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Emissions in the exhaust of fishing boats after adding viscous agents into fuel oils

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ABSTRACT

In order to avoid the illegal use of fishing boat fuel A (FBFA) by traveling diesel vehicles (TDVs) in Taiwan, alternatives that are easily distinguished from premium diesel fuel (PDF) were prepared to evaluate their suitability. Two new ingredients, pyrolysis fuel oil (PFO) and residue of desulfurization unit (RDS), were added into FBFA and formed PFO0.5 and RDS0.5, respectively. Along with FBFA, these three fuels were analyzed for their chemical and physical properties. Furthermore, they were used by three fishing boats with different sizes, output powers, and weights. The engine performances and pollutant emissions were examined and monitored. Experimental results show that there are significant differences in appearance between PDF and the two new blended fuels (PFO0.5 and RDS0.5), and thus misuse or illegal use of FBFA could be substantially reduced. The fuel consumption, which is negatively related to the heating value of fuels, is in order of FBFA < PFO0.5 = RDS0.5. In contrast with using FBFA in the three fishing boats, using RDS0.5 resulted in a decrease in CO and NO_x emissions, while the PM emission factors (g bhp⁻¹ h⁻¹ and g L⁻¹-fuel) were reduced by approximately 36% and 33%, respectively. Owing to the higher total aromatic content in PFO0.5 and RDS0.5, total-PAH concentrations in the exhausts from the three fishing boats using PFO0.5 and RDS0.5 were slightly (1.2 and 1.1 times, respectively) higher than for those using FBFA. Nevertheless, the estimated total BaP_{eq} from the three fishing boats using RDS0.5 was 27.5, 19.5, and 8.25% lower than those using FBFA. With using PFO0.5, they were totally different, at 23.5, 2.79, and 2.58% higher. With regard to looking different to PDF, RDS0.5 is superior to PFO0.5, and is thus recommended as a better alternative to FBFA, particularly because it can help lower more emissions of CO, NO_x, PM and BaP_{eq}.

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1. Introduction

Ships play very important roles in communication and transportation systems worldwide, but have also been reported as significant air pollution sources over the past decade (Cooper, 2003). Corbett et al. (1998) estimated that ships contribute up to 14% of all nitrogen emissions and up to 4% of all sulfur emissions from fossil fuel combustion. Moreover, they are the greatest combustion pollution sources per volume (or mass) of fuel consumed (Corbett et al., 1998). In addition, the emission of nitrogen oxide (NO_x) from ships also increases ozone (O₃) and the hydroxyl radical (OH) concentrations in the troposphere over their background levels, thereby increasing the oxidizing potential of the troposphere, decreasing the atmospheric lifetimes of reactive greenhouse gases, and increasing aerosol production rates (Lawrence and Crutzen, 1999). The sulfur oxide (SO_x) emissions from ships with diesel engines also pollute the

atmosphere, and the accumulation of sulfates may cause acidification and acid rain, resulting in harm to agriculture, ecology, and even human health (Lin and Lin, 2006). Some of the SO_x and NO_x emissions may transform into secondary aerosols (e.g. particulate matter, PM), which mostly will deposit tens to hundreds of km from where they were emitted (Fagerli and Tarrason, 2001). In addition to the commonly regulated air pollutants, there are several toxicants that may be produced by operating engines. Cooper (2005) indicated that the toxic equivalence (WHO-TEQ) of polychlorinated dibenzo-*p*-dioxins and dibenzofuran (PCDD/F) emissions from ships using Swedish fuels were relatively small (1–2%) in comparison to recent estimates for the national total. Similarly, the HCB (hexachlorobenzene) and PCB (polychlorinated biphenyl) emissions for 2002 were also small compared to the estimated Swedish national totals in 1995 (Cooper, 2005). Barfknecht (1983) also indicated that the total-PAH emission factor of diesel engines was 10 times higher than that of gasoline engines in U.S.A.

The price of fishing boat fuel A (FBFA) is lower than that of premium diesel fuel (PDF), which leads to the illegal use of FBFA by

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T1.1	Nomenclature	
T1.2	AST	Automatic stack sampler
T1.3	ASTM	American Society for Testing and Materials
T1.4	BaP _{eq}	The toxicity equivalence of PAHs
T1.5	CO	Carbon monoxide
T1.6	CO ₂	Carbon dioxide
T1.7	CFCs	Chlorofluorocarbons
T1.8	CPC	Chinese Petroleum Corporation
T1.9	DL	Detection limit
T1.10	ECD	Electro-chemical detector
T1.11	EF _{CO}	Emission factor of CO, grams of CO per brake horse power per hour
T1.12	EF _{CO₂}	Emission factor of CO ₂ , grams of CO ₂ per brake horse power per hour
T1.13	EF _{PM-bhp h}	Emission factor of PM, grams of PM per brake horse power per hour
T1.14	EF _{PM-l fuel}	Emission factor of PM, grams of PM per liter fuel
T1.15	FBFA	Fishing boat fuel A
T1.16	GC	Gas chromatography
T1.17	HCB	Hexachlorobenzene
T1.18	HDDEs	Heavy-duty diesel engines
T1.19	LOQ	Limit of quantification
T1.20	MSD	Mass spectrometer detector
T1.21	NDIR	Non-dispersive infrared
T1.22	NO _x	Nitrous oxides, NO and NO ₂
T1.23	·OH	Hydroxyl radical
T1.24	PAHs	Polycyclic aromatic hydrocarbons
T1.25	Acp	Acenaphthene
T1.26	AcPy	Acenaphthylene
T1.27	Ant	Anthracene
T1.28	BaA	Benzo[a]anthracene
T1.29	B[a]P	Benzo(a)pyrene
T1.30	BbC	Benzo[b]chrycene
T1.31	BbF	Benzo[b]fluoranthene
T1.32	BeP	Benzo[e]pyrene
T1.33	Bghip	Benzo[ghi]perylene
T1.34	BkF	Benzo[k]fluoranthene
T1.35	CHR	Chrysene
T1.36	COR	Coronene
T1.37	CYC	Cyclopenta[c,d]pyrene
T1.38	DBA	Dibenzo[a,h]anthracene
T1.39	FL	Fluoranthene
T1.40	Flu	Fluorine
T1.41	IND	Indeno[1,2,3-cd]pyrene
T1.42	Nap	Naphthalene
T1.43	PA	Phenanthrene
T1.44	PER	Perylene
T1.45	Pyr	Pyrene
T1.46	PCDD/Fs	Polychlorinated dibenzo-p-dioxins and dibenzofurans
T1.47	PCB	Polychlorinated biphenyl
T1.48	PDF	Premium diesel fuel
T1.49	PFO	Pyrolysis fuel oil
T1.50	PFO0.5	FBFA blended with 0.5% (v/v) pyrolysis fuel oil
T1.51	PM	Particulate matter
T1.52	PUF	Polyurethane foam
T1.53	RDS	Residue of desulfurization unit
T1.54	RDS0.5	FBFA blended with 0.5% (v/v) residue of desulfurization unit
T1.55	RSD	Relative standard deviation
T1.56	SIM	Selective ion monitoring
T1.57	SO _x	SO ₂ and SO ₃
T1.58	T90	Distillation temperature when 90% fuel has been distilled

TDVs Traveling diesel vehicles
VOCs Volatile organic compounds

traveling diesel vehicles (TDVs) with heavy-duty diesel engines (HDDEs) in Taiwan (Lin et al., 2006). According to statistics from Taiwan's government, during 1988–2007 (Fig. 1) the power per fishing boat (hp boat⁻¹) increased, while the carrying capacity per boat (tonne boat⁻¹) decreased. Consequently, there was an increase in fishing boat power per carrying capacity (hp tonne⁻¹), and this led to more FBFA being used illegally (http://www.faa.gov.tw/chnn/statistics_publish/statistics/year_book/2007c/96tab5_1.xls).

