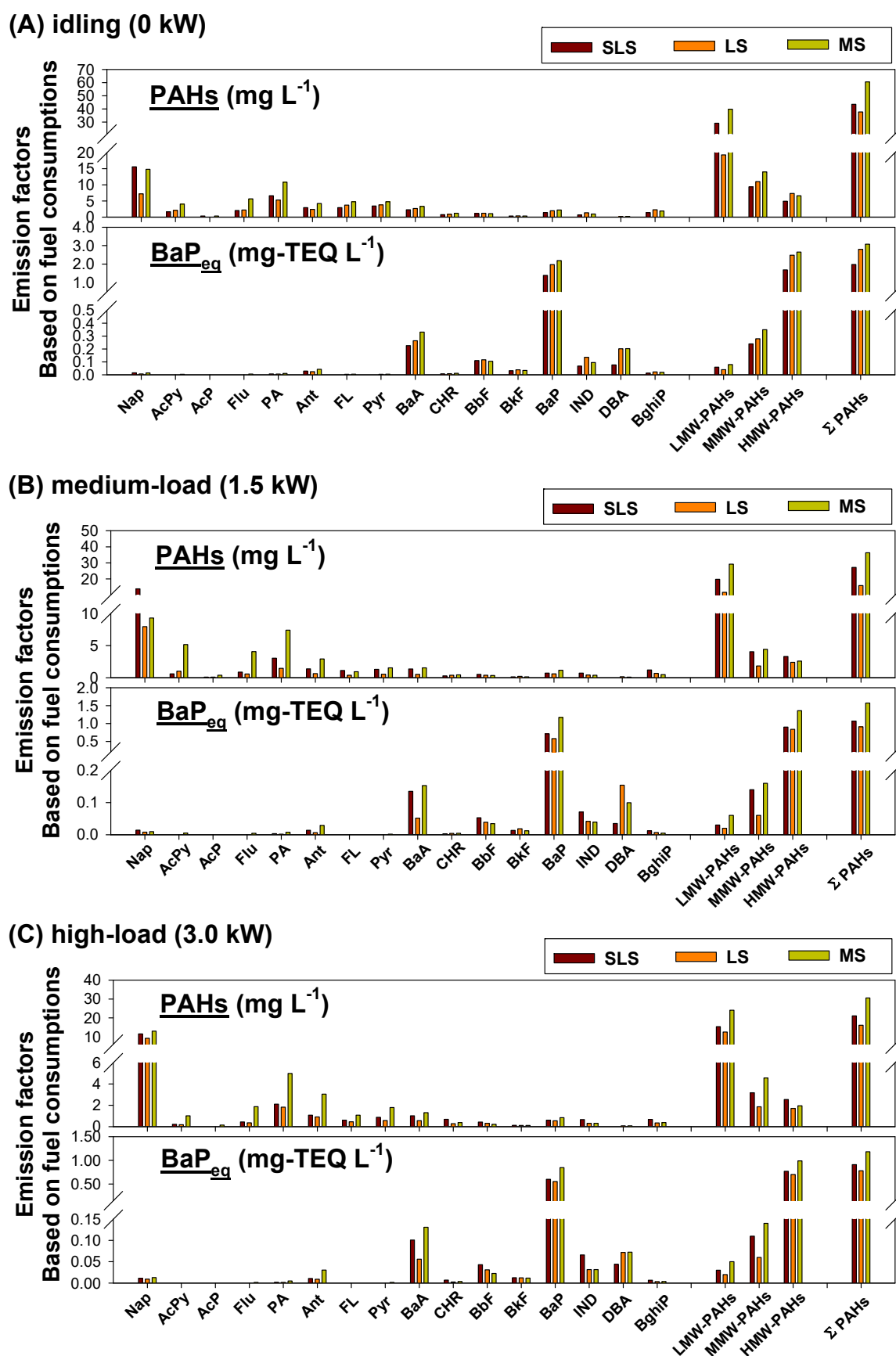


**Fig. 5.** Concentrations of PAH and BaP<sub>eq</sub> congeners emitted from a P2SGE by using SLS, LS, and MS operated at (A) idling (0 kW), (B) medium-load (1.5 kW), and (C) high-load (3.0 kW).



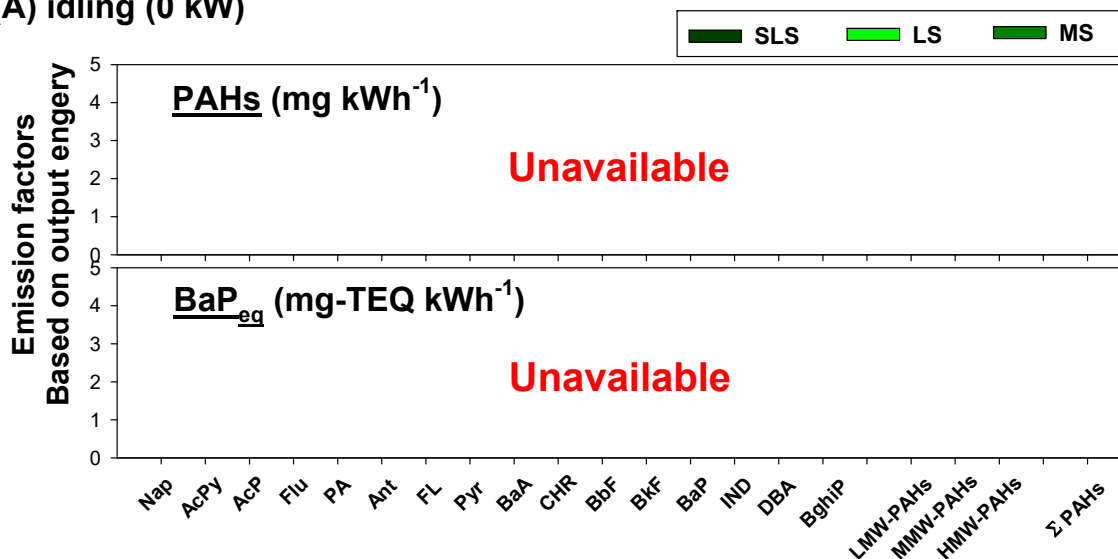


**Fig. 6.** Fractions of PAH and BaP<sub>eq</sub> congeners emitted from a P2SGE by using SLS, LS, and MS operated at (A) idling (0 kW), (B) medium-load (1.5 kW), and (C) high-load (3.0 kW).