Heavy-duty diesel engine (HDDE) tests are conducted according to the US HDD Transient Cycle. The engine performance and pollutant emissions are simulated for when heavy-duty diesel vehicles are in cold start, hot start, and other specified conditions. Recently, in order to prevent the illegal use of FBFA, 0.5% of pyrolysis fuel oil (PFO) and 0.5% of the residue of desulfurization unit (RDS) were added to FBFA, and two new blended fuels, PFO0.5 and RDS0.5, were thus produced. A preliminary HDDE test conducted by our laboratory showed that using the new blended fuels in automobiles, especially RDS0.5, lead to lower emissions of particulate matter (PM), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), and total BaP_{eq}, but slightly higher fuel consumption and emissions of smoke and nitrogen oxides. These results imply that using RDS0.5 could not only reduce the illegal use of FBFA, but also reduce the emission of pollutants. However, there has been no research that investigates whether using the two new blended fuels is actually feasible for small fishing boats, and whether there are any new or additional emissions. With regard to the fuels used and the size and horsepower of the engines, there are great differences between marine vessels (such as fishing boats) and land vehicles (such as TDVs). Therefore, the emission control requirements for road vehicles are not suitable for ships, and more appropriate control strategies and air pollution control devices must thus be developed to effectively reduce air pollution from ships (Hirata, 1995). As mentioned previously, the HDDE tests showed that using RDS0.5 could reduce the emissions of PM, CO, and total BaP_{eq}. In order to ascertain whether the blended fuels will have the same positive influences on the engine performance and pollution emissions in the HDDE test mentioned above, it is necessary to test the blended fuels using real fishing boats.

There are several regulations to reduce the air pollution from ships, including: (1) emission standards for nitrogen oxides in accordance with the power output of HDDE, and the required installation of exhaust gas cleaning systems to reduce NO_x emissions; (2) limits on the sulfur content in fuel oil to reduce SO_x emissions, and requirements for exhaust gas cleaning systems; (3) installation of vapor collection systems to reduce the emissions of volatile organic compounds (VOCs); (4) use of shipboard incinerators; and (5) restricted use of CFC refrigerants, Halon, and other ozone-depleting substances (Lin and Lin, 2006). However, these regulations only apply to ships which sail internationally and berth in commercial ports, but not to small fishing craft which operate along coastlines.

In this study, the two new blended fuels (PFO0.5 and RDS0.5) and FBFA were tested in three small fishing craft. The fuels' properties, consumption, regulated pollutants (CO₂, CO, NO_x, and PM), PAH concentrations and toxicity (BaP_{eq}) were analyzed. Based on these results, the engine performances and pollutant emissions were discussed and a suitable alternative to FBFA was recommended.

2. Materials and methods

2.1. Test fuels

There were four test fuels in this study: (1) premium diesel fuel (PDF), (2) fishing boat fuel A (FBFA), (3) FBFA blended with 0.5% (v/v)

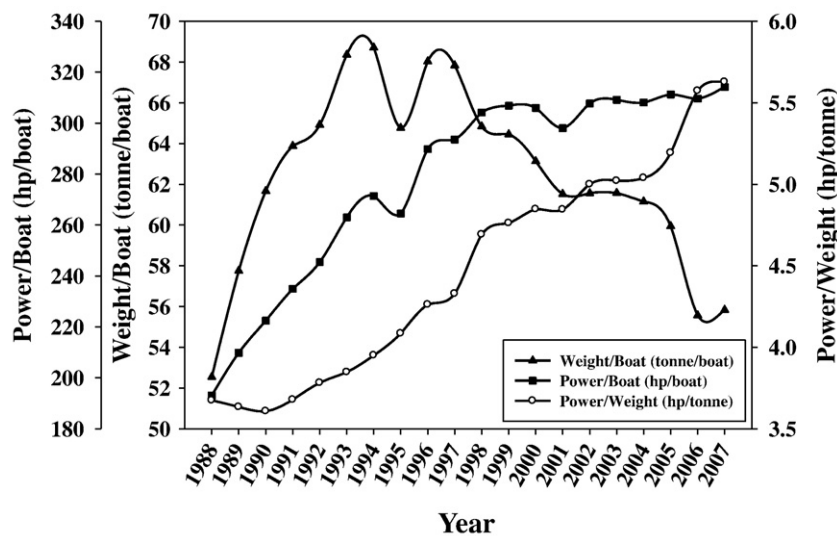


Fig. 1. Average weight, power of fishing boats and output power per tonne from 1988 to 2007 in Taiwan (http://www.fa.gov.tw/chnn/statistics_publish/statistics/year_book/2007c/96tab5_1.xls).

pyrolysis fuel oil (PFO0.5), and (4) FBFA blended with 0.5% (v/v) residue of desulfurization unit (RDS0.5). Both PDF and FBFA were produced by the Chinese Petroleum Corporation (CPC). PFO is a byproduct from polymerization in the naphtha cracking process. RDS is a residue produced in atmospheric distillation and desulfurization units in the oil refinery process. In order to prepare sufficient and accurate amounts of PFO0.5 and RDS0.5, a 20 L container was first quantitatively determined using a 1 L flask. Based on a similar procedure, 200 L barrel was then determined using the 20 L container. One liter of neat PFO or RDS was added into this 200 L barrel which already had been filled with approximately 190 L FBFA. This barrel was then eventually filled to 200 L with FBFA, thus producing PFO0.5 and RDS0.5. Stirring was conducted with an 850 rpm cement mixer for 10 min each barrel. The test fuels were first analyzed by the standard methods according to the American Society for Testing and Materials (ASTM), and their properties and contents are shown in Table 1.

Based on a comprehensive search of the Internet and related databases, there has been no research on using PFO and RDS as additives for FBFA. The main purpose of this study was thus to add these economical and widely available additives to FBFA, with the aim of producing diesel fuels that are inappropriate for diesel vehicles. Specifically, it is hoped that adding these substances to FBFA will increase the viscosity and reduce the heating value of the blended fuel. This will thus increase the fuel consumption and reduce the illegal use of FBFA.

2.2. Fishing boats and test processes

In this study, three small fishing boats were tested with three different fishing boat fuels, and each boat (i.e. A, B, and C) is described in Table 2. Each boat was first sailed from Kaohsiung harbor to the coastal fishing ground (State 1, in Table 3) without controlled engine loadings. State 2 in Table 3 shows the engine condition of each boat during sampling while the engines operated at 75% of full loading. Generally, the brake specific fuel consumption (BSFC) curve of a diesel engine exhibits one minimum BSFC at 70–80% engine load (Raheman and Ghadge, 2007; http://www.wartsila.com/Wartsila/global/docs/en/ship_power/media_publications/technical_papers/sulzer/fuel_saving.pdf). Thus, this interval of engine load is usually employed by fishing boats for sailing. Additionally, fuel consumption and concentration of the pollutants emitted are both higher when such boats are operated at higher horsepower output (higher engine load), which aids both measurement and identification. However, if fishing boats operate at full engine load they may suffer from unstable engine operation. Consequently, to simulate real sailing conditions in the present study, 75% engine load was specified in the fishing boat test processes.