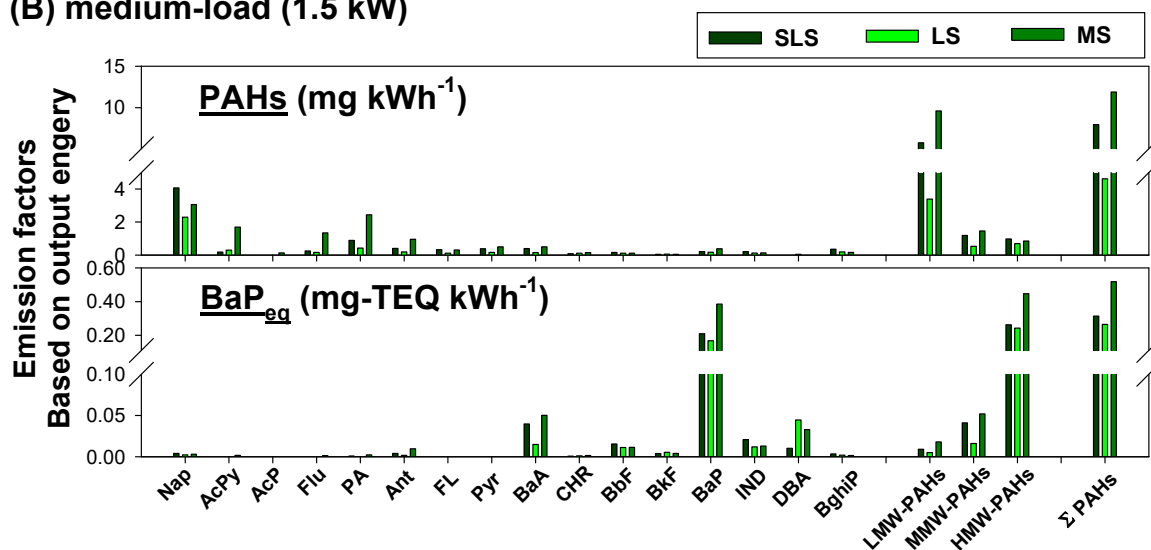


**Fig. 7.** Emission factors of PAH and BaP<sub>eq</sub> congeners based on fuel consumptions emitted from a P2SGE by using SLS, LS, and MS operated at (A) idling (0 kW), (B) medium-load (1.5 kW), and (C) high-load (3.0 kW).

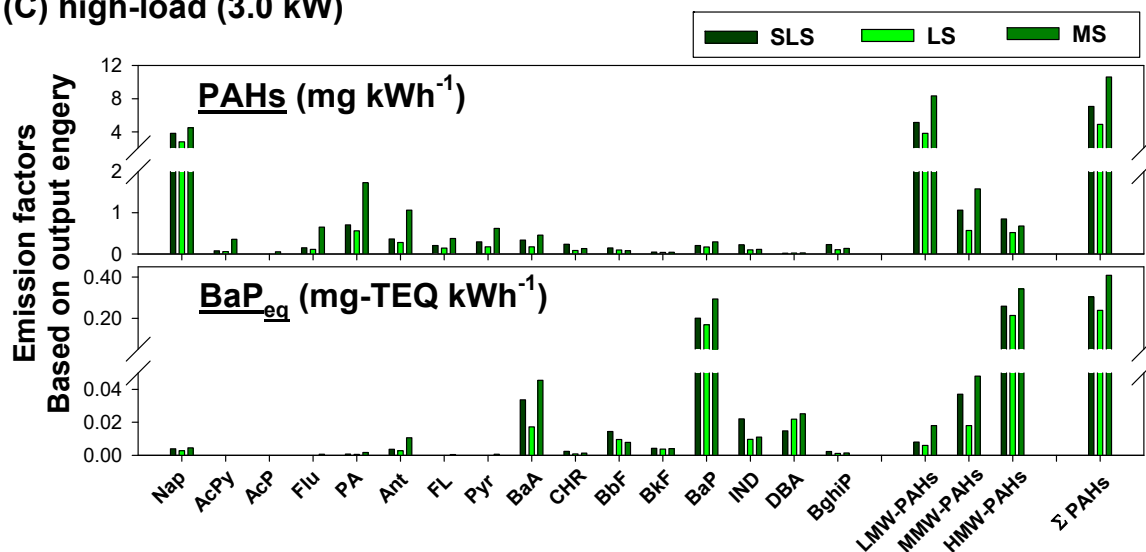
## (A) idling (0 kW)



## (B) medium-load (1.5 kW)



## (C) high-load (3.0 kW)



**Fig. 8.** Emission factors of PAH and BaP<sub>eq</sub> congeners based on output power emitted from a P2SGE by using SLS, LS, and MS operated at (A) idling (0 kW), (B) medium-load (1.5 kW), and (C) high-load (3.0 kW).

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