After sampling, the test ships were sailed back to Kaohsiung harbor as State 3. Several engine parameters, such as fuel consumption rates and output horsepower, were recorded while the loadings and rotation speeds of the boat engine were maintained during the sampling time. Because of the different weights of each boat, the standard fuel consumption ($L h^{-1}$) would be affected by different

Table 1

Properties and contents of FBFA, PFO, RDS, PFO0.5 and RDS0.5.

Parameters	FBFA	PFO	RDS	PFO0.5	RDS0.5	Regulatory standard
Viscosity, at 40 °C cSt	4.078	5.351	7.863	4.136	4.674	ASTM D445
Density, at 15 °C g mL ⁻¹	0.8703	0.8838	0.8633	0.8700	0.8716	ASTM D4052
Flash point, °C	88	80	81	82	83	ASTM D93
Water and sediment, vol.%	0.005	6.005	4.005	0.035	0.025	ASTM D2709
Sulfur, ppm _w	5600	23,780	180	5050	4720	ASTM D5453
Ash and suspended solid, wt.%	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ASTM D482
Pour point, °C	-3	9	3	-3	-12	ASTM D97
Cetane index	46.4	52.3	50.4	46.4	46.4	ASTM D976
Aromatic content, vol.%	37.0	63.1	59.0	41.1	40.2	ASTM D6591
Heating value (net calorific), cal g ⁻¹	10,111	9963	10,062	10,074	10,088	ASTM WK15564
Distillation point T90, °C	353.8	405.2	377.4	352.2	351.8	ASTM D86

Table 2
Specification of three fishing boats.

	Boat A	Boat B	Boat C
Length	10.3 m	12.1 m	13.2 m
Weight	18.5 tonne	4.8 tonne	6.2 tonne
Engines	280 bhp, 1500 rpm	190 bhp, 2000 rpm	180 bhp, 1600 rpm

levels of friction, and this would cause some errors. Thus, the fuel consumption was defined as the amount of fuel consumed by an engine per output horsepower (L bhp⁻¹). The practical output horsepower of each engine was calculated from the rotation speeds of the engine, which were measured with a torsion meter at 75% of full output power (found in each engine booklet). The fuel inlets did not have any pretreatment devices, and thus there might be several abnormal operating conditions, such as an unstable fuel supply, high exhaust gas temperature, abnormal noises, and abnormal vibrations. The abnormal performances were directly observed and considered as signs of fuel unsuitability.

2.3. Sample collection and analysis

2.3.1. Regulated pollutant emissions

In this study, IMR 2800 was employed to simultaneously examine CO, CO₂, NO, NO₂, and O₂ in exhausts from fishing boats. The limited space and the unstable status of sampling when the small fishing boats are sailing should be considered. In order to reduce the inaccuracies caused by time variations and to measure the emissions of multiple pollutants at the same time, a small scale measuring instrument (such as IMR) is an appropriate choice. Specifically, CO₂ and CO were analyzed with a non-dispersive infrared (NDIR) analyzer, while NO_x was measured with an electro-chemical detector (ECD), which has a measurement range between 0 and 500 ppm with an accuracy of ± 20 to 20 ppm. The relative standard deviation (RSD) was less than 2% for CO₂, CO, and NO_x. An automatic stack sampler (AST) was used to harvest particulate matter (PM) on two silicon glass filters. The PM mass on each filter was determined gravimetrically by the difference in mass before and after each test using an electronic analytical microbalance (Sartorius ME 5-F) with an accuracy of 0.01 mg.

2.3.2. PAH sampling

In this study, sampling and analyses of PAHs were conducted according to the method promoted by the National Institute of Environmental Analysis (NIEA) in Taiwan. This method, NIEA A730.70C, employs a gas chromatograph/mass spectrometer to examine the PAHs in the flue gases.

PAH samples of both the particulate- and gas-phase were collected by using a PAH sampling system. Particulate-phase PAHs were collected on a glass-fiber filter, which was placed in an oven at 450 °C for 8 h before sampling to burn off all organic compounds that might be interferences. The cleaned filters were then stored in a desiccator for at least 8 h to reach the humidity equilibrium before weighing. After sampling, the filters were put into the desiccator again for another 8 h to remove moisture, and were then weighed again for the net mass of particles. Gas-phase PAHs were collected in three-stage glass cartridges, which were packed with 5.0 cm of XAD-16 resin sandwiched between two 2.5 cm polyurethane foam (PUF)

plugs. Silicone glue was used to seal and hold these two PUF pieces to prevent resin from leaking out during the sampling and extraction processes. After 8 h of adherence, the new PUF/resin cartridges were extracted in a Soxhlet extractor for 24 h each with methanol, dichloromethane, and finally *n*-hexane for a total of three days, and then the PUF/resin cartridges were placed in a vacuum oven at 60 °C for 2 h to dry and to remove the residual solvent. After drying, each PUF/resin cartridge was individually wrapped in hexane-washed aluminum foil, stored in a refrigerator at 4 °C, and transported in clean screw-capped jars with Teflon cap liners before sampling. Each glass-fiber filter was transported to and from the field in a glass box, which was also wrapped in aluminum foil.

2.3.3. PAH analysis

After sampling, each collected sample (including particulate and gaseous PAH samples) was extracted in a Soxhlet extractor with a mixed solvent for 24 h. The volume ratio of *n*-hexane/dichloromethane was 1/1, and the total solvent volumes were 250 mL and 700 mL for particulate and gaseous samples, respectively. The extract was then concentrated by purging with ultra-pure nitrogen to 2 mL for the subsequent cleanup process. The eluents from the cleanup process were reconcentrated again to exactly 1 mL. The PAH contents were determined with a gas chromatograph (GC) (HP 6890N; Hewlett-Packard, Wilmington, DE, USA), a mass spectrometer detector (MSD) (HP 5972), and a computer workstation (Aspire C500; Acer, Taipei, Taiwan). This GC/MSD was equipped with a capillary column (HP Ultra 2, 50 m × 0.32 mm × 0.17 mm) and an automatic sampler (HP-7673A), and operated under the following conditions: injection volume of 1 µL; splitless injection at 310 °C; ion source temperature at 310 °C; oven temperature from 50 to 100 °C at 20 °C min⁻¹, 100 to 290 °C at 3 °C min⁻¹, and held at 290 °C for 40 min. The masses of primary and secondary PAH ions were determined by using the scan mode for pure PAH standards. The PAHs were quantified by using the selective ion monitoring (SIM) mode. PAH homologues were classified by the number of rings, as follows: naphthalene (Nap) for two rings; acenaphthylene (AcPy), acenaphthene (Acp), fluorine (Flu), phenanthrene (PA), and anthracene (Ant) for three rings; fluoranthene (FL), pyrene (Pyr), benzo[a]anthracene (BaA), and chrysene (CHR) for four rings; cyclopenta[*c,d*]pyrene (CYC), benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF), benzo[*e*]pyrene (BeP), benzo[*a*]pyrene (B[a]P), perylene (PER), dibenzo[*a,h*]anthracene (DBA), benzo[*b*]chrycene (BbC) for five rings; indeno[1,2,3-*cd*]pyrene (IND), benzo[*ghi*]perylene (Bghip) for six rings; and coronene (COR) for seven rings. According to the molecular weight, these 21 individual PAHs were divided into three categories: low molecular weights (LM-PAHs containing two- and three-ring PAHs); middle molecular weights (MM-PAHs containing four-ring PAHs); and high molecular weights (HM-PAHs containing five- to seven-ring PAHs). The total-PAH data for the heavy-duty diesel engine (HDDE) exhaust were the summation of the 21 individual PAHs. The GC/MSD was calibrated with a diluted standard solution of 16 PAH compounds (PAH mixture-610M; Supelco, Bellefonte, PA, USA), plus five additional individual PAHs obtained from Merck (Darmstadt, Germany). Analysis of serial dilutions of PAH standards showed that the detection limit (DL) for GC/MSD was between 25 and 321 pg for the 21 PAH compounds. The limit of quantification (LOQ) was defined as DL divided by the sampling volume or sampling time. The LOQ for individual PAHs was between 22 and 284 pg m⁻³, while values for the sampling time were between 75 and 963 pg h⁻¹. Ten consecutive injections of a PAH 610-M standard yielded an average relative standard deviation of GC/MSD integration area of 6.86%, within a range of 4.29–9.67%. Following the same experimental procedures used for sample treatment, recovery efficiencies were determined by processing a solution containing known PAH concentrations. The results showed that the recovery efficiencies for the 21 PAH compounds ranged from 0.799 to 0.901,

Table 3
Processes of fishing boat test.

State	Location	Engine load	Samples
1	Port to fishing ground	Not controlled	Not collected
2	Fishing ground	75% of full load	Collected
3	Fishing ground to port	Not controlled	Not collected

with an average value of 0.842. Analyses of field blanks, including aluminum foil, glass-fiber filters, and PUF/XAD-16 cartridges, revealed no significant contamination (GC/MSD integrated area < detection limit). The total PAH_s adsorbed in the third stage cartridge was less than 3% of the total amount contained in all three stages, which means that the breakthrough effect can be ignored.

3. Results and discussion

Many studies have suggested that pollutant emissions from HDDE are directly related to some properties and indexes of diesel fuel, such as the cetane index, dynamic viscosity, density, distillation temperature at 90% (T90), total aromatic contents, sulfur content, and operation parameters (Westerholm and Li, 1994; Collier et al., 1995; Sjögren et al., 1995; Hori et al., 1997; Yang et al., 1998; Mi et al., 2000). In other words, fuel properties and contents would influence the emission of pollutants when a given type of HDDE is operated in controlled conditions. In an HDDE dynamometer test, mean sulfur and aromatic contents in FBFA were 43.0 and 1.04 times higher than those of premium diesel fuel (PDF), respectively; while the emission factors of total PAHs and total Ba_{Peq} found by using FBFA were 3.41 and 5.82 times higher than those found by using PDF, respectively (Lin et al., 2006). The properties and several specific contents of the test fuels (FBFA, PFO0.5, RDS0.5) are shown as follows.

3.1. Appearance and properties of test fuels

In order to avoid the illegal use of FBFA, improving the distinction among FBFA, PDF and the two blended fuels is an important aim. The additives used in this study (PFO, RDS) are almost black in color, and when added into FBFA, the appearance of the resulting fuels eventually turns dark brown and dark blue. Although the resulting fuels are still hard to distinguish by appearance in barrels, they are obviously different in color when placed in test tubes, due to the shorter optical path. As shown in Fig. 2, the order of the four fuels from dark to light is RDS0.5, PFO0.5, FBFA, and PDF. With the significant differences in appearance between PDF and the two new blended fuels (PFO0.5 and RDS0.5), misuse or illegal use could be readily detected by visual inspection.

Generally, fuels with high viscosity are hard to nebulize, and tend to cause high carbon deposit formation, injector coking, piston ring sticking and lubrication oil dilution and oil degradation (Avinash, 2007). As illustrated in Table 1, PFO and RDS, with viscosities of 5.351 and 7.863 cSt, were added into FBFA (4.078 cSt) and raised the viscosities to 4.136 (PFO0.5) and 4.674 (RDS0.5), with RDS0.5 being about 14.5% (0.596/4.078) higher. This result implies that adding a viscous agent into FBFA is detrimental to engine performance.

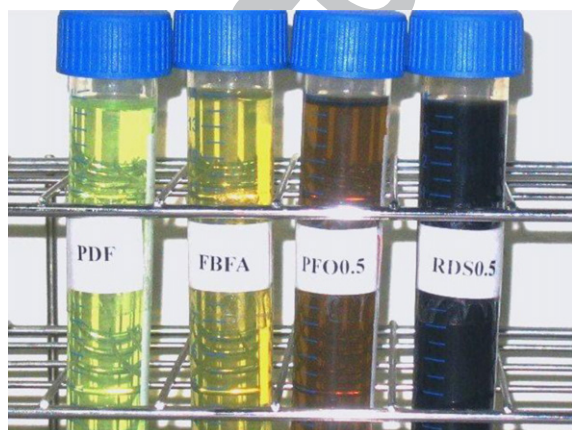


Fig. 2. Appearances of PDF, FBFA, PFO0.5, and RDS0.5.

T90 is defined as the temperature at which 90% of a fuel is distilled. This means that the higher T90 is, the lower evaporation potential the fuel has before combustion. Based on this definition, the effect on engine performance of higher T90 seems to be the same as that of kinetic viscosity. Although the T90s of PFO and RDS (405.2 and 377.4 °C) are obviously higher than that of FBFA (353.8 °C), those of PFO0.5 and RDS0.5 (352.2 and 351.8 °C) were still very close to that of FBFA, as shown in Table 1. The probable reason may be the limited amount of additives, which did not cause significant variation of T90. However, the T90s for these three fuels were all higher than that of PDF (327.2 °C).

The cetane index is generally used to indicate the flammability of diesel fuel. Table 1 shows that three fishing boat fuels have similar cetane index values, about 46.4, meaning that there are no different effects with regard to the combustion caused by the flammability of fuels. With regard to the influence of the additives on FBFA, the cetane index had the same effect as T90. This means that addition of additives with higher cetane indexes did not significantly alter the indexes of the blended fuels.

When two fuels with significantly different densities are mixed together, the blended fuels will be more easily stratified, and this leads to its unstable combustion. The densities of PFO (0.8838 g mL⁻¹) and RDS (0.8633 g mL⁻¹) are very close to that of FBFA (0.8703 g mL⁻¹), indicating that the blended fuels will not be stratified, and instead be well homogenized. It could thus be expected that these fuels will provide more stable combustion.

The pour point of a liquid is the lowest temperature at which it will pour or flow under prescribed conditions, and it is a rough indication of the lowest temperature at which oil is readily pumpable. As illustrated in Table 1, the pour point did not change (-3 to -3 °C) after 0.5% of PFO was added into FBFA, while there was a significant reduction (-3 to -12 °C) after 0.5% of RDS was added. These results imply that the ease of flow of FBFA did not vary with the addition of 0.5% of PFO, but that the flow became much easier with the addition of RDS.

The amount of water and sediment also increased after adding PFO and RDS, as shown in Table 1. They will also have harmful effects on diesel engines, as water may result in inhomogeneous and varied fuel injection, and the fuel filter will be stuck due to the accumulated sediment. These negative effects will greatly help to reduce the illegal use of FBFA.

However, as shown in Table 1, the flash point of FBFA (88 °C) is higher than that of PFO0.5 (82 °C) or RDS0.5 (83 °C). This is because additives with lower flash points (80 and 81 °C) were added into FBFA. This result implies that the new blended fuels will be more easily ignited and better combusted than FBFA, as the flash point of a flammable liquid is the lowest temperature at which it can form an ignitable mixture in air. With regard to the positive effect on engine performance, this result conflicts with the negative effects of increased viscosity.

Due to the lower heating values of the neat PFO and RDS (9963 and 10,062 cal g⁻¹) in comparison to FBFA (10,111 cal g⁻¹), the heating values of the two blended fuels (10,074 and 10,088 cal g⁻¹) were lower than that of FBFA after PFO and RDS were added (Table 1). This result closely resembles that of Hsieh et al. (2002).

Fuel consumption is defined as the fuel quantity consumed per output energy, and is expressed as follows: fuel volume consumed/(output horse power × duration), where output horse power is 75% of full engine load. Fuel consumptions using FBFA, PFO0.5 and RDS0.5 were thus determined according to this definition. The heating value is usually considered the major factor that affects the fuel consumption, and a higher heating value results in lower fuel consumption. In the present study, the order of the heating value was as follows: FBFA > RDS0.5 > PFO0.5 (Table 1). The estimated fuel consumptions of FBFA, PFO0.5, and RDS0.5 were thus 5.63, 6.89, and 6.89 L bhp⁻¹ h⁻¹ (liters per brake horse power per hour), respectively. This result

agrees with the description given above. The reason why these two additives (0.5% PFO and RDS) made such significant differences in fuel consumption may be partially attributed to the measurement of fuel volume consumed, as the output horse power employed was constant on one fishing boat and measurement errors from the duration were limited. However, while the fuel consumption is not influenced by one specific factor (e.g. heating value), it may be by the combined effects of the various factors analyzed in this study. Consequently, kinetic viscosity, T90, cetane index, flash point, and heating value are all considered factors that might influence engine performance and emission of air pollutants.

3.2. Sulfur and total aromatic contents

Basically, sulfur and aromatic content could enhance the lubrication of the diesel engines, indicating that they will positively influence engine performance. Nevertheless, sulfur content could result in the emission of SO_x and PM, while aromatic content could increase PAH emission. Notably, the sulfur content of RDS0.5 (4720 μppm_w) is significantly lower than that of FBFA (5600 μppm_w) after neat RDS (180 μppm_w) was added (Table 1). The sulfur content of RDS0.5 is expected to decrease after a relatively low amount of sulfur (180 μppm_w) was added. The variations of the experimental results may be partly due to experimental uncertainties. PFO and RDS, with aromatic contents of 63 and 59%, were added into FBFA and raised the aromatic contents to 41.1 (PFO0.5) and 40.2 (RDS0.5), as expected in advance.

As shown in Table 1, even though the sulfur contents of PFO0.5 and RDS0.5 (5050 and 4720 μppm_w) are much higher than that of PDF (50 μppm_w) regulated at the beginning in 2007 in Taiwan (http://en.wikipedia.org/wiki/Ultra-low_sulfur_diesel#Taiwan), they are 9.82% (550/5600) and 15.7% (880/5600) lower than FBFA (5600 μppm_w), respectively. In addition, the total aromatic contents of PFO0.5, and RDS0.5 were about 11.1% (4.1/37) and 8.65% (3.2/37) higher than that of FBFA. These results imply that PFO0.5 and RDS0.5 might cause lower PM and higher PAH emissions from exhaust gas than FBFA does.

3.3. Regulated pollutant emissions

In order to evaluate the impact of exhaust emission from the two new blended fuels, it is necessary to compare the emissions of FBFA, PFO0.5, and RDS0.5.

3.3.1. Gaseous pollutant emissions

In this study, three regulated gaseous pollutants were considered, namely: carbon dioxide (CO_2), carbon monoxide (CO), and nitrous oxides (NO_x). CO_2 is considered one of the products of complete combustion, and CO_2 emission from ships is independent of engine output power and directly related to the carbon contents of the fuel (Carlton et al., 1995). The mean CO_2 emission factors of three boats using FBFA, PFO0.5, and RDS0.5 were 312, 327, and 338 $\text{g bhp}^{-1} \text{h}^{-1}$ (grams per brake horse power per hour), respectively (Fig. 3a). The higher CO_2 emission factors (EF_{CO_2}) of PFO0.5 and RDS0.5 might result from the high carbon-containing additives (PFO and RDS) in the two new blended fuels. Moreover, Fig. 3a also shows that boat A, which had the largest output power (Table 2), had the highest CO_2 emission. In addition, CO is not only a regulated pollutant, but also the most common indicator to determine the combustion condition. Fig. 3b shows the mean CO emission factors (EF_{CO}) of each test fuel from three identical tests on three fishing boats. Unlike CO_2 emissions, CO emissions from ships are related to engine output power, with higher emissions resulting from engines with less power. Test boat A thus had a lower EF_{CO} value than boats B and C, while it had the best combustion result with regard to CO_2 emission. The relative concentrations of CO_2 and CO are usually used to evaluate whether the combustion is complete, because the carbon content in the fuel is

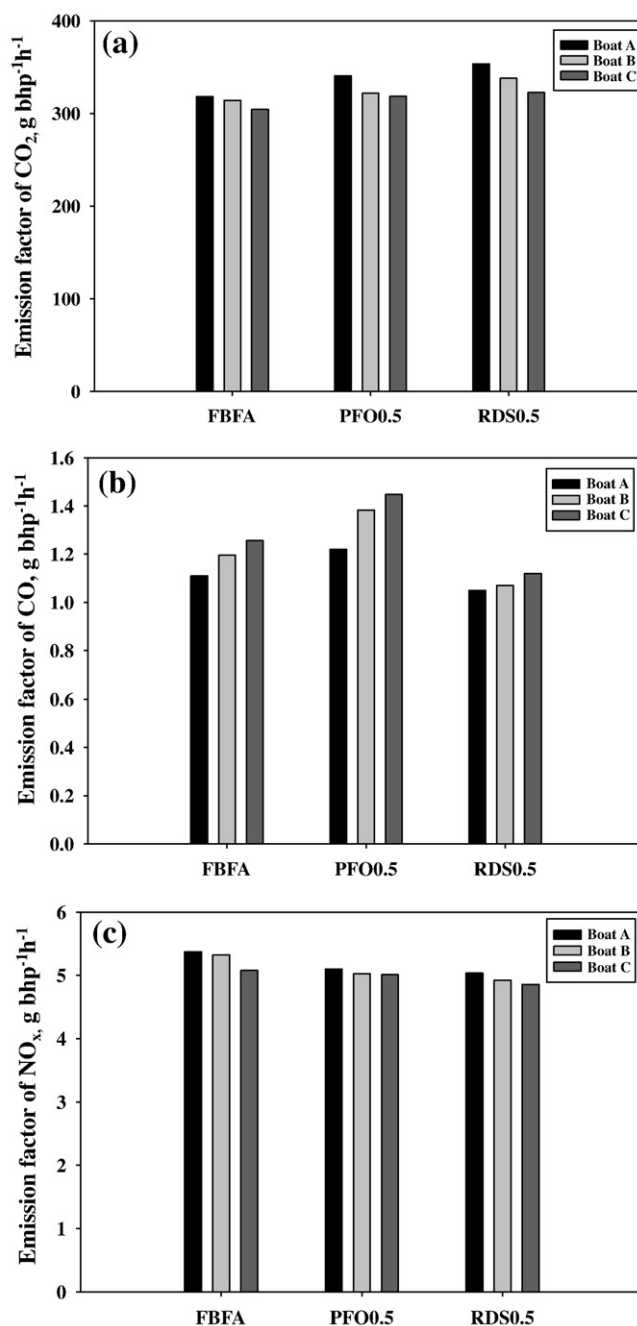


Fig. 3. Emission factors of CO_2 , CO, and NO_x using FBFA, PFO0.5, and RDS0.5.

constant. At the same combustion conditions (such as the same boat, fuel, and output power), complete combustion will tend to produce more CO_2 , and more CO will be formed during incomplete combustion. In addition, RDS0.5 has the lowest mean of EF_{CO} , and this is probably due to the competition between the highest viscosity and the lower flash point that it has.

Notably, emission of NO_x from ships would increase hydroxyl radical (OH) and tropospheric ozone (O_3) over their background levels, thus raising the oxidizing potential in the troposphere, decreasing the atmospheric lifetimes of reactive greenhouse gases (GHGs), and increasing aerosol production rates (Lawrence and Crutzen, 1999). As illustrated in Fig. 3c, FBFA has a higher mean EF_{NO_x} (5.36 $\text{g bhp}^{-1} \text{h}^{-1}$) than the other two fuels (5.06 of PFO0.5 and 4.96 of RDS0.5) used on the three test boats. According to the combustion mechanisms, high NO_x emission is usually associated with high peak temperature in combustion. In addition, because more powerful

490 combustion systems usually operate at higher temperatures, so the
 491 emission of NO_x is positively related to the power of the ship engine.
 492 Fig. 3c shows that boat A, with the highest engine power (Table 2), had
 493 the highest EF_{NO_x} for the three fuels. In addition, the higher the heating
 494 value of a fuel, the higher the adiabatic flame temperature it produced.
 495 Since FBFA had the highest heating value of $10,111 \text{ kcal kg}^{-1}$ (Table 1),
 496 it would produce the highest flame temperature and thus the highest
 497 emission of NO_x , as shown in Fig. 3c.

498 3.3.2. PM emission

499 In many studies, PM has been indicated to be harmful to the
 500 human respiratory system, especially in the form of fine particles. As
 501 illustrated in Fig. 4a, the average EF_{PMs} of three fishing boats using
 502 FBFA, PFO0.5, and RDS0.5 were 0.386, 0.370, and 0.247 $\text{g bhp}^{-1} \text{ h}^{-1}$,
 503 respectively, and these EF_{PMs} closely resemble the results of Lin et al.
 504 (2006) from the HDDE dynamometer test ($0.296 \text{ g bhp}^{-1} \text{ h}^{-1}$ of
 505 FBFA). The EF_{PM} of FBFA is 4.1 ($0.386/0.094$) times higher than that of
 506 PDF used in automobiles ($0.094 \text{ g bhp}^{-1} \text{ h}^{-1}$). This means that the
 507 unit ship PM emission contributes much more to atmospheric
 508 pollution than that of automobiles. Moreover, adding 0.5% RDS into
 509 FBFA on average decreased the PM emission by approximately 36%
 510 ($0.139/0.386$) due to the average EF_{PMs} using FBFA and RDS0.5 which
 511 were 0.386 and 0.247 $\text{g bhp}^{-1} \text{ h}^{-1}$, while PFO reduced by only 4.15%
 512 ($0.016/0.386$). There are several formation mechanisms of PM,
 513 including: (1) accumulation/condensation mode (10–100 nm), (2)
 514 nucleation mode (0.1–1 μm), and (3) coarse mode (1–10 μm). The
 515 first mode is the major pathway to form fine particles in diesel engines
 516 (Maricq et al., 2002; Vogt et al., 2003), and can occur with incomplete
 517 combustion. Lyyräinen et al. (2002) have reported that the presence of
 518 sulfur in diesel fuels leads to the formation of sulfuric acid in the
 519 exhaust gases at a temperature that is lower than that in the engine.

The sulfuric acid could then form PM by accumulation or condensation
 on the soot and metallic ash (Lyyräinen et al., 2002). In addition,
 Scheer et al. (2005) indicates that the particles which are formed by
 the nucleation mode are completely volatile, and consist mainly of
 sulfate (Scheer et al., 2005). Compared with that in FBFA, the lowest
 (~15.7%) sulfur content in RDS0.5 thus causes the lowest nucleation
 mode (i.e., a low accumulation mode) of PM formation. Fig. 4b shows
 that the emission factor based on unit fuel consumption ($\text{EF}_{\text{PM-fuel}}$)
 has the same trend with that based on unit energy output ($\text{EF}_{\text{PM-bhp h}}$),
 and it is also supported by the lowest CO emission as proof of more
 complete combustion. In addition, the different output power of all
 three boats might affect the PM emissions. Obviously, the higher
 powered fishing boat engine causes lower PM emissions (as shown in
 Fig. 4), which is also shown by the same trends of CO emissions in the
 three test boats (Fig. 3b). Generally speaking, more complete
 combustion causes low PM but higher NO_x emissions. Nevertheless,
 in this study reduction of the heating value of RDS0.5 (Table 1)
 resulted in the lower peak temperature during combustion. This could
 inhibit the formation of thermal NO_x , and eventually decrease the
 emission of NO_x .

As illustrated in Fig. 1, the power of fishing boats has obviously
 increased over time, from 1998 to 2007. The variation of pollutant
 emissions needs to be monitored and further controlled, particularly
 when the pollutant emissions are positively related to the power of
 such boats. Moreover, when the power of fishing boats increases
 significantly, the extra pollutant emissions will draw much attention.
 Using the same fuels, boats A and C with rather different output
 powers (280 and 180 bhp as listed in Table 2) exhibited significantly
 different CO, PM, CO_2 , and NO_x emissions (as shown in Figs. 3 and 4).
 In other words, the fishing boats with higher power will cause lower
 CO and PM emissions, while the emissions of CO_2 and NO_x increased.

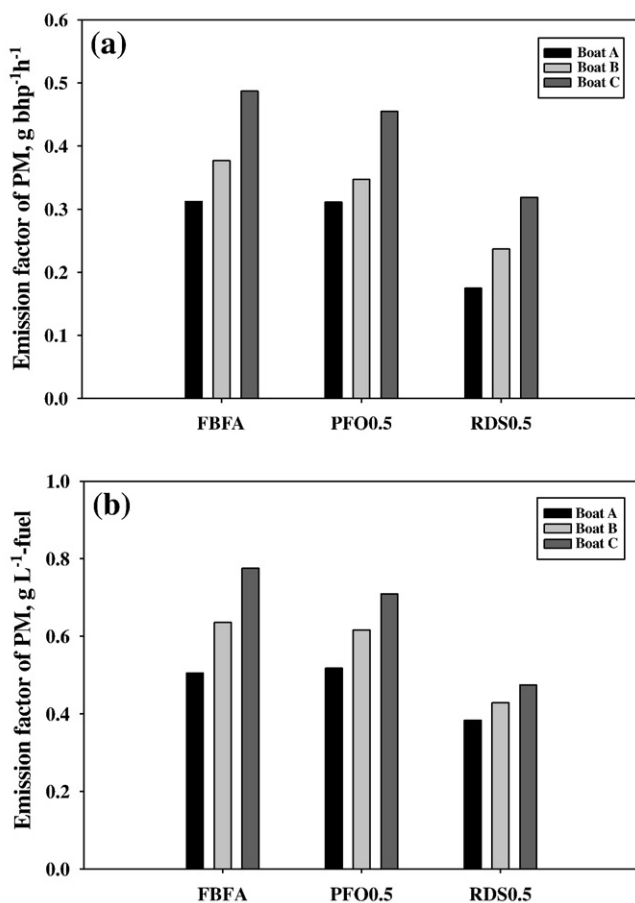


Fig. 4. Emission factors of PM using FBFA, PFO0.5, and RDS0.5.

3.4. PAH emissions

Table 4 lists the total-PAH concentrations (gas- + particulate-phase) in exhausts from three fishing boats using three test fuels (FBFA, PFO0.5, and RDS0.5). Firstly, we found that the two blended fuels (PFO0.5 and RDS0.5) had higher total-PAH concentrations than FBFA. The total-PAH concentrations of PFO0.5 were 1.21 (4193/3474), 1.18 (4223/3573), and 1.24 (4595/3700) times higher than those of FBFA for boats A, B, and C, respectively. The total-PAH concentrations of RDS0.5 were 1.10 (3814/3474), 1.09 (3895/3573), and 1.10 (4054/3700) times higher. The ratios of total-PAH concentration between the two blended fuels and FBFA closely resembled those of total aromatic content. This result indicates that the aromatic content of the fuels is the major factor that directly influences the total-PAH concentration in exhaust gas. Notably, this result might be due to one of the major PAH forming mechanisms, i.e. that they are directly emitted from unburned aromatic-containing fuels (Williams et al., 1989). Additionally, Table 4 also shows that total-PAH concentrations for each fuel increased with decreasing output power of the test boats. The reasonable explanation for this could be that less power results in incomplete combustion of PAHs.

Regarding the estimated PAH toxicity concentration (gas- + particulate-phase), total BaP_{eq} in the exhaust from three test boats using PFO0.5 was approximately 23.5% (3.5/14.9), 2.79% (0.5/17.9), and 2.58% (0.5/19.4) higher than those using FBFA. Nevertheless, with using RDS0.5, they were totally different, at 27.5% (4.1/14.9), 19.6% (3.5/17.9), and 8.25% (1.6/19.4) lower. Based on the PAH forming mechanism of unburned aromatic-containing hydrocarbons, since the total aromatic contents of PFO0.5 and RDS0.5 are higher than that of FBFA, the total BaP_{eq} should exhibit the same trend as the aromatics content, and also be the same as for the total-PAH emissions. As can be seen in Table 4, the sum of the concentrations of the two most toxic PAH compounds ($\text{BaP} + \text{DBA}$) using RDS0.5 in each boat was smaller than that from using FBFA and PFO0.5. This result can probably

Table 4
PAH concentrations and toxicity in exhaust from three fishing boats using FBFA, PFO0.5, and RDS0.5 ($\mu\text{g N m}^{-3}$).

PAHs	Boat A						Boat B						Boat C					
	FBFA (n=4)		PFO0.5 (n=4)		RDS0.5 (n=4)		FBFA (n=4)		PFO0.5 (n=4)		RDS0.5 (n=4)		FBFA (n=4)		PFO0.5 (n=4)		RDS0.5 (n=4)	
	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
Nap	2953	14.3	3155	27	2845	13.5	2776	15.5	3200	20.4	2965	18.4	3266	18.3	3803	15.6	3377	24.3
AcPy	29.0	15.2	81.5	25.2	60.1	18.7	30.9	24.5	114	23.6	61.6	25.6	26.7	22.7	67.4	23.1	24.8	26.4
Acp	7.56	22.4	144	18.1	120	21.5	109	18.4	91.8	25.4	128	23.1	45.4	23.4	86.6	27.3	81.9	25.6
Flu	56.9	35.4	371	29.7	224	21.4	183	10.1	332	27.8	198	18.3	67.3	20.6	112.5	25.6	127	22.6
PA	238	10.1	274	20.7	366	13.5	303	17.8	299	24.3	377	17.1	183	22.1	382	21.5	349	21.0
Ant	26.0	20.7	14.1	18.4	31.3	14.6	20.5	16.9	33.4	28.3	29.5	22.5	10.4	21.3	31.0	28.6	10.3	25.8
FL	35.8	26.8	29.3	21.3	38.4	27.3	30.7	28.7	31.4	15.4	21.5	17.8	11.4	23.5	25.3	24.7	15.7	26.2
Pyr	62.0	30.1	22.7	22.8	72.3	22.1	41.8	27.3	41.0	21.4	54.7	10.1	27.0	17.5	26.1	18.7	26.0	17.6
CHR	8.78	32.6	37.3	17.8	10.3	26.8	5.68	32.4	5.27	17.1	3.03	15.5	3.40	26.4	4.81	22.7	3.24	28.4
B(a)A	6.37	25.1	3.68	16.9	7.28	21.5	5.02	22.3	5.57	26.2	4.28	20.8	2.37	21.6	3.43	21.9	2.01	18.5
CYC	9.83	24.3	7.38	15.4	6.92	18.3	14.2	26.8	15.5	10.1	11.5	21.4	2.66	20.5	7.20	25.1	2.82	20.9
B(b)F	5.23	11.3	6.35	21.4	5.54	17.1	4.60	21.5	4.45	24.4	4.42	13.5	1.69	18.7	3.22	24.7	1.13	21.9
B(k)F	2.44	15.5	6.83	35.4	2.42	28.4	3.67	15.5	3.42	25.4	3.28	14.6	4.83	18.3	2.03	26.1	2.08	22.7
B(e)P	4.31	24.5	5.45	10.1	4.03	16.5	7.28	26.3	7.97	23.4	4.88	17.5	7.77	27.4	6.35	19.6	3.03	18.6
B(a)P	2.56	18.4	4.39	22.0	3.41	32.3	2.72	31.6	3.33	18.7	2.50	24.5	6.62	26.5	7.16	31.3	6.44	19.5
PER	5.43	26.2	5.74	33.6	5.00	20.7	7.29	28.4	7.99	19.2	5.90	27.1	5.22	29.5	7.13	23.5	3.95	26.3
IND	1.60	24.5	3.98	32.3	1.84	14.7	2.50	21.7	2.11	21.9	2.50	27.3	6.86	28.3	2.49	27.1	1.25	29.9
DBA	6.70	27.1	6.89	21.1	1.59	24.6	8.93	34.9	7.95	28.1	5.59	18.4	7.36	21.2	6.34	26.9	6.48	26.8
B(b)C	6.38	27.3	5.29	36.5	4.74	12.3	7.45	20.7	7.85	30.7	4.64	16.5	5.21	32.1	5.88	28.4	5.68	30.1
B(ghi)P	2.17	32.4	4.35	36.5	1.14	22.7	4.63	14.7	4.82	27.9	4.14	24.3	6.03	27.1	2.19	30.2	1.10	25.7
COR	3.80	22.3	3.92	20.9	3.79	30.4	3.91	24.6	3.17	26.5	3.37	25.6	3.15	25.5	3.28	27.9	3.13	24.3
LM-PAHs	3311	19.7	4039	23.1	3646	17.2	3422	17.2	4071	25.0	3759	20.8	3599	21.4	4482	23.6	3970	23.3
MM-PAHs	123	27.8	100	18.8	135	23.2	97.3	27.5	98.7	18.0	95.0	17.1	46.8	21.9	66.9	22.6	49.7	22.3
HM-PAHs	40.6	23.0	53.2	27.0	33.5	22.0	53.0	24.0	53.1	24.6	41.2	20.9	54.7	25.5	46.1	26.6	34.3	24.6
Total PAHs	3474	23.5	4193	23.0	3814	20.8	3573	22.9	4223	22.5	3895	19.6	3700	22.9	4595	24.3	4054	23.4
Total BaP _{eq}	14.9	21.60	18.4	26.70	10.8	25.30	17.9	24.3	18.4	22.4	14.4	20.1	19.4	21.5	19.9	26.6	17.8	25.9

explain why using RDS0.5 had a lower BaP_{eq} than using FBFA, while using PFO0.5 had a higher one perhaps because it had a relatively higher total-PAH concentration. Again, total BaP_{eq} was significantly influenced by the output power of the test boats, as the more output power the boat had, the less total BaP_{eq} that was produced (see Table 4).

In addition, the PAH homologue distributions of different test fuels are also shown in Table 4. The mean fractions of \sum LM-PAHs, \sum MM-PAHs, and \sum HM-PAHs in the total PAHs are slightly different among FBFA (96.1%, 2.51%, and 1.38%), PFO0.5 (96.8%, 2.06%, and 1.18%), and RDS0.5 (96.7%, 2.40%, and 0.93%). These results show that LM-PAHs are the major group in the total PAHs emitted from combustion, especially naphthalene (Nap). RDS0.5 had a much lower fraction of HM-PAHs (0.93%) than the other two fuels (1.38 and 1.18%), because RDS0.5 had a much lower concentration of PM, which is considered as an adsorbent of low volatile HM-PAHs. In addition, since the HM-PAH compounds have higher toxicity (BaP_{eq}), RDS0.5 with the lowest \sum HM-PAH fraction thus led to the lowest BaP_{eq}.

PAH emission factors ($\text{mg L}^{-1}\text{-fuel}$ or $\text{mg bhp}^{-1}\text{ h}^{-1}$) for both total PAHs and total BaP_{eq} (denoted EF_{total PAHs} and EF_{total BaP_{eq}}, respectively) were calculated in this study. As shown in Table 5, the EF_{total PAHs} and EF_{total BaP_{eq}} in $\text{mg L}^{-1}\text{-fuel}$ are in the order of PFO0.5 > RDS0.5 > FBFA and PFO0.5 > FBFA > RDS0.5, respectively. This total-PAH emission factor might be caused by the aromatic content of the fuels. In addition, the total-BaP_{eq} emission factor had the same trend as the \sum HMW-PAHs and BaP + DBA concentrations. A similar trend is found with another kind of emission factor based on output energy (bhp h), EF_{total PAHs} and

EF_{total BaP_{eq}}: PFO0.5 > RDS0.5 > FBFA and PFO0.5 > FBFA > RDS0.5. The above results indicate that in real ship HDDE operating cases, the order of the total mass of PAH emission per energy output depends on the aromatic contents in the fuel. However, PAHs with a higher molecular weight (HW-PAHs) are considered as having higher carcinogenic potencies, which explains why the highest EF_{total PAHs}, but not the critical EF_{total BaP_{eq}}, are found in RDS0.5. According to the above results, the more power the boat had, the less total BaP_{eq} was produced. While RDS0.5 had lower total BaP_{eq} than FBFA, the reduction fraction increased as the output power decreased, which means RDS0.5 is more suitable for high power HDDEs.

4. Conclusions

The results of this study's experiment showed that the appearance of the fuels obviously turned from light yellow into dark brown or dark blue after adding viscous agents into FBFA. This result makes it easier to visually distinguish the new fishing boat fuels (RDS0.5 and PFO0.5) from PDF, and thus could substantially reduce the illegal use of FBFA. In addition, by using RDS0.5 in the fishing boats, the CO and NO_x emission factors were significantly reduced while CO₂ emissions increased accordingly. Moreover, the PM emission factors ($\text{g bhp}^{-1}\text{ h}^{-1}$ and $\text{g L}^{-1}\text{-fuel}$) were significantly reduced by approximately 36% and 33%. Notably, the reduction of PM emission by using PFO0.5 is much less than that achieved by using RDS0.5. Fishing boats with higher output power (such as boat A) had lower CO and PM emissions. The lower heating values of the new blended fuels compared to FBFA caused the lower thermal NO_x emissions,

Table 5
Emission factors of PAHs in exhaust from three fishing boats using FBFA, PFO0.5, and RDS0.5.

	Boat A			Boat B			Boat C		
	FBFA	PFO0.5	RDS0.5	FBFA	PFO0.5	RDS0.5	FBFA	PFO0.5	RDS0.5
EF _{total PAHs} $\text{mg L}^{-1}\text{-fuel}$	54.3	80.4	77.8	37.7	54.3	57.3	42.4	64.5	41.0
EF _{total BaP_{eq}} $\text{mg L}^{-1}\text{-fuel}$	0.233	0.352	0.221	0.189	0.237	0.212	0.223	0.279	0.180
EF _{total PAHs} $\text{mg bhp}^{-1}\text{ h}^{-1}$	3.72	4.49	4.09	5.64	6.67	6.15	6.17	7.66	6.76
EF _{total BaP_{eq}} $\text{mg bhp}^{-1}\text{ h}^{-1}$	0.0160	0.0197	0.0116	0.0283	0.0290	0.0228	0.0323	0.0331	0.0297

636 and thus lowered the potential of the hydroxyl radical and ozone
 637 formation in the troposphere. Owing to the higher total aromatic contents
 638 in PFO0.5 and RDS0.5, total-PAH concentrations in the exhaust from
 639 fishing boats using PFO0.5 and RDS0.5 were slightly higher (1.2 and 1.1
 640 times) than from those using FBFA. Nevertheless, the estimated total-PAH
 641 toxicity (BaP_{eq}) from the three fishing boats using RDS0.5 were 27.5, 19.5,
 642 and 8.25% lower than from those using FBFA. As an alternative of FBFA,
 643 RDS0.5 is superior to PFO0.5, primarily because of the lower pollutant
 644 emissions. With ease to visually distinguish from PDF, RDS0.5 is suggested
 645 as an alternative fishing boat fuel, particularly as it could help lower the
 646 emissions of traditional pollutants (such as CO, NO_x, PM) and PAH toxicity.

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